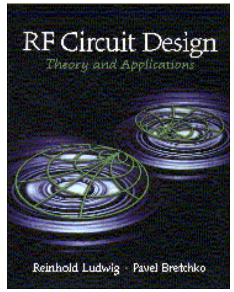
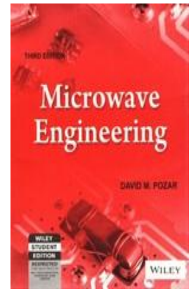
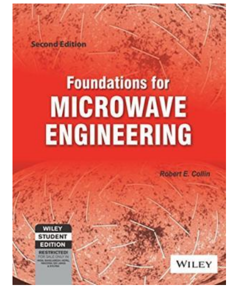
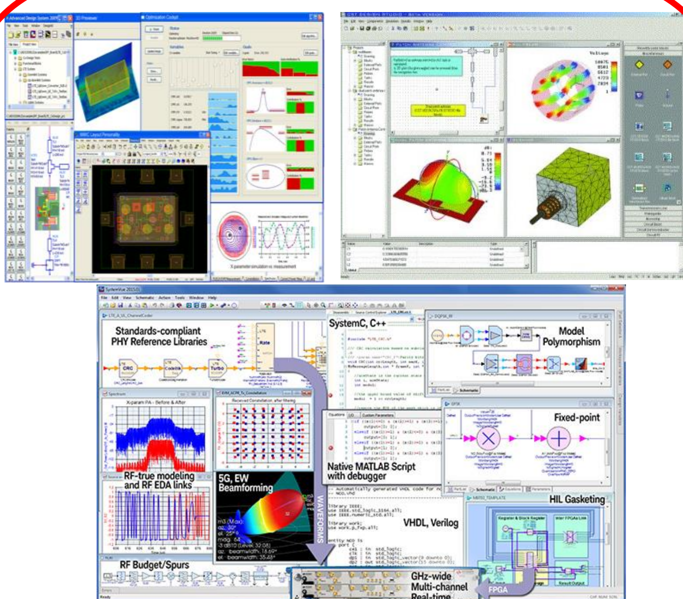
RF Circuit Design



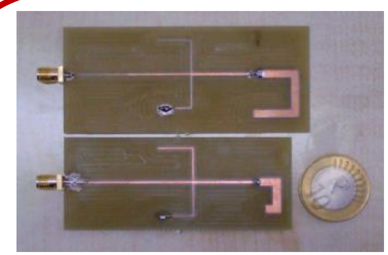


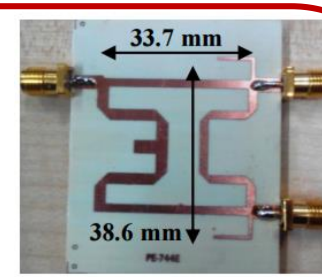


Theory and Fundamentals



Simulation (Schematic to Layout and Optimization)





Prototyping and Measurements

RF Circuit Design (ECE321/521)

Instructor: Dr. Mohammad S. Hashmi

Class Timings: Monday & Thursday (10:00 – 11:30)

Lab/Project Timings: TBA

Office Hours: Thursday (17:00 – 18:00)

TAs: Dinesh Rano and Deepayan Banerjee

Lecture-1 Date: 02.01.2017

- Introduction
- Differentiating factor between low and high frequency circuits
- Behavior of Passive Components at High Frequency
- Transmission Line (Intro.)

RF Circuit Design

Teacher: "*Mogli*, do you even know your multiplication tables?"
Mogli: "*Well*, I know of them".

Like Mogli and his multiplication tables, many electrical engineers know of the concepts of RF Circuit Design.

However, Concepts such as characteristic impedance, scattering parameters, Smith charts and the like are familiar, but we often find that a **complete**, **thorough**, and **unambiguous** understanding of these concepts can be somewhat lacking.

Thus, the goals of this class are for you to:

- Obtain a complete, thorough, and unambiguous understanding of the fundamental concepts on RF and High Frequency Engineering
- Apply these concepts to the design and analysis of useful high frequency devices

Pre-requisites:

Circuit Theory Fundamentals, Fields and Waves Fundamentals

Course Focus:

High Frequency Circuit and System Design for Cellular, WIFI, WLAN, and Bluetooth Applications

Lab Components:

- Introduction to ADS, CST and SystemVue (mostly self learning, required for course projects) – Rahul and TAs can help
- Introduction to VNA and Spectrum Analyzer and their Usage
- Rahul Gupta will be your contact point for Labs

Course Outline and Details:

http://www.iiitd.edu.in/~mshashmi/teaching

Evaluation Mechanism

- **Assignments (20%)**
- **[Pen & Paper + ADS] based**

- **Surprise Quizzes (15%)**
- **all compulsory!**

- **Exams and Project**
  - **Project (30%)**
  - **Mid-Sem (20%)**
  - **End-Sem (15%)**

Text Book:

"RF Circuit Design: Theory and Applications" ***by*** R. Ludwig, 2nd Ed., Pearson International

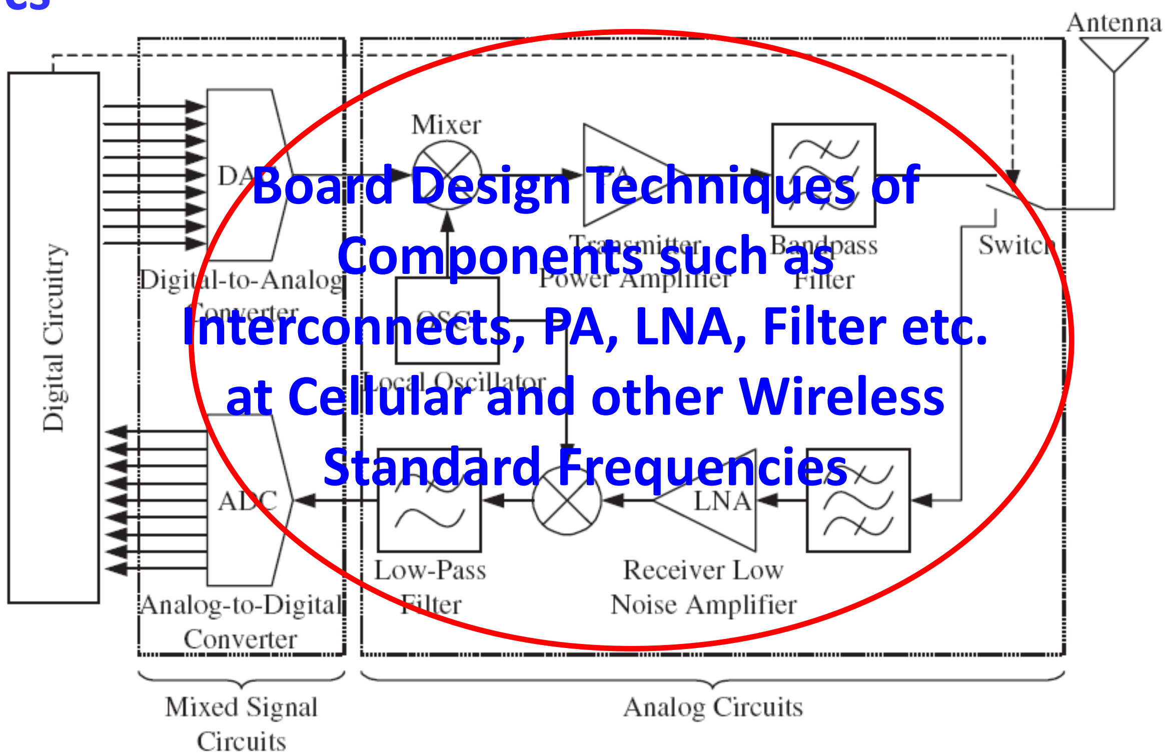
Other Recommended Resources:

- Microwave Engineering ***by*** D. M. Pozar, 4th Ed., John Wiley and Sons Inc.
- RF Circuit Design ***by*** C. Bowick, 2nd Ed., Newnes
- Secrets of RF Circuit Design ***by*** Joseph J. Carr, 3rd Ed., McGraw Hill
- RF Transistor Amplifier ***by*** G. Gonzalez, 2nd Ed., Prentice Hall
- IEEE Xplore, IEL, etc.

Motivation

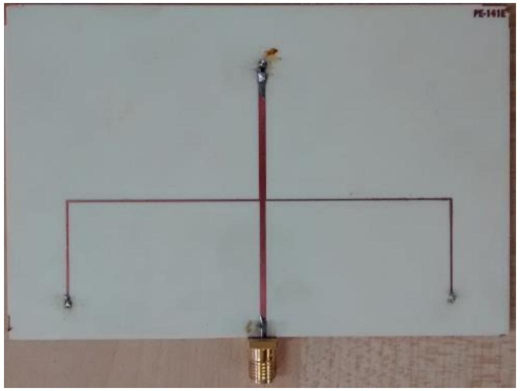
- Importance of RF Circuit Design
  - Wireless/Wirebased Communication Circuits → multi-band and multi-standard transceivers
  - Global Positioning System (GPS)
  - Increased clock speeds in ASICs/SoCs
  - Automotive Electronics

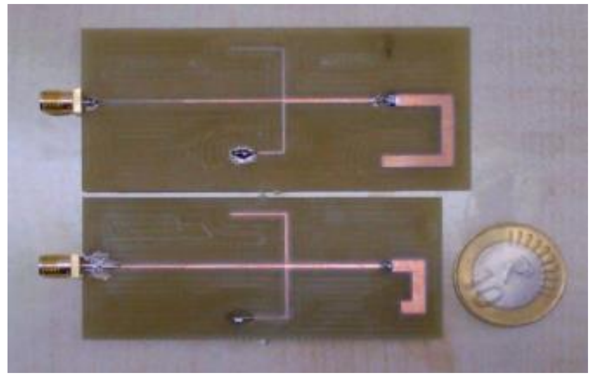
Design Focus in this Course

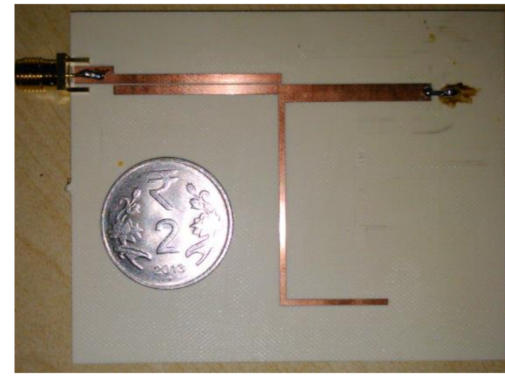


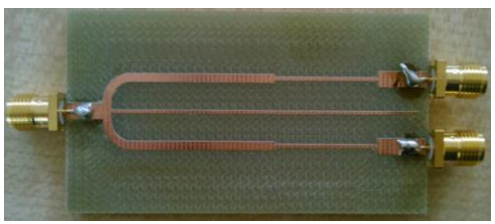
Board Design Techniques of Components such as Interconnects, PA, LNA, Filter etc. at Cellular and other Wireless Standard Frequencies

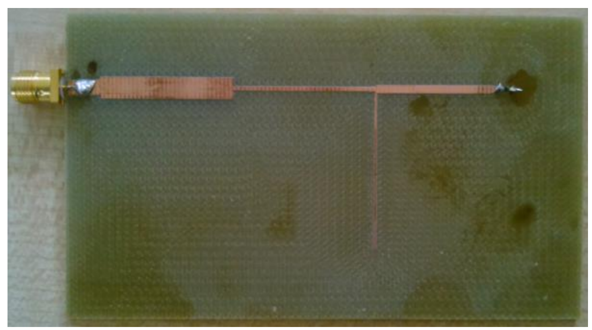
Some design examples from Lab

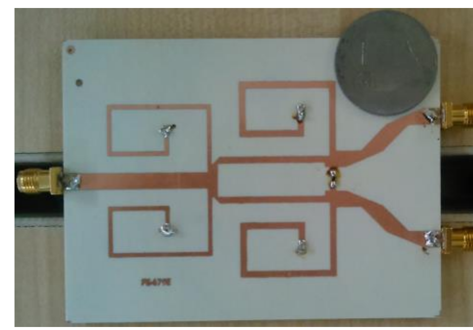


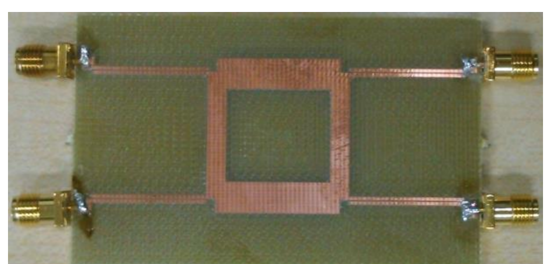












Motivation (contd.)

Frequency Spectrum

Band
ELF
VLF
LF
MF (MW)
HF (SW)
VHF
UHF
SHF
EHF
IR

Frequency
100 Hz
10 kHZ
100 kHz
1 MHz
3 MHz
30 MHz
300 MHz
1 GHz
30 GHz
300 GHz

300 MHz – 3 GHz

Radio Frequency
- TV
- Wireless Phones
- GPS

8 GHz to 40 GHz

Microwave Frequency
- Radar
- Remote Sensing

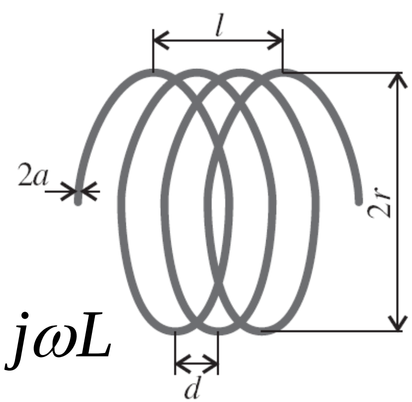
Why this course?

- Lumped components (wires, resistors, capacitors, inductors, connectors etc.) behave differently at low and high frequencies.
- Why?
  - current and voltage vary spatially over the component size
  - Leads to the concept of distributed components!

The KCL and KVL are no more applicable

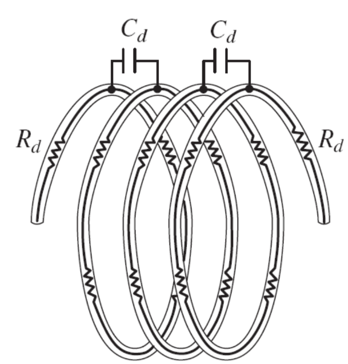
- **What do we mean by distributed? :-> Example – Inductor**

Low Frequency (Lumped)



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

High Frequency (Distributed)



$$Z = ?$$

RF Behavior of Passive Components

- Why do inductors, capacitors, and resistors behave differently at Radio Frequency?
- What is skin effect?
- Equivalent Circuit Model?

For conventional AC circuit analysis:

- R is considered frequency independent
- Ideal Inductor (L) possesses an impedance $(X_L = j\omega L)$
- Ideal capacitor (C) possesses an impedance $\left(X_C = {}^{1}/_{j\omega C}\right)$

Capacitor behaves as open circuit at DC and low frequency **whereas** an Inductor behaves as short circuit at DC and low frequencies

RF Behavior of Resistors

At low frequency:

- Resistances, inductances, and capacitances are formed by wires, coils, and plates etc.
- Even a single wire or a copper line on a PCB possesses resistance and inductance.
- this cylindrical copper conductor has a DC resistance:

$$R_{DC} = \frac{l}{\pi a^2 \sigma_{cond}}$$

Length of cylinder

conductivity

Radius of cylinder

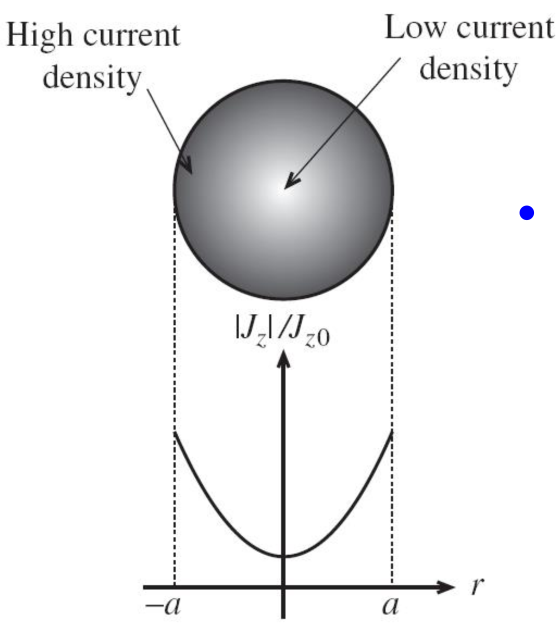
- At DC, current flows uniformly distributed over the entire conductor cross-sectional area.

DC Current Density: $\boxed{J_{z0} = \frac{I}{\pi a^2}}$

RF Behavior of Resistors (contd.)

- At AC, the alternating charge carrier flow establishes a magnetic field that induces an electric field (Faraday's Law) whose associated current density opposes the initial current flow → this effect is very strong at the center (r=0) where the impedance is substantially increased → as a result the current flow resides at the outer periphery with the increasing frequency.

→ **Skin Effect**



- The current density at AC is given by:

$$J_z = \frac{pI}{2\pi a j\sqrt{r}} \exp\left(-(1+j)\frac{a-r}{\delta}\right)$$

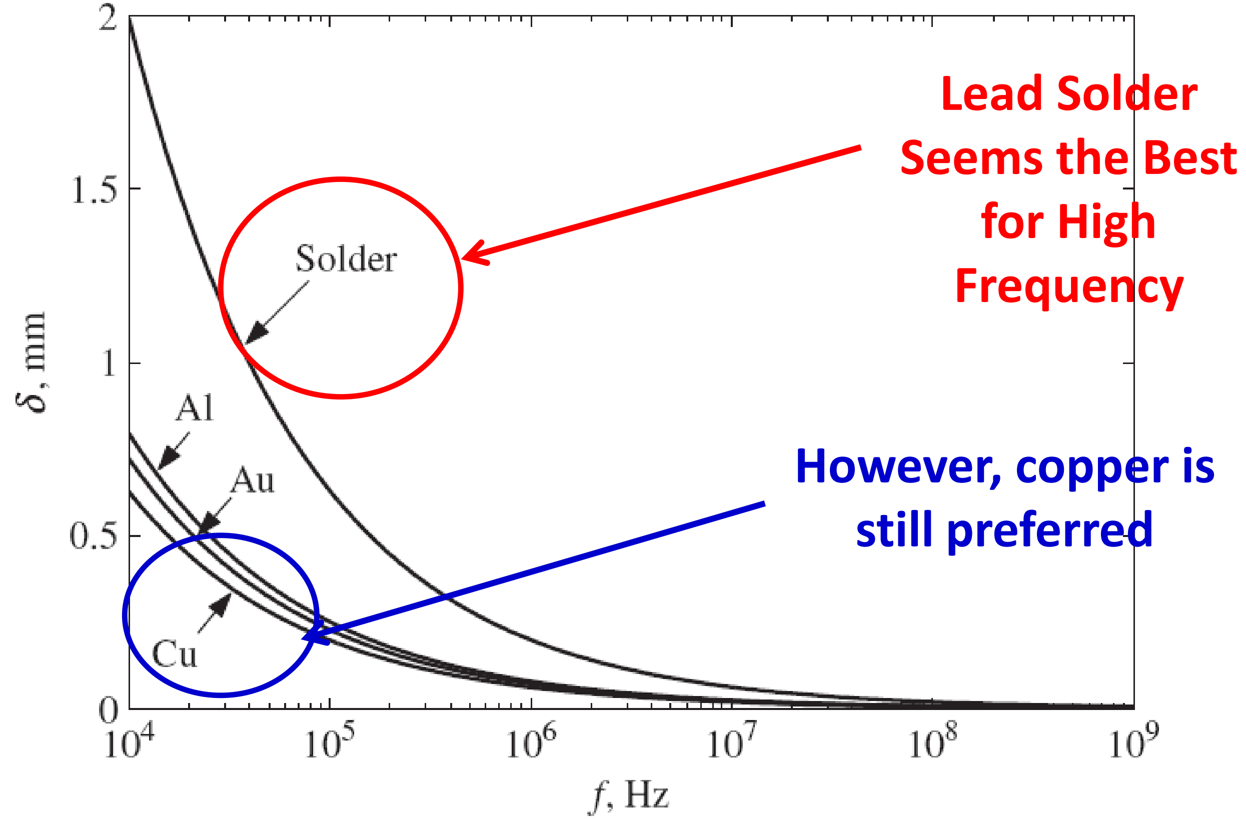
$$\boxed{p^2 = -j\omega\mu\sigma_{cond}}$$

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma_{cond}}}$$

Skin Depth

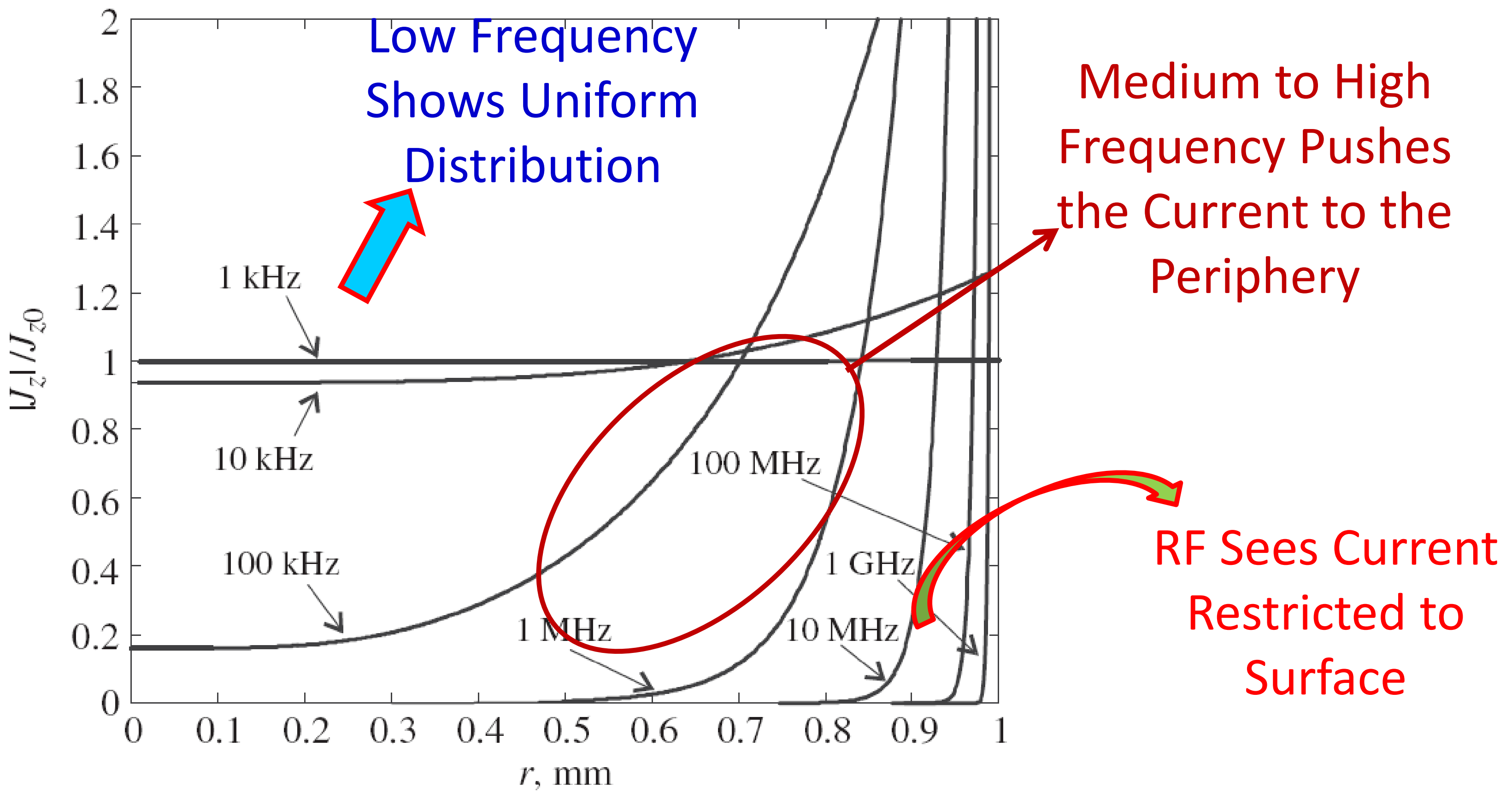
RF Behavior of Resistors (contd.)

- J_z drops with decrease in r (proximity to the center)
- δ decreases with increase in frequency (skin depth from periphery reduces with increased frequency) → the path for current conduction remains nearer to the periphery (skin effect) → current density towards center decreases with increase in frequency and increase in conductivity



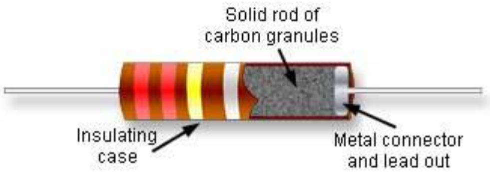
RF Behavior of Resistors (contd.)

Frequency sweep: For a fixed wire radius of $a = 1mm$, the plot $|J_z|/|J_{z0}|$ as a function of depth r:



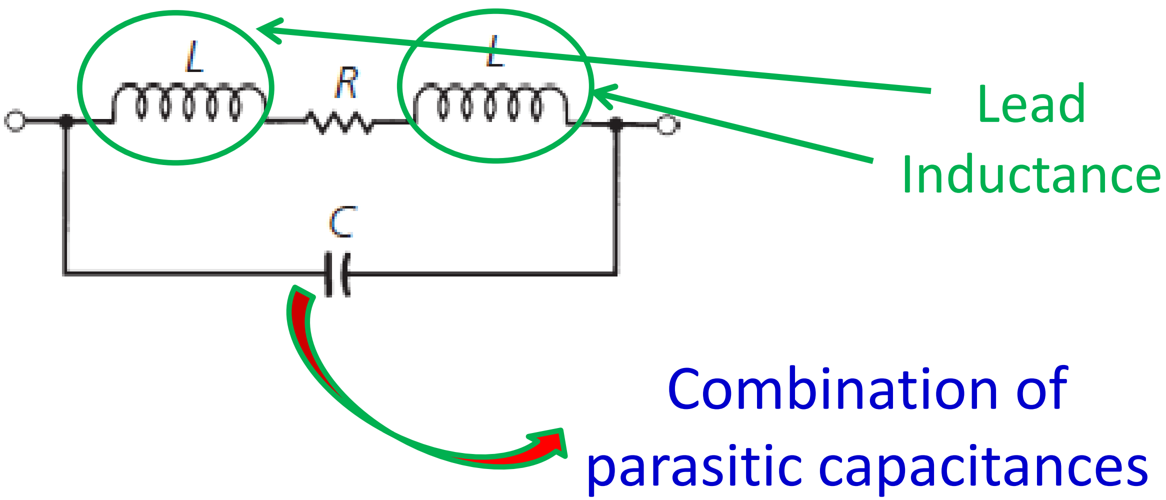
Resistors at High Frequencies

1. Carbon-composition resistors:



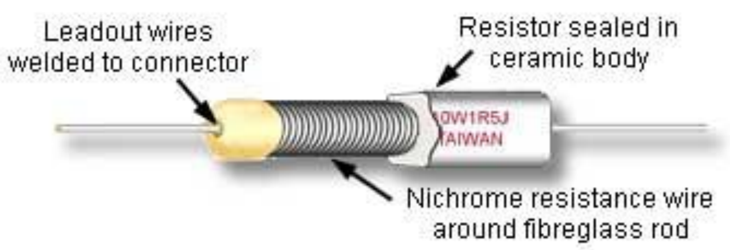
- Consists of densely packed dielectric particulates or carbon granules.
- **Between each pair of carbon granules is very small parasitic capacitor.**
- These parasitics, in aggregate, are significant → **primarily responsible for notoriously poor performance at high frequencies.**

Equivalent Ckt Model:



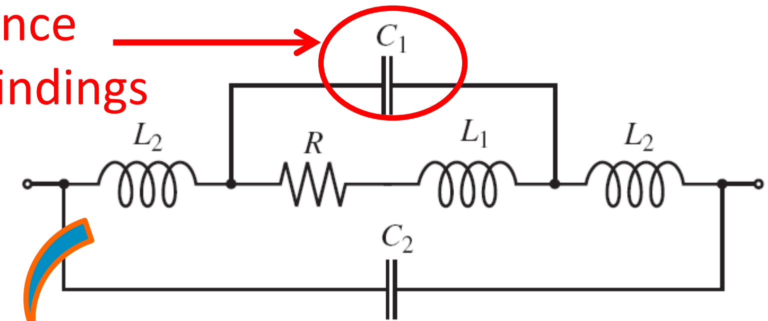
Resistors at High Frequencies (contd.)

2. Wire-wound Resistors:



Equivalent Ckt Model:

Capacitance between Windings

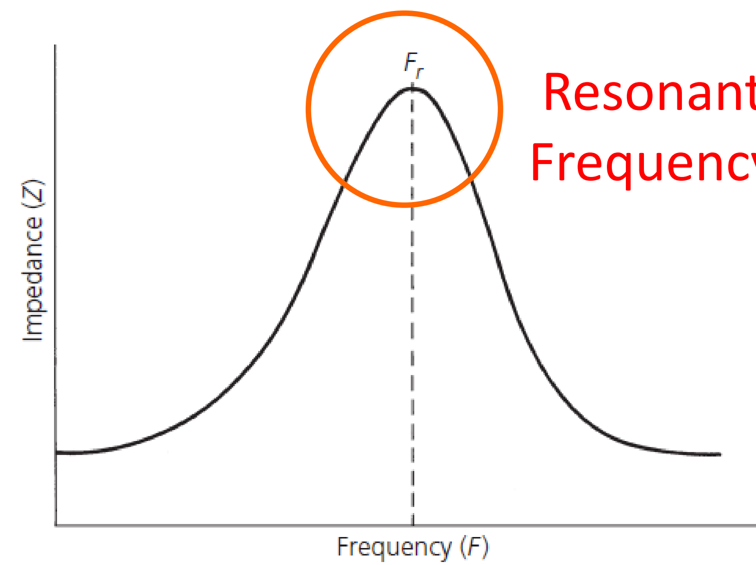


L_2: lead inductance

L_1: inductance of resistive wires

C_2: Interlead Capacitance

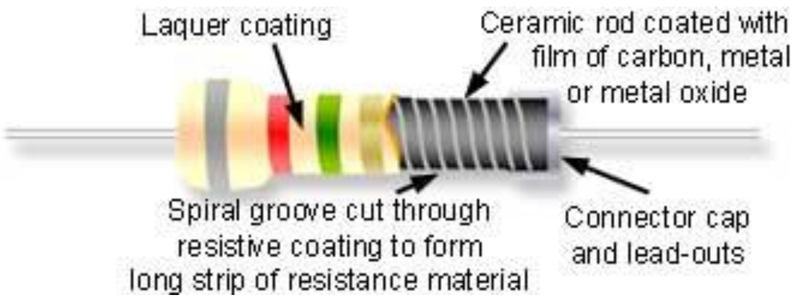
- Exhibit widely varying impedances over various frequencies.
- The inductor L is much larger here as compared to carbon-composition resistor.
- These resistors look like inductors → impedances will increase with increase in frequency.
- At some frequency F_r, the inductance will resonate with shunt capacitance → leads to decrease in impedance.



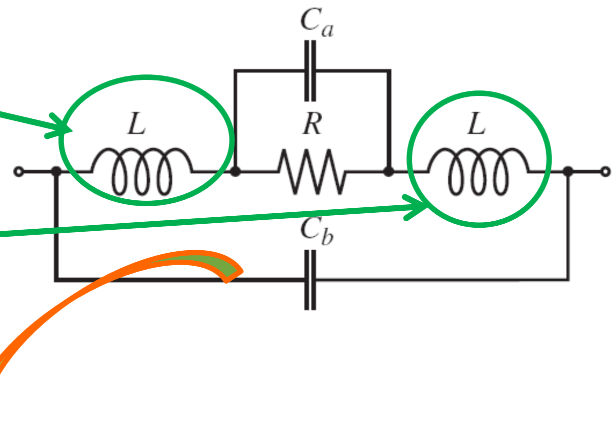
Resonant Frequency

Resistors at High Frequencies (contd.)

3. Metal-film Resistors:



Equivalent Ckt Model:



C_a models charge separation effects and C_b models interlead capacitance

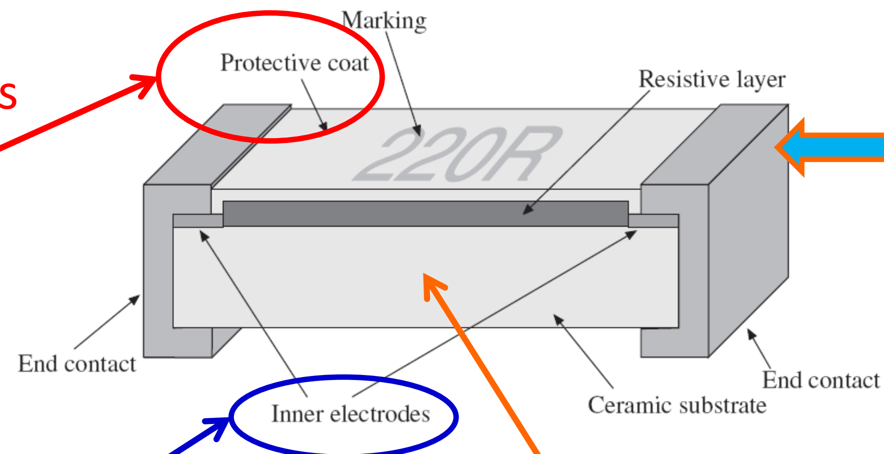
- Seems to exhibit very good characteristics over frequency.
- Values of L and C are much smaller as compared to wire-wound and carbon-composition resistors.
- It works well up to 10 MHz → useful up to 100 MHz

Resistors at High Frequencies (contd.)

4. Thin-film Chip Resistors:

- The idea is to eliminate or reduce the stray capacitances associated with the resistors
- Good enough up to 2 GHz.

Protective coat prevents variations from any environmental interferences



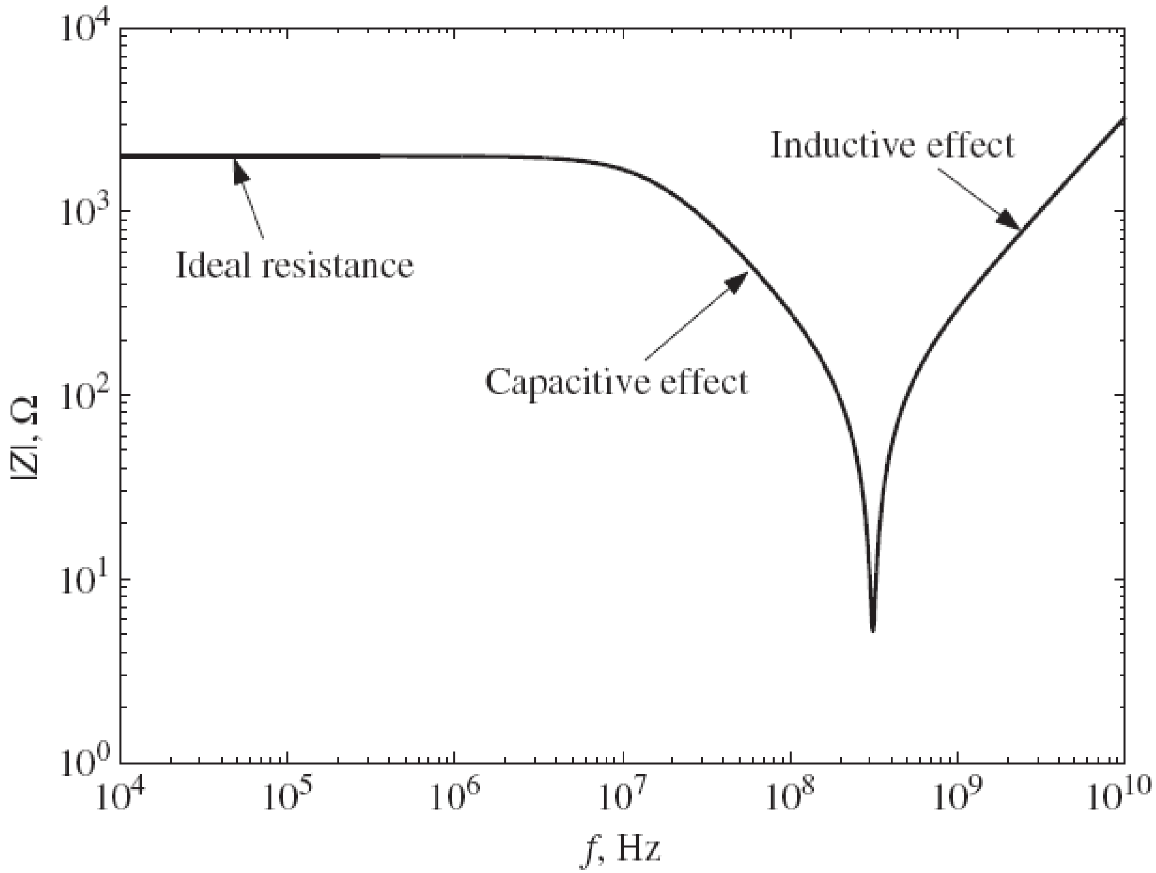
The end contacts are required for soldering purposes

electrodes are inserted after trimming the resistive layer to the desired value

A metal film (usually nichrome) layer is deposited on this ceramic substrate → this layer works as resistor

Resistors at High Frequencies (contd.)

What is the reason for following behavior of a 2000Ω thin-film resistor?



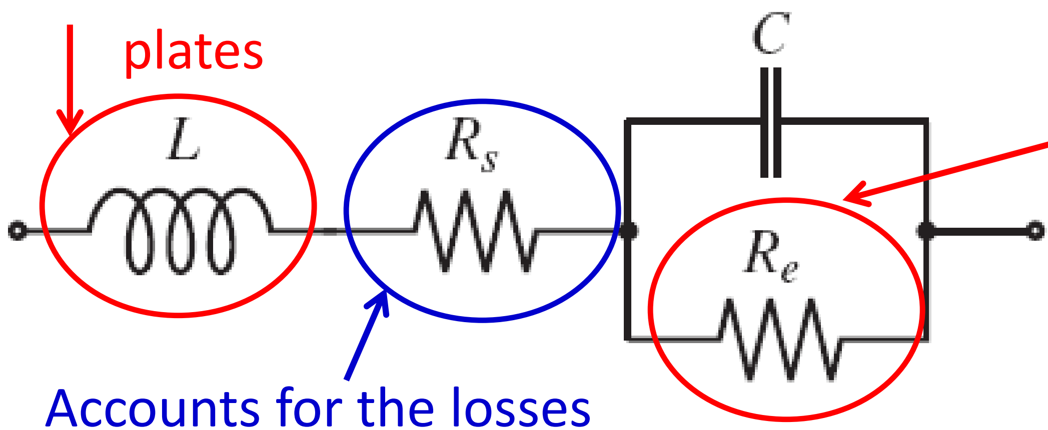
HW # 0

Demonstrate using either ADS or MATLAB

Capacitors at High Frequencies

Equivalent Circuit Representation of a Capacitor → for a parallel-plate

Inductance of the leads and plates



Represents Insulation Resistance

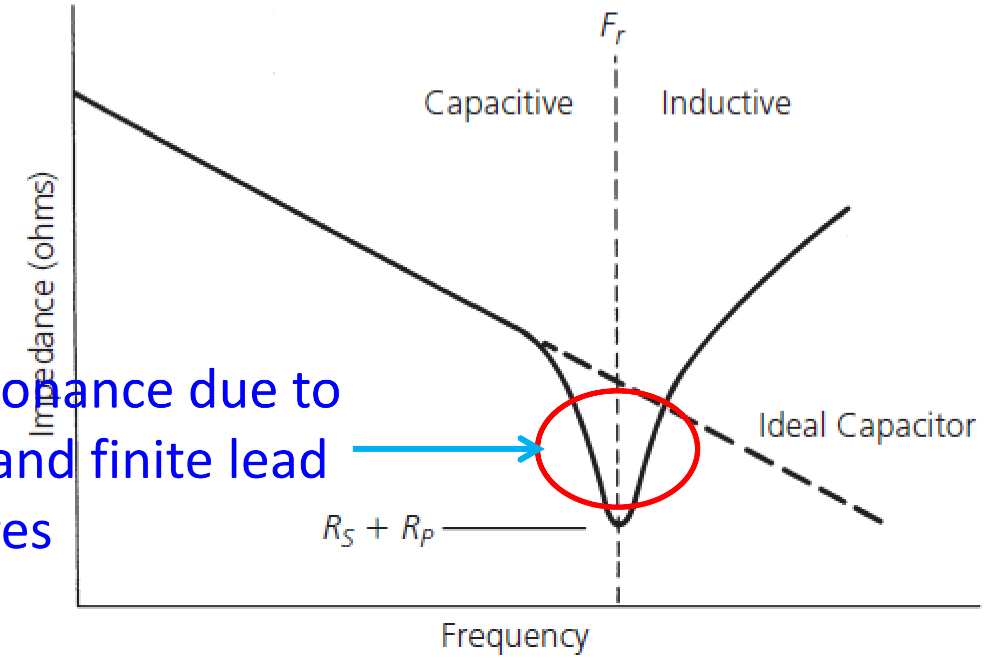
Accounts for the losses in the leads

$$C = \frac{\varepsilon A}{d} = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

At high frequency, the dielectric become lossy i.e., there is conduction current through it

impedance of capacitor becomes a parallel combination of C and conductance G_e

Capacitors at High Frequencies (contd.)

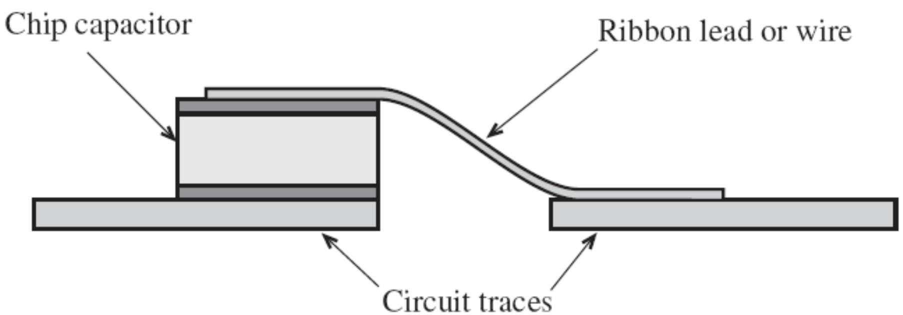


Presence of resonance due to dielectric loss and finite lead wires

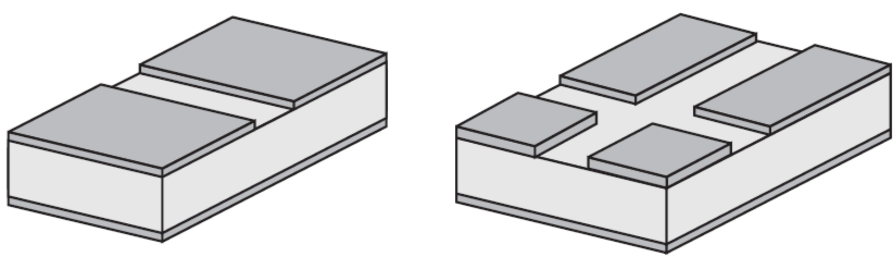
- Above F_r, the capacitor behaves as an inductor.
- In general, larger-value capacitors tend to exhibit more internal inductance than smaller-value capacitors.
- Therefore, it may happen that a $0.1\mu F$ may not be as a good as a $300pF$ capacitor in a bypass application at $250\ MHz$.
- The issue is due to significance of lead inductances at higher frequencies.

Capacitors at High Frequencies (contd.)

Chip Capacitors



Cross-section of a single-plate capacitor connected to the board

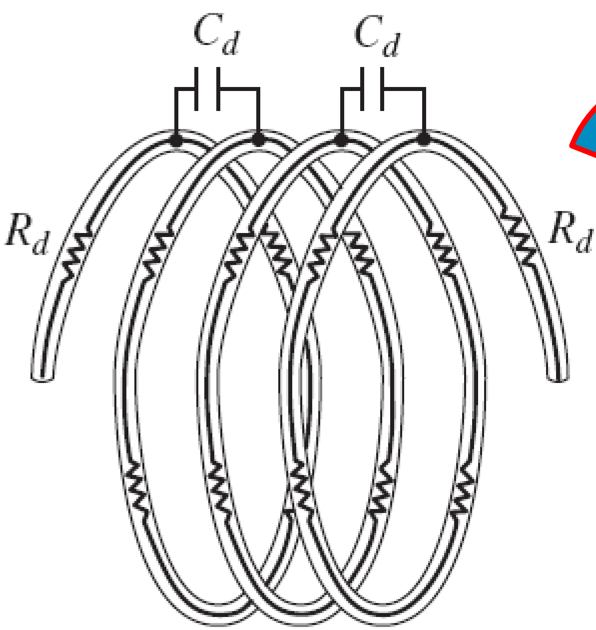


Dual capacitor

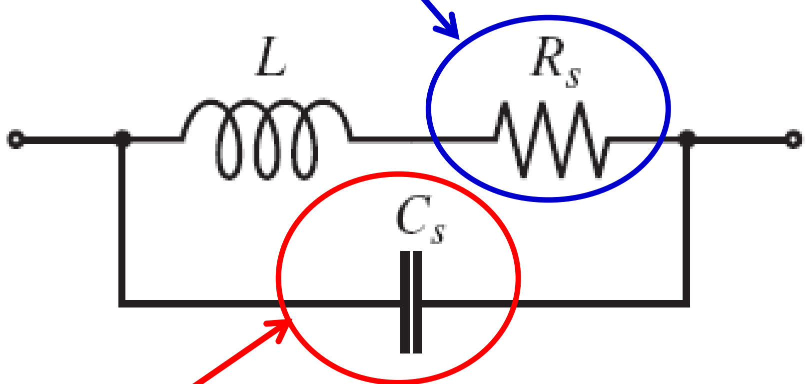
Quadrupole capacitor

Inductors at High Frequencies

Equivalent Circuit Representation of an Inductor → coil type



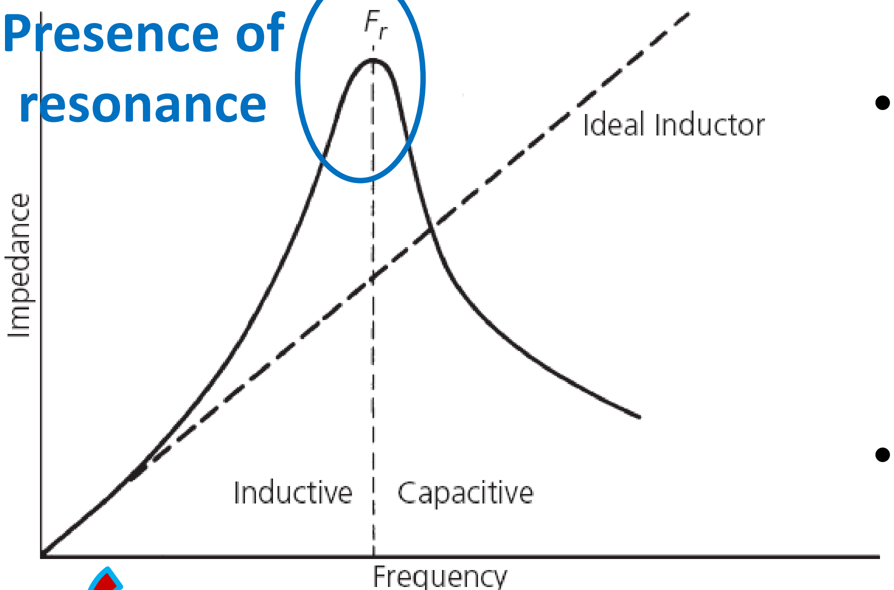
Composite Effect of all the distributed R_d



Composite Effect of all the distributed C_d

Inductors at High Frequencies (contd.)

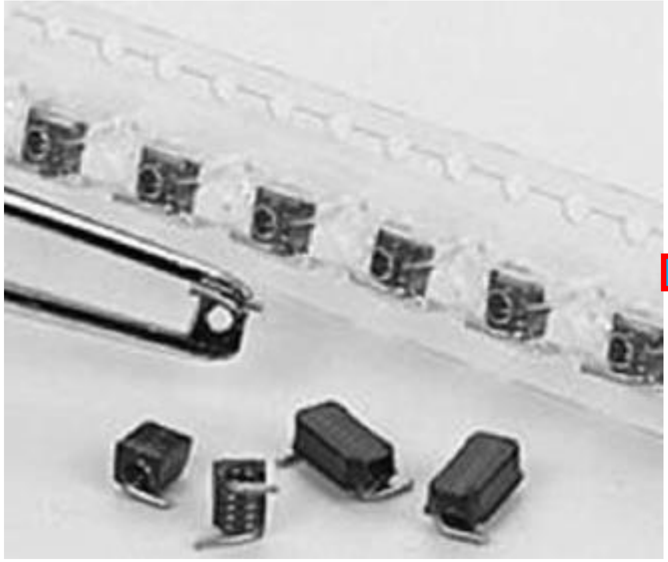
Presence of resonance



- Initially the reactance of inductor follows the ideal but soon departs from it and increases rapidly until it reaches a peak at the inductor's resonant frequency (F_r). **Why?**
- Above F_r, the inductor starts to behave as a capacitor.

Implement this in MATLAB or ADS **HW#0**

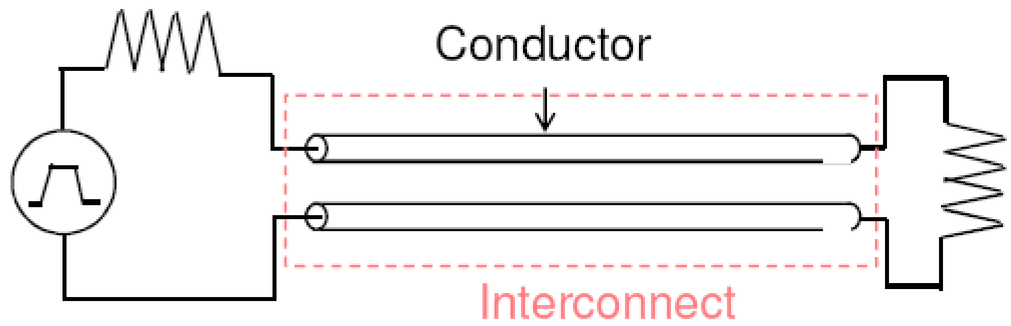
Chip Inductors



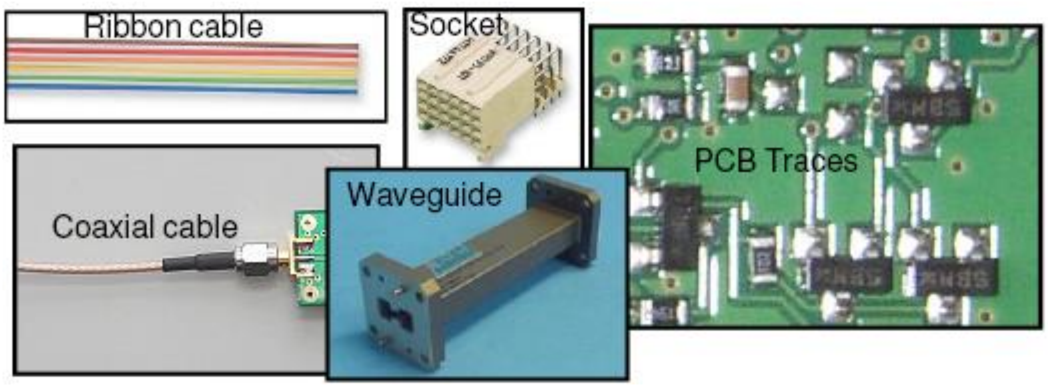
Surface mounted inductors still come as wire-wound coil →these are comparable in size to the resistors and capacitors

Transmission Line

- It is a standard practice to use **metallic conductors** for transporting electrical energy from one point of a circuit to another. These conductors are called **interconnects**.



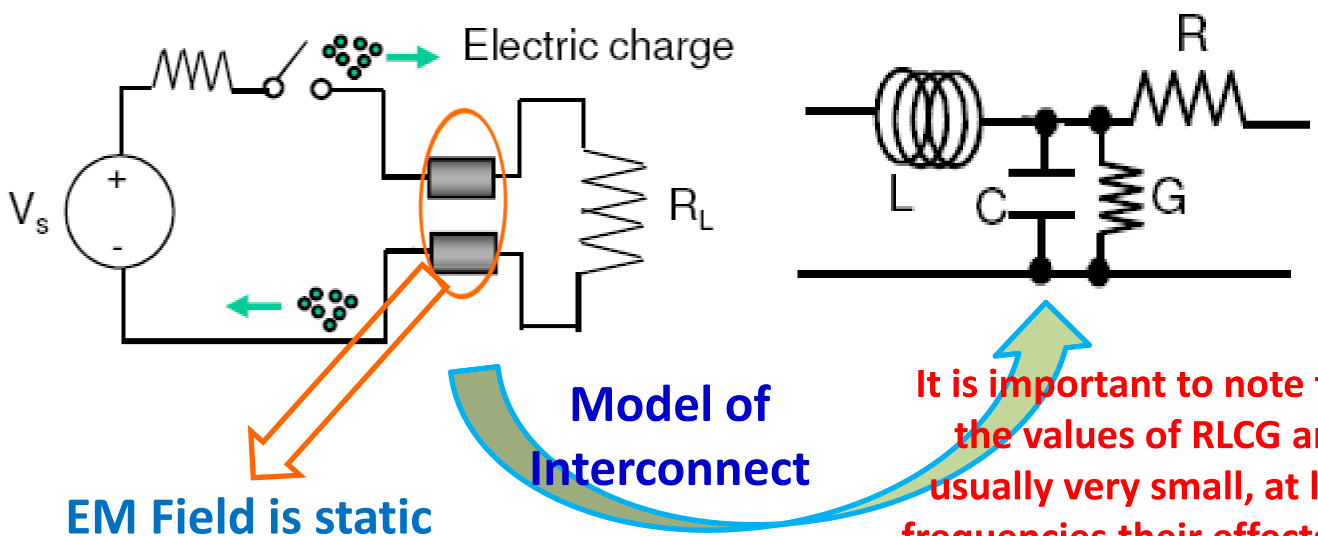
- Therefore **cables**, **wires**, **conductive tracks** on printed circuit boards (**PCBs**), **sockets**, **packaging**, **metallic tubes** etc are all examples of interconnect.



Transmission Line (contd.)

- For <u>short interconnect</u>, the moment the switch is closed, a voltage will appear across R_L as current flows through it. The effect is instantaneous.
- Voltage and current are due to electric charge movement along the interconnect.
- Associated with the electric charges are **static electromagnetic (EM) field** in the space surrounding the short interconnect.
- The short interconnect system can be modelled by lumped RLC circuit.

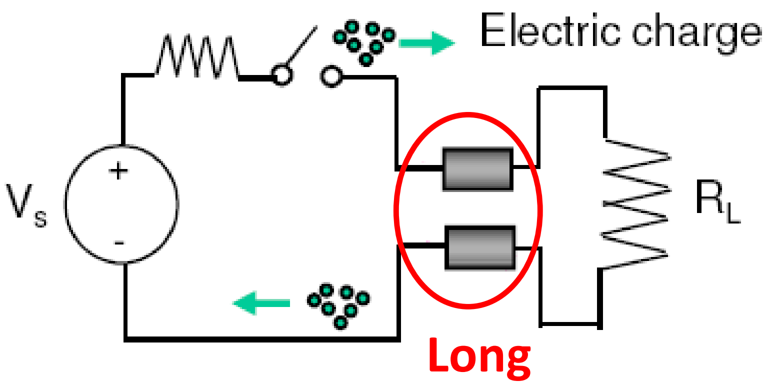
Static EM Field changes uniformly i.e, when field at one point increases, field at other location also increases



It is important to note that the values of RLCG are usually very small, at low frequencies their effects can be simply ignored

Transmission Line (contd.)

- If the interconnection is **long** (in comparison to the wavelength of the signal frequency), it takes some time for the voltage and current to appear on the R_L when the switch is closed.



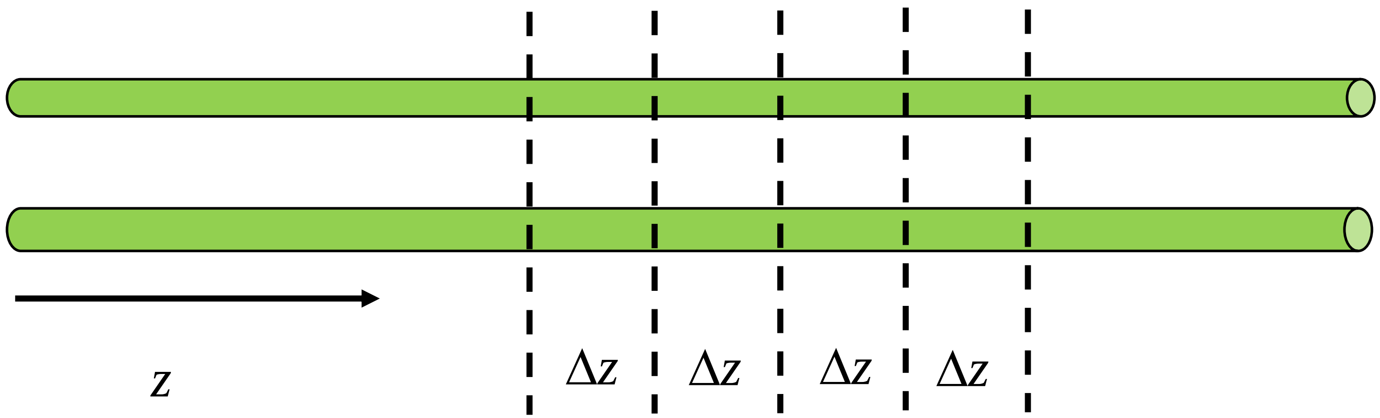
Electric charges move from V_S to the R_L. As the charge move, there is an associated EM field which travels along with the charges

In effect, there is propagating EM field along the interconnect. The propagating EM field is called wave and the interconnect guiding the wave is called transmission line.

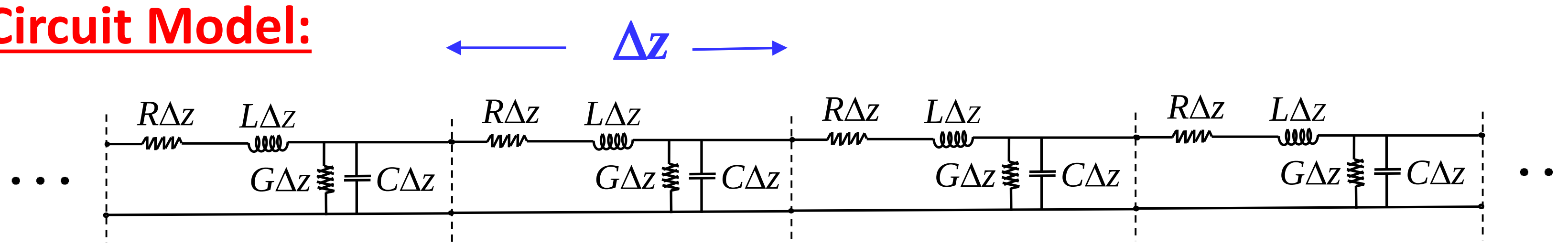
A transmission line is a two-conductor system that is used to transmit a signal from one point to another point.

Transmission Lines (contd.)

- Variations in current and voltage across the circuit dimensions → KCL and KVL can't be directly applied → **This anomaly can be remedied** if the line is subdivided into elements of small (infinitesimal) length over which the current and voltage do not vary.

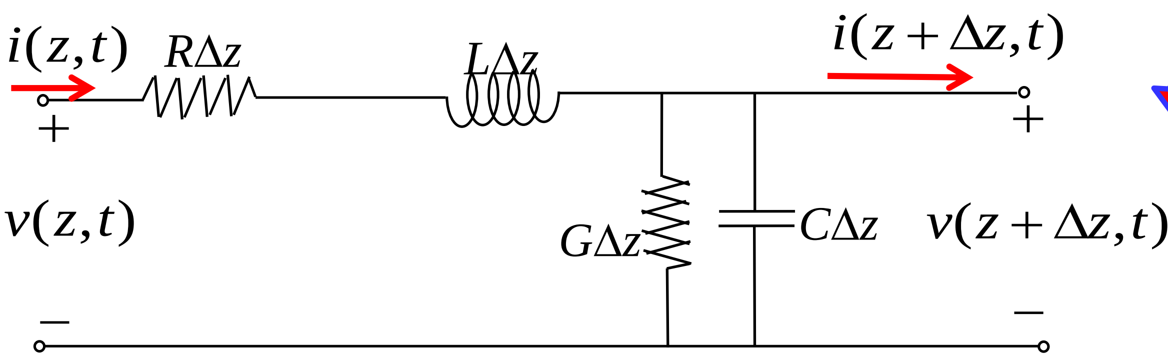


Circuit Model:



$\lim_{\Delta z \to 0} \Rightarrow$ Infinite number of infinitesimal sections

Transmission Lines (contd.)



Lossy Transmission Line Circuit Model

Apply KVL:

$$v(z,t)-v(z+\Delta z,t)=R\Delta z i(z,t)+L\Delta z\frac{\partial i(z,t)}{\partial t} \Rightarrow \frac{v(z,t)-v(z+\Delta z,t)}{\Delta z}=Ri(z,t)+L\frac{\partial i(z,t)}{\partial t}$$

Describes the voltage along the transmission lines

$$\therefore -\frac{\partial v(z,t)}{\partial z}=Ri(z,t)+L\frac{\partial i(z,t)}{\partial t}$$

For $\Delta z \rightarrow 0$

KCL on this line segment gives: $i(z,t)-i(z+\Delta z,t)=G\Delta z v(z+\Delta z,t)+C\Delta z\frac{\partial v(z+\Delta z,t)}{\partial t}$

Simplification results in: $\frac{\partial i(z,t)}{\partial z}=-Gv(z,t)-C\frac{\partial v(z,t)}{\partial t}$

For $\Delta z \rightarrow 0$

Describes the current along the transmission lines

Transmission Lines (contd.)

Solution for Voltage and Current:

- For a sinusoidal excitation [i.e, $V_s(t) = V_s\{cos(\omega t)\}$], the steady state voltages and currents along the transmission line are also sinusoidal functions of time whose dependence on position and time can be expressed as:

$$v(z,t) = f(z)\cos(\omega t + \varphi(z))$$

$$i(z,t) = g(z)\cos(\omega t + \eta(z))$$

- $f(z)$ and $g(z)$ are real functions of position and $\varphi(z)$ and $\eta(z)$ describe the positional dependence of the phase.

- **Alternatively,**

$$v(z,t) = f(z)\cos(\omega t + \varphi(z)) = \text{Re}\left[f(z)e^{j\varphi(z)}e^{j\omega t}\right]$$

$$i(z,t) = g(z)\cos(\omega t + \eta(z)) = \text{Re}\left[g(z)e^{j\eta(z)}e^{j\omega t}\right]$$

- **Let us define these phasors:** $V(z) = f(z)e^{j\varphi(z)}$ $\quad I(z) = g(z)e^{j\eta(z)}$

The phasors $I(z)$ and $V(z)$ are complex functions of position and express the variations of current/voltage as a function of position along the transmission line.

Transmission Lines (contd.)

- **Therefore the current and voltage functions can be expressed as:**

$$v(z,t) = \mathrm{Re}\left[V(z)e^{j\omega t}\right] \qquad i(z,t) = \mathrm{Re}\left[I(z)e^{j\omega t}\right]$$

- The time-harmonic form of the telegrapher equations are:

$$\mathrm{Re}\frac{\partial\left(f(z)e^{j\varphi(z)}e^{j\omega t}\right)}{\partial z} = -Re\left(R.g(z)e^{j\eta(z)}e^{j\omega t} + j\omega L.g(z)e^{j\eta(z)}e^{j\omega t}\right)$$

$$\mathrm{Re}\frac{\partial\left(g(z)e^{j\eta(z)}e^{j\omega t}\right)}{\partial z} = -Re\left(G.f(z)e^{j\varphi(z)}e^{j\omega t} + j\omega C.f(z)e^{j\varphi(z)}e^{j\omega t}\right)$$

- With the substitution of phasors, the equations of voltage and current wave result in:

$$\mathrm{Re}\frac{\partial\left(V(z)e^{j\omega t}\right)}{\partial z} = -Re\left(RI(z)e^{j\omega t} + j\omega LI(z)e^{j\omega t}\right)$$

$$\mathrm{Re}\frac{\partial\left(I(z)e^{j\omega t}\right)}{\partial z} = -Re\left(GV(z)e^{j\omega t} + j\omega CV(z)e^{j\omega t}\right)$$

Transmission Lines (contd.)

- The differential equations for current and voltage along the transmission line can be expressed in phasor form as:

$$Re\frac{d\left(V(z)e^{j\omega t}\right)}{dz} = -Re\left(RI(z)e^{j\omega t} + j\omega LI(z)e^{j\omega t}\right)$$

$$Re\frac{d\left(I(z)e^{j\omega t}\right)}{dz} = -Re\left(GV(z)e^{j\omega t} + j\omega CV(z)e^{j\omega t}\right)$$

As $I(z)$ and $V(z)$ are function of only position

$$\frac{\partial V(z)}{\partial z} = \frac{dV(z)}{dz}$$

$$\frac{\partial I(z)}{\partial z} = \frac{dI(z)}{dz}$$

Transmission Lines (contd.)

- The equations can be simplified as:

$$\Rightarrow Re\left[\left(\frac{d\left(V(z)\right)}{dz}+RI(z)+j\omega LI(z)\right)e^{j\omega t}\right]=0$$

$$\Rightarrow \mathrm{Re}\left[\left(\frac{d\left(I(z)\right)}{dz}+GV(z)+j\omega CV(z)\right)e^{j\omega t}\right]=0$$

For further simplification

At ωt=0, $e^{j\omega t}$=1:

$$\Rightarrow Re\left[\left(\frac{d\left(V(z)\right)}{dz}+RI(z)+j\omega LI(z)\right)\right]=0$$

At ωt=π/2, $e^{j\omega t}$=j:

$$\Rightarrow Re\left[\left(\frac{d\left(V(z)\right)}{dz}+RI(z)+j\omega LI(z)\right)j\right]=0$$

Transmission Lines (contd.)

- Finally we can write:

$$\frac{d\,\mathrm{V}(z)}{dz} = -\left(R + j\omega L\right)\mathrm{I}(z)$$

$$\frac{d\,\mathrm{I}(z)}{dz} = -\left(G + j\omega C\right)\mathrm{V}(z)$$

These differential equations can be solved for the phasors along the transmission line

Differentiating with respect to z gives

$$\frac{d^2\,\mathrm{V}(z)}{dz^2} - \gamma^2 V(z) = 0$$

$$\frac{d^2\,\mathrm{I}(z)}{dz^2} - \gamma^2 I(z) = 0$$

Transmission Line Wave Equations

Here

Complex Propagation Constant

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

$$\gamma = \alpha + j\beta$$

Attenuation Constant (nepers/m)

Phase Constant (radians/m)

Transmission Lines (contd.)

- For lossless transmission line (i.e, transmission line where R and G are negligible) - most common scenario in our transmission line based circuit design:

$$\boxed{\gamma = j\beta = j\omega\sqrt{LC}}$$

No Attenuation

Phase Constant is also Propagation Constant for a Lossless Line

Oh please, continue wasting my valuable time. We both know that a **lossless transmission** line is a **physical impossibility**.

True! However, a **low-loss** line **is** possible – in fact it is **typical!** **If $R \ll \omega L$ and $G \ll \omega C$,** we find that the lossless transmission line equations are excellent **approximations!!!**

Transmission Lines (contd.)

- For a lossless transmission line the second order differential equation for phasors are:

$$\beta = \omega\sqrt{LC}$$

$$\frac{d^2 V(z)}{dz^2} + \beta^2 V(z) = 0$$

$$\frac{d^2 I(z)}{dz^2} + \beta^2 I(z) = 0$$

General Solution For Voltage Phasor

V_0^+ and V_0^- are complex constants

$$V(z) = V_0^+ e^{-j\beta z} + V_0^- e^{j\beta z}$$

- Similarly the current phasor for a lossless line can be described:

$$I(z) = -\frac{1}{j\omega L}\frac{dV(z)}{dz} = -\frac{1}{j\omega L}\frac{d}{dz}\left[V_0^+ e^{-j\beta z} + V_0^- e^{j\beta z}\right]$$

$$\Rightarrow I(z) = \frac{\beta}{\omega L}\left[V_0^+ e^{-j\beta z} - V_0^- e^{j\beta z}\right]$$

Gives the Definition of Characteristic Impedance

Transmission Lines (contd.)

$$Z_0 = \frac{\omega L}{\beta} = \frac{\omega L}{\omega\sqrt{LC}} = \sqrt{\frac{L}{C}}$$

Completely Dependent on L and C

Characteristic Impedance for a Lossless Line is Real

$$\therefore I(z) = \frac{V_0^+}{Z_0} e^{-j\beta z} - \frac{V_0^-}{Z_0} e^{j\beta z}$$

Opposite Signs in these Terms Gives a Clue about Current Flow in Two Different Directions

- The time dependent form of the voltage and current along the transmission line can be derived from phasors as:

$$v(z,t) = \mathrm{Re}\left[V(z)e^{j\omega t}\right] = \mathrm{Re}\left[V_0^+ e^{-j(\beta z-\omega t)} + V_0^- e^{j(\beta z+\omega t)}\right]$$

$$i(z,t) = \mathrm{Re}\left[I(z)e^{j\omega t}\right] = \mathrm{Re}\left[\frac{V_0^+}{Z_0} e^{-j(\beta z-\omega t)} - \frac{V_0^-}{Z_0} e^{j(\beta z+\omega t)}\right]$$

Transmission Lines (contd.)

- For the simple case of $\boldsymbol{V_0}^+$ **and** $\boldsymbol{V_0}^-$ being real, the voltage and current along the transmission line can be expressed as:

$$v(z,t) = V_0^+ \cos(\omega t - \beta z) + V_0^- \cos(\omega t + \beta z)$$

$$i(z,t) = \frac{V_0^+}{Z_0} \cos(\omega t - \beta z) - \frac{V_0^-}{Z_0} \cos(\omega t + \beta z)$$

$$V_0^+ \cos(\omega t - \beta z) \qquad V_0^- \cos(\omega t + \beta z)$$

Wave Functions

- Let us examine the wave characteristics of $\boxed{v_1(z,t) = V_0^+ \cos(\omega t - \beta z)}$