Differential Impedance …finally made simple

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Overview

- What's impedance
- Differential Impedance: a simple perspective
- Coupled Transmission line formalism
- Measuring differential impedance
- Emulating effects of a split in return path
- Calculating differential impedance

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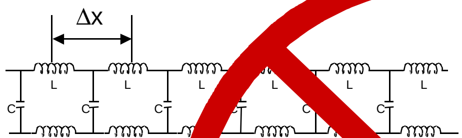
First Order Model of a Transmission Line (Loss Less Model)



(unbalanced transmission line)

$C = C_L\ \Delta x$ capacitance

$L = L_L\ \Delta x$ inductance

The circuit analysis result:

$$Z_0 = \sqrt{\frac{L_L}{C_L}} \qquad TD = \sqrt{L_{total} C_{total}} \qquad v = \frac{1}{\sqrt{L_L C_L}}$$

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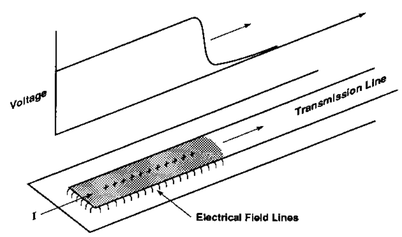
"…be the signal"



courtesy ICE

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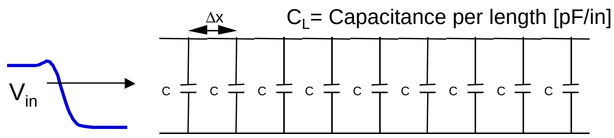
0th Order Model of Transmission Line



$$C = C_L \, \Delta x$$

$$\Delta Q = CV,$$

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

I, V definition of Transmission Line: $$I = \frac{\Delta Q}{\Delta t} = \frac{v C_L \Delta x V}{\Delta x} = v C_L V$$

What's the impedance?

Instantaneous Impedance of a Transmission Line

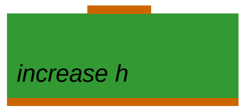
$$I = v C_L V$$

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

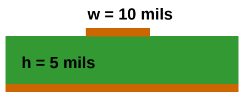
$$Z_0 = \frac{1}{v C_L}$$

Features of the impedance:
- looks like a resistor
- dependant on intrinsic properties only
- is an intrinsic property
- independent of length
- defined as the "characteristic impedance" = Z_0
- also called the “surge impedance” or “wave impedance”

Characteristic Impedance and Capacitance per Length



What happens to the capacitance per length? The characteristic impedance?



50 Ohm PCB cross section

What happens to the capacitance per length? The characteristic impedance?

$$Z_0 \sim \frac{1}{C_L}$$

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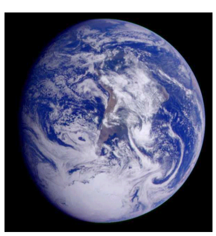
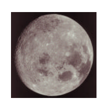
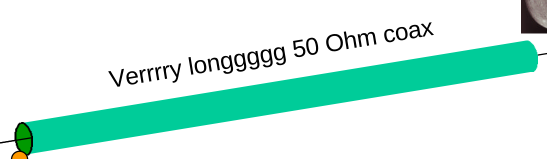
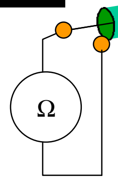
What Does it Mean to Have a 50 Ohm Line?









What will Ohm-meter read?

For the first second? After 3 seconds? After 10 sec?

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An important Distinction

- THE impedance of the transmission line (may be time dependent)
- The instantaneous impedance of the transmission line
- The Characteristic impedance of the transmission line

Just referring to "…the impedance" may be a bit ambiguous

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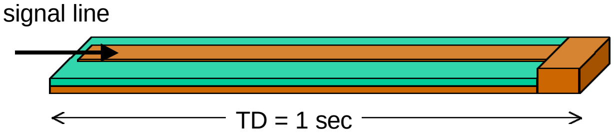
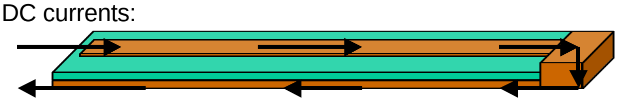
Return Path in T Lines

Current into signal line



Where is the return path?

For DC currents:



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

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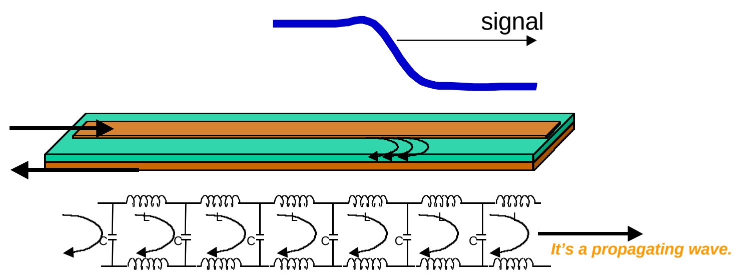
Current Flow in the Transmission Line



What happens initially if the end is open?, shorted?, terminated?

To control impedance, manage the return path as carefully as the signal path

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The Growing Importance of Differential Pair Use

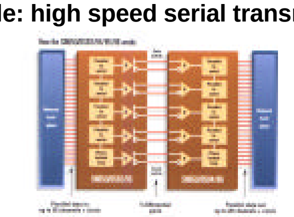
Early Applications for Differential Pairs

MECL I	**1962**
MECL II	**1966**
MECL III	**1968**
MECL 10k	**1979**
MECL 10kH	**1981**

ANSI/TIA/EIA-644-1995 is the generic physical layer standard for LVDS. It was approved in November of 1995, and first published in *March of 1996*.

Example: high speed serial transmission

TI 1.8 Gbps LVDS TRX



- **→ IEEE1394**
- **→ IEEE488**
- **→ Gigabit Ethernet**

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What's a Differential Pair Transmission Line?

???

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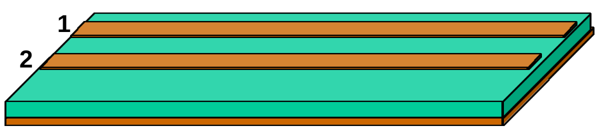
What's a Differential Pair Transmission Line?

Answer: …..any two, coupled transmission lines (with their return paths).



A special case: a symmetric pair

What's differential impedance?

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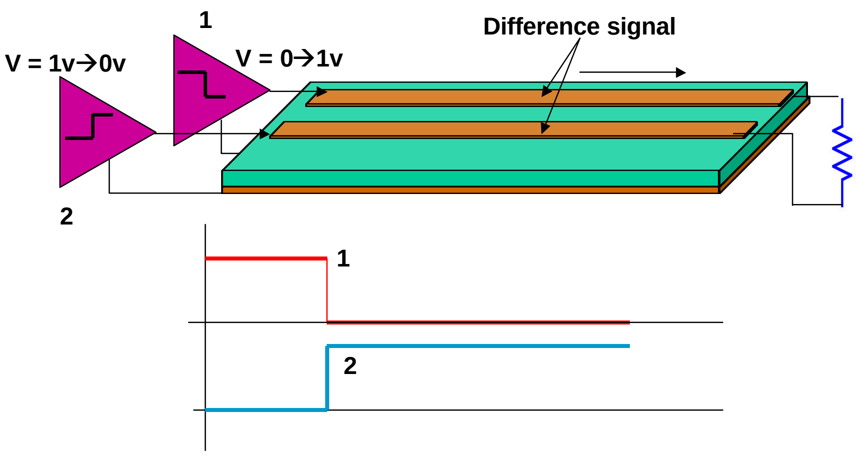
Differentially Driving a Differential Pair



What is the difference signal?

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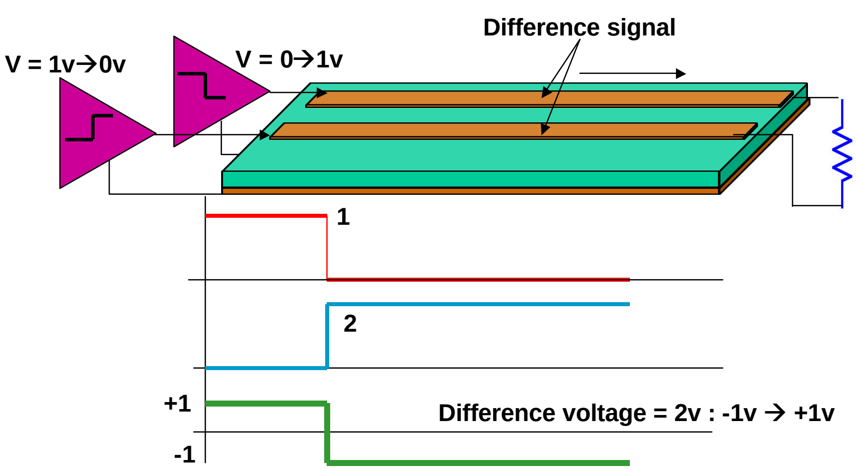
The Difference Signal



What is the impedance the difference signal sees?

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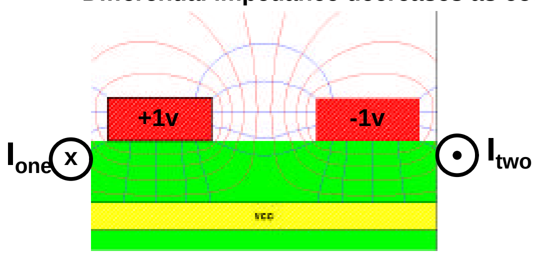
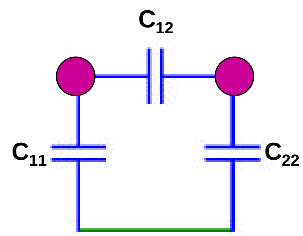
Differential Impedance

Differential Impedance: the impedance the difference signal sees

$$Z(diff) = \frac{V(diff)}{I_{one}} = \frac{2V}{I_{one}} \approx 2(Z_0 - small)$$

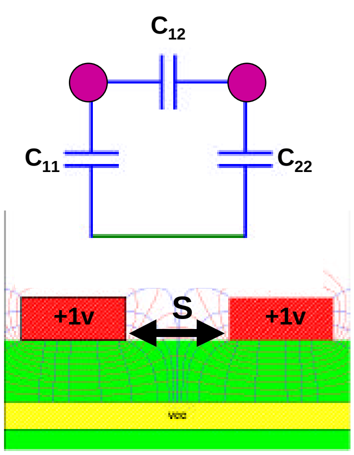
Differential impedance decreases as coupling increases

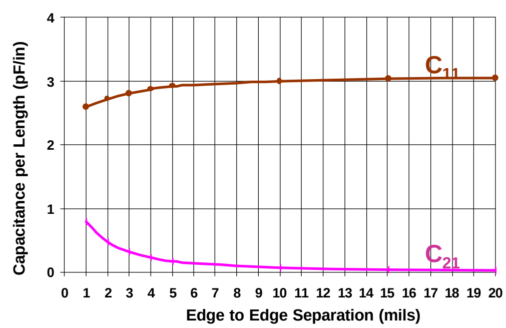




How will the capacitance matrix elements be affected by spacing?

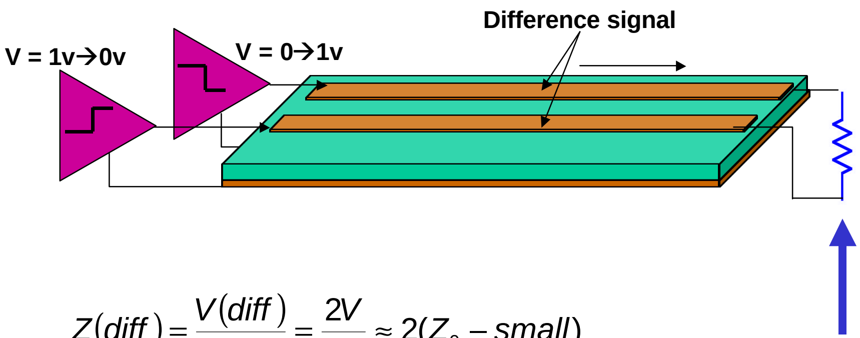
Capacitance Matrix Elements





What happens to the differential impedance as S gets smaller?

How to Terminate the Difference Signal?



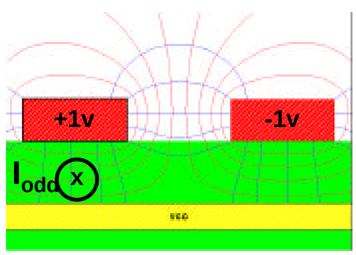
$$Z(diff) = \frac{V(diff)}{I_{one}} = \frac{2V}{I_{one}} \approx 2(Z_0 - small)$$

If there is no coupling, and each line is 50W, what resistor terminates the differential pair?

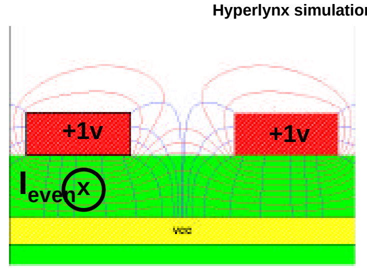
Terminate with a resistor to match impedance of the difference signal

Formalism: Mode Pattern for Identical Traces

Hyperlynx simulation



Mode: odd, or 1, or a



Mode: even, or 2, or b

Corresponds to differential driven

Corresponds to common driven

What is I_{odd} compared to I_{even}?
How do they vary with spacing?

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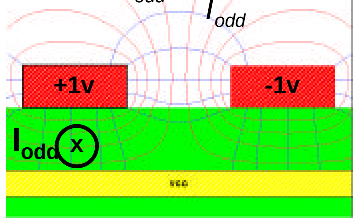
Odd and Even Mode Impedance

$$Z_{odd} = \frac{V}{I_{odd}}$$



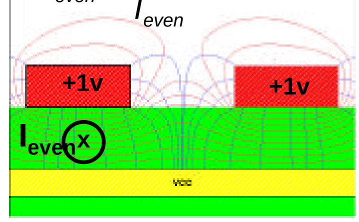
Mode: odd, or 1, or a

Odd mode current increases as traces are brought together

Odd mode impedance decreases

$$Z_{even} = \frac{V}{I_{even}}$$

Hyperlynx simulation



Mode: even, or 2, or b

Even mode current decreases as traces are brought together

Even mode impedance increases

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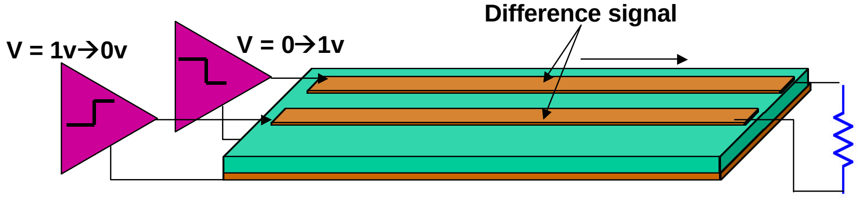
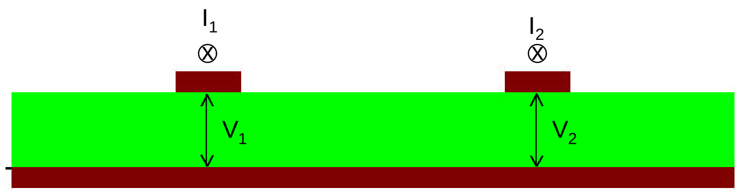
Differential Impedance and Odd Mode Impedance



$$Z(diff) = \frac{V(diff)}{I_{one}} = \frac{2V}{I_{one}} = 2 \text{ x } Z_{odd}$$

The Characteristic Impedance Matrix

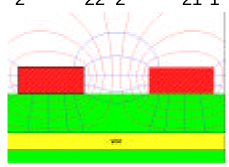


Define a Characteristic Impedance Matrix

$$V_1 = Z_{11}I_1 + Z_{12}I_2$$

$$V_2 = Z_{22}I_2 + Z_{21}I_1$$

How is Z_{12} influenced by coupling?
Is Z_{12} large or small?



Characteristic Impedance Matrix [ohms]:

	1	2
1	**49.6**	**6.4**
2	**6.4**	**49.6**

Hyperlynx simulation

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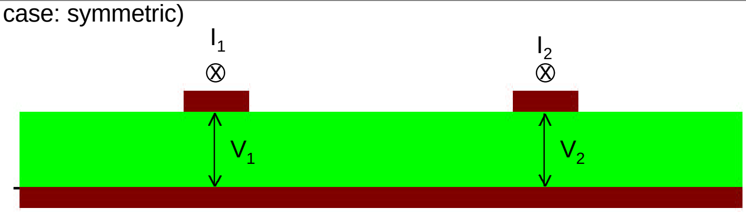
Definition of Odd and Even Mode Impedance

(Special case: symmetric)



Define:

$$V_{odd} = \frac{1}{2}(V_1 - V_2) \qquad Z_{odd} = \left.\frac{V_{odd}}{I_1}\right|_{V_{even}=0}$$

$$V_{even} = \frac{1}{2}(V_1 + V_2) \qquad Z_{even} = \left.\frac{V_{even}}{I_1}\right|_{V_{odd}=0}$$

What is the voltage when V_{even} = 0? When V_{odd} = 0?

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Odd and Even Mode Impedance

$$V_1 = Z_{11} I_1 + Z_{12} I_2$$

$$V_2 = Z_{22} I_2 + Z_{21} I_1$$

Odd Mode: $I_1 = -I_2$ $\quad V_{odd} = \frac{1}{2}(V_1 - V_2) = (Z_{11} - Z_{12}) I_1$

$$Z_{odd} = (Z_{11} - Z_{12})$$

Odd mode impedance is reduced with coupling

Even Mode: $I_1 = I_2$ $\quad V_{even} = \frac{1}{2}(V_1 + V_2) = (Z_{11} + Z_{12}) I_1$

$$Z_{even} = Z_{11} + Z_{12}$$

Even mode impedance is increased with coupling

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Mode Impedances

Odd mode impedance is the impedance of one line when the pair is driven differentially $\quad Z_{odd} = (Z_{11} - Z_{12})$

Differential impedance: $Z(diff) = \frac{V(diff)}{I} = \frac{2V}{I} = 2(Z_{odd}) = 2(Z_{11} - Z_{12})$

Even mode impedance is the impedance of one line when the pair is driven commonly $\quad Z_{even} = Z_{11} + Z_{12}$

Common impedance: $Z_{common} = Z_{even} = Z_{11} + Z_{12}$

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Summary So Far

- A differential pair is any two transmission lines
- Special case: symmetric lines
- Differential driving has symmetric, opposite signal on each line
- Differential impedance is the impedance the difference signal sees
- With no coupling, current into one line depends on capacitance per length of the line
- With coupling, current into one line depends on how the other line is driven
- The impedance of one line will depend on how the other line is driven

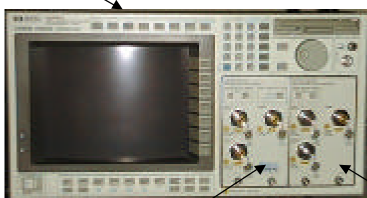
The differential impedance will be twice the impedance of one line when the pair is driven differentially

How can differential impedance be measured?

TDR Equipment

HP 83480A
Digital Communications Analyzer (mainframe)

TDR: Time Domain Reflection
TDT: Time Domain Transmission
DTDR: Differential Time Domain Reflection
DTDT: Differential Time Domain Transmission



HP 54754A
Differential TDR Module
Two independent TDR channels
- **simultaneous TDR/TDT**
- **simultaneous differential TDR**

HP 83484A
2 Channel 50 GHz Module
Two independent voltage channels

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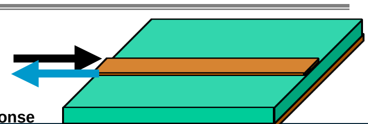
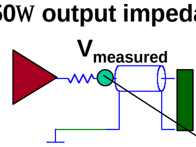
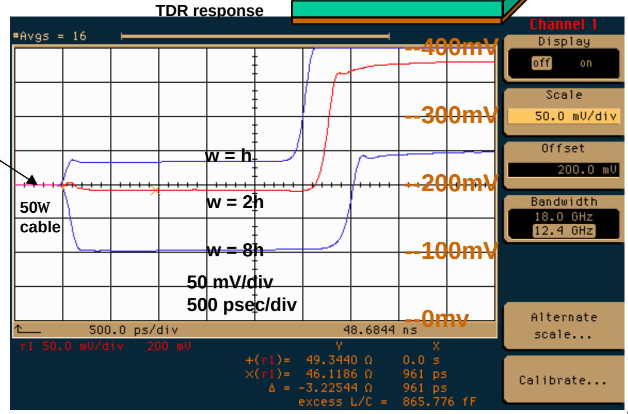
Conventional Single Channel TDR



TDR: 400 mV output, unloaded
50W output impedance



TDR response



3 different line width microstrips, each 9 inches long

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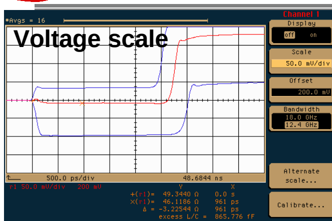
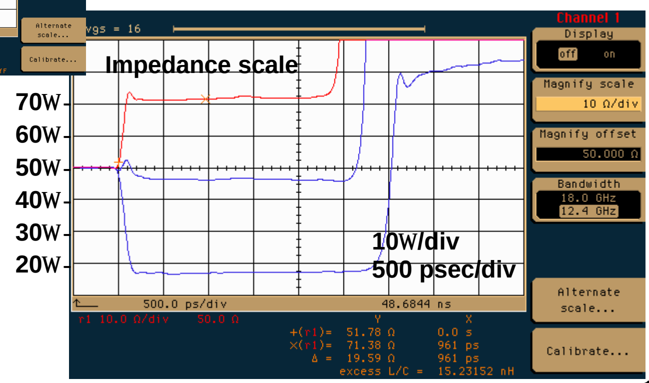
Converting Reflected Voltage into Impedance



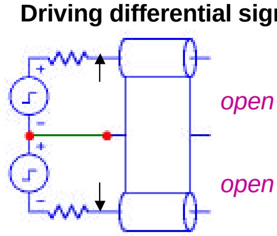
$$\rho = \frac{V_{reflected}}{V_{incident}} \qquad Z_{DUT} = 50\Omega \frac{1-\rho}{1+\rho}$$

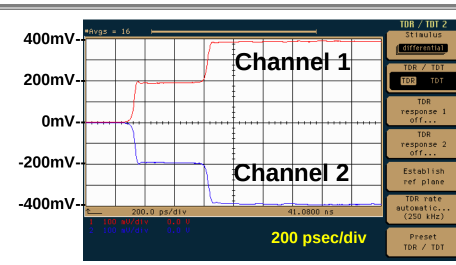
Plotting impedance directly



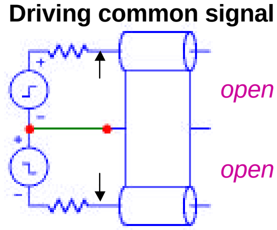
Two Channel Differential TDR: Differential or Common Driven

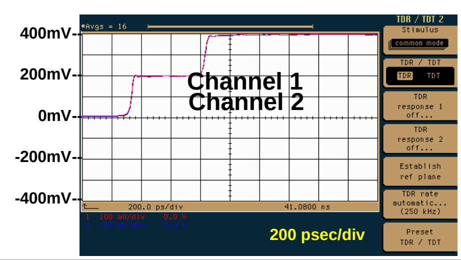
Driving differential signal





Driving common signal





Measuring Odd and Even Impedance of Tightly Coupled Lines

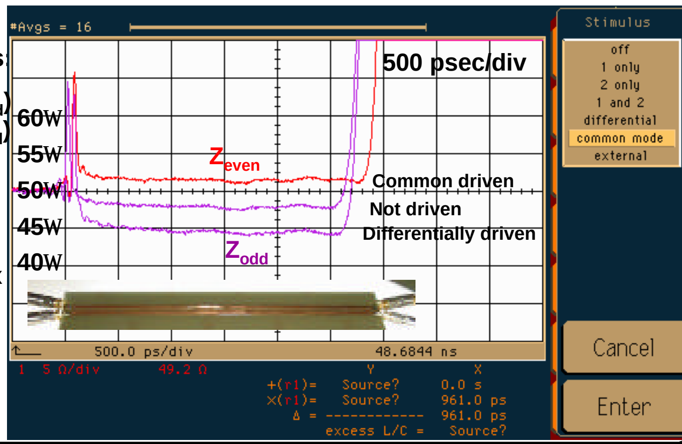
Measured Impedance of *one trace*, as the other is driven:
Odd mode impedance: differentially driven pair
Even mode impedance: commonly driven pair

For identical lines:

$$Z_{11} = ½ (Z_{even} + Z_{odd})$$
$$Z_{12} = ½ (Z_{even} − Z_{odd})$$

Extracted Characteristic impedance matrix

48.5	3.5
3.5	48.5



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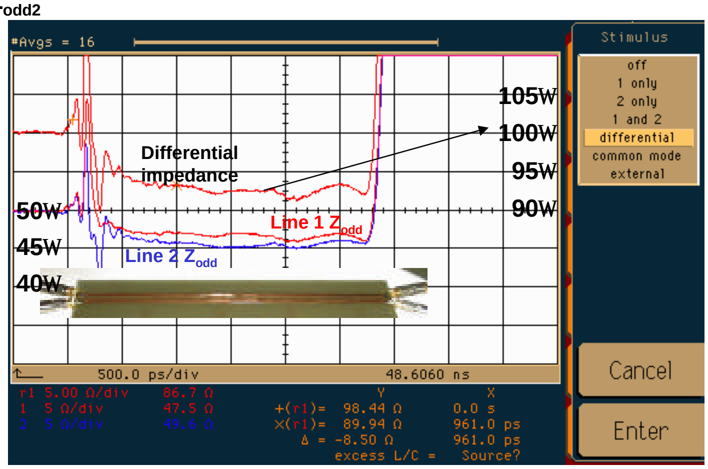
Direct Measurement of Differential Impedance

$$Z_{diff} = Z_{odd1} + Z_{odd2}$$



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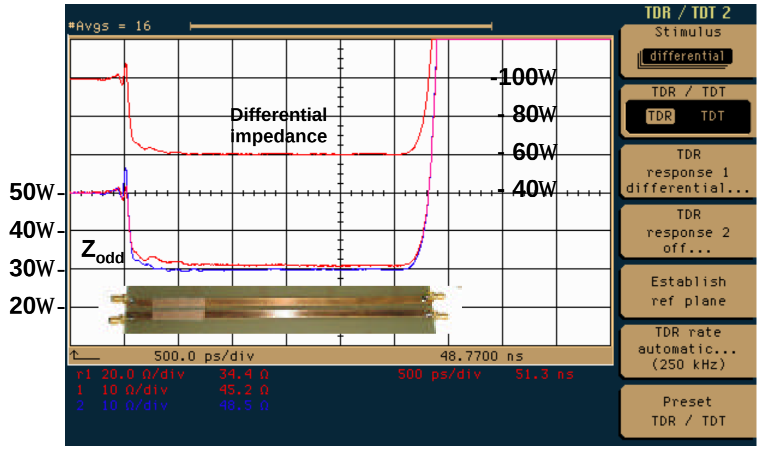
Measuring Differential Impedance of Low Impedance Traces



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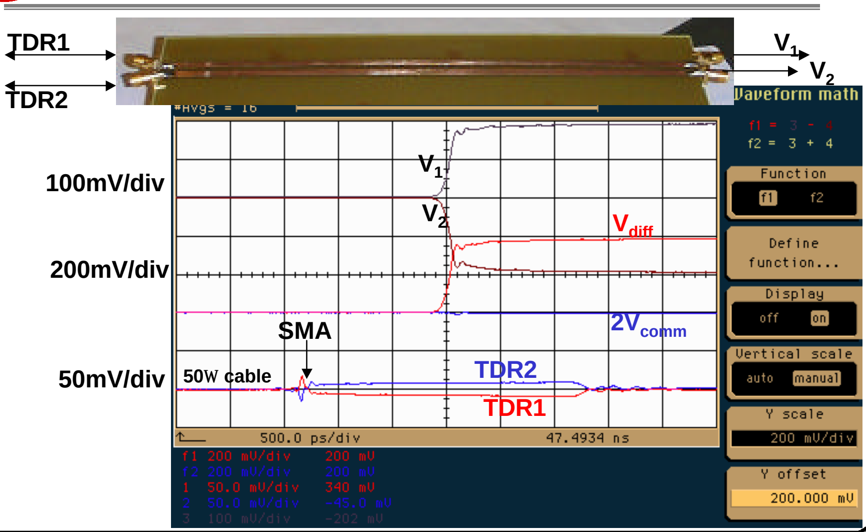
Full Characterization of a Differentially Driven, Differential Pair



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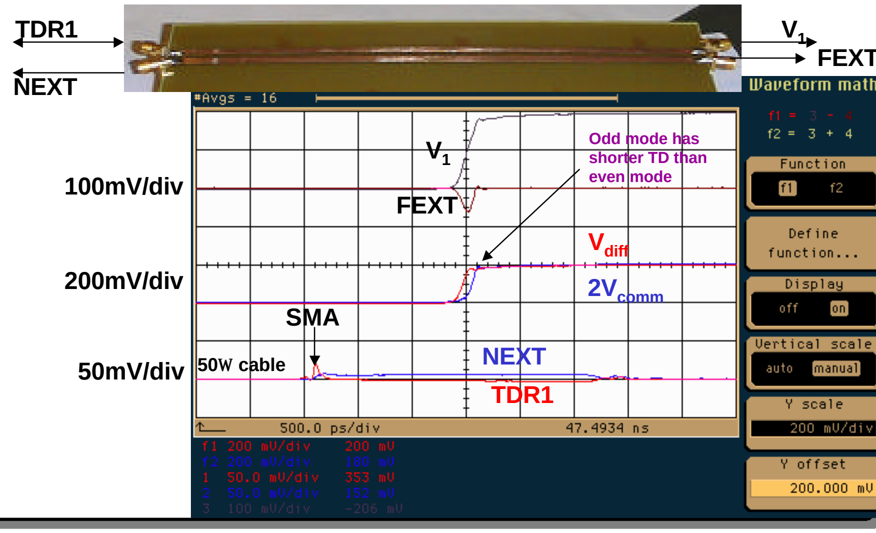
Full Characterization of a Single End Driven, Differential Pair



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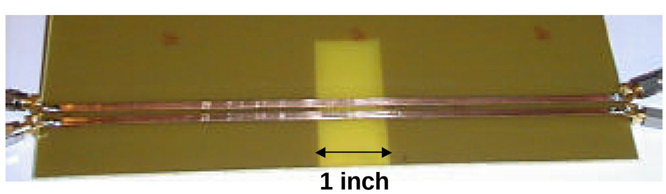
Differential Pair Over Split in the Return Path



What will be the behavior when:

→ single end driven

→ differentially driven?

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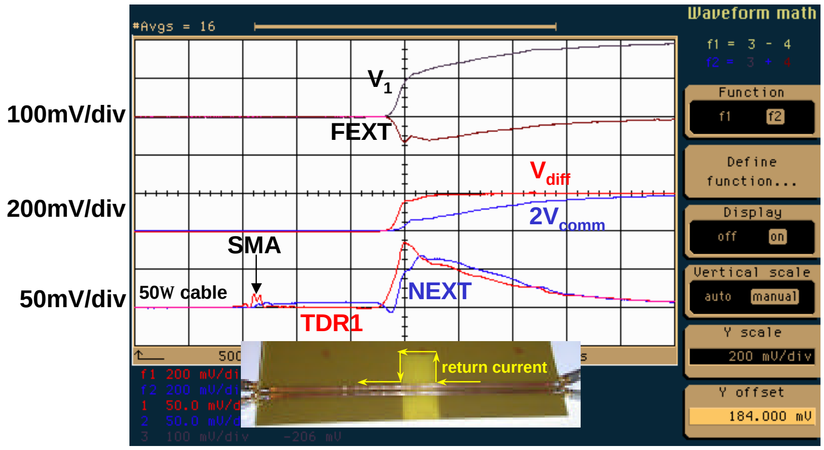
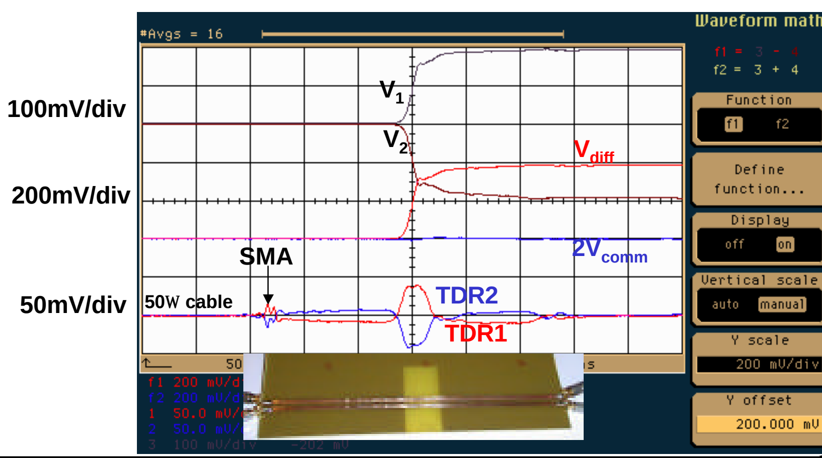
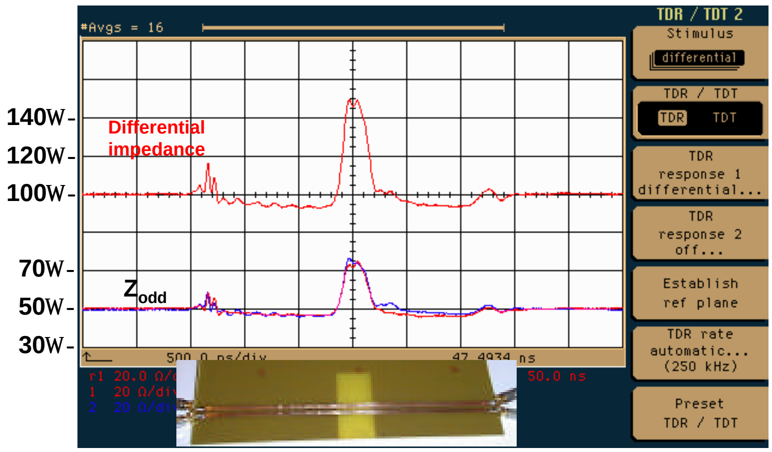
Full Characterization of a Single End Driven, Differential Pair Over a Split in the Return Path



Full Characterization of a Differentially Driven, Differential Pair Over a Split in the Return Path



Measured Impedances



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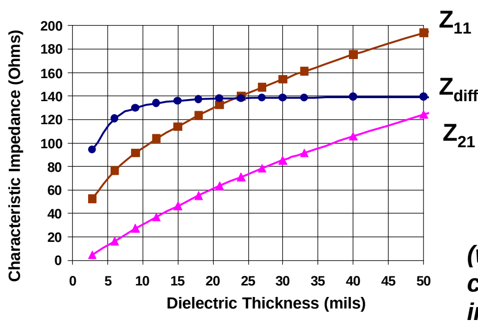
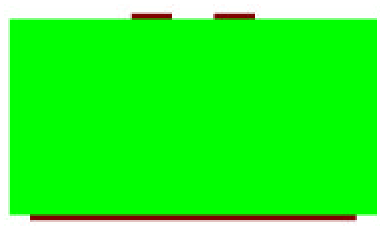
Impedance as the Dielectric Thickness Increases

Ansoft Maxwell 2D Extractor





Z_{diff} ~ 140 Ohms with the bottom plane as the return path, when far away

(when Z_{21} is a large fraction of Z_{11}, coupling dominates, differential impedance approaches single ended impedance)

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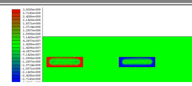
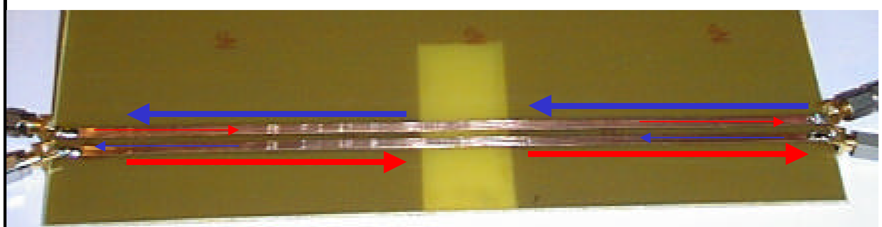
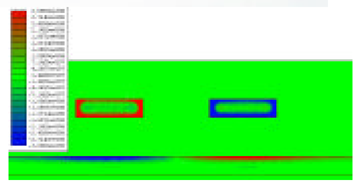
What Are the Return Currents When Driven Differentially?







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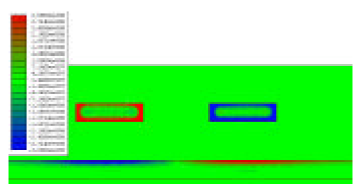
Return Currents in Differential Pairs

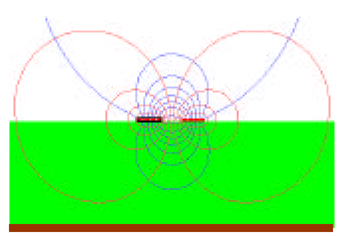
Most return current is carried by the plane when trace to plane coupling >> trace to trace coupling

Ex: most board level interconnects



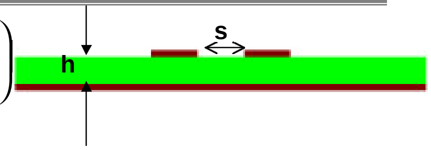
Most return current is carried by the other trace when trace to plane coupling << trace to trace coupling

Ex: most connectors, shielded twisted pair, twisted pair

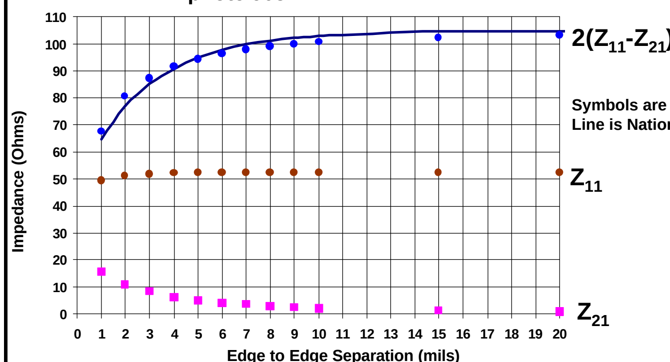


First Order Approximations to Differential Impedance: Microstrip

$$Z_{diff} = 2Z_0\left(1 - 0.48\exp\left(-0.96\frac{s}{h}\right)\right)$$



National Semiconductor model
Apnote 905



Symbols are extracted with field solver
Line is National model

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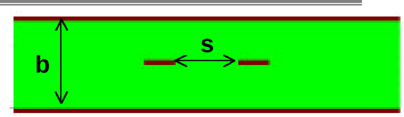
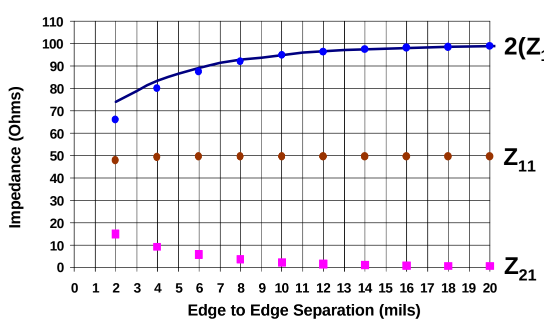
First Order Approximations to Differential Impedance: Stripline

$$Z_{diff} = 2Z_0\left(1 - 0.347\exp\left(-2.9\frac{s}{b}\right)\right)$$



National Semiconductor model
Apnote 905



Symbols are extracted with field solver
Line is National model

Note, accurate only for Z_0 values near 50 Ohms!

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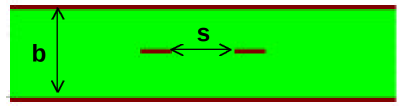
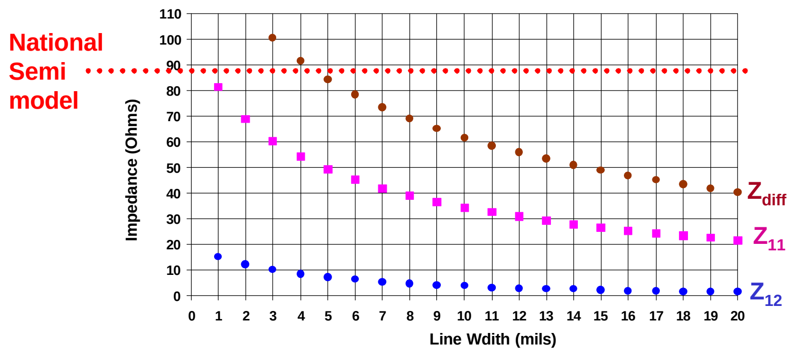
Impact from Width of the Line

b = 15 mils
s = 5 mils
Sweeping w





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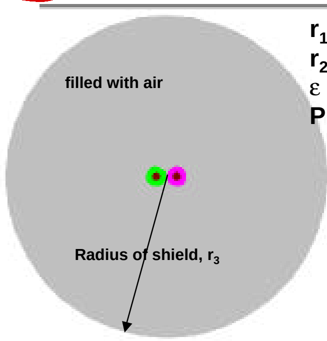
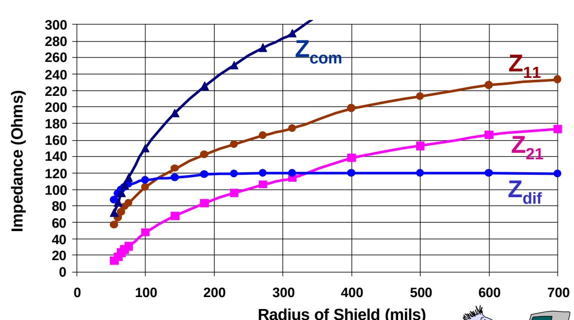
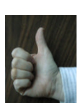
Shielded Twin Leads, Changing Shield Size



r_1 = 10 mils
r_2 = 25 mils
ε = 4
Pitch = 50 mils

Single ended impedance = 120W





differential impedance approaches single ended impedance when r_s > 3 x pitch

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Summary

- The impedance of one line in a differential pair depends on how the other is being driven:
  - ✓ Measure odd impedance by driving differentially
  - ✓ Measure even impedance by driving in common
  - ✓ Requires Differential TDR (DTDR)
- Characteristic impedance matrix elements can be extracted from odd and even impedances
- A gap in the return path causes huge increase in cross talk in single ended lines due to high mutual inductance
- If you must cross a split plane, better to use a diff pair
  - ✓ Some increase in differential impedance
  - ✓ Very little distortion of differential signal
  - ✓ Very little common voltage created
- Full characterization of differential pairs is possible with DTDR and dual channel amplifier module

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For more information on resources and references, visit our web site:

www.BogatinEnterprises.com