Separating Myth From Reality in Signal Integrity

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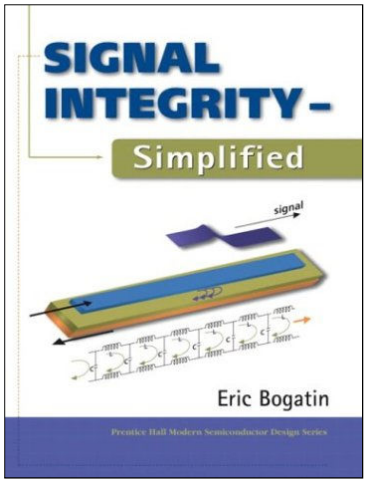
Outline

- What's a myth
- The general process to separate myth from reality
- Some examples

For More Information



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- Master Class Workshops
- Resources

Some Common Signal Integrity Myths

A myth: a statement that may apply to one situation, but is incorrectly generalized to all situations

1. **Signals travel at the speed of the electrons in the conductor**
2. **Return current in differential pair is carried by the other line**
3. **Corners affect signal integrity and should be avoided**
4. **FR4 won't work at high frequency**

What is the most common answer to all signal integrity questions?

- **Do corners affect signals and should they be avoided?**
- **Is the return current of one trace in a differential pair really carried by the other?**

"…it depends"

How do we know when to worry and when the question is a distraction?

Put in the <u>Numbers</u>!

"no myths allowed"™

Quantifying is the only way to distinguish Myth from Reality

Analysis ⟷ Calculation

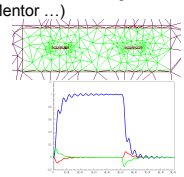
Characterization ⟷ Measurement

"…when you can measure what you are speaking about, and express it in numbers, you know something about it… and you have, in your thoughts, advanced to the stage of science"

--- William Thomson, Lord Kelvin, 1894

Three Analysis Tools for Every Tool Box

Numerical simulation: field solver, parasitic extraction, SPICE, IBIS simulations, can base a design on this (such as Ansoft, Agilent, Mentor …)



1st order approximations: Analytic approximations, useful for quick estimates and early design tradeoffs

$$L_{self} = 5d\left[\ln\left(\frac{2d}{w+t}\right)+\frac{1}{2}\right]nH$$

Rules of Thumb: Feeds your intuition, useful for order of magnitude estimating

Self inductance ~ 25 nH/inch

Accuracy

Effort required to get answer

Do's and Don'ts

Don't:

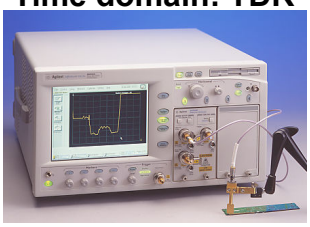
- **Sign off on a design based on a rule of thumb estimate**
- **Sign off on a design based on an analytic approximation**
- **Automatically reach for a field solver for every answer**
- **Spend days running one simulation just to get a quick estimate**

Do:

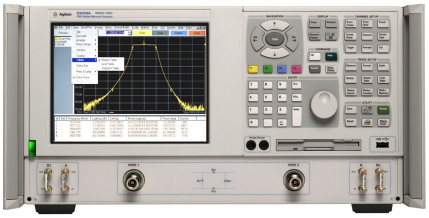
- **Memorize rules of thumb**
- **Use a rule of thumb as the starting place for every estimate**
- **Know where to quickly locate appropriate approximations**
- **Use an approximation in a spread sheet to explore design space, tolerance analysis and tradeoffs**
- **Use a numerical simulation tool where accuracy is important**
- **Sign off on a design based on a verified numerical simulation tool**

Characterization Instruments

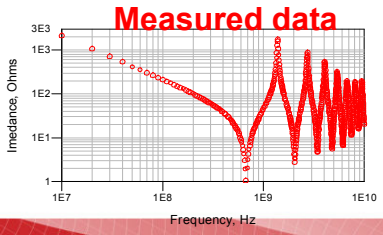
Time domain: TDR

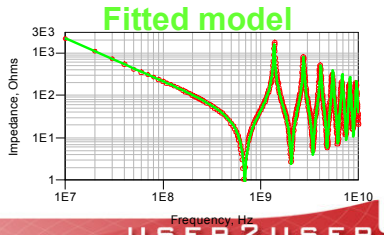


Frequency Domain: VNA



Measurement analysis tools: ADS, …





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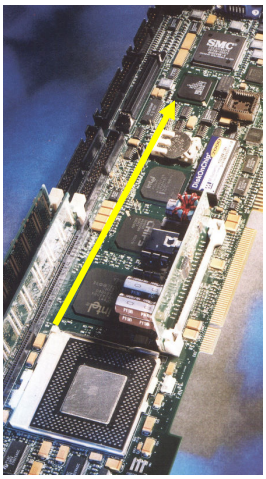
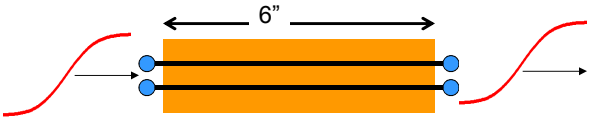
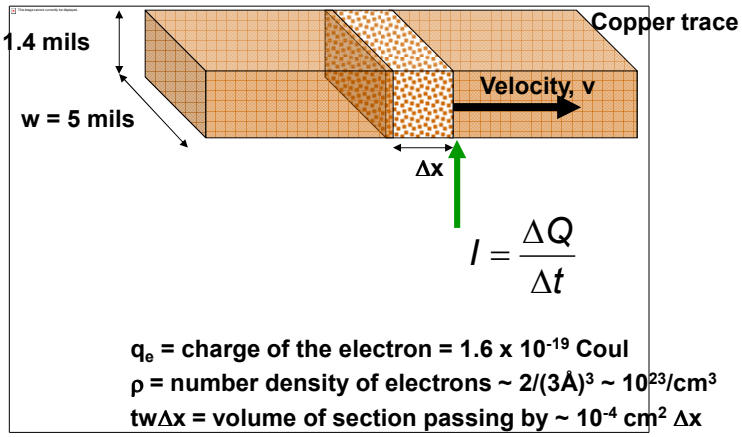
What Determines the Speed of a Signal in an Interconnect?





Myth #1:
the speed of the signal is the speed of the electrons in the wire

What is the Speed of Electrons in Copper?



q_e = charge of the electron = 1.6×10^{-19} Coul
ρ = number density of electrons ~ $2/(3Å)^3 \sim 10^{23}/cm^3$
$tw\Delta x$ = volume of section passing by ~ 10^{-4} cm^2 Δx
Δt = how long it takes for Δx of electrons to pass by

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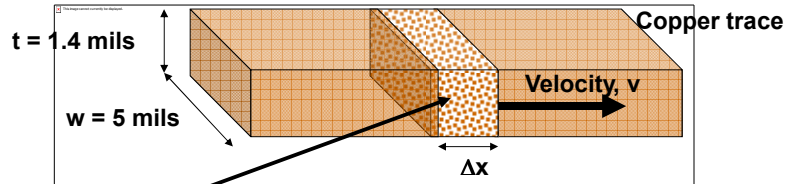

$$\Delta Q = q_e \rho t w \Delta x$$

q_e = charge of the electron = 1.6 x 10^{-19} Coul
ρ = number density of electrons ~ 2/(3Å)^3 ~ 10^{23}/cm^3
twΔx = volume of section passing by ~ 10^{-4} cm^2 Δx
Δt = how long it takes for Δx of electrons to pass by

$$I = \frac{\Delta Q}{\Delta t} = q_e \rho t w \frac{\Delta x}{\Delta t} = q_e \rho t w\, v$$

$$v = \frac{I}{q_e \rho t w}$$

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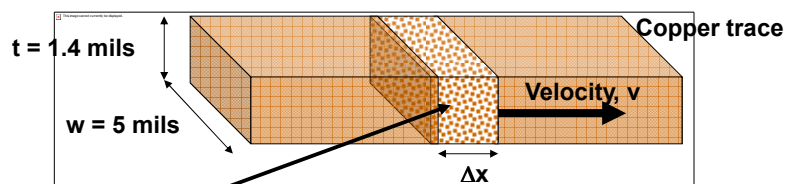

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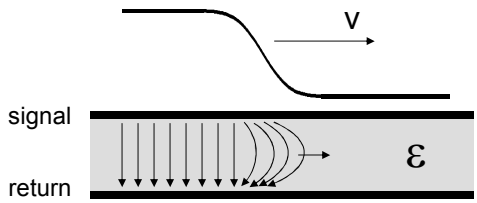
$$I = \frac{\Delta Q}{\Delta t} = q_e \rho t w \frac{\Delta x}{\Delta t} = q_e \rho t w\, v$$

$$v = \frac{I}{q_e \rho t w} = \frac{1A}{10^{-19} 10^{23} 10^{-4}} = \mathbf{1\ cm/sec}$$

What Determines The Speed of a Signal?

Ans: the dielectric constant of the laminate



in air: v = 186,000 miles per sec v = 12 inches/nsec

$$v = \frac{12\,\frac{inches}{n\sec}}{\sqrt{4}} = \frac{12\,\frac{inches}{n\sec}}{2} = 6\,\frac{inches}{n\sec}$$

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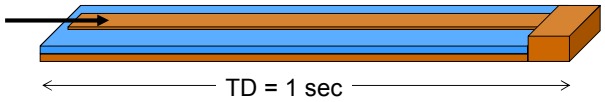
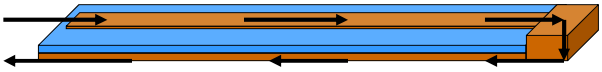
Return Current Path in Transmission Lines

Current into signal line



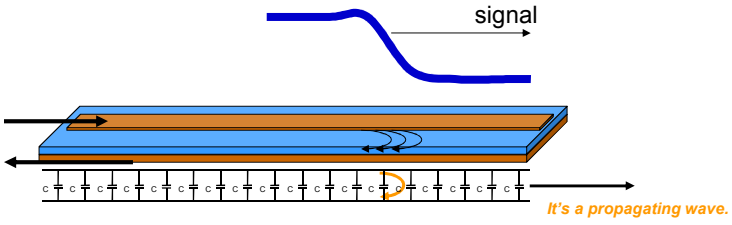
Where is the return path?

For DC currents:

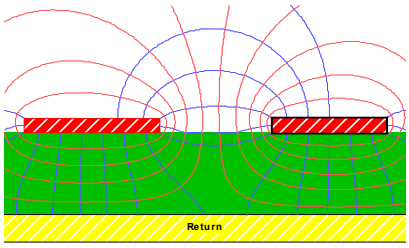


For RF currents? When does current come out return path?

Current Flow in the Transmission Line



Where is the return current in a differential pair?

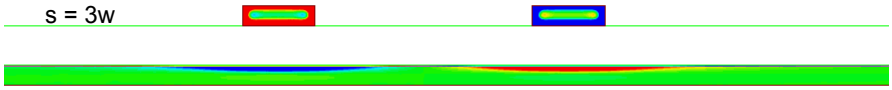


Myth #2:
The return current in a differential pair is carried by the other line

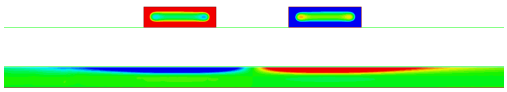
Return Current in Microstrip Differential Pair

@ 100 MHz

s = 3w



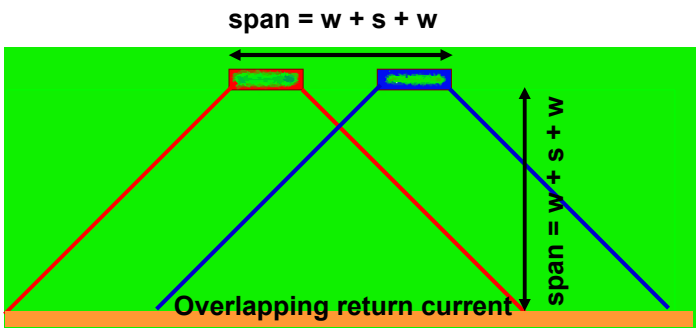
s = w



Calculated with Ansoft 2D field solver

Return Current in Closely Coupled Differential Pair: Plane Close and Far

Condition for Return Currents to Overlap:

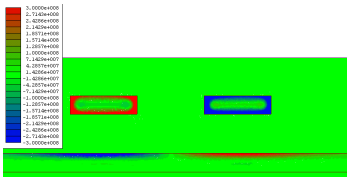


When distance to return plane > span of signal traces, return currents overlap and second line carries return current of first line

Return Currents in Differential Pairs

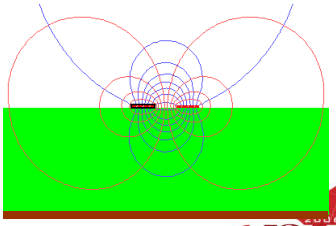
Most return current is carried by the plane when signal to return coupling >> signal to signal coupling

Ex: most board level interconnects



Most return current is carried by the other signal when signal to plane coupling << signal to signal coupling

Ex: most connectors, shielded twisted pair, twisted pair, sockets



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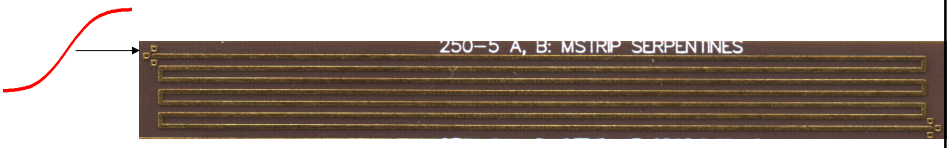
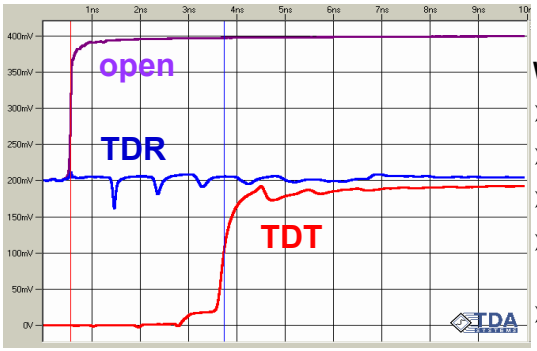
Eric's Belief in the Origin of the Myth About Corners





Why corners:

- We see dips
- Appear every 1 nsec
- There are 6 dips
- Decreasing amplitude due to line losses
- What else could it be?

20% dip @ 50 psec rise time!

The Impact of a Corner

What will be the impact from these 90 degree bends?

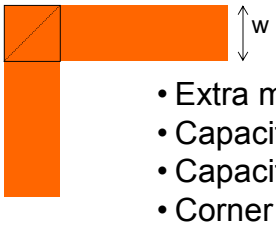
How do we separate myth from reality?

…by putting in the numbers:

Calculation:
- rules of thumb
- analytical approximations
- numerical simulation

Measurement:
- TDR
- VNA

Simple Model For A Corner

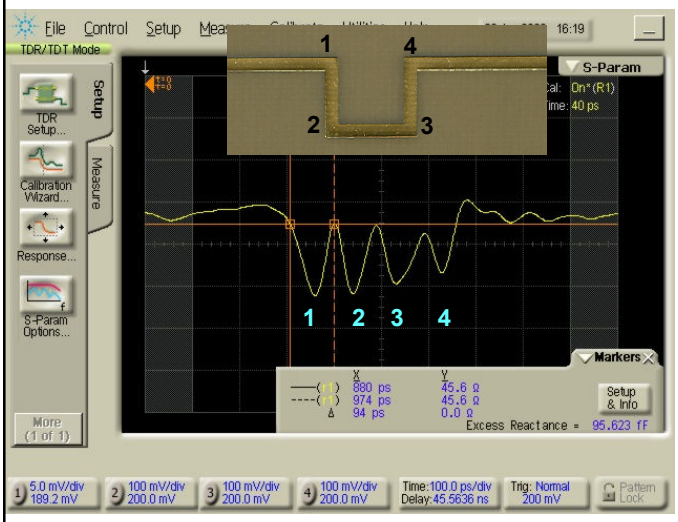


- Extra metal is ~ 1/2 a square
- Capacitance of a square = 3.4 pF/inch x w
- Capacitance of a corner = 1/2 x 3.4 pF/inch x w
- Corner has ~ 1.7 pF x w (in inches) of capacitance
- Corner has ~ 1.7 fF x w (in mils) of capacitance

For 50 Ohm lines:

Line width	capacitance
5 mils	~ 1.7 fF x 5 = 9 fF
10 mils	~ 1.7 fF x 10 = 17 fF
60 mils	~ 1.7 pF x 60 = 100 fF
120 mils	~ 1.7 pF x 120 = 200 fF

The 50-d Pattern in the BTS620revC Board

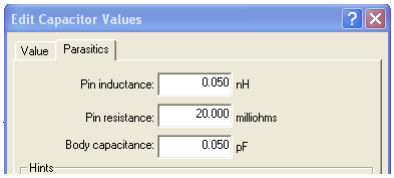


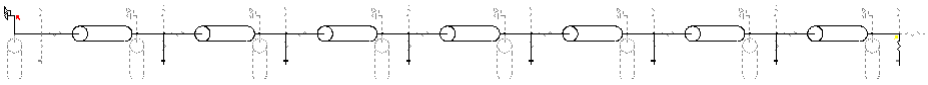
Corners cause reflections!!

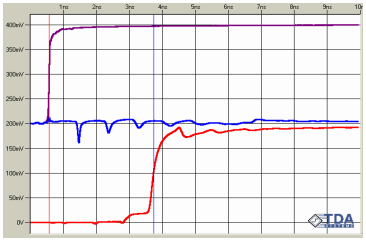
w = 60 mils
Expect C ~ 100 fF
Measured C = 96 fF

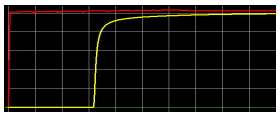
Simulating Effects of Corners

- **w = 20 mils**
- **C = 1.7 fF x 20 mils = 34 fF**
- **Default limit to capacitor parasitic is 50 fF (2x larger)**

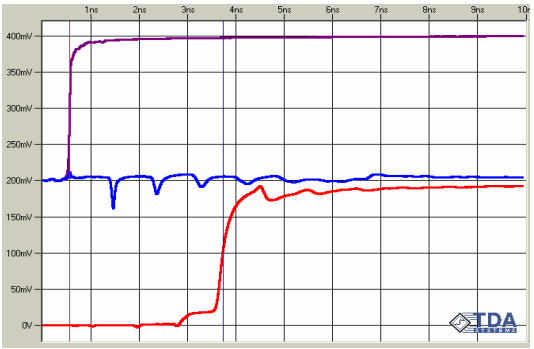




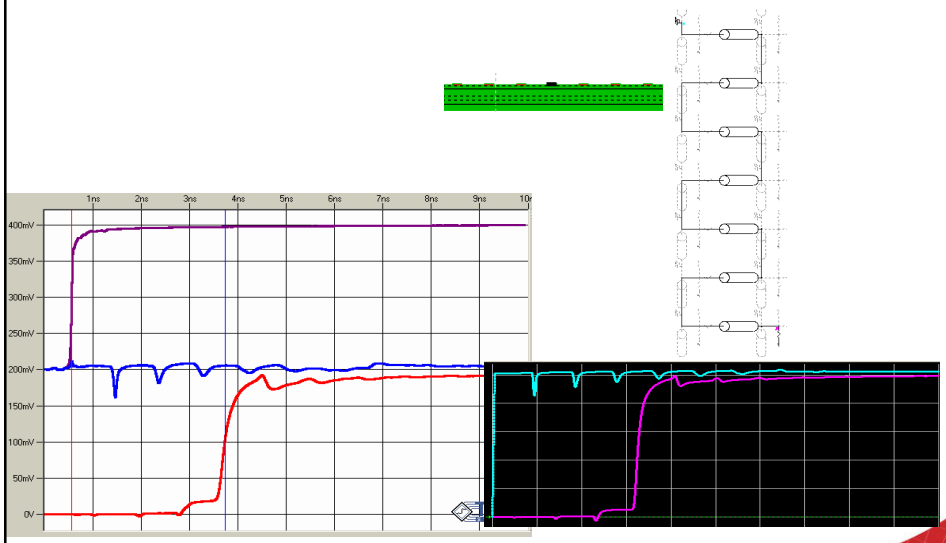




Alternate Explanation



Simulating Coupled Microstrips



The Lesson

- Corners can affect signal integrity
- Equivalent circuit model is C
- C ~ 1.7 fF x w (mils)
- For 10 mils wide line, corner looks like C ~ 17 fF
- Worry about corners? If 17 fF is important.

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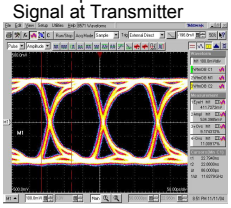
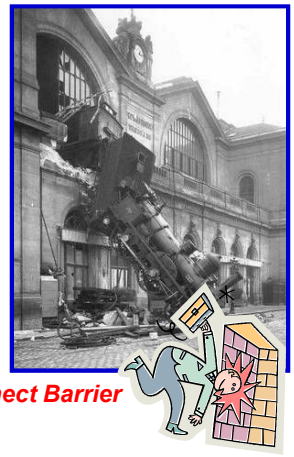
The Coming Train Wreck:

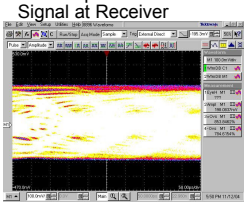
The Bit Banger's Dilemma

6.25-Gbps XAUI Bitstream Signal at Transmitter





6.25-Gbps XAUI Bitstream Signal at Receiver

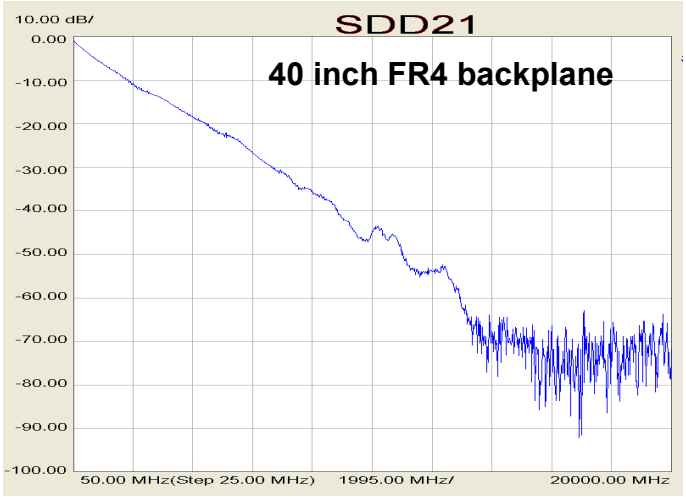


- Intersymbol interference (ISI)
- Collapse of the eye diagram
- Deterministic jitter

The Interconnect Barrier

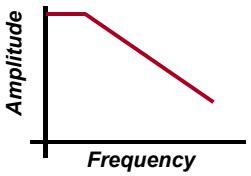
The "Gagabit" Regime

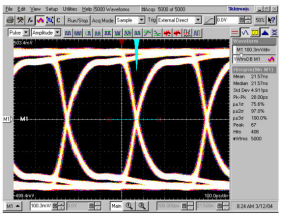
Fundamental Limitations From Dielectric Loss



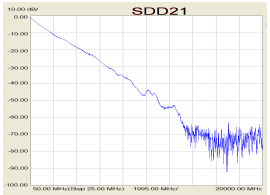
What Happens to a Square Wave Through This Backplane Sdd21?

Input Spectrum



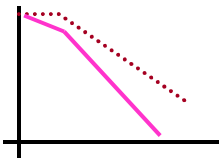


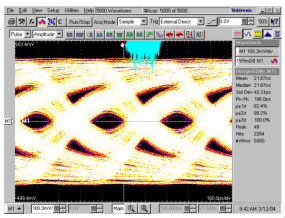
Transfer Function of Interconnect



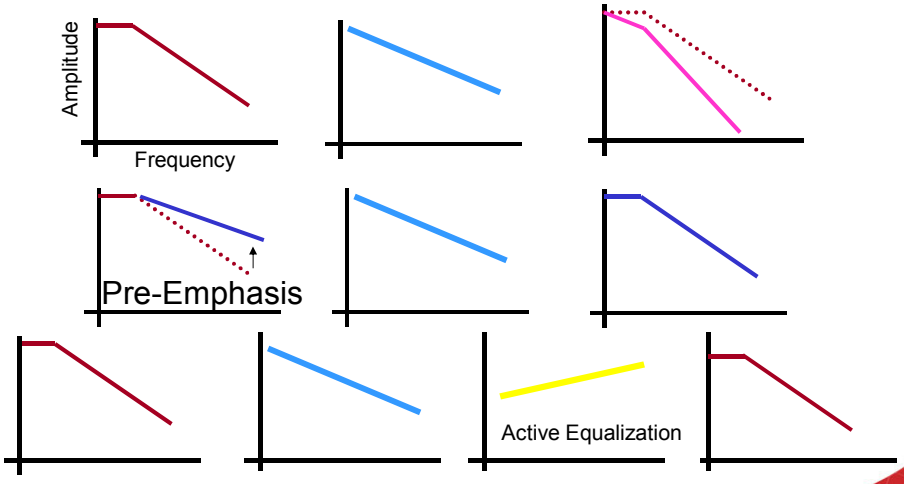
42" in FR4

Output Spectrum



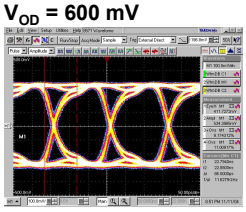


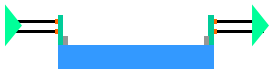
Minimize Rise-Time Degradation by Preserving the Original Spectrum at the Receiver



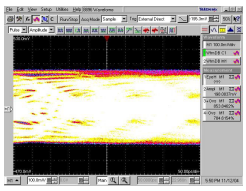
Example: 6.25-Gbps Pre-Emphasis

V_{OD} = 600 mV

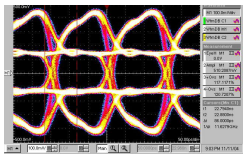


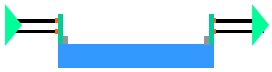


1-meter
FR4
interconnect

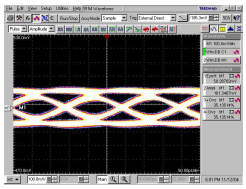


9.5 dB per emphasis





1-meter
FR4
interconnect



Stratix II GX eye diagrams courtesy: Altera

Lesson

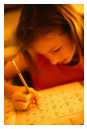
- FR4 can work at high frequency, but
- Fundamental limits from attenuation in FR4 type materials
- Must use silicon processing
  - Pre-emphasis
  - Equalization

Eric's Philosophy

- Sometimes an okay answer now is better than a good answer late.
- Watch out for mink holes: focus on the goal.
- Question authority and "experts".
- The only way to separate myth from reality is by putting in the numbers: rules of thumb, approximations, numerical simulations, measurements on well-characterized test vehicles.
- Every designer should be empowered with the skill, tools, and technologies to find their own optimized cost/performance solution for each specific design.

Empowering Designers

The Successful Designers' Ecosystem

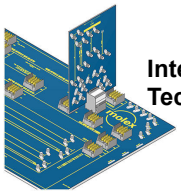


Skill:
Principles
Understanding
Methodology

Analysis Tools

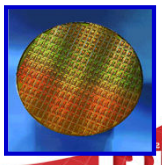
Characterization Tools

You are here

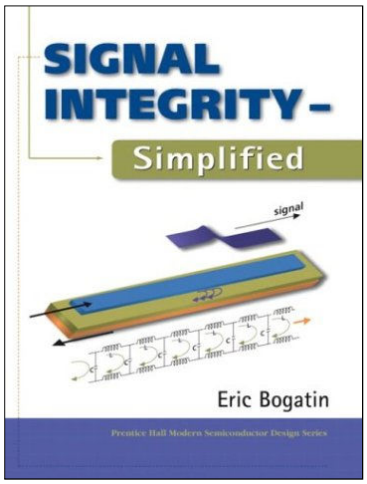


Interconnect Technology

Silicon Technology



For More Information



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