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Online Lecture 105:
Impedance in the Time and Frequency Domains

- Why this online lecture is important
  - ✓ Impedance is the most fundamental electrical quality to describe many signal integrity effects
  - ✓ The most important quality a signal cares about when it interacts with an interconnect is the impedance of the interconnect
  - ✓ Yet, some aspects of impedance are very confusing because they are commonly miss understood and miss reported in presentations
  - ✓ A good, solid, fundamental understanding of impedance will make you much more efficient at solving many signal integrity problems.

- Recommended prerequisites:
  - ✓ None
  - ✓ OLL-115 Intro to Characteristic Impedance
- Level
  - ✓ introductory

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Outline

- Why do we care about impedance
- What is impedance
- Equivalent circuit models
- Common circuit elements
- Impedance in the time domain
- Impedance in the frequency domain
- Simulating Impedance
- RLC circuits
- Real elements vs. ideal elements

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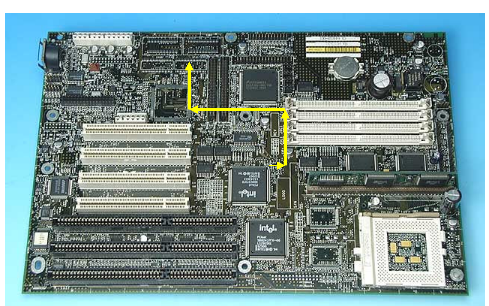
Impedance is THE most important electrical term influencing how a signal interacts with an interconnect



Impedance relates how a signal's voltage and current are affected by the interconnect

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Why Do We Care About Impedance?

All signal integrity problems can be understood in terms of the interaction of impedance and signals

- ✓ Reflections are caused by impedance changes
- ✓ Cross talk is caused by the impedance between traces
- ✓ Rail collapse noise is caused by high impedance in the power distribution system
- ✓ EMI is contributed by the impedance of the power distribution system

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Design Rules Can Be Created Based on the Impedance of the Interconnects

Performance → Impedance of the interconnects → Design rules

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Confusion About Impedance

- It's just the resistance
- It's about how a resistor impedes the flow of current
- It only makes sense in the frequency domain
- It's jωL for an inductor
- The terms "resistor" or "capacitor" or "transmission line" are used to refer to either a real component or an ideal element, without distinction
- A transmission line is just a collection of LC sections

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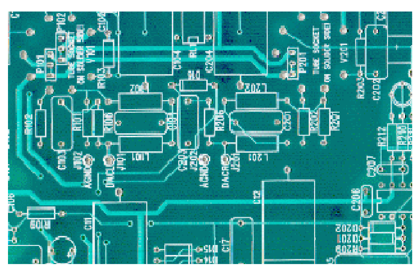
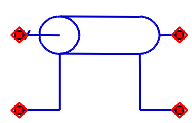
An Unfortunate Coincidence

A "transmission line" is the name we use to refer to a real, physical interconnect



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

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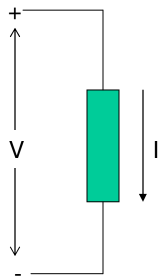
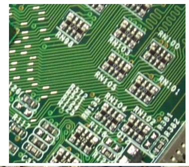
What is Impedance?

- Fundamental Definition- applies for ALL situations:

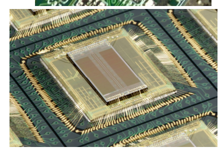


$$Z = \frac{V}{I}$$

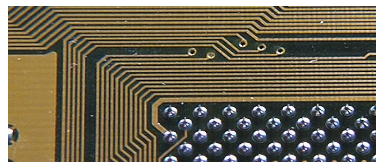
Discrete components



Leads in a package



Traces on a board
Pins in a connector



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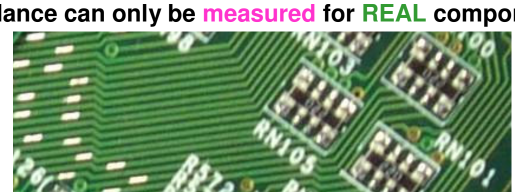
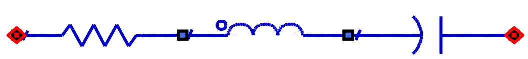
Measured vs. Simulated

Impedance can only be measured for REAL components



Impedance can only be calculated for IDEAL components



It is possible to find a combination of ideal circuit elements that closely matches the measured impedance of real components to very high bandwidth

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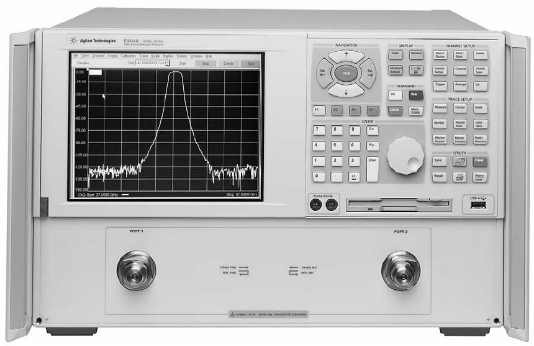
Measuring Impedance



- Agilent E8363B VNA
- Convert S11 to impedance with: $Z = 50\Omega \ x \ \frac{1+S_{11}}{1-S_{11}}$
- See OLL-140 S parameters and the VNA

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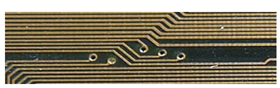
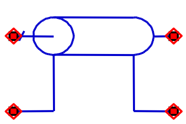
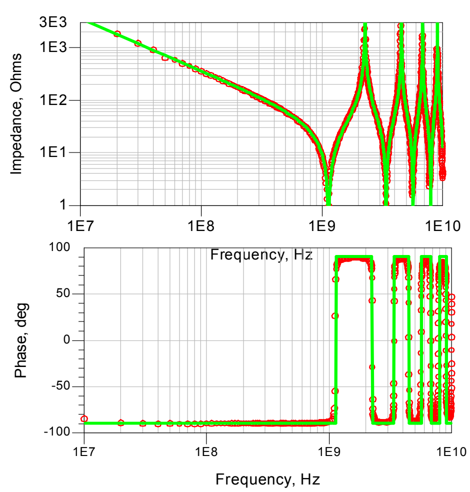
Measured and Simulated Impedance of a Short Transmission Line



Red: measured impedance, 2 inch long trace on board

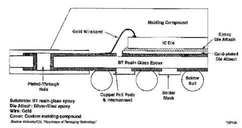


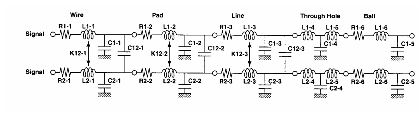
Green: simulated impedance of open terminated ideal lossless transmission line



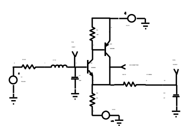
Two Critical Processes for Designing it Right the First Time

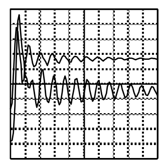
Modeling: Translating the physical world into an equivalent electrical circuit model (Schematic)





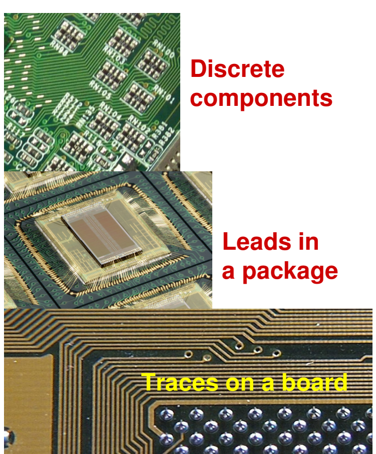
Simulation: Predicting voltage/current waveforms based on the circuit behavior





Ideal Circuit Elements

Real Components



Ideal Components

- Common
  - ✓ Resistors (R)
  - ✓ Capacitors (C)
  - ✓ Inductors (L)
  - ✓ Ideal lossless transmission lines (T)
- Coupled elements:
  - ✓ Mutual inductor (k)
  - ✓ Coupled transmission lines: ideal, lossless differential pair
- Lossy lines
  - ✓ Ideal lossy transmission line
    - $R \sim \sqrt{f}$
    - $G \sim f$
  - ✓ Ideal lossy differential pair

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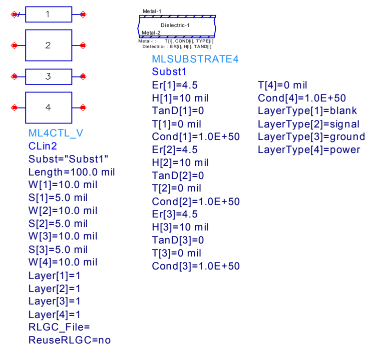
Generalized Coupled Elements: Matrix Elements

- Matrices:
  - ✓ Resistance (per length) matrix
  - ✓ Capacitance (per length) matrix
  - ✓ Inductance (per length) matrix
  - ✓ Characteristic impedance matrix

$$\begin{matrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{matrix}$$

- Physical model → field solver based matrix elements and integrated simulator
  - ✓ Agilent ADS
  - ✓ Synopsis- HSPICE
  - ✓ Ansoft Designer
  - ✓ Mentor HyperLynx
  - ✓ Mentor ICX
  - ✓ Mentor XTK
  - ✓ Cadence Sig XP
  - ✓ Cadence SpectraQuest



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A Caution!

- We use the terms resistor, capacitor, inductor and transmission line for the real components
- We use these same terms to refer to the ideal circuit elements
- They are not the same
- One is a real component and can be measured
- One is an ideal element and can only be simulated
- The ideal element is a very good approximation to the real structure, but they are not the same.
- Always try to identify which one is being used

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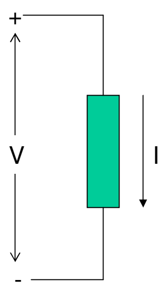
Definition of Impedance (for two terminals)

FUNDAMENTAL DEFINITION



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

- Fundamental definition:
  - ✓ Ratio of voltage across the terminals to the current into and out of the terminals
- Always
  - ✓ In the time domain
  - ✓ In the frequency domain
  - ✓ For real components
  - ✓ For ideal circuit elements

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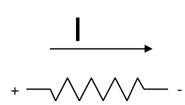
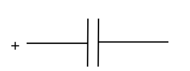
Definitions for Ideal Circuit Elements

Resistor



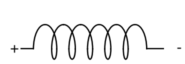
$V = I \times R$

Capacitor



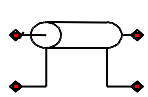
$$I = C\frac{dV}{dt}$$

Inductor



$$V = L\frac{dI}{dt}$$

Transmission line



See OLL-115: Intro to Characteristic Impedance

What is the impedance of an R, C, L, T element?

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Impedance of a Resistor

Symbol: + -

Definition: $V = I \times R$

Impedance: $Z = \frac{V}{I} = \frac{IR}{I} = R$

Units: Ohms

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Using SPICE to Simulate ANY Combination of Circuit Elements

SPICE: Simulation Program with Integrated Circuit Emphasis

- ✓ PSPICE from OrCAD/Cadence
- ✓ IsSPICE from Intusoft
- ✓ Advanced Design System (ADS) from Agilent
- ✓ Micro-CAP from Spectrum-Soft

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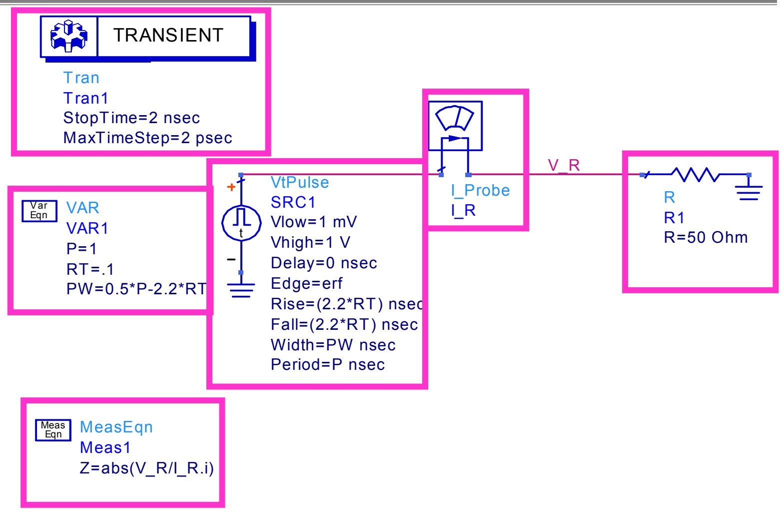
Circuit Simulation with Agilent ADS



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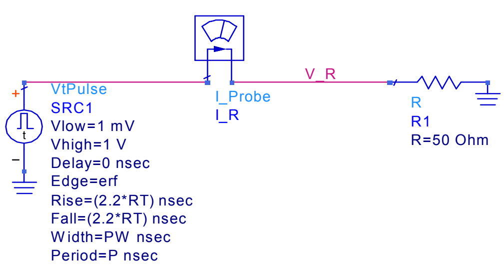
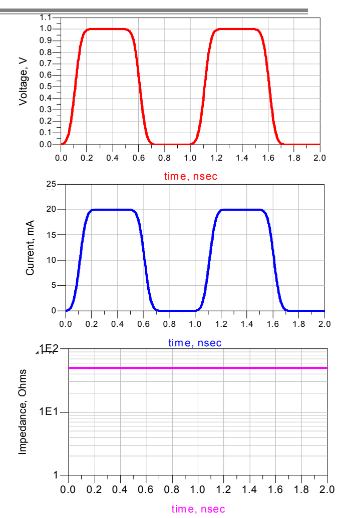
Impedance of an Ideal Resistor in the Time Domain

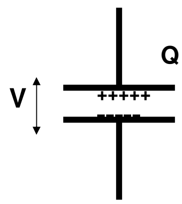




1 GHz clock
Gaussian edge, 0.1 nsec rise time

Impedance of an ideal resistor is constant in the time domain

Basic Property of a Capacitor



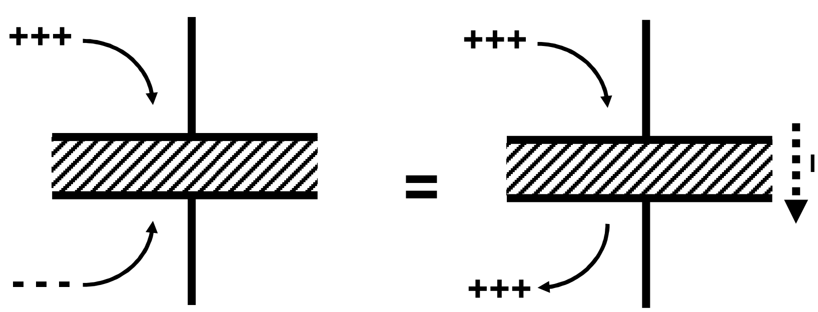
$$C = \frac{Q}{V}$$

Capacitance is independent of the voltage

Capacitance is strictly a geometry and material property

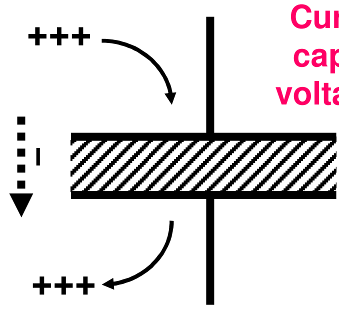
How does current flow through a capacitor?

Equivalent Views



Do actual + charges move through the insulating dielectric?

Very Important Principle



Current flows through a capacitor whenever the voltage across it changes

$$Q = CV$$

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$

$$I = C\frac{dV}{dt}$$

Impedance of an Ideal Capacitor in the Time Domain

$$Q = C\ V$$

$$\frac{dQ}{dt} = I = C\frac{dV}{dt}$$

$$Z = \frac{V}{I} = \frac{V}{C\frac{dV}{dt}}$$

Impedance of a capacitor depends on applied voltage behavior:
- faster the change, lower the impedance
- higher the voltage, higher the impedance

Very complicated behavior in the time domain!!!!

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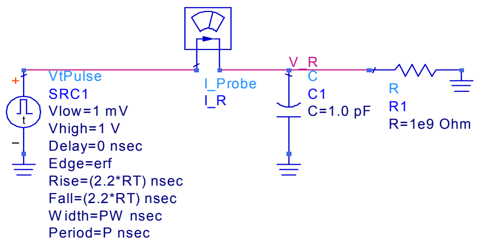
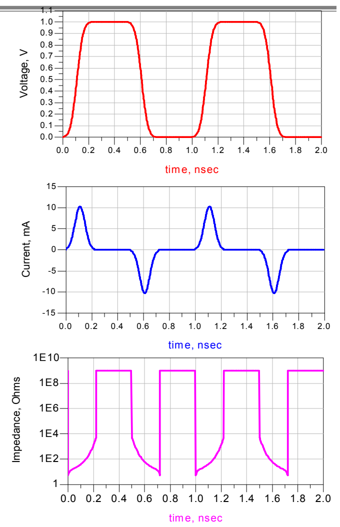
Impedance of a 1 pF Ideal Capacitor in the Time Domain





Impedance of an ideal capacitor is complicated in the time domain

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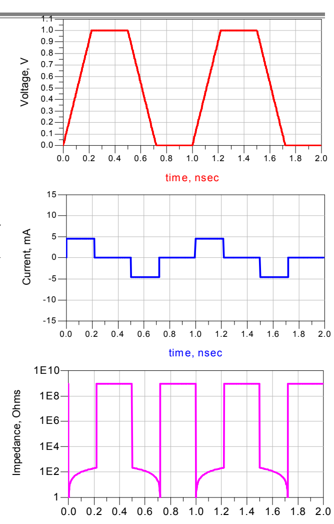
Even With A Linear Ramp Voltage, Impedance Of A Capacitor Is Complicated In The Time Domain

$$\frac{dQ}{dt} = I = C\frac{dV}{dt}$$

$$Z = \frac{V}{I} = \frac{V}{C\frac{dV}{dt}}$$



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What is Inductance?

(see OLL-110 Introduction to Inductance)

Inductance is the number of loops of magnetic field lines around a conductor, per amp of current through it.

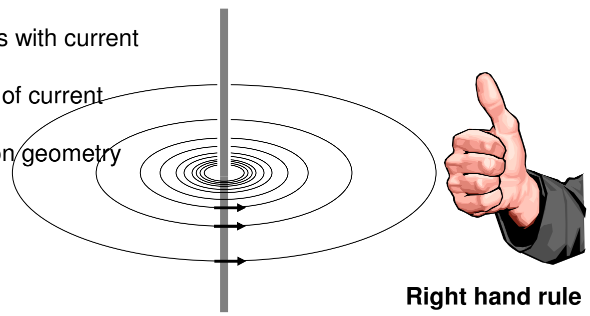
Units are : Webers of field lines/amp of current = Henrys

Double the current, double the number of field lines, ratio is constant

Number of field lines scales with current

Inductance is independent of current

Inductance depends only on geometry



Right hand rule

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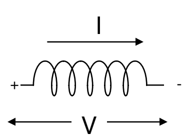
Basic Property of an Inductor



$$V = L\frac{dI}{dt}$$

If current doesn't change, there is no voltage.

If current changes, a voltage appears.

Sign of voltage is similar as for a resistor.

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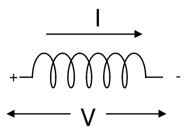
Impedance of an Ideal Inductor (in the time domain)



$$V = L\frac{dI}{dt}$$

$$Z = \frac{V}{I} = \frac{L\frac{dI}{dt}}{I}$$

Impedance of an inductor depends on current behavior:
- faster the change, higher the impedance
- higher the current, lower the impedance

Conclusion: impedance is complicated and not very intuitive in the time domain

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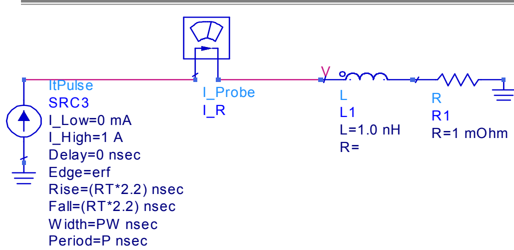
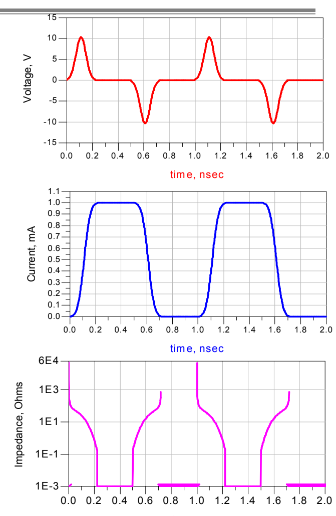
Impedance of a 1 nH Ideal Inductor in the Time Domain





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

Impedance of an ideal inductor is complicated in the time domain

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You have reached the end of session a.

Please go back to the BeTheSignal.com web site and select session b

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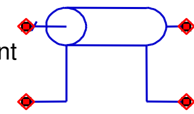
An Ideal Transmission Line

- Four terminals
  - ✓ Front end, 2 terminals
  - ✓ Back end, 2 terminals



- Impedance looking into a transmission line
  - ✓ The input impedance
  - ✓ THE impedance
- Depends on:
  - ✓ The length
  - ✓ The termination at the other end
- Three different "impedances"
  - ✓ The instantaneous impedance
  - ✓ The characteristic impedance
  - ✓ The input impedance or THE impedance

See OLL-115 Introduction to Characteristic Impedance

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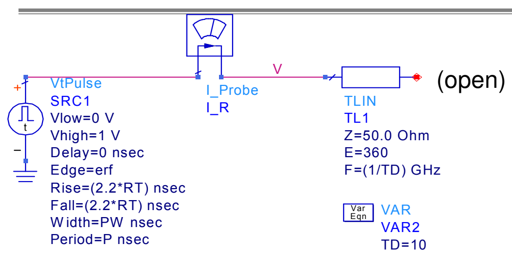
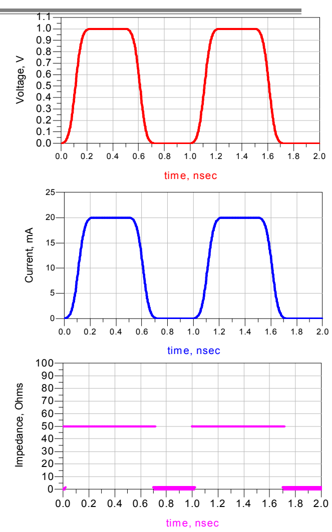
Impedance of an Ideal Transmission Line in the Time Domain





TD = 10 nsec

Simulation time = 2 nsec

Input can't see the end of the line during the simulation

Characteristic impedance of the T line = 50 Ohms

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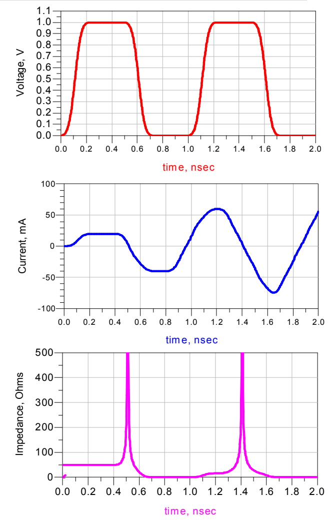
If Simulation Time > 2 x TD

Simulation time = 2 nsec

TD = 0.2 nsec

Multiple reflections complicate the input impedance of the line

Can vary from 50 Ohms to 0 to > 1 k Ohms



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Impedance in the Time Domain

- ALWAYS correct
- Not always the easiest way of looking at the impedance of an ideal or real element
- Depends very strongly on the precise waveform: the applied voltage, the current through the device
- Hard to generalize and feed our intuition

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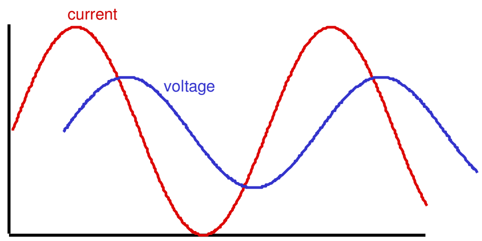
Sometimes we can get to an answer faster by going through the frequency domain

Current and voltage are sine waves:



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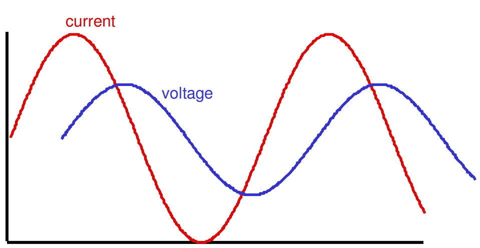
Impedance in the Frequency Domain

For all linear elements, the current and voltage will ALWAYS be at the same frequency



$$Z(\omega) = \frac{V(\omega)}{I(\omega)}$$

need to account for:

- ratio of the amplitudes
- phase shift

$$|Z(\omega)| = \frac{|V(\omega)|}{|I(\omega)|}$$

The ratio of two sine waves is a magnitude and a phase shift

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Describing Impedance in Frequency Domain

- Magnitude and phase $|Z(\omega)|, \quad \theta(\omega)$
- Real and imaginary $Z(\omega) = \dfrac{V(\omega)}{I(\omega)} = Z'(\omega) + iZ''(\omega)$
- Complex notation $\tilde{Z}(\omega) = |Z(\omega)| \exp(i\omega t)$

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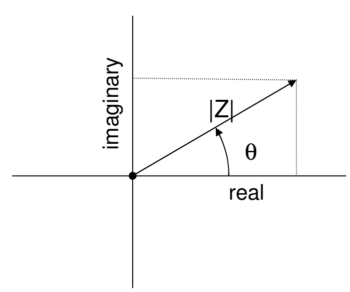
Complex Impedance in the Frequency Domain

- Magnitude and Phase $|Z|, \theta$
- Real and imaginary Z', Z''

$Z' = |Z| \times \sin(\theta)$

$Z'' = |Z| \times \cos(\theta)$



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Impedance of a Resistor in the Frequency Domain

$$V = I \times R$$

Suppose $I(\omega,t) = I_0 \exp(i\omega t)$

Then $V(\omega,t) = I_0 \exp(i\omega t) \times R$

$$Z(\omega) = \frac{V(\omega,t)}{I(\omega,t)} = \frac{I_0 \exp(i\omega t) x R}{I_0 \exp(i\omega t)} = R$$

Impedance of a resistor has only a real component, no imaginary component

Impedance of a resistor in the frequency domain is very boring
- constant with frequency
- no imaginary component

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Impedance of a Capacitor in the frequency domain

$$Q = C\,V \qquad \frac{dQ}{dt} = I = C\frac{dV}{dt}$$

Suppose $V(\omega,t) = V_0 \exp(i\,\omega\,t)$ $\qquad \frac{dV}{dt} = V_0\, i\omega \exp(i\omega t)$

$$I = CV_0\, i\omega \exp(i\omega t) = i\omega CV$$

$$Z = \frac{V}{I} = \frac{1}{i\omega C} = \frac{-i}{\omega C}$$

Impedance of a capacitor:
- has no real component, only <u>negative</u> imaginary component
- decreases with increasing frequency

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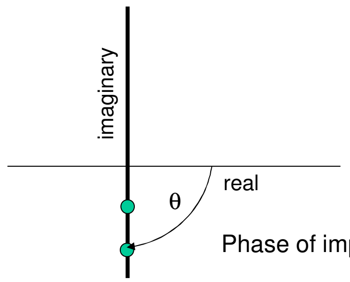
Impedance of a C in Complex Impedance Plane

$$Z = \frac{V}{I} = \frac{1}{i\omega C} = \frac{-i}{\omega C}$$

$$|Z| = \frac{1}{\omega C}$$



Phase of impedance always -90 deg

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Impedance of a Capacitor: examples

1. The capacitance of a 1 inch trace in FR4 is about 4 pF. What is the impedance at 100 MHz? Is this big or small? Does it look like a short or an open?

$$|Z| = \frac{1}{\omega C}$$

$\omega = 2 \times 3.1415 \times 10^8 = 6 \times 10^8$

$$|Z| = \frac{1}{6x10^8 x4x10^{-12}} = 400\Omega$$

2. The capacitance of a decoupling cap is 10 nF (0.01µF). What is its impedance at 1 GHz?

$$|Z| = \frac{1}{6x10^9\,x10x10^{-9}} = \frac{1}{60} = 0.016\Omega$$

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Impedance of an Inductor

$$V = L\frac{dI}{dt}$$ Suppose $I(\omega,t) = I_0 \exp(i\omega t)$

$$\frac{dI}{dt} = I_0 i\omega \exp(i\omega t)$$

$$V = LI_0 i\omega \exp(i\omega t) = i\omega LI$$

$$Z = \frac{V}{I} = \frac{i\omega LI}{I} = i\omega L$$

Impedance of an inductor:

- has no real component, only <u>positive</u> imaginary component
- increases with increasing frequency

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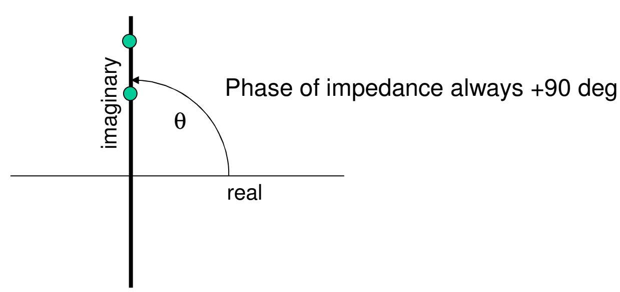
Impedance of an Inductor in Complex Impedance Plane

$$Z = \frac{V}{I} = \frac{i\omega LI}{I} = i\omega L$$

$$|Z| = \omega L$$



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Impedance of an Inductor: examples

1. The loop inductance of a 1 inch trace in FR4, shorted at the far end is about 9 nH. What is the impedance at 100 MHz? Is this big or small? Does it look like a short or an open? How about at 1 GHz?

$$|Z| = \omega L$$

ω = 2 x 3.1415 x 10^8 = 6 x 10^8

$$Z = 6x10^8\, x9x10^{-9} = 5.4\Omega$$

2. The inductance associated with a decoupling cap is 2 nH. What is its impedance at 1 GHz? How does this compare with the impedance of the capacitance? Which one is more important at high frequency?

$$Z = 6x10^9\, x2x10^{-9} = 12\Omega$$

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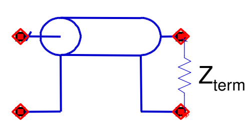
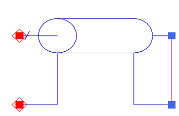
Impedance of a Transmission Line in the Frequency Domain

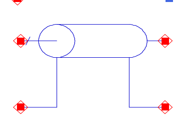
$$Z = Z_0\left\{\tanh\left[i2\pi f\ x\ TD + \tanh^{-1}\left(\frac{Z_{term}}{Z_0}\right)\right]\right\}$$



Shorted end: $Z = Z_0\ x\ i\tan(2\pi f\ x\ TD)$



Open end: $Z = -Z_0\ x\ i\cot(2\pi f\ x\ TD)$



Impedance of transmission line in the frequency looks complicated
- is only imaginary, no real component
- depends on the time delay
- has complicated frequency dependence

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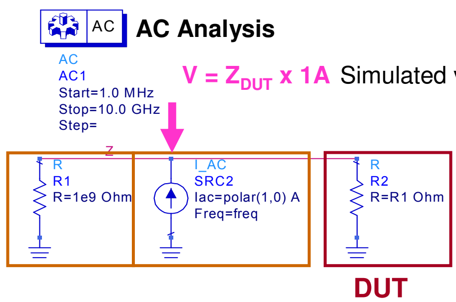
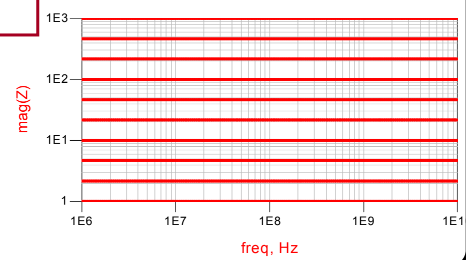
Frequency Domain Impedance Analyzer in SPICE

$V = Z_{DUT} \times 1A$ Simulated voltage numerically = DUT impedance



R = 1 Ohms to 1000 Ohms



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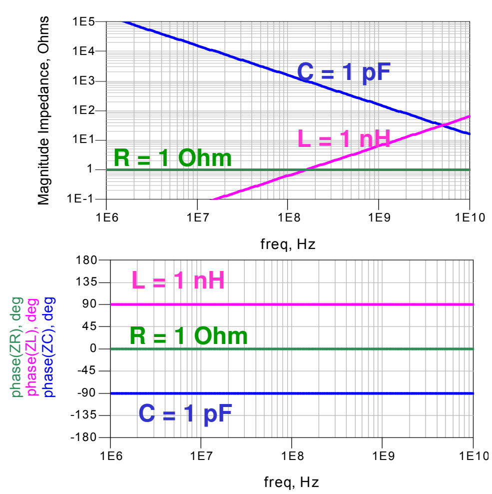
Impedance of R, L , C elements



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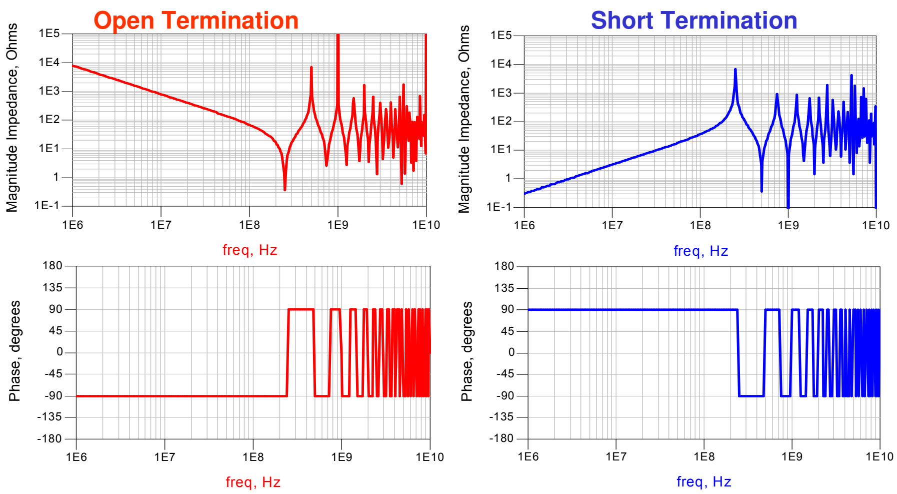
Impedance of a Transmission Line



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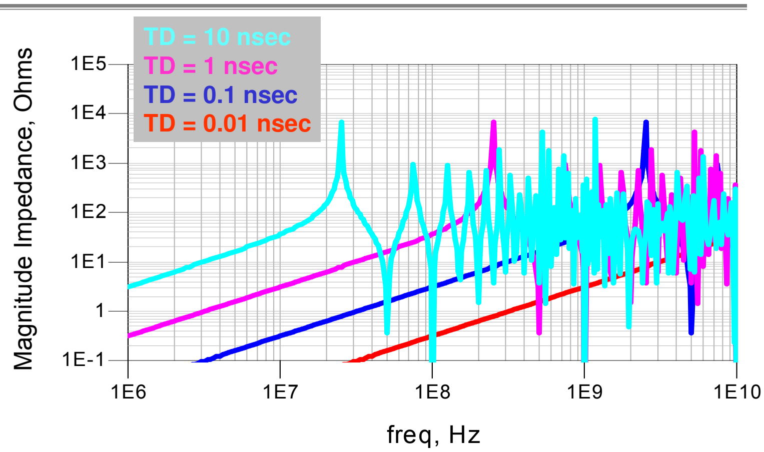
Changing TD



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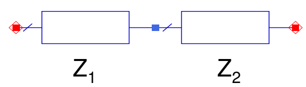
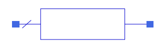
Combining Impedances

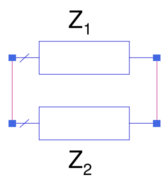
In series

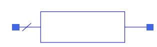




$$Z_{equiv} = Z_1 + Z_2$$

In parallel





$$Z_{equiv} = \frac{Z_1 \ x \ Z_2}{Z_1 + Z_2}$$

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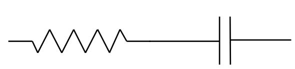
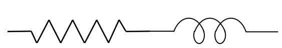
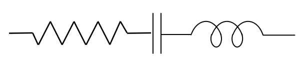
Impedance of Simple Circuits



$$Z = R - i\frac{1}{\omega C}$$



$$Z = R + i\omega L$$



$$Z = R + i\left(\omega L - \frac{1}{\omega C}\right)$$

- Real part relates to resistance
- Imaginary part relates to L or C (reactance)

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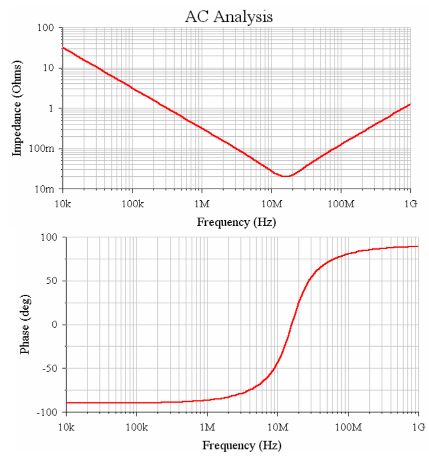
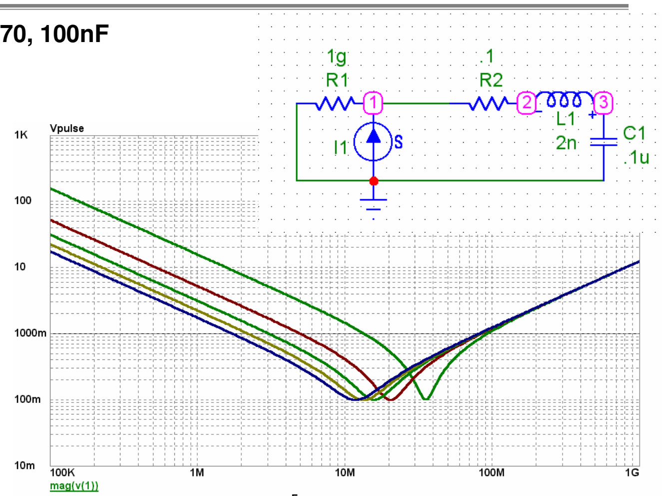
Simulating Impedance of RLC Circuit with SPICE



Simulated Impedance of a RLC Circuit, varying C

C = 10n, 30, 50, 70, 100nF
R = 0.1 Ohm
L = 2 nH

Note: high freq impedance of capacitor dominated by inductance of fixed body size



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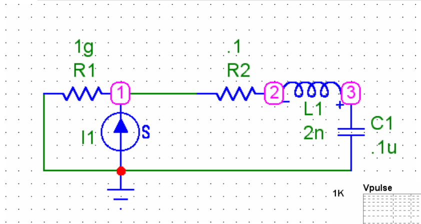
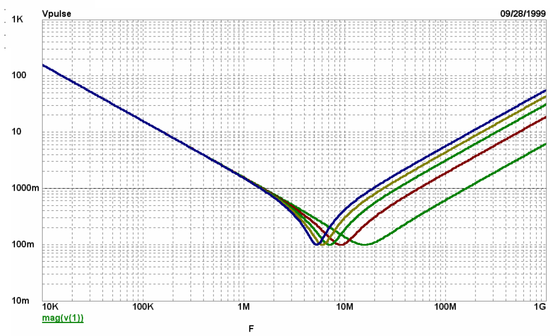
Simulated Impedance of a RLC Circuit, Varying L



Similar to real capacitors with different body sizes

R = 0.1 Ohm
L = 2 nH
C = 100 nF

L = 1n, 3, 5, 7, 10nH



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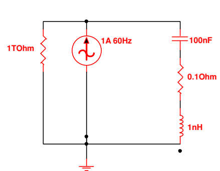
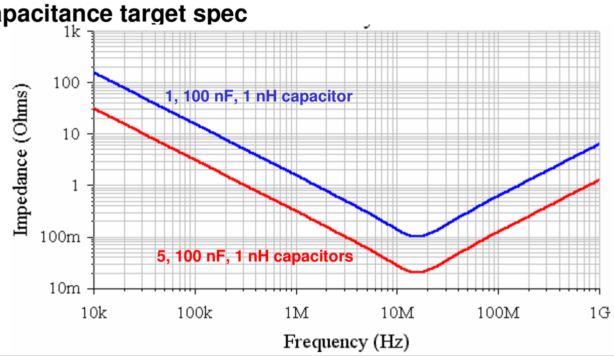
Optimizing Decoupling Capacitors

Step 1: use smallest body size

Step 2: highest capacitance capacitor in this body size

Step 3: add N identical capacitors to reach the total capacitance target spec





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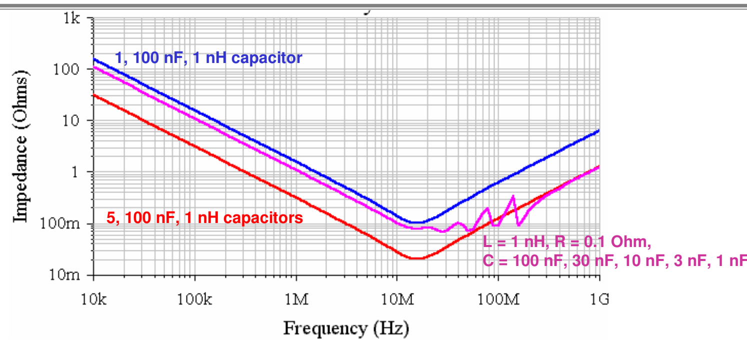
Multiple Capacitors with Distribution of Capacitances



Step 1: use smallest body size

Step 2: highest capacitance capacitor in this body size

Step 3: add enough high value capacitors for the low frequency impedance, enough total capacitors for the high frequency impedance, with values distributed over a few decades to flatten the impedance curve

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The impedance of real components closely matches the impedance of ideal circuit elements,

But, every model has a bandwidth!

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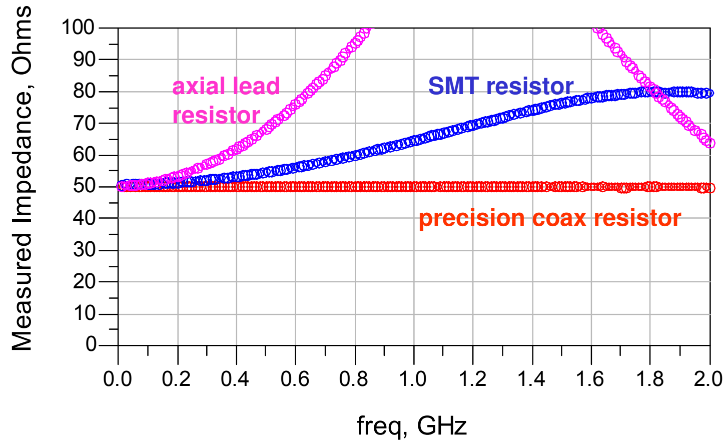
Measured Impedance of Real Resistor Components



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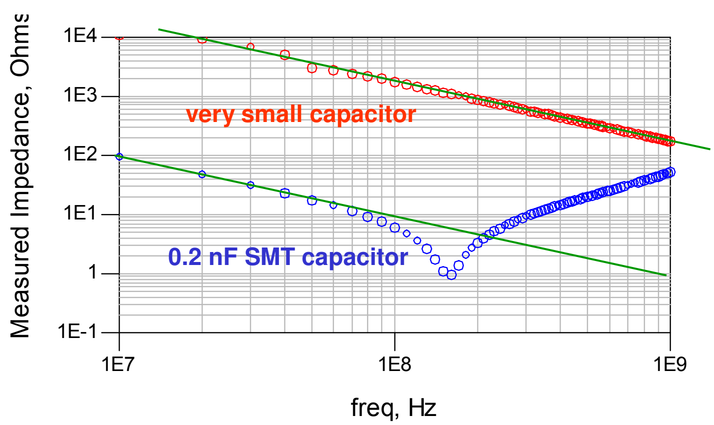
Measured Impedance of Real Capacitor Components



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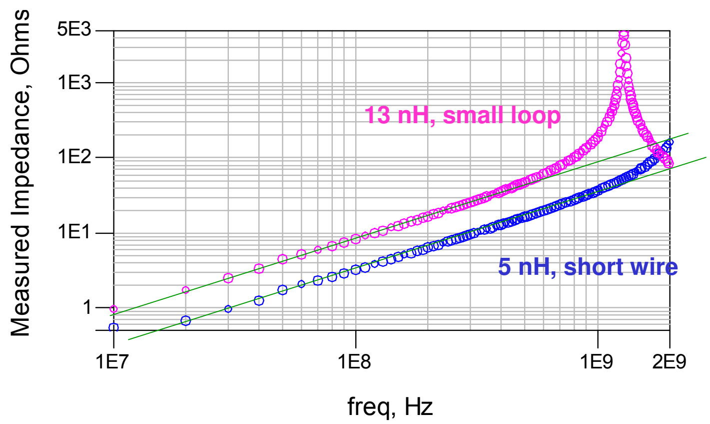
Measured Impedance of Real Inductor Components



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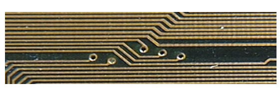
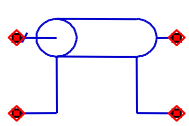
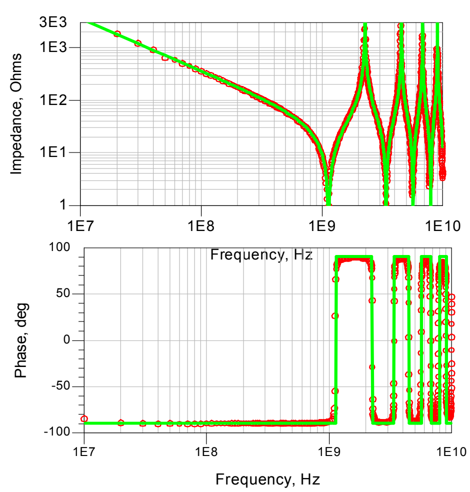
Measured and Simulated Impedance of a Short Transmission Line



Red: measured impedance, 2 inch long trace on board

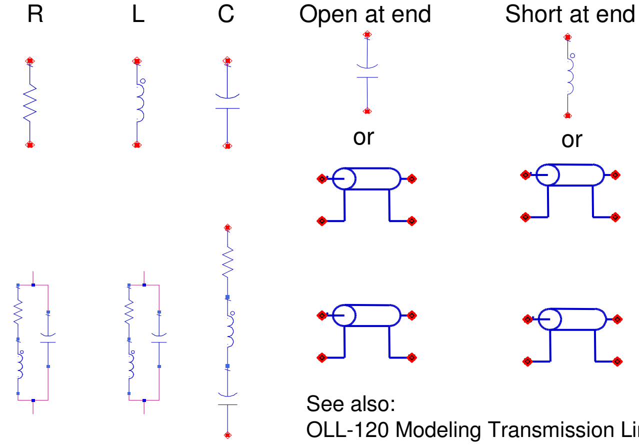


Green: simulated impedance of open terminated ideal lossless transmission line



SPICE models of typical components

	Real R	Real L	Real C	Real interconnect Open at end	Real interconnect Short at end
Low Frequency					
High Frequency					



See also:
OLL-120 Modeling Transmission Lines
OLL-181 Bandwidth of models

VERY *Important Distinctions*

1. When we model real R, L, C, T components, the parameter values of the ideal of R, L, C, T elements in the model are independent of frequency, voltage and current.
2. The impedance of an ideal inductor, capacitor, transmission line or circuit containing them generally changes with frequency.
3. Ideal circuit elements are the only elements that can be simulated by a circuit simulator
4. The impedance of a real interconnect can be closely approximated by combinations of ideal elements

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Summary of General Principles

- Impedance is a powerful concept to describe the electrical performance of all interconnects and passive components.
- At low frequency EVERY real component will ALWAYS look like an ideal R, L, C or T element
- A Transmission line is ALWAYS a good model for a uniform interconnect
- There will always be a frequency beyond which a simple RLCT model breaks down
- Beyond this frequency
  - ✓ May need more elements (new topology)
  - ✓ May need new elements (losses?)
  - ✓ May not be able to get there from here (plane resonances, frequency dependent L) need new circuit components- n coupled elements, LaPlacian for arbitrary impedance profile
- Critically important step in signal integrity analysis is converting the real physical interconnects into an equivalent circuit composed of combinations of ideal circuit elements so the impedance can be calculated.

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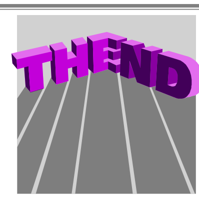

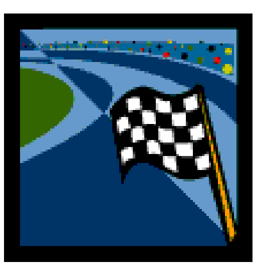

Thanks for listening!

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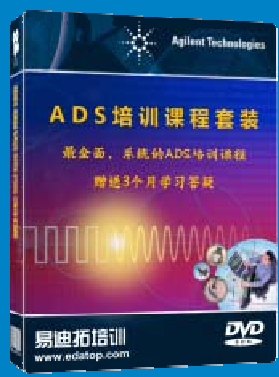

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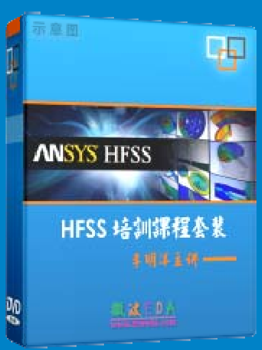

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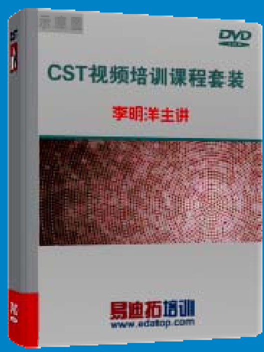

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课程网址：http://www.edatop.com/peixun/cst/24.html

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