Lesson EPSI-02-01 Download the pdf file

Course EPSI:
Essential Principles of Signal Integrity

With Eric Bogatin,
Signal Integrity Evangelist,
Teledyne LeCroy Front Range Signal Integrity Lab

- EPSI-02-10: recorded live, Dec 1, 2013
  - Differential pairs
  - A secret to immunize confusion about diff pairs
  - Don’t use Differential mode impedance
  - Differential pairs, differential signals and odd and even mode impedance

Lesson EPSI-02-10 Intro to Diff Pairs

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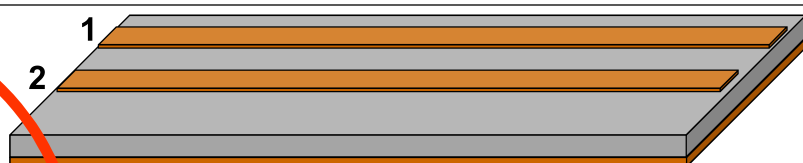
- Day 1
  - EPSI 1 Transmission Lines
  - EPSI 2 Differential Pairs and Lossy Lines
  - Lunch
  - EPSI 3 Reflections and Terminations
  - EPSI 4 Routing Topologies and Discontinuities
- Day 2
  - EPSI 5 Eliminating Ground Bounce
  - EPSI 6 Navigating Return Path Discontinuities
  - Lunch
  - EPSI 7 NEXT and FEXT Features
  - EPSI 8 PDN and EMI Design

A Secret to Minimize Confusion About Differential Impedance



Differential mode

Common mode

Think:

Differential signals

Common signals

Odd mode

Even mode

Lesson EPSI-02-20 Differential Signals

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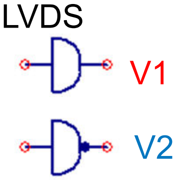
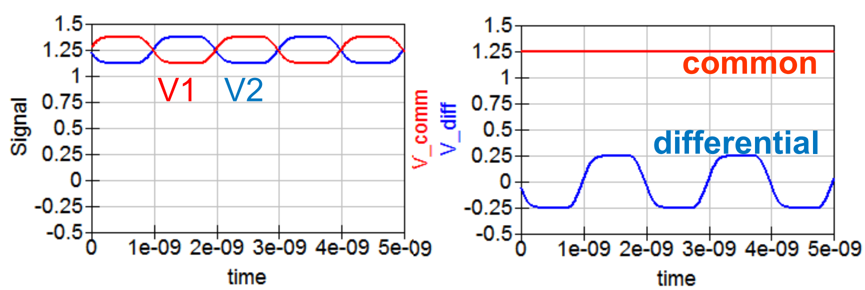
- EPSI-02-20: recorded live, Dec 1, 2013
  - Differential and common signals in LVDS drivers
  - Decomposing any signal into diff and common components
  - What is the impedance the differential signal sees
  - When microstrip traces are far apart what is the differential impedance

Differential and Common Refer to SIGNALS

LVDS

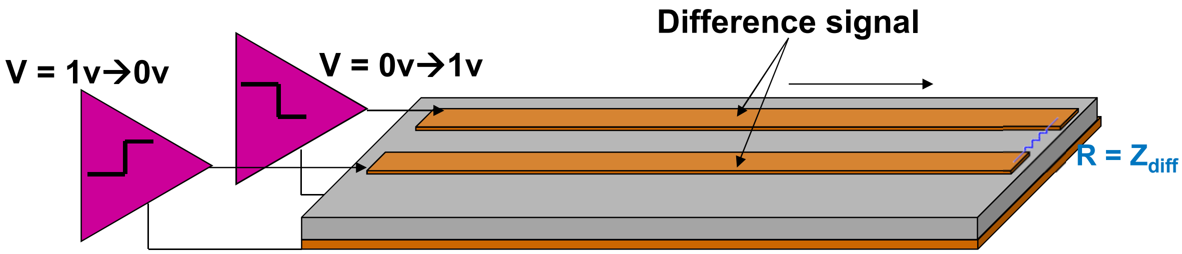




- Definitions:
  - $V_{diff} = V1 - V2$
  - $V_{comm} = ½ (V1 + V2)$

Differential and common signals propagate independently on differential pairs

Very Important Principle

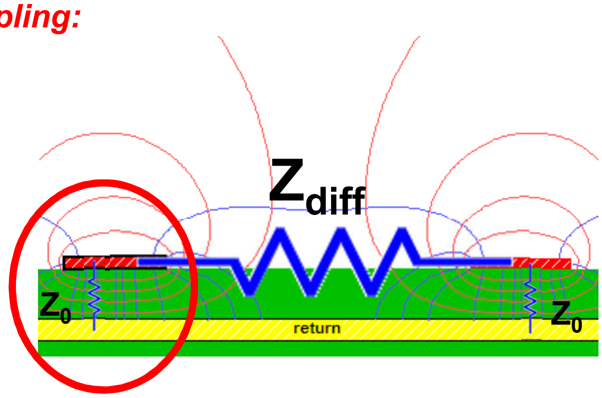


Differential impedance is the instantaneous impedance the differential signal sees

Differential Impedance and Single-ended Impedance

What is the equivalent impedance between the two signal lines?

with no coupling:



$$Z_{diff} = Z_0 + Z_0$$

$$Z_{diff} = 2 \times Z_0$$

What happens to Z0 when traces move closer together?

Lesson EPSI-02-30 Differential Impedance and Coupling

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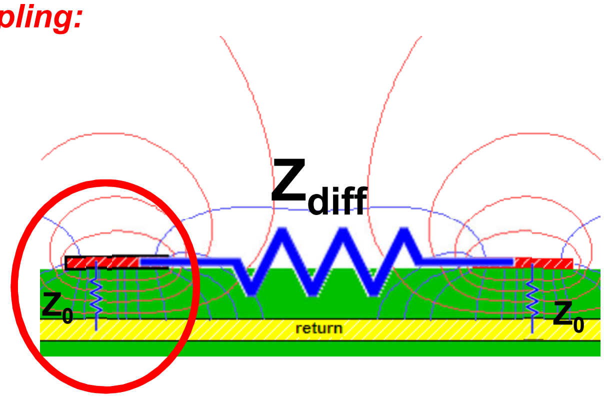
- EPSI-02-30: recorded live, Dec 1, 2013
  - Impedance of one line when the other line is driven opposite
  - Differential impedance and coupling
  - Why tightly coupled differential pairs should be the first choice
  - How to maintain 100 Ohms and tight coupling

Differential Impedance and Single-ended Impedance

What is the equivalent impedance between the two signal lines?

with no coupling:



$$Z_{diff} = Z_0 + Z_0$$

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What happens to Z0 when traces move closer together?

Differential Impedance and the Impedance of Each Line

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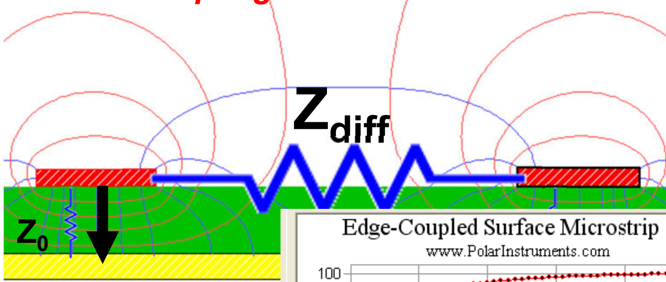
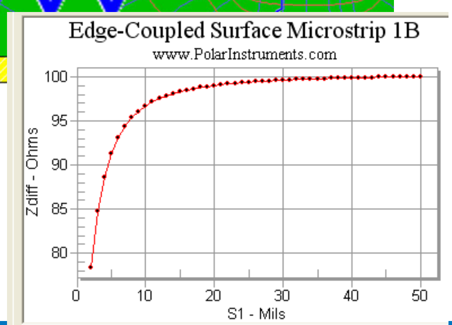
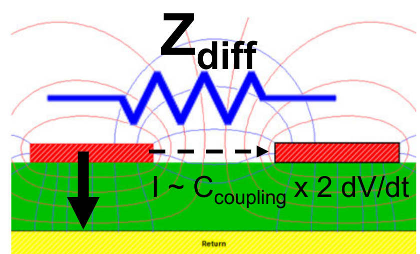




$$Z_{diff} = Z_0 + Z_0$$

$$Z_{diff} = 2 \times Z_0$$

with coupling:



Current increases, impedance decreases

$$Z_{diff} = 2 \times (Z_0 - \Delta Z)$$

The larger the coupling, the lower the differential impedance

Lesson EPSI-02-40 Currents on Differential Pairs

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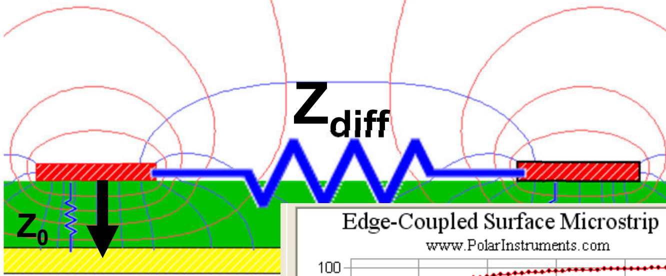
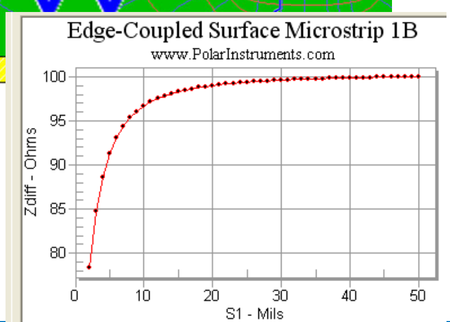
- EPSI-02-40: recorded live, Dec 1, 2013
  - The most important principle of differential signal propagation
  - How to think about how a differential signal propagates
  - Design Space for constant differential impedance
  - The Johnny Cash Principle for diff pair design
  - TDR example of single ended and differential impedance

Differential Impedance and the Impedance of Each Line

What is the equivalent impedance between the two signal lines?

with no coupling:

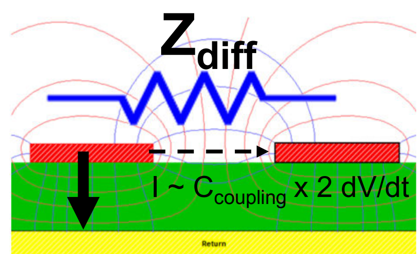




$$Z_{diff} = Z_0 + Z_0$$

$$Z_{diff} = 2 \times Z_0$$

with coupling:



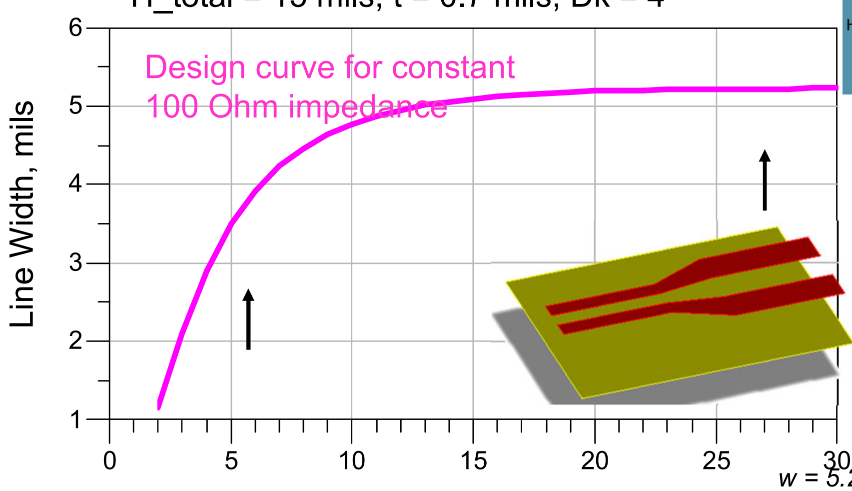
Current increases, impedance decreases

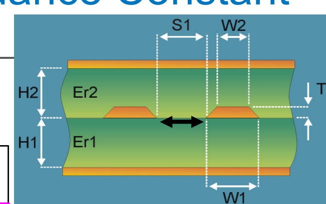
$$Z_{diff} = 2 \times (Z_0 - \Delta Z)$$

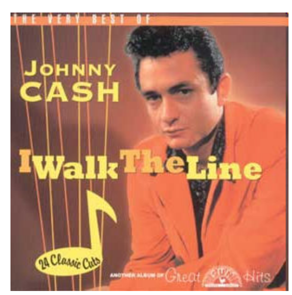
The larger the coupling, the lower the differential impedance

Keeping The Instantaneous Differential Impedance Constant in Stripline

Nominal 5 mil line width, 100 Ohms, uncoupled
H_total = 13 mils, t = 0.7 mils, Dk = 4



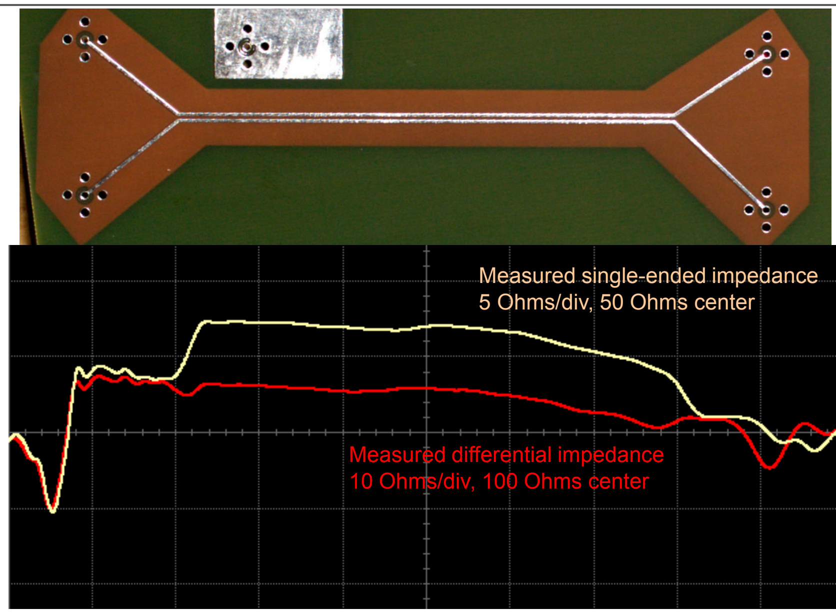




w = 5.2 mils, uncoupled
w = 3.5 mils for tightly coupled
30% narrower line for tightly coupled

MS diff pair Designed for Uniform Diff Impedance

To keep diff impedance constant as coupling changes, requires line width change



Lesson EPSI-02-50 Tight to Loose Coupling

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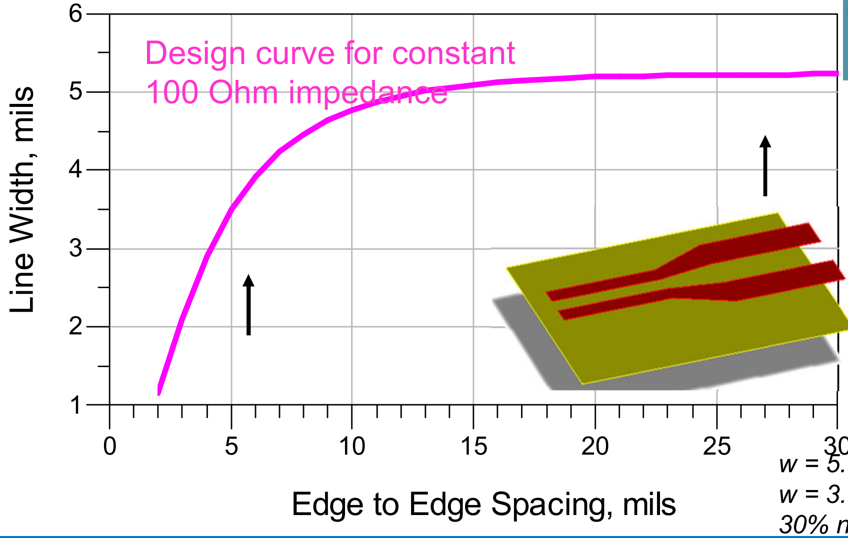
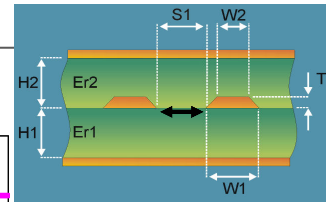
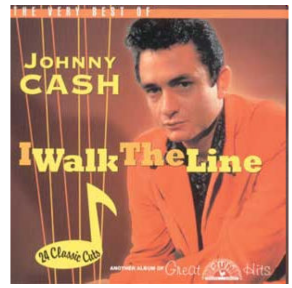
- EPSI-02-50: recorded live, Dec 1, 2013
  - The most important consequence of tight coupling
  - Trade off analysis: tight or loosely coupled diff pairs?
  - The cost-bandwidth-loss tradeoffs

Keeping The Instantaneous Differential Impedance Constant in Stripline

Nominal 5 mil line width, 100 Ohms, uncoupled
H_total = 13 mils, t = 0.7 mils, Dk = 4







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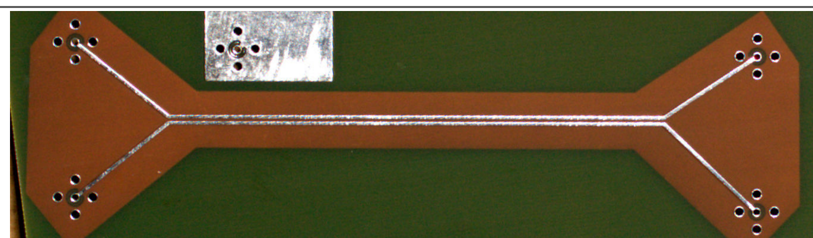
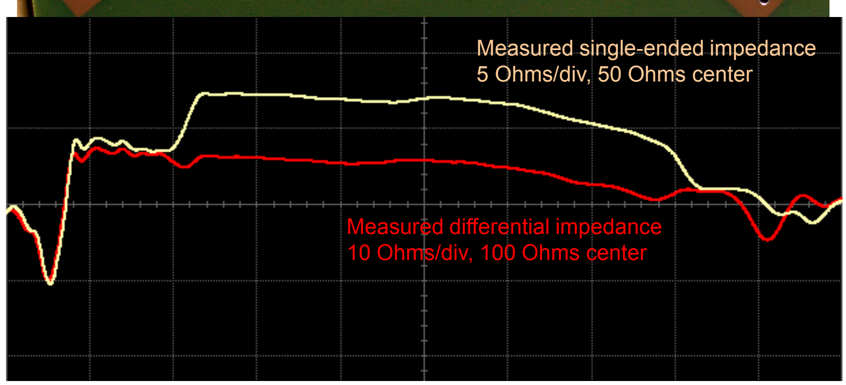
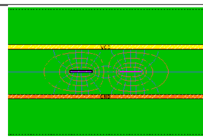
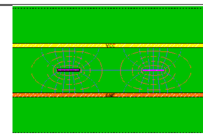




Which is Better, Tight or Loose Coupling?



?



- Lowest cost will always be with highest interconnect density:
  - Tight coupling should always be the first choice.
- What is the downside to tight coupling?
  - Narrower line width → more loss
  - If loss is important, > 2-3 Gbps, ***and*** long lines, consider loose coupling

    (Can actually be ***slight increase*** in channel to channel cross talk from tighter coupling!)
  - @ > 10 Gbps, loss is critical: loose coupling should be first choice
- ***Regardless of bit rate, always do your own analysis***

Lesson EPSI-02-60 Frequency dependent loss- so what

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- EPSI-02-60: recorded live, Dec 1, 2013
  - The typical attenuation in a channel
  - The rise time of the signal out of a lossy channel
  - Consequence of the frequency dependence of loss
  - Why lossy interconnects can completely close eyes

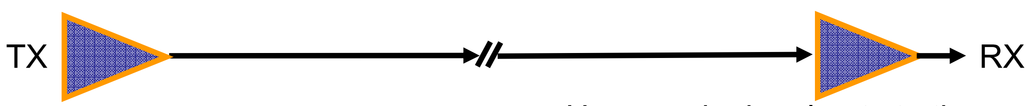
The Most Important Building Block Circuit Element: A Differential Pair Transmission Line

What is a differential pair transmission line?
Ans: ***Any Two Single-ended Transmission Lines***

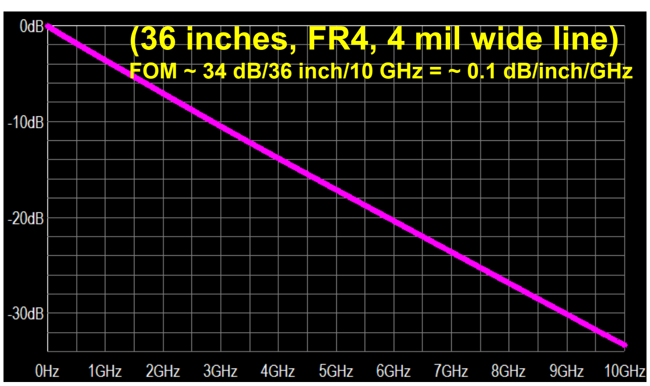
- Primary features for optimized performance:
  - (L) Wide lines, low Df laminate
  - (R) Uniform differential impedance (controlled impedance)
  - (N) Far from other channels
  - (M) Symmetric lines: matched length, cross section
- What is the optimum coupling? tight or loose?

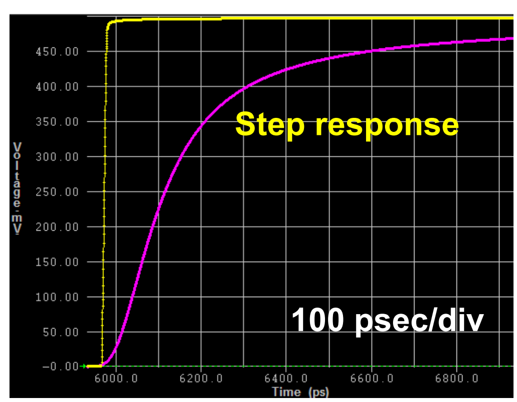
"it depends!"

Frequency Domain and Time Domain Responses of the Channel



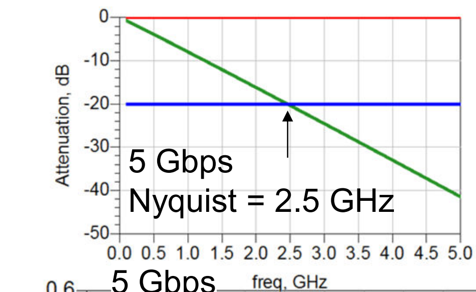
How much signal gets to the receiver?

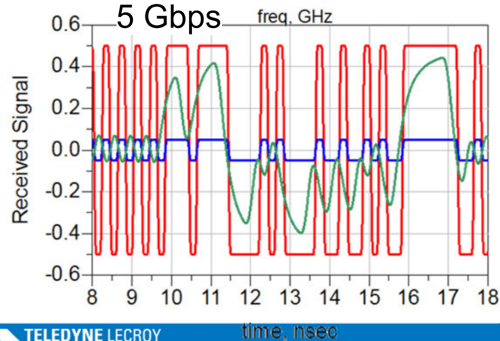


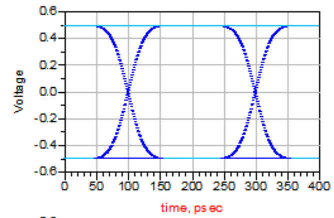


What will the eye look like if the UI is 1 nsec, 0.5 nsec, 0.1 nsec?

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

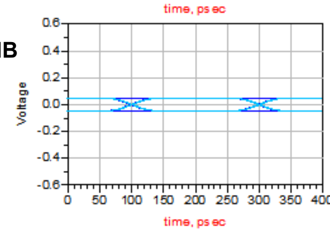






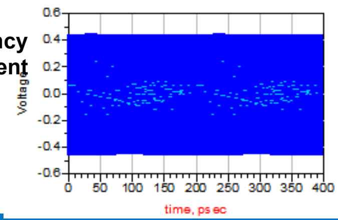
No attenuation: Perfect eye

-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

Lesson EPSI-02-70 How much attenuation is too much?

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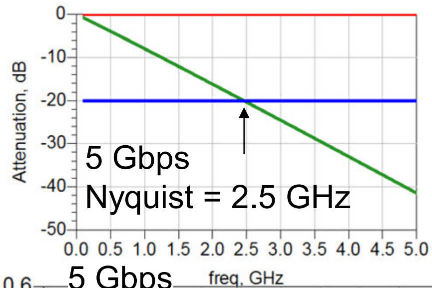
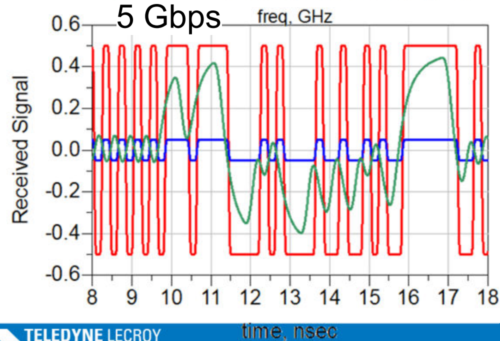
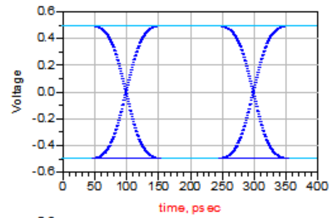
- EPSI-02-70: recorded live, Dec 1, 2013
  - Attenuation in a channel
  - A quick review of the dB
  - Eye diagram at different data rates
  - How much attenuation at the Nyquist is too much?
  - Instantly estimating channel bandwidth from the attenuation

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

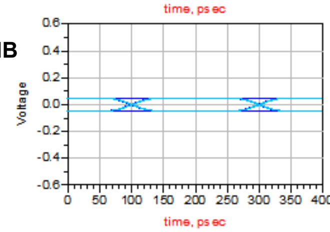






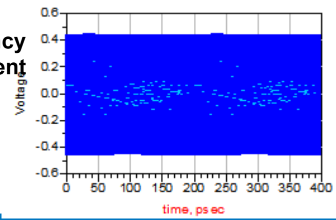
No attenuation: Perfect eye

-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

Quick Review of the dB

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

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

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

0 dB = 1

-20 dB is:

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

-40 dB is:

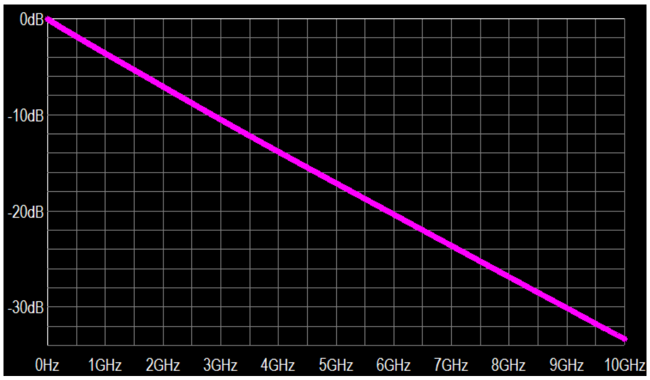
$$\frac{V_{output}}{V_{input}} = 10^{\frac{-40}{20}} = 0.01 = 1\%$$

-10 dB is:

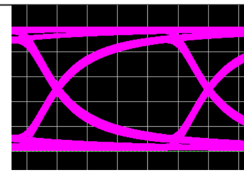
$$\frac{V_{output}}{V_{input}} = 10^{\frac{-10}{20}} = \frac{1}{\sqrt{10}} \sim 30\%$$

Attenuation at Nyquist and Eye Diagram

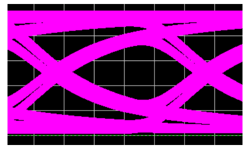
- What is the connection between attenuation at Nyquist and the eye diagram?
- Define xx dB-Bandwidth as the highest frequency at which the attenuation is less than xx dB
- What BW is required for eye opening?



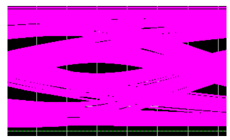
Atten @Nyquist:



2 Gbps -4 dB
(little impact from losses)



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



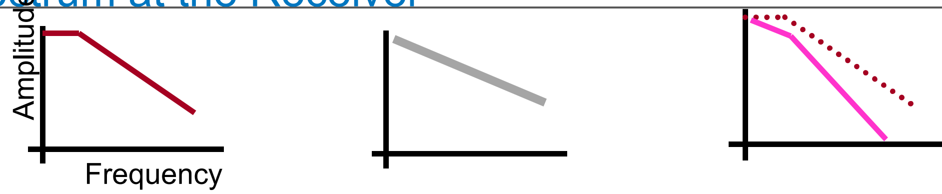
7 Gbps -12 dB
(eye barely open)

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

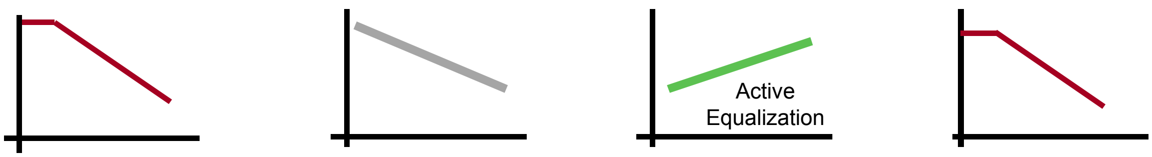
What if Attenuation @ Nyquist is > |-8| dB?

- 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

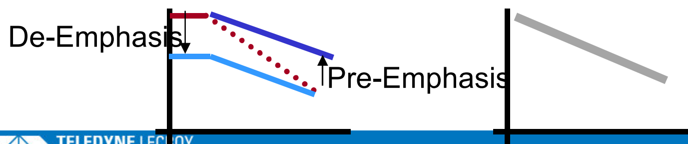
Minimize Rise-Time Degradation by Preserving the Original Spectrum at the Receiver



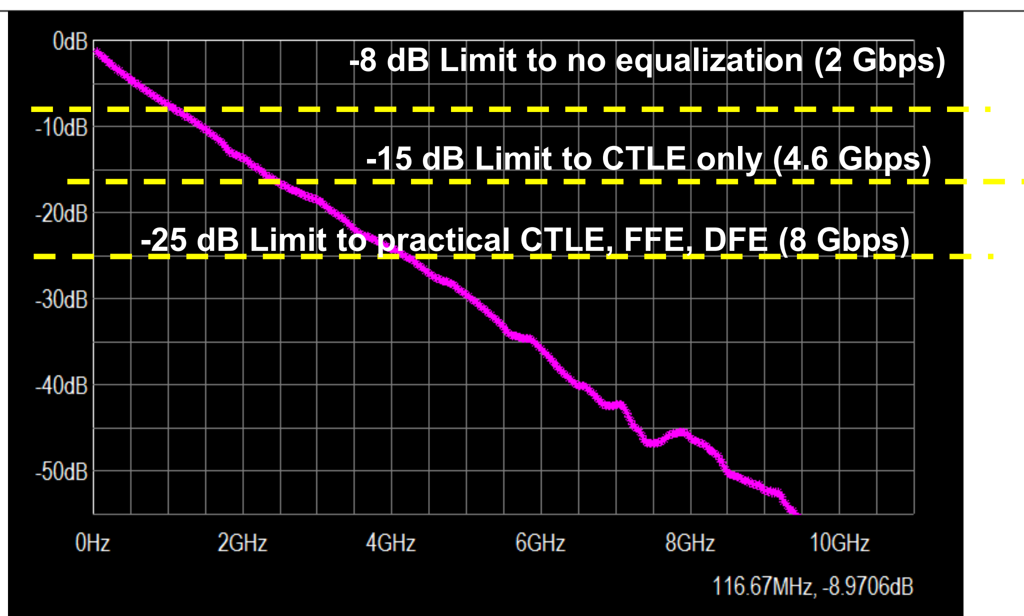
Solution #1: make the response of the interconnect flatter



Solution #2: adjust the spectrum of the signal



Example: Typical 40 inch Backplane



Lesson EPSI-02-80 Estimating attenuation in a channel

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- EPSI-02-80: recorded live, Dec 1, 2013
  - A simple model for estimating attenuation
  - Dielectric loss and material properties like dissipation factor
  - Conductor loss and skin depth
  - Impact from surface roughness

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**

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

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

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

<u>Attenuation from dielectric loss:</u>
- 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

FR4:

Attenuation from Dielectric: Figure of Merit

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

@ ~ 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

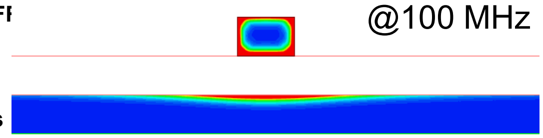
Typical Vendors: Isola, Taconics, Rogers, Park-Nelco, Panasonic, Gore

Skin Depth Limited Current Distributions: Smooth Copper

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

@ 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

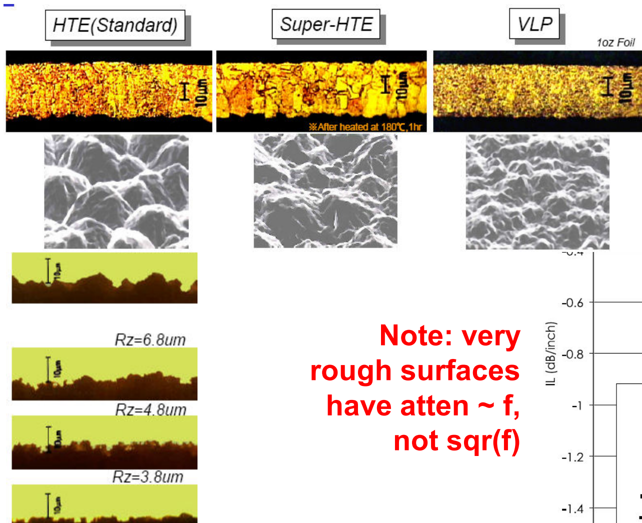
Ansoft SI 2D

- 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, …

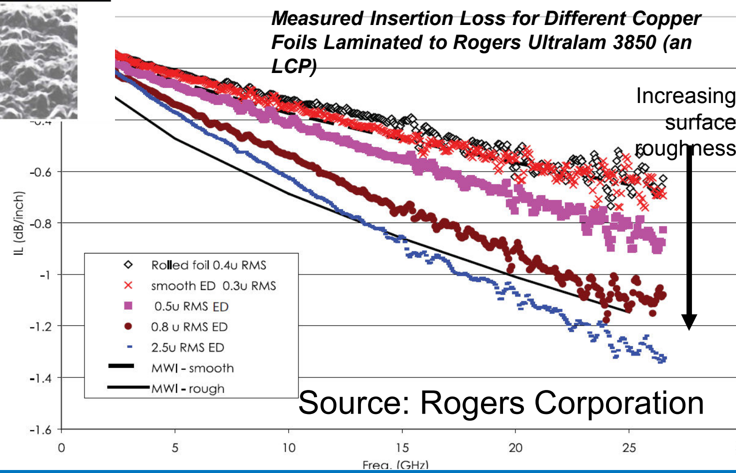
Estimating conductor loss:

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

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



Currently no good analytical predictions of measured copper surface texture and resulting attenuation- MUST rely on measurement characterization



Note: very rough surfaces have atten ~ f, not sqr(f)

Courtesy of John Andresakis

OAK-MITSUI TECHNOLOGIES

Source: Rogers Corporation

Typical Worst Case: Total Attenuation in FR4

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

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

- 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

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

Lesson EPSI-02-90 Examples of attenuation in channels

Course EPSI:
Essential Principles of Signal Integrity

With Eric Bogatin,
Signal Integrity Evangelist,
Teledyne LeCroy Front Range Signal Integrity Lab

- EPSI-02-90: recorded live, Dec 1, 2013
  - Estimating attenuation in lossy and low loss channels
  - The most important figure of merit for a channel
  - Examples of attenuation figure of merit in a few interconnects
  - How to engineer lower attenuation in an interconnect

Typical Worst Case: Total Attenuation in FR4

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

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

- 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

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

Figure of Merit ~ 0.3 dB/in/GHz

$$0.2dB/in + 0.1dB/in = 0.3dB/in$$

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

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

Figure of Merit ~ 0.22 dB/in/GHz

$$0.4dB/in + 0.5dB/in = 0.9dB/in$$

Typical Best Case: 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

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

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

Figure of Merit ~ 0.15 dB/in/GHz

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

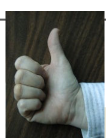
$$\text{atten}[\text{dB/in}] \sim \frac{1}{7}\sqrt{4} + 2.3 \text{ x } 4 \text{ x } 0.002 \text{ x } \sqrt{3.7} =$$

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

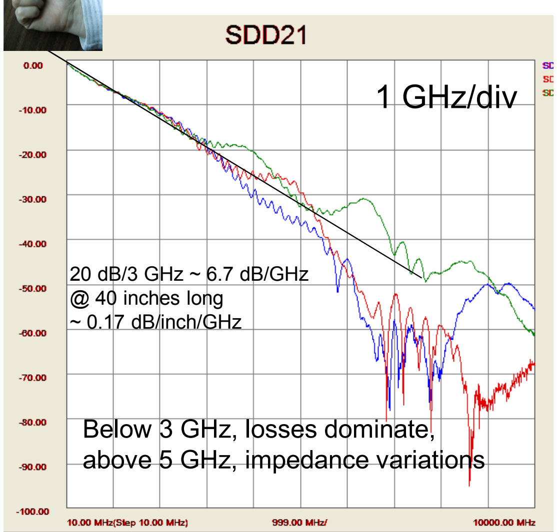
Figure of Merit ~ 0.08 dB/in/GHz

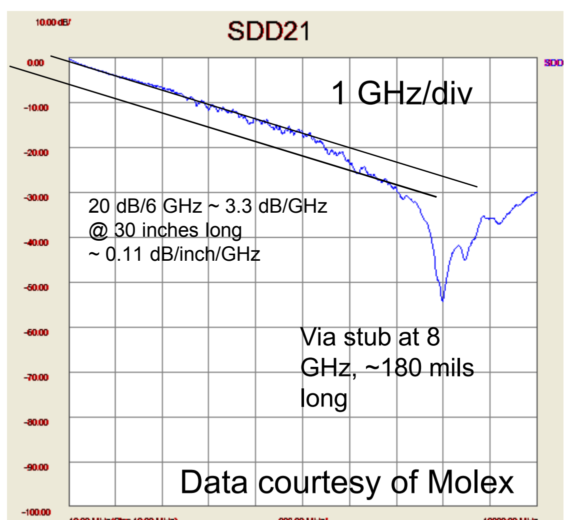
Very expensive material wasted by conductor loss

Attenuation and SDD21: Measured Backplane Channels



Simple rule of thumb: 5-15 mil wide line in FR408 ~ 0.3 → 0.1 dB/inch/GHz





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

- Shortest interconnects practical:
  - For low loss FOM ~ 0.1 dB/inch/GHz, @ 5 GHz (10 Gbps), atten ~ 0.5 dB/inch. 50 inches max length for < -25 dB
- 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