Course EPSI: Essential Principles of Signal Integrity

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

Build your engineering intuition about Signal Integrity

The starting place for all design engineers

TELEDYNE LECROY Everywhereyoulook | Teledyne LeCroy Signal Integrity Academy | 2014 | 1

EPSI-01 Transmission lines and the Essential Principles

Course EPSI:
Essential Principles of Signal Integrity

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

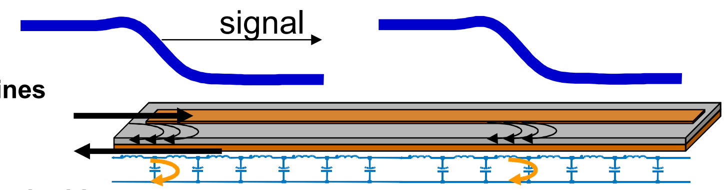
Build your engineering intuition about Signal Integrity

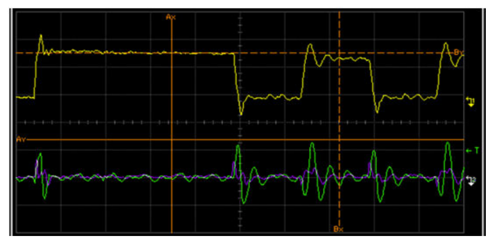
The starting place for all design engineers

TELEDYNE LECROY Everywhereyoulook | Teledyne LeCroy Signal Integrity Academy | 2014 | 2

EPSI: A 2-Day Workshop

- **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**





TELEDYNE LECROY Everywhereyoulook™ 2014

Lesson EPSI-01-10 Why the essential principles are important

Course EPSI: Essential Principles of Signal Integrity

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

- EPSI-01-10 recorded live, Dec 1, 2013
  - Design methodology to get it right the first time
  - The right way to think about signals on interconnects
  - The most important essential principles for solving SI problems
  - Avoiding reflection noise cross talk, EMI, PDN noise problems
  - Special treatment on ground bounce and signal transition noise
  - How to use analysis tools to explore design tradeoffs

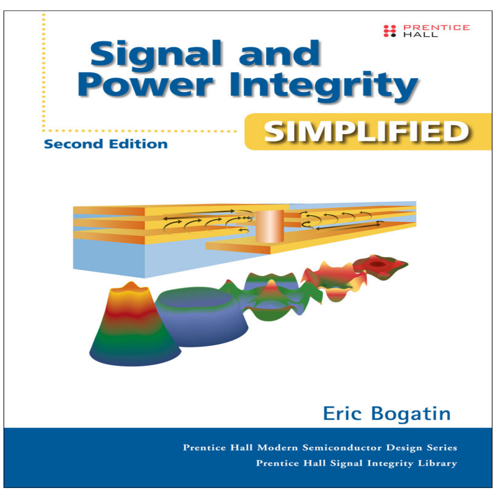
TELEDYNE LECROY Everywhereyoulook™ **Teledyne LeCroy Signal Integrity Academy** 2014 4

EPSI: A 2-Day Workshop

- **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**

TELEDYNE LECROY Everywhereyoulook 2014

For More Information



Published by Prentice Hall, 2009

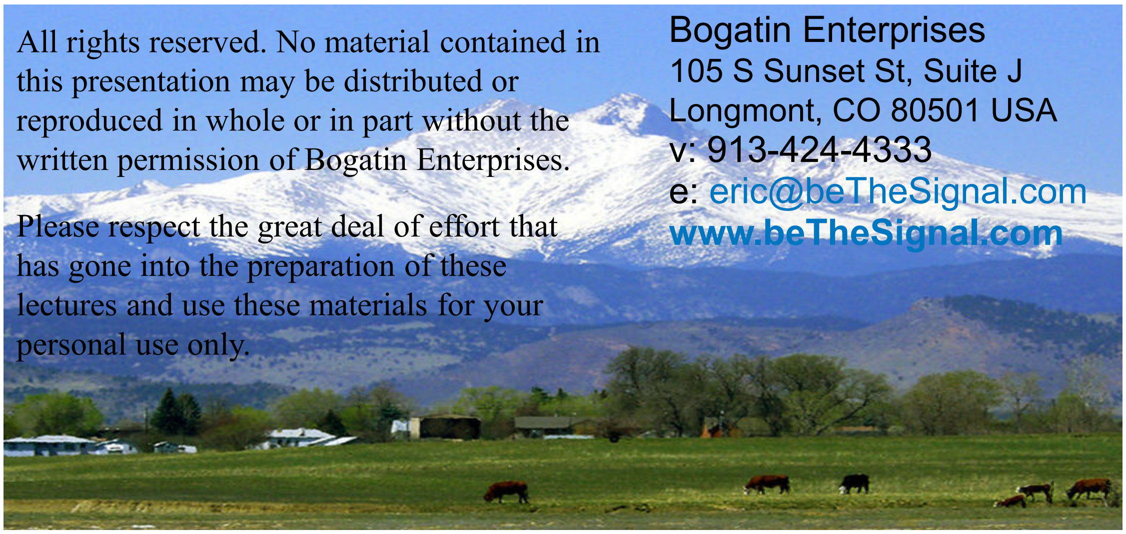
www.BeTheSignal.com

- SI Library
- Webinars, feature articles, presentations, hands on labs
- Class schedules

Blog: www.beTheSignal.com/blog

@beTheSignal

TELEDYNE LECROY Everywhereyoulook 2014



Bogatin Enterprises
105 S Sunset St, Suite J
Longmont, CO 80501 USA
v: 913-424-4333
e: eric@beTheSignal.com
www.beTheSignal.com

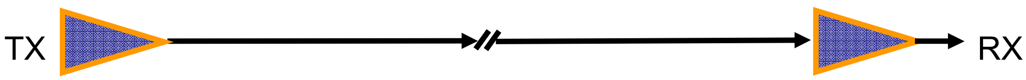
Lesson EPSI-01-20 Design Methodology

Course EPSI: Essential Principles of Signal Integrity

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

- EPSI-01-20: recorded live, Dec 1, 2013
  - What signal integrity is all about
  - Signal integrity problems
  - An efficient design methodology
  - The Youngman Principle
  - The essential principles of SI
  - Balancing tradeoffs

All High-Speed Products Have One Thing in Common



Transmit a signal from one TX to a RX, with acceptable quality

But interconnects are not transparent!

What can go wrong?

Attenuation
Non-monotonic edges
Skin depth
Inductance
Emissions
Terminations
Via stubs
Decoupling capacitors
Losses
Surface roughness
Dissipation factor
Skew
Overshoot

Ringing
Dispersion
Loaded lines
Ground bounce
Cross talk
NEXT
FEXT
Gaps in return path
Data clock skew
Jitter
Changing reference planes
Stub lengths
Branch topology

An Efficient Design Methodology to Eliminate Problems Before the Design is Released

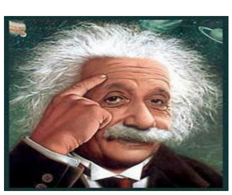
- An efficient methodology: ***understand the "essential principles"***
  - Identify the SI problems
  - Find the root cause
    - ***Apply the "Youngman" principle***
  - Establish practical design guidelines to minimize them
  - If it's "free" always follow the "habits"
  - Use analysis tools to evaluate cost-performance tradeoffs as early in the design process as possible

"If your arm hurts when you raise it, don't raise your arm."

"If problem A happens <u>because</u> your design has feature B,

then eliminate feature B from your design"

Identify the root cause of a problem and fix the root cause



"Are you sure about this Stan? It seems odd that a pointy head and a long beak is what makes them fly"

Lesson EPSI-01-30 Analysis tools

Course EPSI:
Essential Principles of Signal Integrity

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

- EPSI-01-30: recorded live, Dec 1, 2013
  - “Design is geek for tradeoffs”- (Bruce Archambeault)
  - Using analysis tools for tradeoff design
  - Most common answer to all signal integrity questions is “it depends”
  - How do we answer it depends questions
  - Empower you to answer it depends questions using analysis tools

An Efficient Design Methodology to Eliminate Problems Before the Design is Released

- An efficient methodology: ***understand the “essential principles”***
  - Identify the SI problems
  - Find the root cause

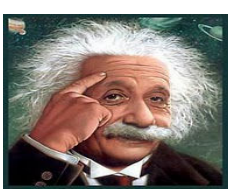
    Apply the “Youngman” principle
  - Establish practical design guidelines to minimize them
  - If it’s “free” always follow the “habits”
  - Use analysis tools to evaluate cost-performance tradeoffs as early in the design process as possible

“If your arm hurts when you raise it, don't raise your arm.”

“If problem A happens <u>because</u> your design has feature B,

then eliminate feature B from your design”

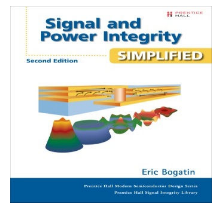
Identify the root cause of a problem and fix the root cause



“Are you sure about this Stan? It seems odd that a pointy head and a long beak is what makes them fly”

But What If It's Not "Free"?

- How do we evaluate "cost-performance" trade offs?, is it worth it? How much benefit a design feature offers? "the bang for the buck?"
- Like:
  - How far apart should I route signal lines?, Do I need a return via adjacent to a signal via? How many capacitors do I need on the PDN?, should I use tightly coupled or loosely coupled differential pairs?
- ***What is the most common answer to ALL signal integrity questions?***
  - ***"…it depends!"***
- We answer "it depends" questions by putting in the numbers using analysis tools: Rules of thumb, approximations, numerical simulation tools
  - Balance accuracy and effort: "***sometimes an OK answer NOW! Is more important than a good answer late***."
  - A good answer can be very expensive: 3D analysis or build it and test it.
- Some numerical simulation tools:
  - Free QUCS: Quite Universal Circuit Simulator
  - LeCroy SI Studio
  - Mentor HyperLynx
  - Polar Si9000
  - Simbeor, Agilent ADS, CST, HFSS



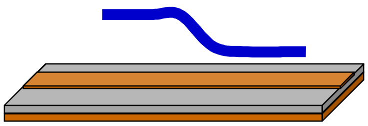
Lesson EPSI-01-40 The Six Families of SI Problems

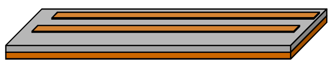
Course EPSI:
Essential Principles of Signal Integrity

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

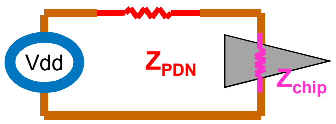
- EPSI-01-40: recorded live, Dec 1, 2013
  - Reflection noise
  - Cross talk
  - Ground bounce
  - Rise time degradation
  - PDN and EMI
  - The essential principles and the habits of successful designers

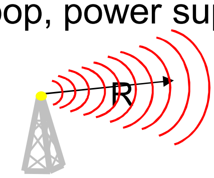
Why Interconnects are Not Transparent: The Six Families of Signal Integrity Problems





1. Reflection noise
2. Cross talk
3. Ground (and power) bounce
4. Losses (@ Gbps)
5. Rail collapse, voltage droop, power supply noise
6. EMI





TELEDYNE LECROY Everywhereyoulook

Teledyne LeCroy Signal Integrity Academy 2014 15

Lesson EPSI-01-50 The First Three Essential Principles

Course EPSI: Essential Principles of Signal Integrity

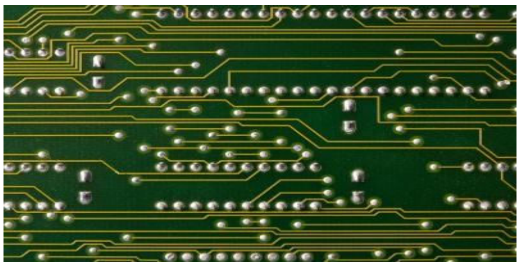
With Eric Bogatin,
Signal Integrity Evangelist,
Teledyne LeCroy Front Range Signal Integrity Lab

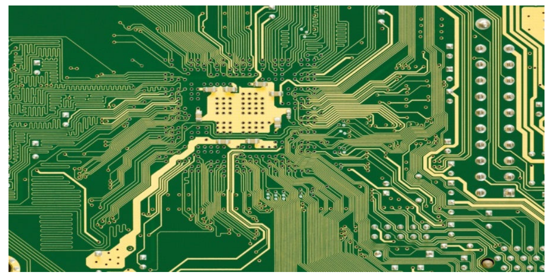
- EPSI-01-50: recorded live, Dec 1, 2013
  - Essential Principle #1: all interconnect are transmission lines
  - Essential Principle #2: signals are dynamic
  - Essential Principle #3: signals see an instantaneous impedance
  - What is impedance

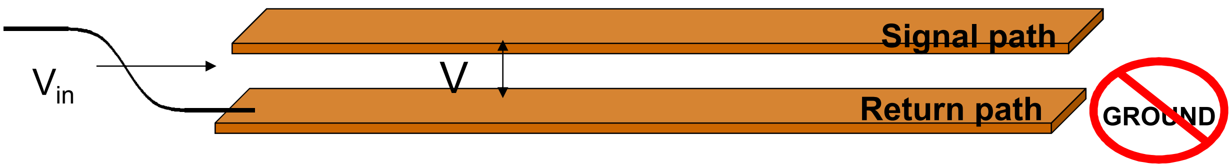
TELEDYNE LECROY Everywhereyoulook

Teledyne LeCroy Signal Integrity Academy 2014 16

Essential Principle #1: All interconnects are transmission lines

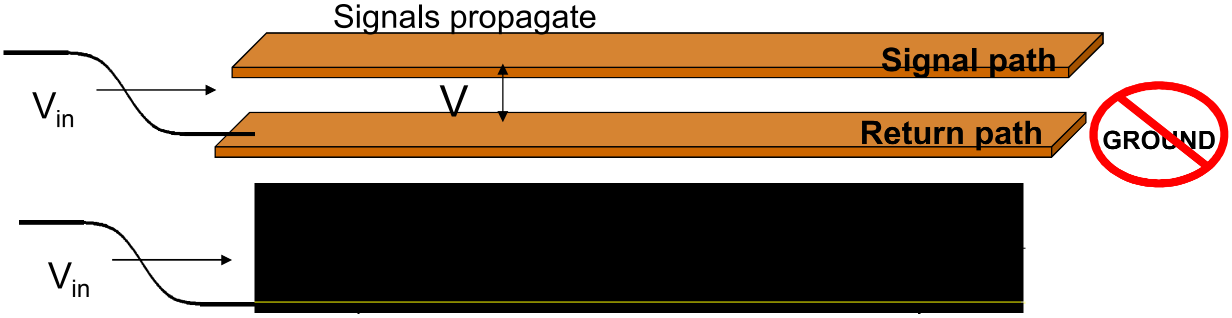


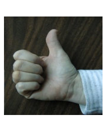




Essential Principle #2: Signals are Dynamic

All interconnects are transmission lines
A signal as a voltage difference
Signals propagate

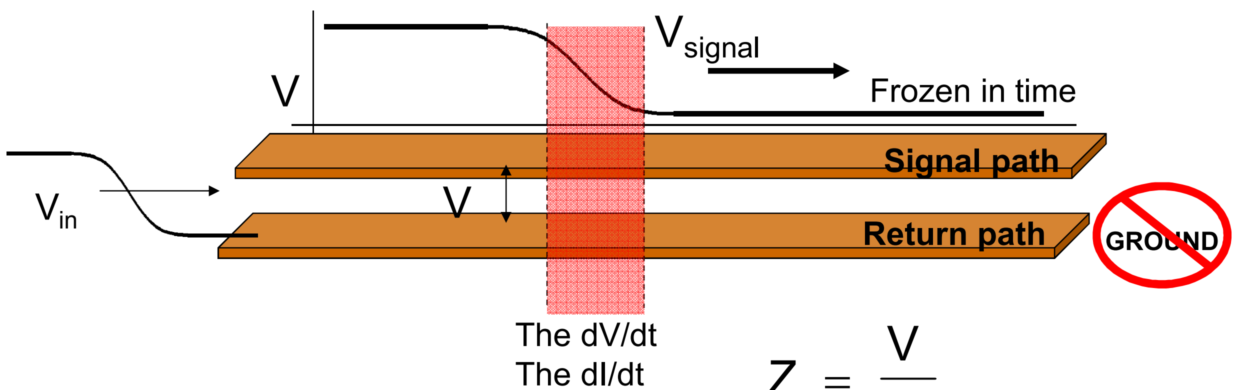




$$v = \frac{12\ \frac{\text{inches}}{\text{n sec}}}{\sqrt{Dk}} = \frac{12\ \frac{\text{inches}}{\text{n sec}}}{\sqrt{4}} = \frac{12\ \frac{\text{inches}}{\text{n sec}}}{2} = 6\ \frac{\text{inches}}{\text{n sec}}$$

Essential Principle #3: Signals see an instantaneous impedance

ALL Signals ALWAYS propagate
The edge has a spatial extent, where the dV/dt, dI/dt is
The edge sees an instantaneous impedance



$$Z = \frac{V}{I}$$

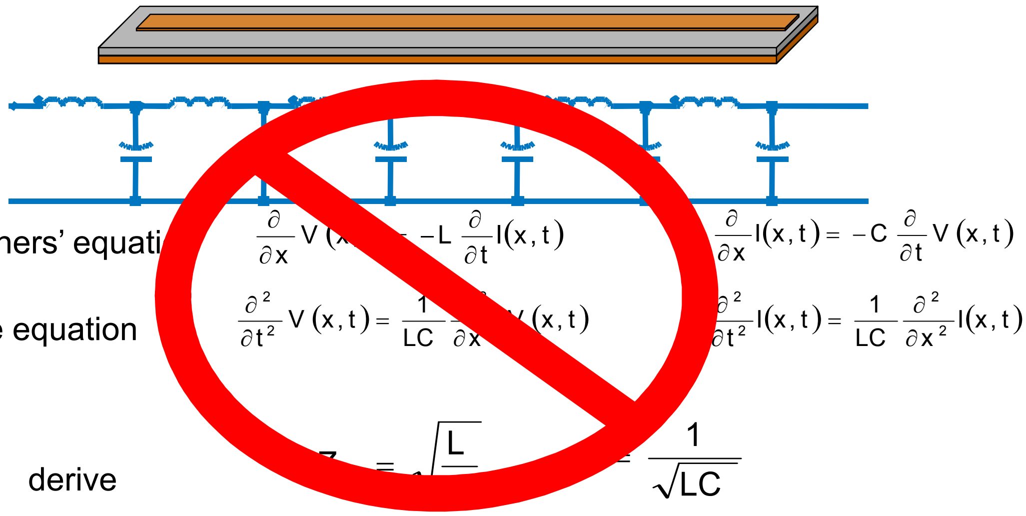
Lesson EPSI-01-60 Instantaneous Impedance

Course EPSI:
Essential Principles of Signal Integrity

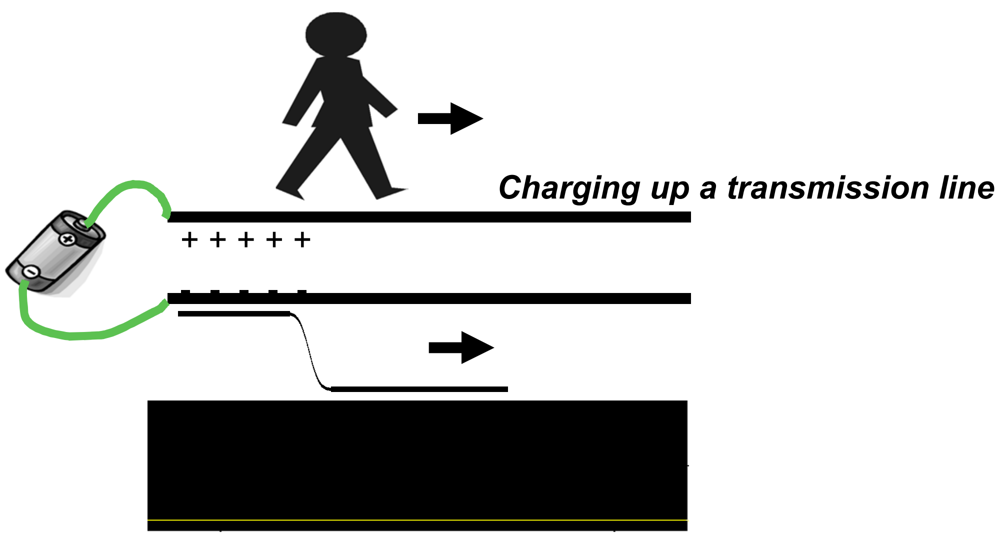
With Eric Bogatin,
Signal Integrity Evangelist,
Teledyne LeCroy Front Range Signal Integrity Lab

- EPSI-01-60: recorded live, Dec 1, 2013
  - Traditional LC model for transmission lines and why it's not very useful
  - Instantaneous impedance: the most useful concept in signal integrity
  - The best way to think about the instantaneous impedance
  - "be the signal"
  - What a signal really sees as it propagates down an interconnect

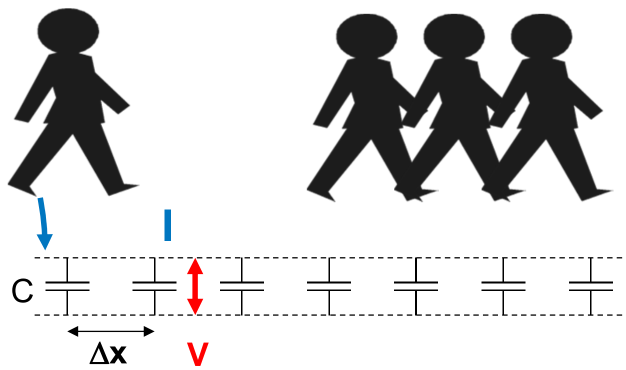
Electrical Model of a Lossless Transmission Line



"…be the signal"



What is the Impedance of a Transmission Line?



$$Z = \frac{\text{Voltage applied}}{\text{Current through}}$$

$$C = C_L \Delta x$$

$$I = \frac{\Delta Q}{\Delta t} \qquad \Delta Q = CV,$$

$$\text{every } \Delta t = \frac{\Delta x}{v}$$

$$I = \frac{\Delta Q}{\Delta t} = \frac{v C_L \Delta x V}{\Delta x} = v C_L V$$

instantaneous impedance of the transmission line

$$Z = \frac{V}{I} = \frac{V}{v C_L V} = \frac{1}{v C_L}$$

The characteristic impedance of a transmission line:
The one value of instantaneous impedance in a uniform transmission line

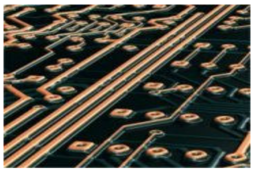
Lesson EPSI-01-70 Characteristic Impedance

Course EPSI:
Essential Principles of Signal Integrity

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

- EPSI-01-70: recorded live, Dec 1, 2013
  - The instantaneous impedance in a uniform transmission line
  - What characteristic impedance really means
  - Characteristic impedance and the length of the transmission line
  - The input impedance of a transmission line
  - Driving a transmission line and the voltage launched into a line

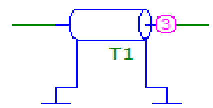
Characteristic Impedance of a Transmission Line



Uniform Transmission Lines

$$Z_0 = \frac{1}{v\ C_L}$$

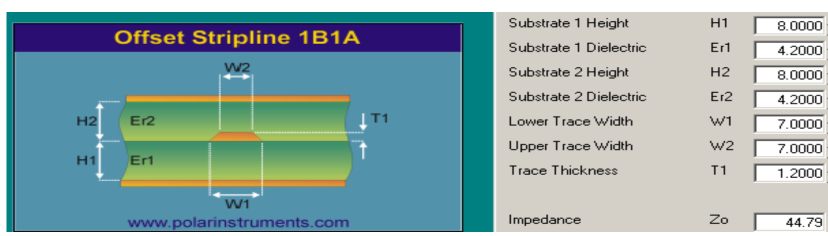
- only applies to uniform transmission lines
- the one instantaneous impedance that "characterizes" a uniform transmission line
- independent of length
- is the instantaneous impedance a signal will see when propagating down a uniform section

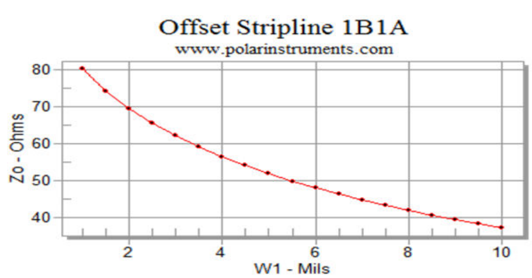


An ideal transmission line model: Z0, TD

Calculating Z0 with the Polar Instruments SI9000 2D Field Solver

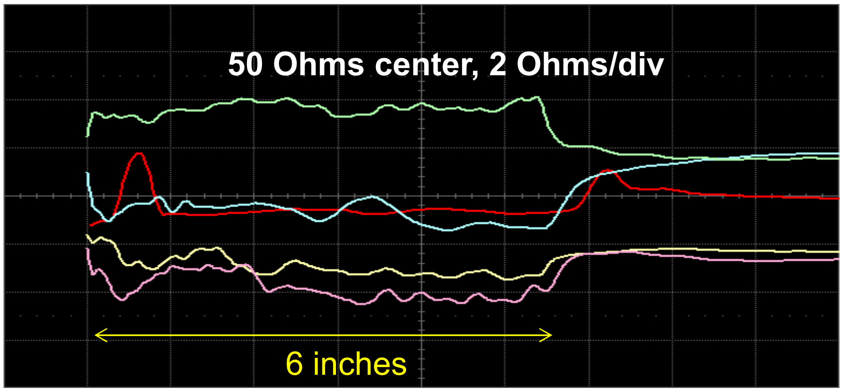
- Select the parameterized cross section
- Input parameter values
- Calculate the Z0
- Explore design space





For 8 mil thick dielectric on each layer, line width should be 5.5 mils for 50 Ohms.
(Dk = 4.2 T = 1.2 mils)

Typical Impedance Variations Down a Circuit Board Trace



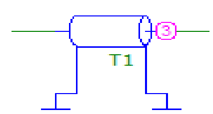
4 different lines, on 4 different boards, 1080 glass

Red trace- stripline, 2116 flatter glass

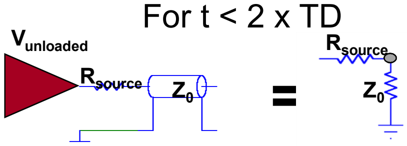
Variation in Z may be a measure of potential sensitivity to glass weave skew

An Ideal Transmission Line Model

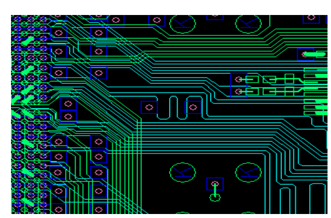
- Ideal lossless transmission line
  - Characteristic impedance, Zo
  - Time delay, TD
  - Accounts for reflection noise, time delays
- The input impedance of a transmission line



For t < 2 x TD



$$V_{launched} = V_{unloaded} \frac{Z_0}{Z_0 + R_{source}}$$



- What's missing?
  - Coupled transmission lines (diff pairs, multiple lines)
  - Lossy transmission lines (impact on rise time degradation)

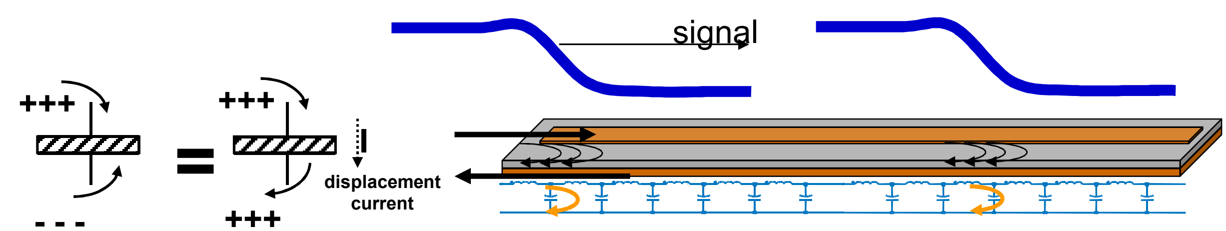
Lesson EPSI-01-80 Return Current

Course EPSI:
Essential Principles of Signal Integrity

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

- EPSI-01-80: recorded live, Dec 1, 2013
  - Essential principle #4: return current
  - How current really propagates in a transmission line
  - Current wave front has 2 directions: propagation and circulation
  - Direction of circulation of the signal-return current wavefront
  - Where return current actually flows in a transmission line

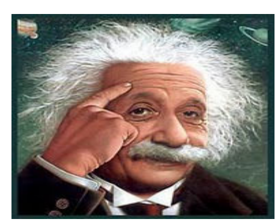
Essential Principle # 4:
The Return Current is Just as Important as the Signal Current



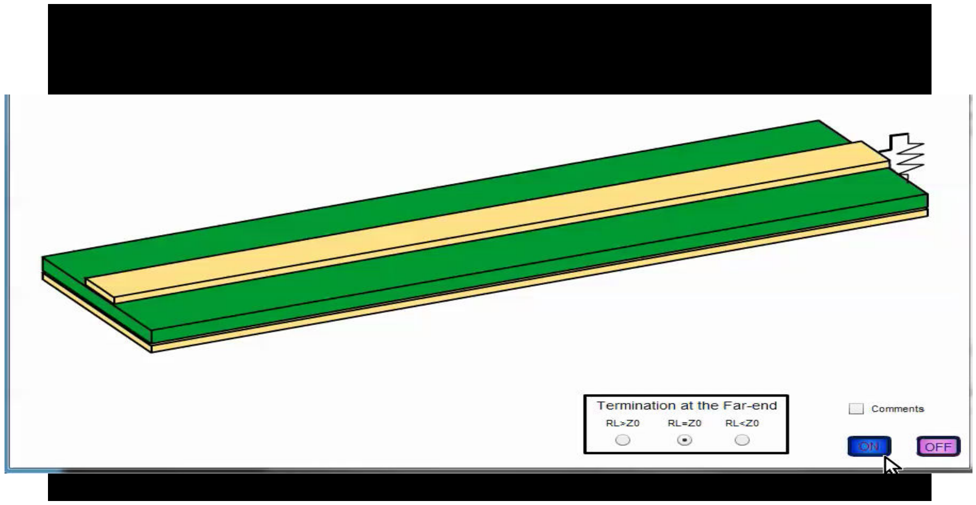
The current loop has two directions associated with it:

1. ***A direction of propagation***
2. ***A direction of circulation***

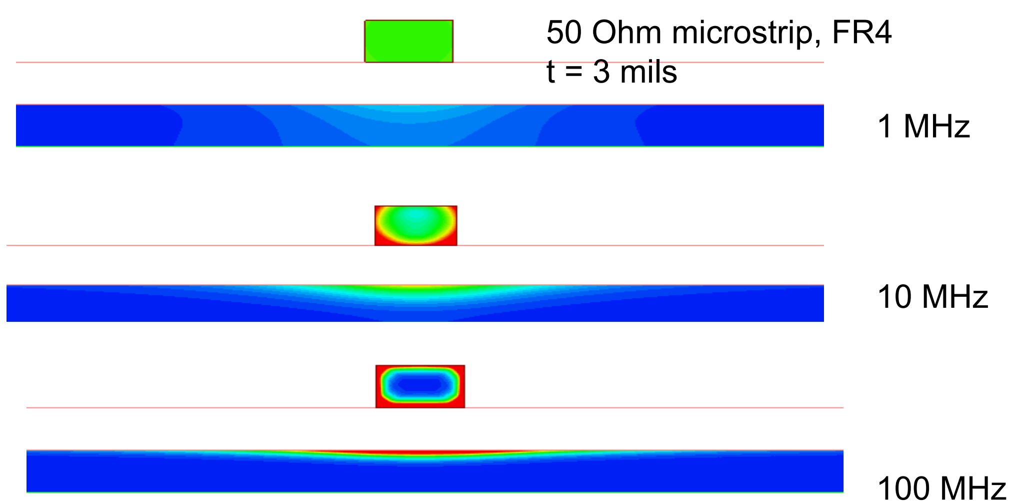
They are independent!



Current Flow in a Transmission Line



Current Distributions



Summary

- The way to avoid signal integrity problems is to
  - Identify the problems
  - Find their root cause
  - Follow design guidelines to prevent them
  - Evaluate with analysis tools
- Most important take always
  - The 9 essential principles of signal integrity
  - The 6 families of signal integrity problems
  - The 10 habits of highly successful designers

The Nine Essential Principles of Signal Integrity

1. All interconnects are transmission lines
2. Signals are dynamic
3. Signals see an instantaneous impedance
4. Current propagates as a signal-return path loop with a direction of propagation and a direction of circulation
5. Reflections occur whenever the instantaneous impedance changes
6. Inductance is fundamentally about how efficient a conductor is in generating rings of magnetic field lines
7. Current in a conductor redistributes at higher frequency driven by minimizing loop inductance
8. Dielectric materials absorb electrical field energy causing attenuation
9. Common currents in conductors radiate and often cause EMC failures

The Ten Habits of Highly Successful Designers

1. Design all interconnects as controlled impedance and terminate when necessary
2. Minimize all branch lengths and stub lengths. Route with linear topology
3. Space out signals as far as possible, or at least 2 x the line width
4. Don't screw up the return path, or share return paths
5. Corollary to #4: Do not allow signals to cross gaps in return planes
6. Corollary to #4: Use return vias adjacent to EVERY signal via
7. Under 1 Gbps, use tightly coupled differential pairs, over 1 Gbps, consider loosely coupled diff pairs, with symmetrical lines
8. Use multiple power and ground planes on adjacent layers with thin dielectric between them, close to the surface
9. Use shortest, widest surface traces possible for decoupling capacitors, as close to via in pad as possible
10. Use enough total capacitance for low frequency and enough capacitors for low inductance at high frequency. Use simulation to optimize capacitor values to minimize peak impedance at parallel resonances

Rule #9: Never do a measurement or simulation without first anticipating what you expect to see.

- If you are wrong, there is a reason- either the set-up is wrong or your intuition is wrong. Either way, by exploring the difference, you will learn something
- If you are right, you get a nice warm feeling that you understand what is going on.


Done!
TELEDYNE LECROY
Everywhereyoulook™