OnLine Lecture 115: Introduction to Characteristic Impedance

- Why this topic is important
  - ✓ Characteristic impedance is the most important topic in signal integrity
  - ✓ It is also the most confusing
  - ✓ There is a simple way of thinking about it that eliminates the confusion
  - ✓ A good understanding of characteristic impedance will train your intuition to help you be a much better designer
- Level
  - ✓ Introduction
- Recommended prerequisites:
  - ✓ none

Outline

- ✓ What is a transmission line
- ✓ What is impedance
- ✓ The instantaneous impedance a signal sees
- ✓ Characteristic impedance and instantaneous impedance
- ✓ Calculating characteristic impedance
- ✓ The impedance of a transmission line
- ✓ Return current in a transmission line

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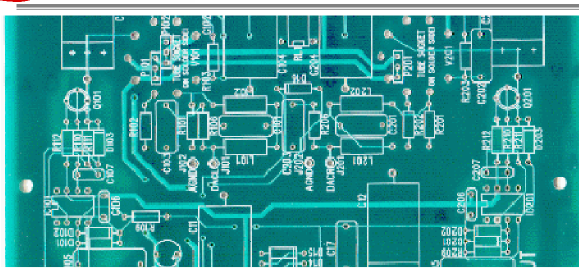
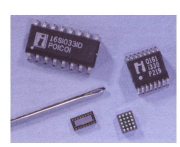
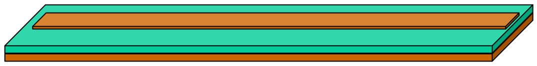


What's a Transmission Line?

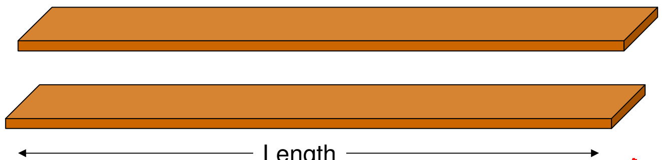


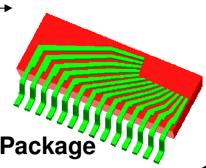
The Simplest Model of a Transmission Line



Microstrip

A "-1" order model:
Any two conductors with length

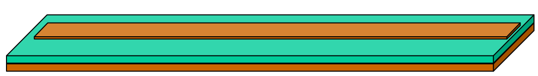




Lead frame of an IC Package

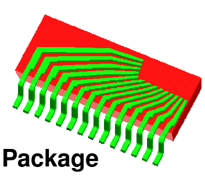
Classifying Transmission Lines by the Geometry of the Conductors

1. Uniform or non uniform down the length
   - ✓ Uniform transmission lines have the same cross section down their length



Microstrip

   - ✓ Non uniform transmission lines a changing cross section down their length

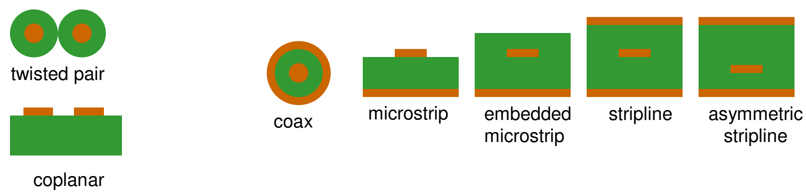


Lead frame of an IC Package
(pick any two leads)

Bogatin Enterprises MYTHS

Classifying Transmission Lines by the Geometry of the Conductors

2. Balanced or unbalanced

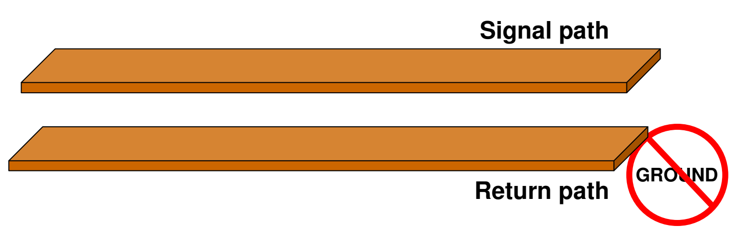


(how identical the two conductors are)

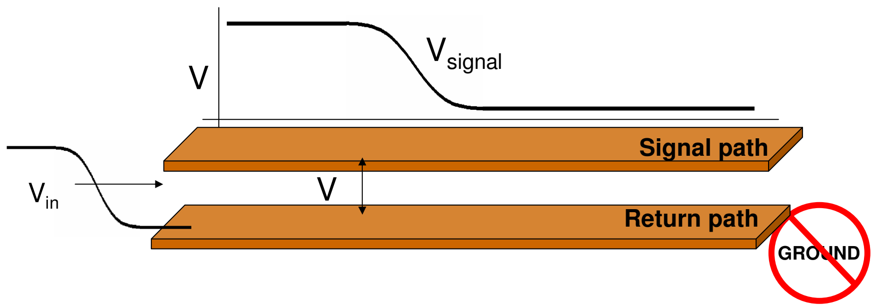
What's a signal?

Bogatin Enterprises MYTHS

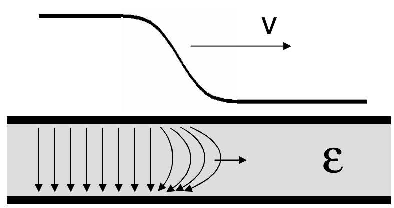
Labeling the Conductors



The Signal

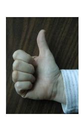


How fast does a signal move down a line?



in air: v = 186,000 miles per sec

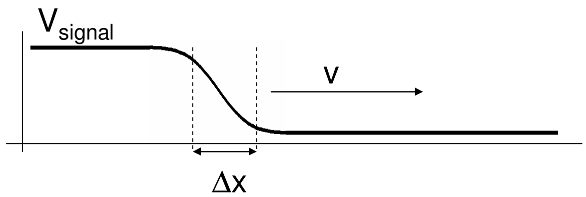
v = 12 inches/nsec



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

Spatial Extent of the Leading Edge

RT = rise time

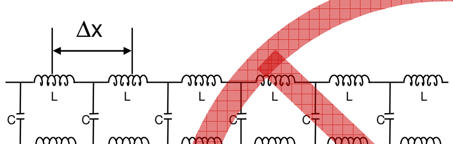


$$\Delta x = v \times RT$$

6 inches = 6 inches/nsec x 1 nsec

1.2 inch = 6 inches/nsec x 0.2 nsec

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



(unbalanced transmission line)

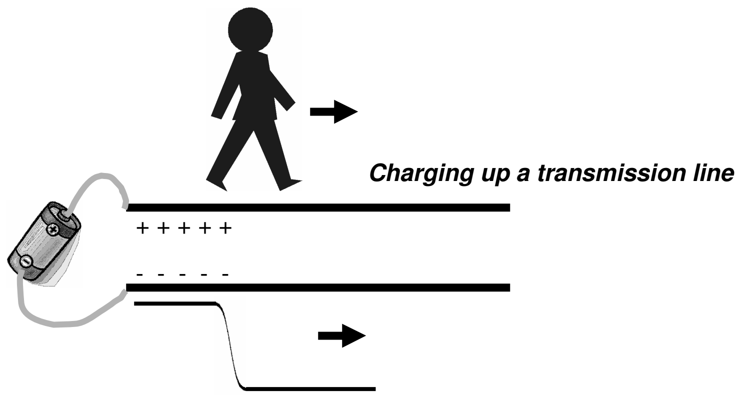
$C = C_L \, \Delta x$ capacitance

$L = L_L \, \Delta x$ inductance (loop)

The circuit analysis result:

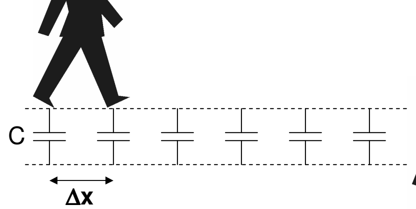
$$Z_0 = \sqrt{\frac{L_L}{C_L}} \qquad TD = \sqrt{L_{total} C_{total}} \qquad \upsilon = \frac{1}{\sqrt{L_L C_L}}$$

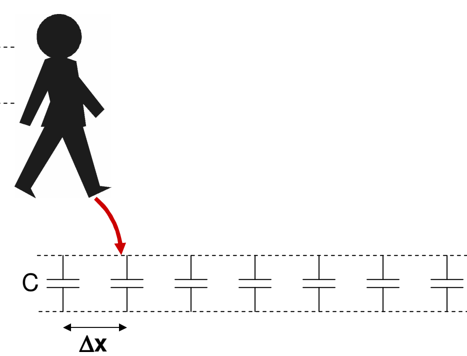
"…be the signal"



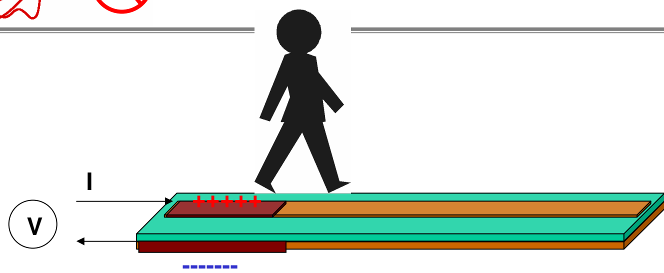
Building a simple model

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

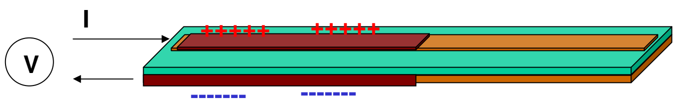




A Propagating Signal

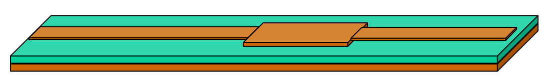


Charged line
after 1 nsec

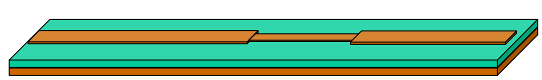


Charged line after 2 nsec

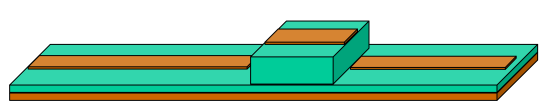
Geometry, Current and Impedance



Line width increases, impedance___**decreases**_____

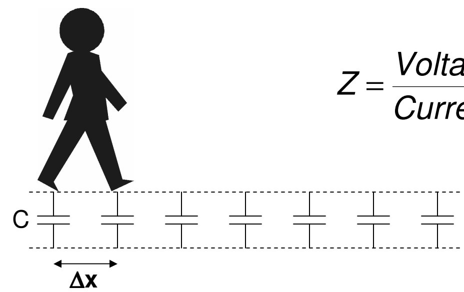


Line width decreases, impedance ___**increases**_____



Dielectric thickness increases, impedance, ___**increases**_____

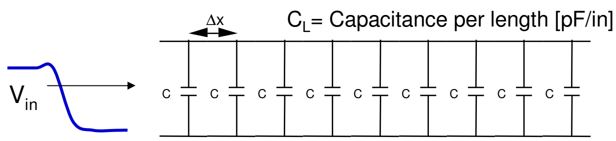
Instantaneous Impedance The Signal Sees



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

instantaneous impedance of the transmission line

0th Order Model of Transmission Line



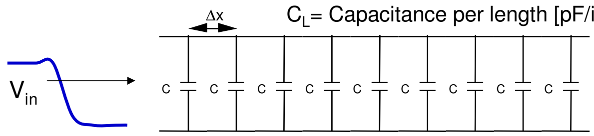
$$C = C_L \Delta x$$

$$\Delta Q = CV, \quad \text{every } \Delta t = \frac{\Delta x}{v}$$

What is the current into the line?

Current Into Transmission Line

C_L = Capacitance per length [pF/in]



$$C = C_L \Delta x$$

$$\Delta Q = CV,$$

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

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

$$I = v C_L V$$

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

<u>**Features of the impedance**</u>:
- looks like a resistor
- dependant on intrinsic properties
- independent of length

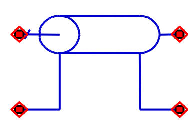
Characteristic Impedance

$$Z_0 = \frac{1}{vC_L}$$

- an intrinsic property of a transmission line
- independent of length
- is a the instantaneous impedance a signal will see when propagating down a uniform section
- also called the “surge impedance” or “wave impedance”

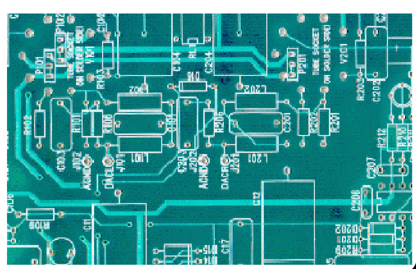
The Ideal, Lossless Transmission Line Model

A “transmission line” is the name we use to refer to the an ideal electrical circuit element



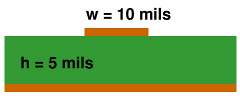
a new, fundamental, ideal circuit element: T
- Characteristic impedance, Z_0,
- Time delay: TD

A “transmission line” is also the name we use to refer to a real, physical interconnect



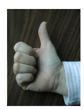
Characteristic Impedance and Capacitance per Length

capacitance per length decreases, the characteristic impedance increases



50 Ohm PCB cross section

the capacitance per length increases, characteristic impedance decreases

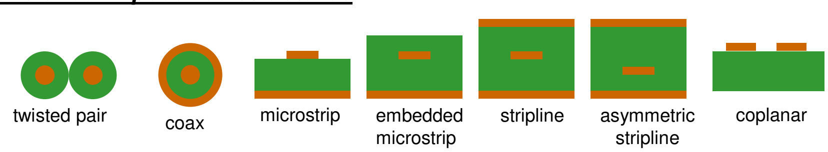


$$Z_0 \sim \frac{1}{C_L}$$

Controlled Impedance

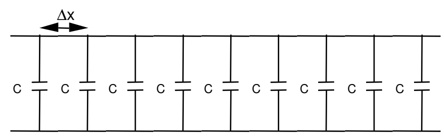
- Z_0 is constant down the length
- uniform capacitance per length: geometry and materials
- uniform velocity: materials
- any value Z_0 can be controlled impedance

Controlled impedance structures

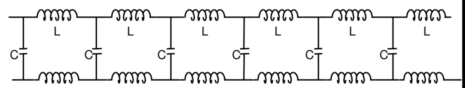


What About the Inductance of the Line?

- Physical model:
  - ✓ capacitance per length
  - ✓ physical distance
  - ✓ finite propagation speed



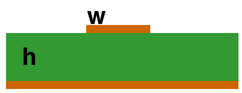
- Electrical model:
  - capacitance per length
  - physical distance
  - Inductance per length



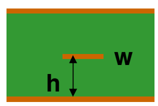
Calculating Characteristic Impedance

- Separating Myths from Reality: (OnLineLecture 000)
- Rules of Thumb (OnLineLecture 180)
- Approximations and 2D field solvers (OnLineLecture 130)
- Capacitance and inductance (OnLineLecture 120)

Calculating Characteristic Impedance: Rules of Thumb

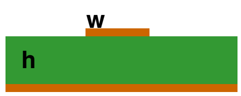


Microstrip:
50 Ohm line in FR4 has w:h = 2:1



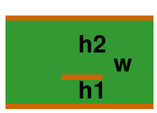
Stripline:
50 Ohm line in FR4 has w:h = 1:1

Calculating Characteristic Impedance: Approximations



$$Z_0 = \frac{87}{\sqrt{(\varepsilon_r + 1.41)}} \ln\left(7.5\frac{h}{w}\right)$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(2.35\frac{b}{w}\right)\Omega$$



$$Z_0 = \frac{80}{\sqrt{\varepsilon_r}} \ln\left(4.75\frac{h1}{w}\right)\left(1 - \frac{h1}{4h2}\right)$$

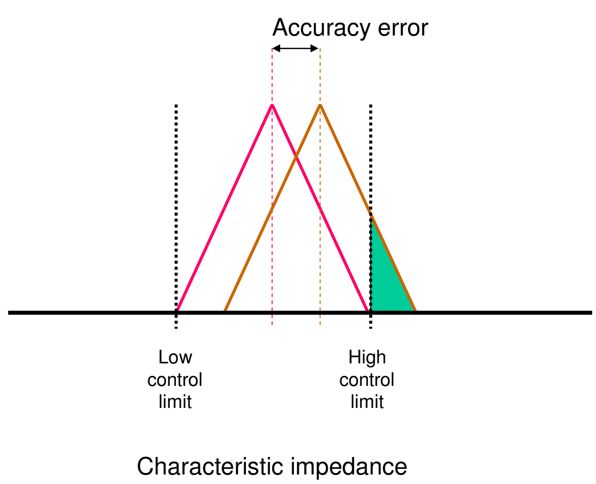
Accurate, Easy to Use 2D Field Solvers (absolute accuracy < 1%)

- Polar Instruments
  - ✓ Simplest to use
  - ✓ Dozens of pre-defined cross sections
  - ✓ No cross talk
- Hyperlynx
  - ✓ Simple
  - ✓ Impedance matrix elements
  - ✓ Integrated IBIS based simulator
- Ansoft SI 2D Extractor
  - ✓ Parameterizing
  - ✓ Mixed dielectrics
  - ✓ Arbitrary cross sections
  - ✓ Current distribution
  - ✓ Frequency dependent effects

Use a 2D field solver if:

1. Assured accuracy better than 20% is important
2. Etch back, solder mask or trace thickness are important
3. Mixed dielectrics are used
4. Cross talk is important

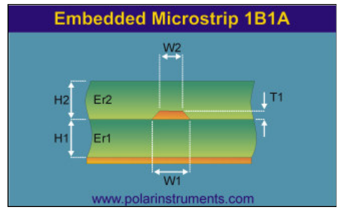
Why High Accuracy Can Save Money

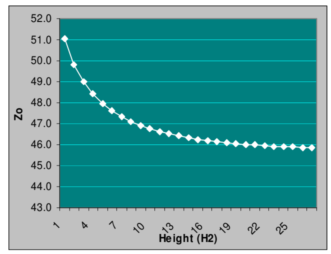


Simplest to use 2D field solver

Polar Embedded Microstrip 1B1A www.polarinstruments.com

H1	Er1	H2	Er2	W1	W2	T1	Calc Type	Zo
6	4.2	1	4.2	10	10	0.7	Zo	51.1
6	4.2	2	4.2	10	10	0.7	Zo	49.8
6	4.2	3	4.2	10	10	0.7	Zo	49.0
6	4.2	4	4.2	10	10	0.7	Zo	48.4
6	4.2	5	4.2	10	10	0.7	Zo	48.0
6	4.2	6	4.2	10	10	0.7	Zo	47.6
6	4.2	7	4.2	10	10	0.7	Zo	47.3
6	4.2	8	4.2	10	10	0.7	Zo	47.1
6	4.2	9	4.2	10	10	0.7	Zo	46.9
6	4.2	10	4.2	10	10	0.7	Zo	46.7
6	4.2	11	4.2	10	10	0.7	Zo	46.6
6	4.2	12	4.2	10	10	0.7	Zo	46.5
6	4.2	13	4.2	10	10	0.7	Zo	46.4
6	4.2	14	4.2	10	10	0.7	Zo	46.3
6	4.2	15	4.2	10	10	0.7	Zo	46.3
6	4.2	16	4.2	10	10	0.7	Zo	46.2
6	4.2	17	4.2	10	10	0.7	Zo	46.1
6	4.2	18	4.2	10	10	0.7	Zo	46.1
6	4.2	19	4.2	10	10	0.7	Zo	46.1
6	4.2	20	4.2	10	10	0.7	Zo	46.0
6	4.2	21	4.2	10	10	0.7	Zo	46.0
6	4.2	22	4.2	10	10	0.7	Zo	46.0
6	4.2	23	4.2	10	10	0.7	Zo	45.9
6	4.2	24	4.2	10	10	0.7	Zo	45.9
6	4.2	25	4.2	10	10	0.7	Zo	45.9
6	4.2	26	4.2	10	10	0.7	Zo	45.9
6	4.2	27	4.2	10	10	0.7	Zo	45.8





Impedance of Controlled Impedance Transmission Lines

Famous Characteristic Impedances:

RG58	52 Ω
RG174	50 Ω
RG59	75 Ω
RG62	93 Ω
TV Antenna	300 Ω
Cable TV	75 Ω
Twisted pairs	100-120 Ω

What's Special About 50Ω ?

1. Became international standard for instrumentation as radar proliferated.
2. Matches with most test and measurement equipment
3. Can be manufactured easily with circuit board technology.
4. Is a reasonable match to IC drivers.
5. Optimum value for high speed digital systems trades off between:
   - → power dissipation with parallel termination
   - → delay adders with capacitive loads
   - → cross talk for reasonable spacing
   - → manufacturability (total board thickness)
   - → interfacing with test equipment and peripherals
   - → "sweet spot" is 40 Ω -80 Ω

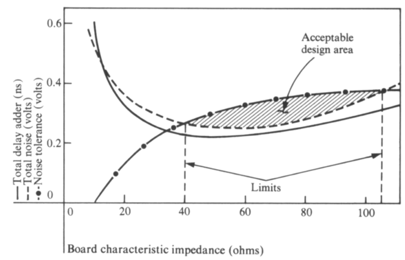
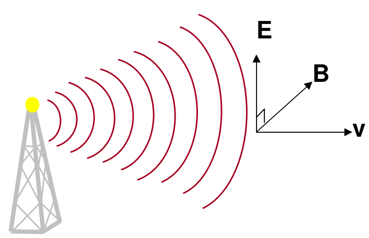


Figure 12 Design space for characteristic impedance.

"Electrical Design of a High Speed Computer Package", Evan Davidson, IBM J. of R&D, vol 26(3) May 1982, p. 349

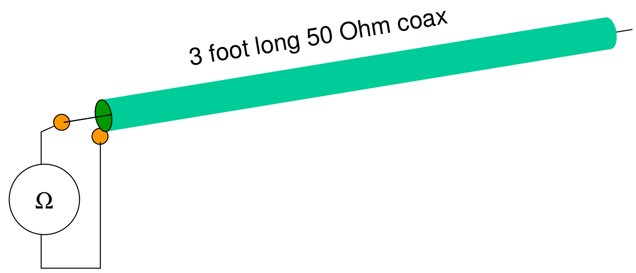
Characteristic Impedance of Free Space



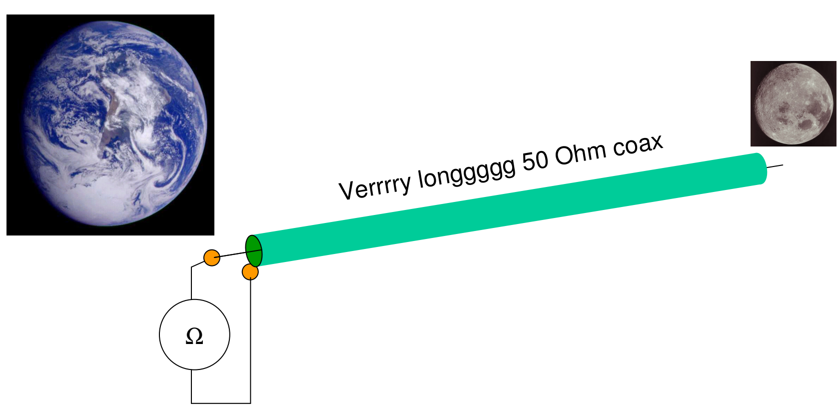
$$Z = \sqrt{\frac{B}{E}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \sqrt{\frac{4\pi 10^{-7}\, H/m}{8.85x10^{-12}\, F/m}} = 376.8\ Ohms$$

Characteristic impedance of Free Space ~ 377 Ohms

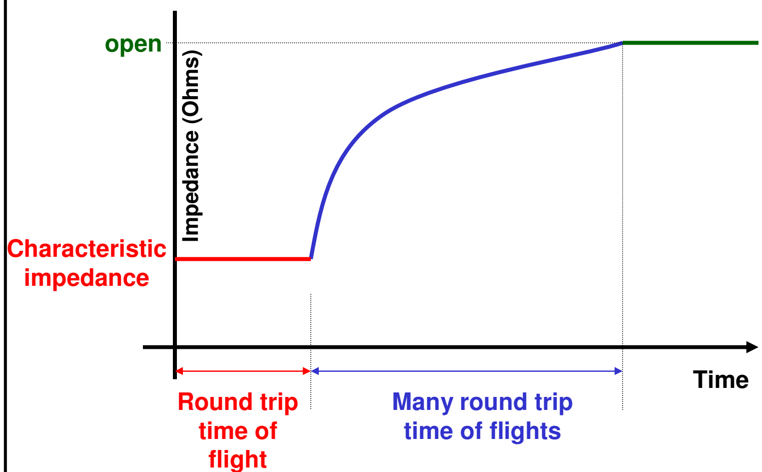
What Is the Measured Impedance of a 50 Ohm Cable?



What Does it Mean to Have a 50 Ohm Line?



The Impedance of a Transmission Line is Time Dependent



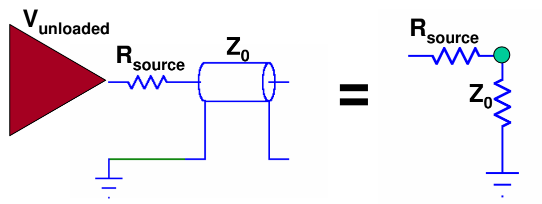
An important Distinction

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

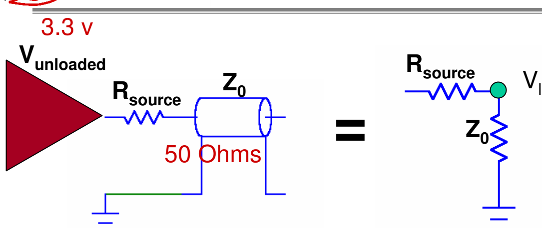
Just referring to "…the impedance" may be a bit ambiguous

The Input Impedance of the Transmission Line

If rise time < 2 x TD, what impedance does driver see during transition?



Voltage Launched into the Line

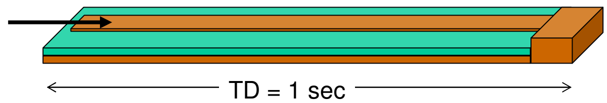


$$V_{launched} = V_{unloaded} \frac{Z_0}{R_{source} + Z_0}$$

R_{source}	$V_{launched}$
20 Ohms	1.2 v
10 Ohms	2.75 v
5 Ohms	3.0 v
2 Ohms	3.17 v

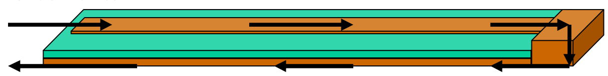
Return Path in T Lines

Current into signal line



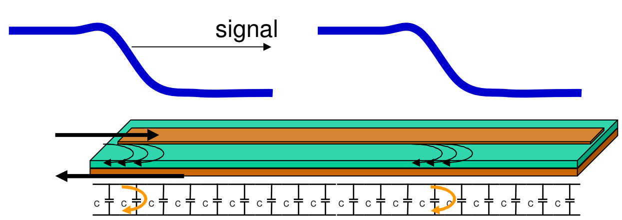
When does the return current return?

For DC currents:



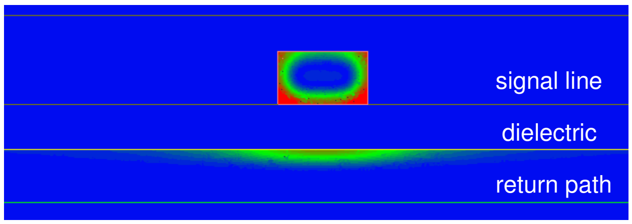
For RF currents? When does current come out return path?

Return Current Paths in Transmission Lines



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

Current Distribution in a Microstrip

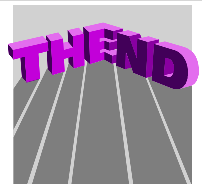


Current density at 500 MHz

Let's Review

- What's a transmission line?
  - ✓ Any two conductors with length
- What is the impedance of a transmission line?
  - ✓ The ratio of the voltage to the current for a signal propagating down the line
- What is characteristic impedance?
  - ✓ An intrinsic property of uniform cross section transmission lines that is equal to the instantaneous impedance the signal would see as it propagates
- What happens to the characteristic impedance of a microstrip if the line width is increased?
  - ✓ The capacitance goes up so the characteristic impedance would go down
- When a signal is launched into a transmission line, when does the return current come out?
  - ✓ At exactly the same time the current goes into the signal line, The current returns through the capacitance between the signal and return paths

The End



Thanks for listening!

射 频 和 天 线 设 计 培 训 课 程 推 荐

易迪拓培训(www.edatop.com)由数名来自于研发第一线的资深工程师发起成立，致力并专注于微波、射频、天线设计研发人才的培养；我们于 2006 年整合合并微波 EDA 网(www.mweda.com)，现已发展成为国内最大的微波射频和天线设计人才培养基地，成功推出多套微波射频以及天线设计经典培训课程和 ADS、HFSS 等专业软件使用培训课程，广受客户好评；并先后与人民邮电出版社、电子工业出版社合作出版了多本专业图书，帮助数万名工程师提升了专业技术能力。客户遍布中兴通讯、研通高频、埃威航电、国人通信等多家国内知名公司，以及台湾工业技术研究院、永业科技、全一电子等多家台湾地区企业。

易迪拓培训课程列表：http://www.edatop.com/peixun/rfe/129.html

射频工程师养成培训课程套装

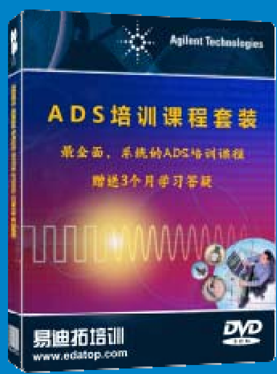
该套装精选了射频专业基础培训课程、射频仿真设计培训课程和射频电路测量培训课程三个类别共 30 门视频培训课程和 3 本图书教材；旨在引领学员全面学习一个射频工程师需要熟悉、理解和掌握的专业知识和研发设计能力。通过套装的学习，能够让学员完全达到和胜任一个合格的射频工程师的要求…

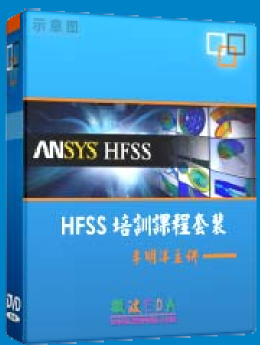
课程网址：http://www.edatop.com/peixun/rfe/110.html

ADS 学习培训课程套装

该套装是迄今国内最全面、最权威的 ADS 培训教程，共包含 10 门 ADS 学习培训课程。课程是由具有多年 ADS 使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了 ADS 在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用 ADS，迅速提升个人技术能力，把 ADS 真正应用到实际研发工作中去，成为 ADS 设计专家...

课程网址： http://www.edatop.com/peixun/ads/13.html



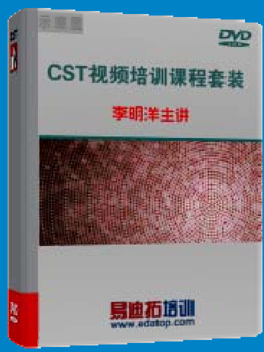


HFSS 学习培训课程套装

该套课程套装包含了本站全部 HFSS 培训课程，是迄今国内最全面、最专业的HFSS培训教程套装，可以帮助您从零开始，全面深入学习HFSS的各项功能和在多个方面的工程应用。购买套装，更可超值赠送 3 个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您的 HFSS 学习更加轻松顺畅…

课程网址：http://www.edatop.com/peixun/hfss/11.html

CST 学习培训课程套装



该培训套装由易迪拓培训联合微波 EDA 网共同推出，是最全面、系统、专业的 CST 微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习 CST 微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送 3 个月免费学习答疑…

课程网址：http://www.edatop.com/peixun/cst/24.html

HFSS 天线设计培训课程套装

套装包含 6 门视频课程和 1 本图书，课程从基础讲起，内容由浅入深，理论介绍和实际操作讲解相结合，全面系统的讲解了 HFSS 天线设计的全过程。是国内最全面、最专业的 HFSS 天线设计课程，可以帮助您快速学习掌握如何使用 HFSS 设计天线，让天线设计不再难…

课程网址：http://www.edatop.com/peixun/hfss/122.html

13.56MHz NFC/RFID 线圈天线设计培训课程套装

套装包含 4 门视频培训课程，培训将 13.56MHz 线圈天线设计原理和仿真设计实践相结合，全面系统地讲解了 13.56MHz 线圈天线的工作原理、设计方法、设计考量以及使用 HFSS 和 CST 仿真分析线圈天线的具体操作，同时还介绍了 13.56MHz 线圈天线匹配电路的设计和调试。通过该套课程的学习，可以帮助您快速学习掌握 13.56MHz 线圈天线及其匹配电路的原理、设计和调试…

详情浏览：http://www.edatop.com/peixun/antenna/116.html

我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，

※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求

※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

联系我们：

※ 易迪拓培训官网：http://www.edatop.com

※ 微波 EDA 网：http://www.mweda.com

※ 官方淘宝店：http://shop36920890.taobao.com