Lecture-1 Date: 04.01.2016

- Introduction
- Why this course?
- Differentiating factor between low and high frequency circuits
- Transmission Line (Intro.)

RF Circuit Design (ECE321/521)

Instructor: Dr. Mohammad S. Hashmi

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

Lab Timings: Wednesday (11:30 – 13:30)

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

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

Course Outline:

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

ECE321/ECE521: RF Circuit Design

Instructor: Mohammad Hashmi
Teaching Assistants: Sushant, Vijay
RF Lab Contact Person: Rahul Gupta

Lecture: Mon & Thu (10:00-11:30) in C24
Lab: Wed 11:00-13:00 in RF & Applied EM Lab

Office Hour: Mon (16:00 to 17:00)

Outline | Announcements | Resources | Lecture Schedule

Course Outline and Policy

Description

This course is designed for exposure to circuits and systems design techniques for radio communications leading towards the recent research in the domain of advanced radio technology. In the first half of the course, students will be exposed to the fundamental concepts of passive and active circuits design at radio frequencies. These fundamental concepts require substantial understanding of transmission line theory and Smith chart and therefore this course will start with thorough discussion on these two topics. This half also includes training of students on the commercial software tool known as Advanced Design System (ADS). There will be tutorials on schematics, layout and optimization techniques to familiarize the students with the ADS. The students will have to subsequently do several design assignments using ADS. In the second half of the course, students will be introduced to design aspects of components such as matching networks, couplers, and power dividers etc. As part of the course projects, the students will have opportunity to carry out projects from conception to realization, PCB manufacture and then measurements using VNA.

Postconditions

On the completion of this course the students will be able to:
1. Learn various RF Circuit design techniques.
2. Acquire hands-on skills to analyze and design simple components, such as matching networks, coupler, power divider etc, used in the Radio Communication Circuits.
3. Gain skills in using software tool ADS, PCB machine, and Vector Network Analyzer

Evaluation

Following components are part of the overall evaluation:

Home Assignment	20%
Surprize Class Tests	15%
Mid-sem Exam	20%
Final Exam	15%
Project	30%

Home assignments are to be submitted by the due date.

Plagiarism is forbidden and will be seriously dealt with as per institute policy.

Tentative Break-up of Lecture Contents

- **Lecture 1-2:** Introduction, Fundamentals, RF Behavior of Circuit Components
- **Lecture 3-5:** Transmission Line (TL) Analysis, Equivalent Circuit Representation, General TL Equations, Terminated Lossless TL, Special Termination Conditions
- **Lecture 6-7:** The Smith Chart
- **Lecture 8-11:** Single- and Multi-port Networks, S-Parameters, Signal Flow Graphs
- **Lecture 12-14:** Impedance Matching and Tuning
- **Lecture 15-17:** Power Dividers, Splitters, and Directional Couplers
- **Lecture 18-20:** RF Filter Design
- **Lecture 20-22:** Multi-Frequency Design Techniques
- **Lecture 23:** Vector Network Analyzer and Simple Calibration Approach
- **Lecture 24-26:** RF Amplifier Design

Lab Components:

- Introduction to ADS (It will be mostly self learning, will be 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

Attendance and Classroom Behavior:

- Attendance not necessary
- Students will be responsible for any notes, announcements etc. made during the class
- Prompt arrival to the class is requested
- No eating, drinking, smoking allowed in the class

Evaluation Mechanism

- Assignments – 20% weightage
- [Pen & Paper + ADS] based (all compulsory!)

- Surprise Quizzes – 15% weightage
- all compulsory!

- Exams and Project – 65% weightage
- Project (30%)
- Mid-Sem (20%)
- End-Sem (15%)

Projects Grading and Evaluation

1. Each student team (2 people max.) must work alone on projects – the design and analysis must represent each team's effort and knowledge only. Working with other teams will be considered academic misconduct and all students involved will receive **zero marks**. You are forbidden from viewing the report of other project teams

2. However, you may ask your colleagues about how to operate/use **ADS**

3. Likewise, you may confer with fellow students about any **general** questions about the theory associated with the projects. However, these questions must be **general**

4. A report that receives top marks will exhibit three characteristics:
   - **Accurate** – the design and analyses are correctly done
   - **Professional** – the results are clearly, completely, and unambiguously presented
   - **Insightful** – the report convinces me that you understand what you have done and why the result appear the way they do. In other words, after reading your report, I wish to be **impressed** with your knowledge and insight of the subject

Projects Grading and Evaluation

5. You may **extend** the projects beyond what is called for in the project description. If done correctly, this will likely impress me and help me conclude that you are a very motivated, knowledgeable, and professional student! Your grade will thus reflect this favorable opinion

However, this does not mean that an extension of projects scope is required – you will get full credit with a well-done report that addresses only the projects scope

Text Book:

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

Other Recommended Books:

- 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.

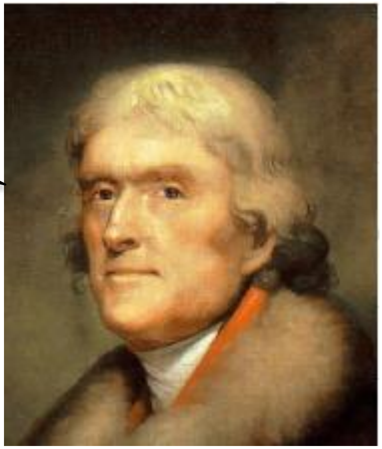
Course Website:

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

Info related to ECE321/521 can be found here

Hints for Success in RF Circuit Design

These tips are Gul-Durn important! Only a SUPERMAN type student can choose to ignore them!



1. **Be thorough** – The text and lecture slides are **not** an encyclopedia or manual! Each slide builds on the previous one – you must read them **completely** and in **order**. When you come to a line, paragraph or page that you **don't understand**, do you **stop** and figure it out, or just skip it and go on?
2. **Get help!** – **Office hours** are a great time to learn. All I ask is that you be **knowledgeable** of your **ignorance!**
3. **Be prepared for each lecture** – Attend each class having **read the notes** from the previous lecture, and having read the relevant **text** for the **current** lecture. Come to class prepared to learn!

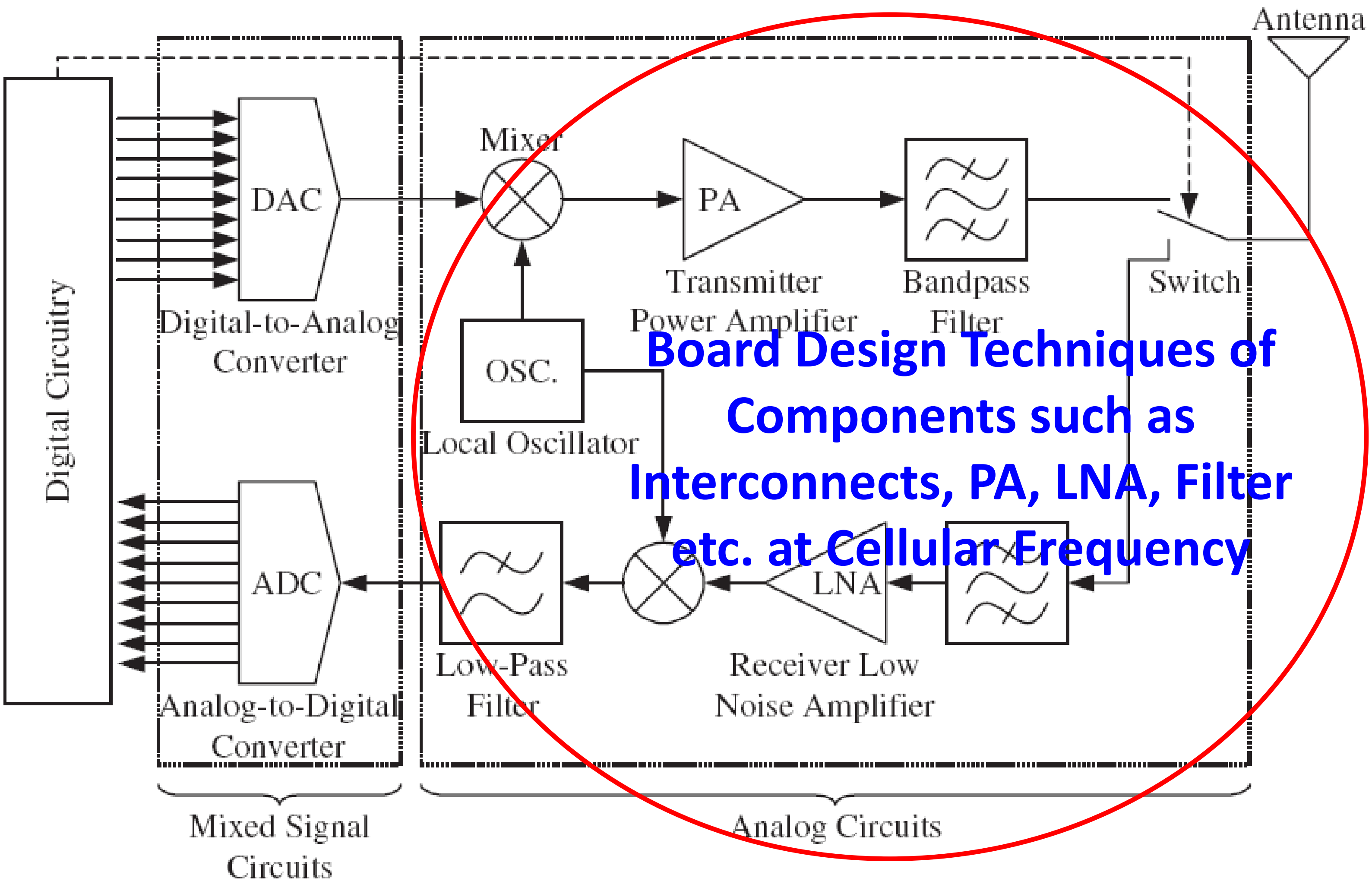
Motivation

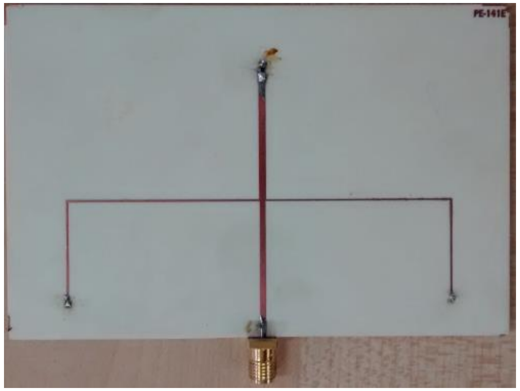
- Importance of RF Circuit Design
  - Wireless/Wirebased Communication Circuits → multi-band and multi-standard transceivers
  - Global Positioning System (GPS)
  - Increased clock speeds in ASICs/SoCs
  - Automotive Electronics

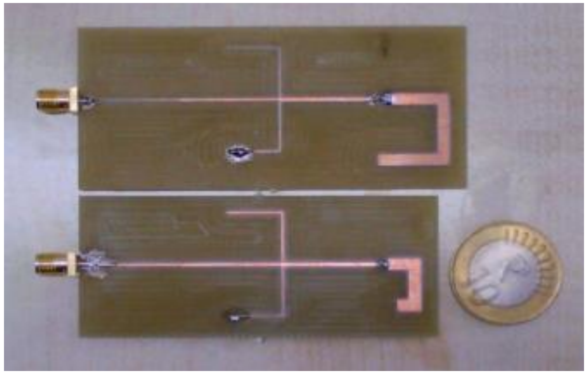
- Why this course
  - Lumped no more applicable!
  - Solution? → **distributed!!!**

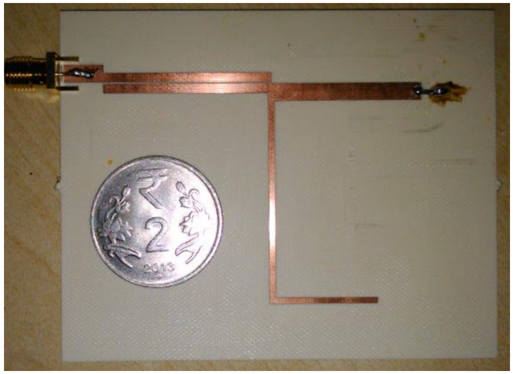
Motivation (contd.)

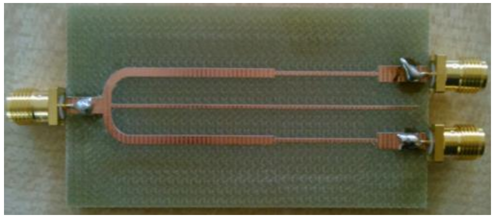
Design Focus in this Course

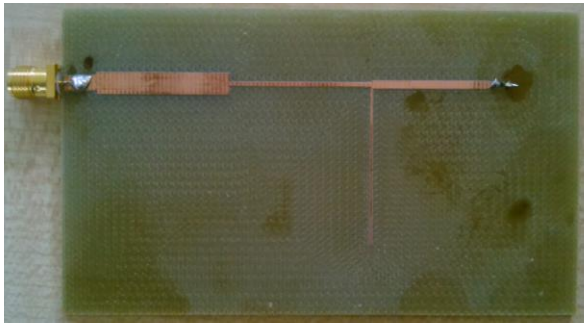


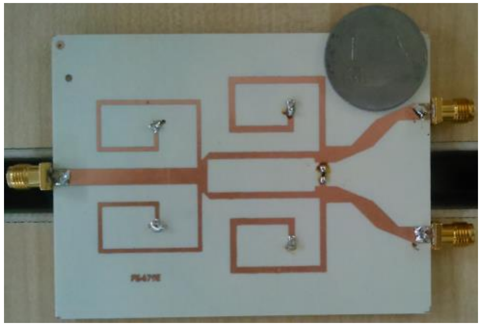


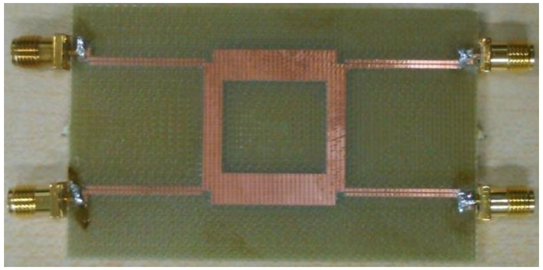












Motivation (contd.)

Frequency Spectrum

ELF	100 Hz
VLF	10 kHZ
LF	100 kHz
MF (MW)	1 MHz
HF (SW)	3 MHz
VHF	30 MHz
UHF	300 MHz
SHF	1 GHz
EHF	30 GHz
IR	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?

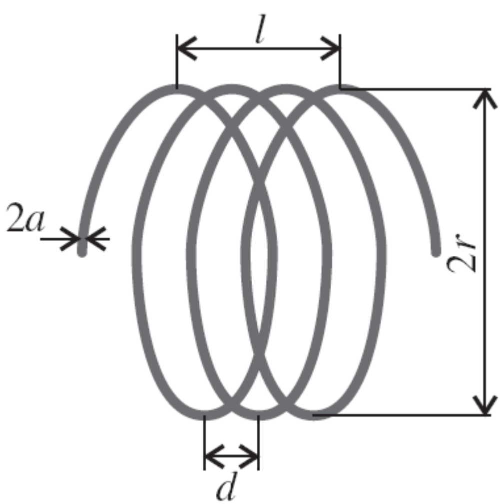
- Lumped components (wires, resistors, capacitors, inductors, connectors etc.) behave differently at low and high frequencies.
- Why?
  - current and voltage vary spatially over the component size
  - Leads to the concept of distributed components!

The KCL and KVL are no more applicable

Why this course?

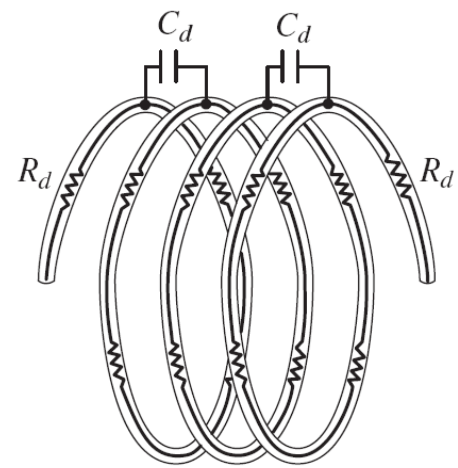
- What do we mean by distributed?
  - Example – Inductor

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:

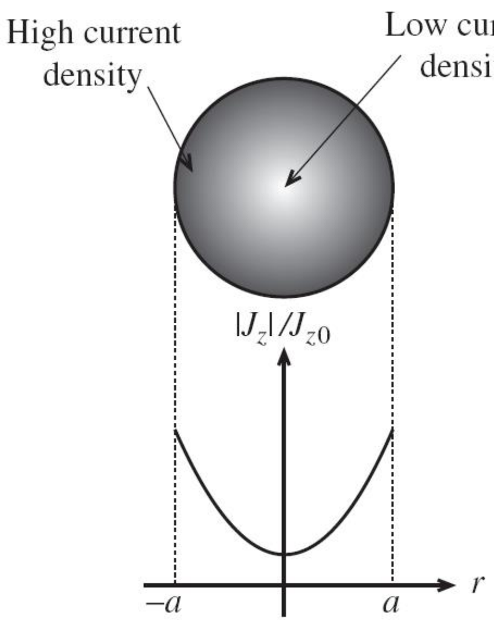
$$R_{DC} = \frac{l}{\pi a^2 \sigma_{cond}}$$

Length of cylinder

Radius of cylinder

conductivity

RF Behavior of Resistors (contd.)



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

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

- 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**

RF Behavior of Resistors (contd.)

- The current density at AC is given by:

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

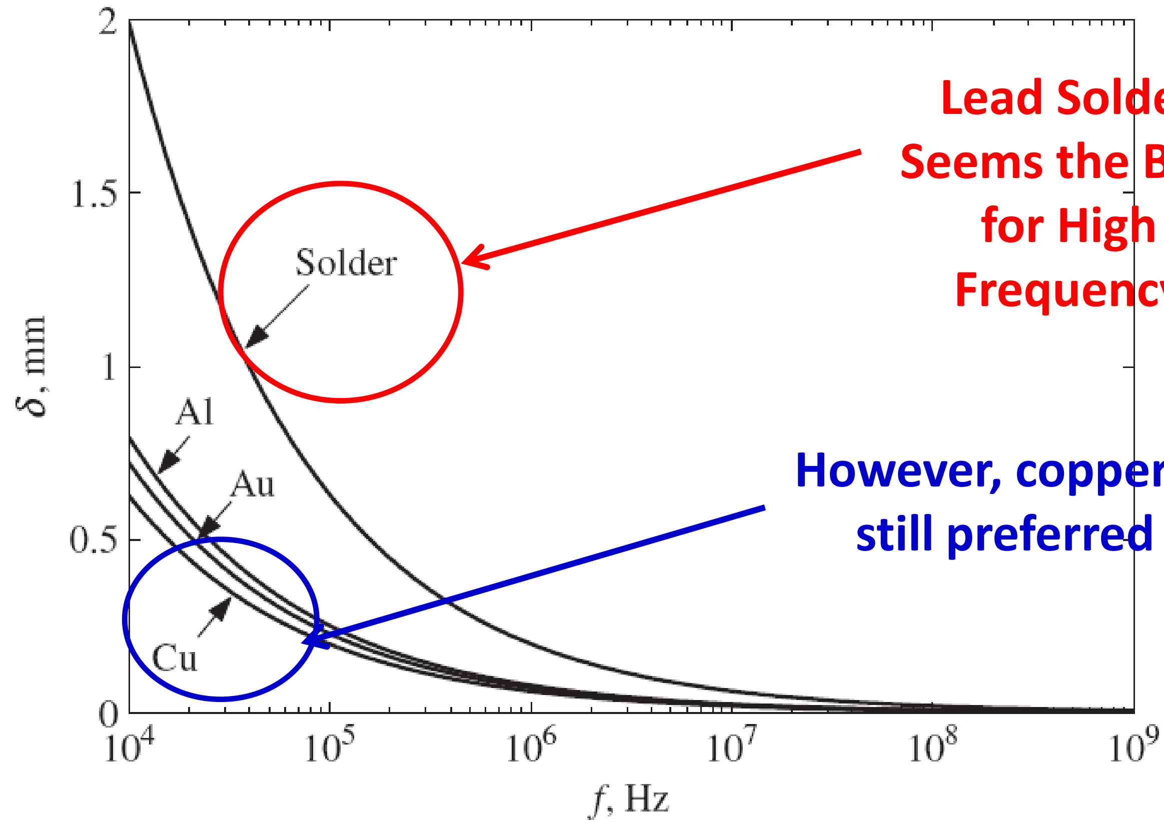
$$p^2 = -j\omega\mu\sigma_{cond}$$

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

Skin Depth

- 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) → means the path for current conduction remains nearer to the periphery (skin effect) → means, current density towards center decreases with increase in frequency and increase in conductivity

RF Behavior of Resistors (contd.)

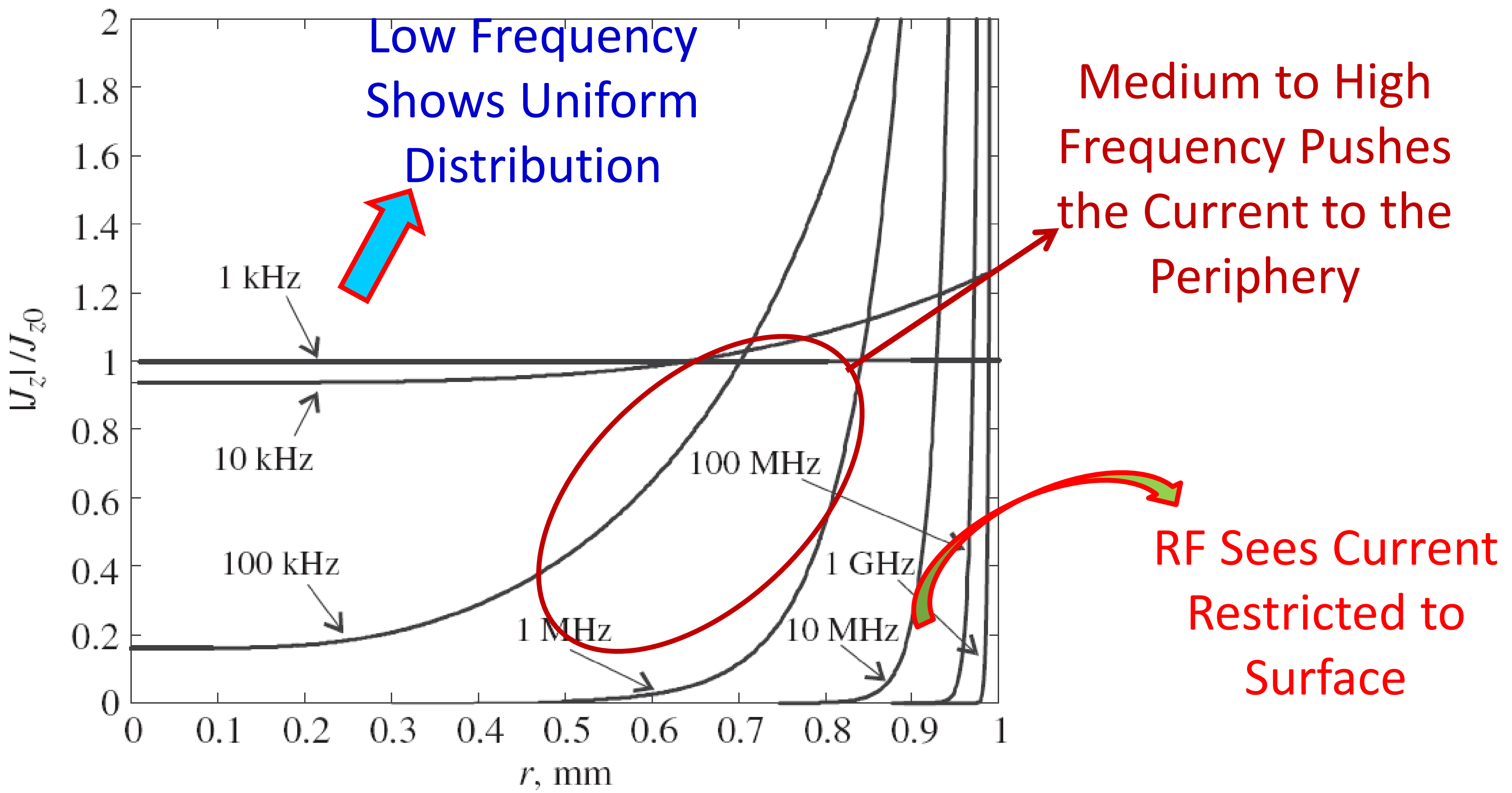


Lead Solder Seems the Best for High Frequency

However, copper is still preferred

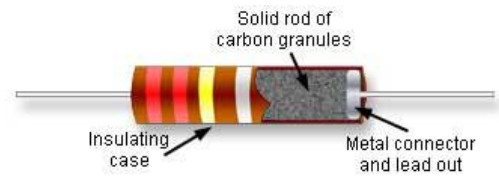
RF Behavior of Resistors (contd.)

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



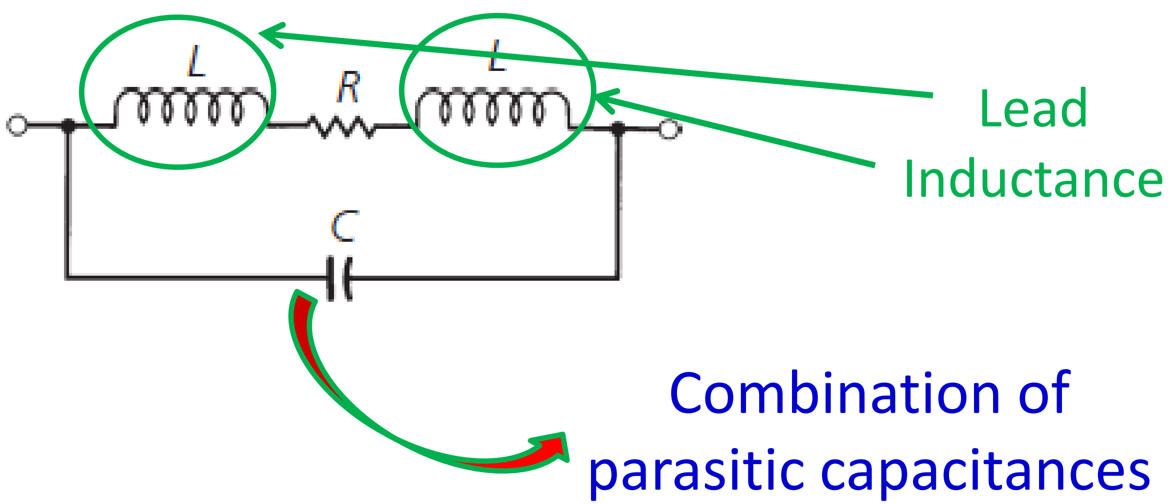
Resistors at High Frequencies

1. Carbon-composition resistors:



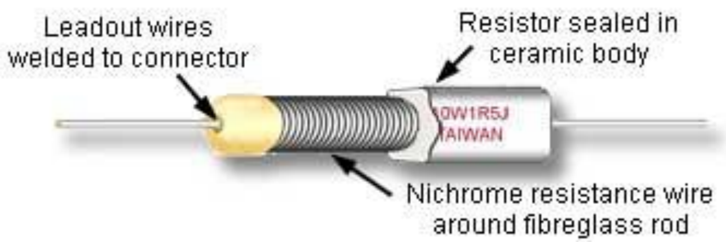
- Consists of densely packed dielectric particulates or carbon granules.
- **Between each pair of carbon granules is very small parasitic capacitor.**
- These parasitics, in aggregate, are significant → **primarily responsible for notoriously poor performance at high frequencies.**

Equivalent Ckt Model:



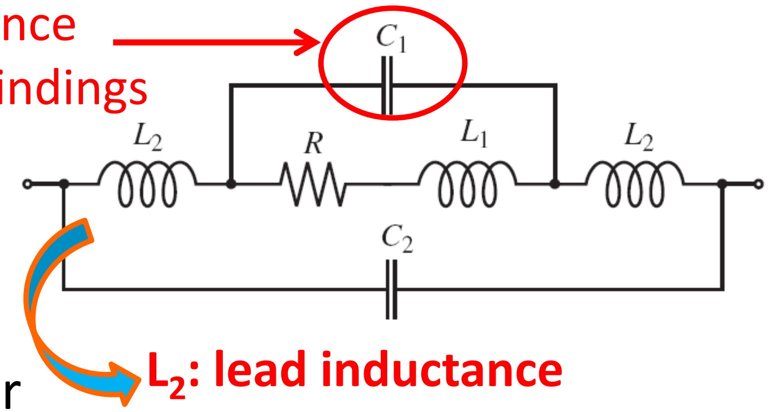
Resistors at High Frequencies (contd.)

2. Wire-wound Resistors:



Equivalent Ckt Model:

Capacitance between Windings

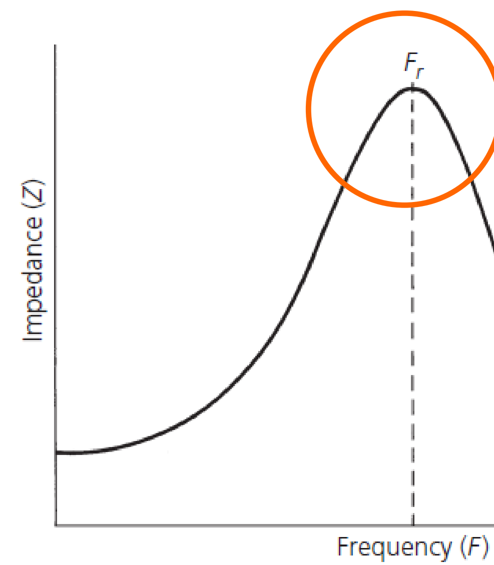


L_2: lead inductance

L_1: inductance of resistive wires

C_2: Interlead Capacitance

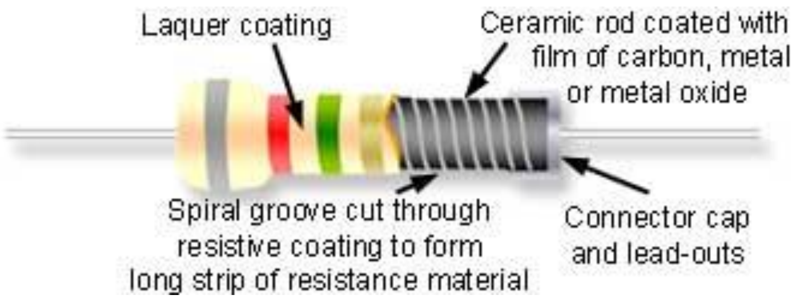
- Exhibit widely varying impedances over various frequencies.
- The inductor L is much larger here as compared to carbon-composition resistor.
- These resistors look like inductors → impedances will increase with increase in frequency.
- At some frequency F_r, the inductance will resonate with shunt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



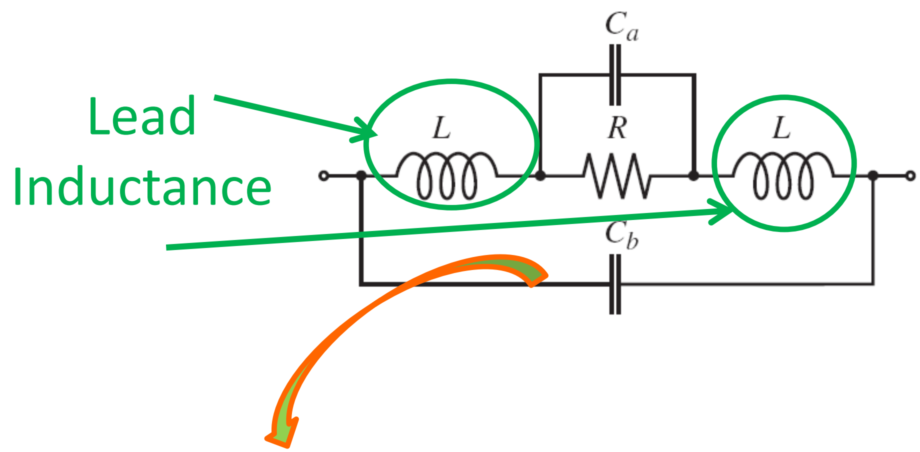
Resonant Frequency

Resistors at High Frequencies (contd.)

3. Metal-film Resistors:



Equivalent Ckt Model:



C_a models charge separation effects and C_b models interlead capacitance

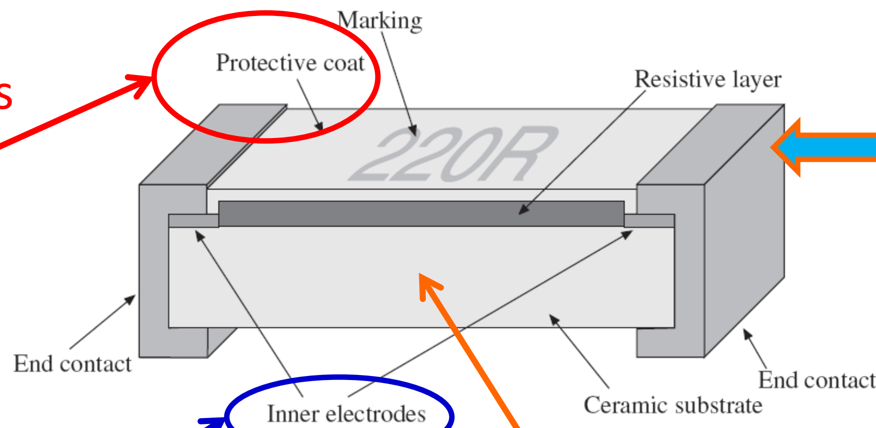
- Seems to exhibit very good characteristics over frequency.
- Values of L and C are much smaller as compared to wire-wound and carbon-composition resistors.
- It works well up to 10 MHz → useful up to 100 MHz

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



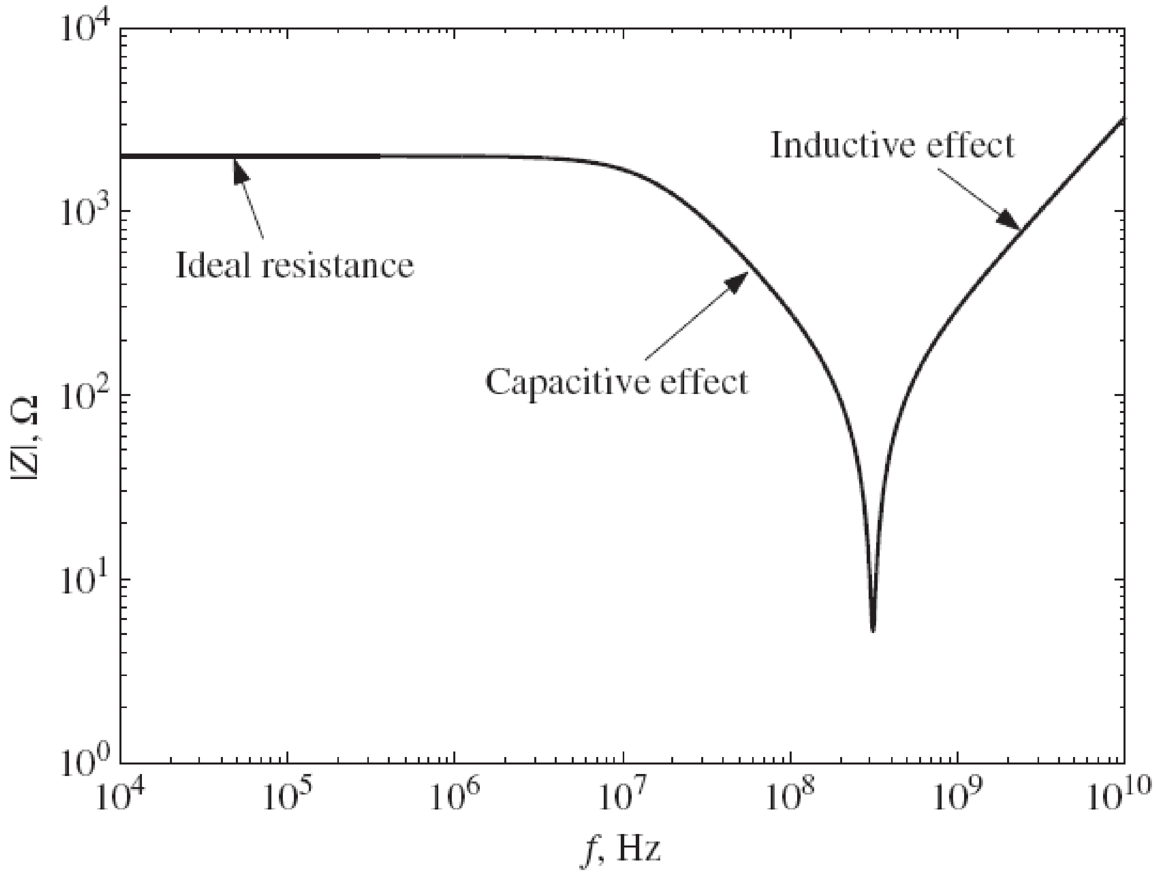
The end contacts are required for soldering purposes

These 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?



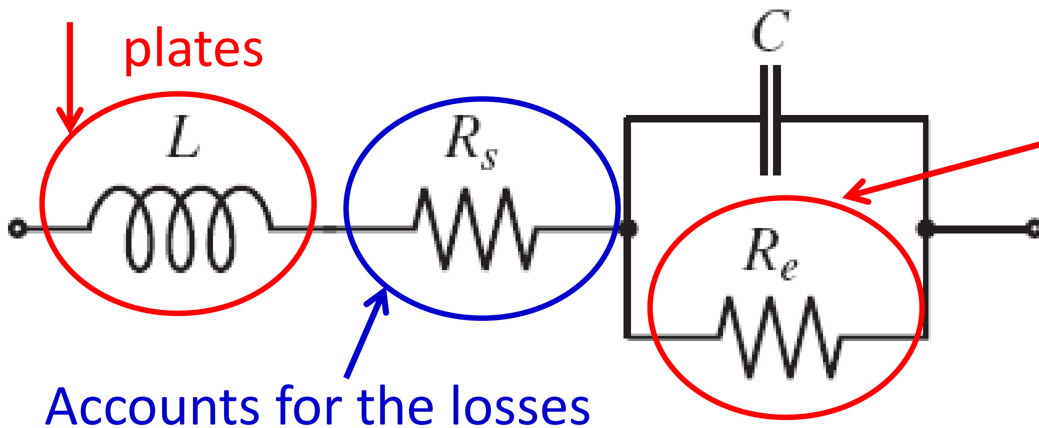
HW # 0

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

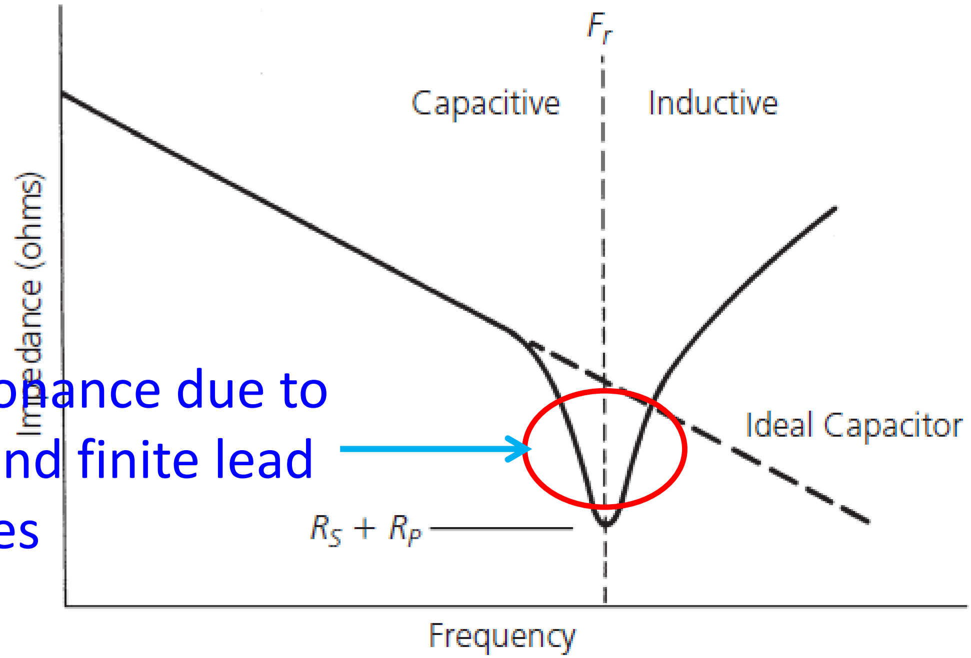
Accounts for the losses in the leads

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

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

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

Capacitors at High Frequencies (contd.)

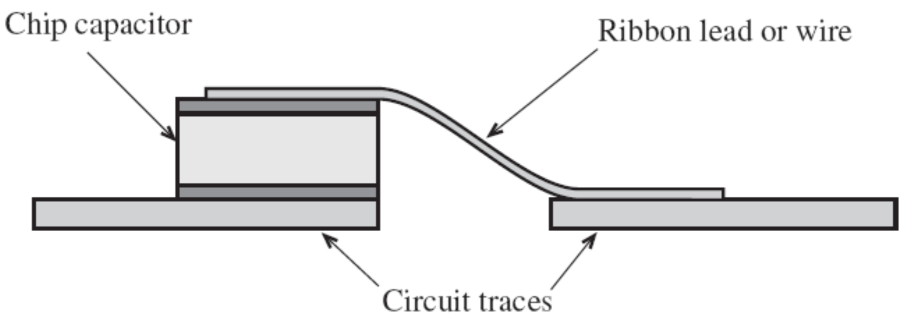


Presence of resonance due to dielectric loss and finite lead wires

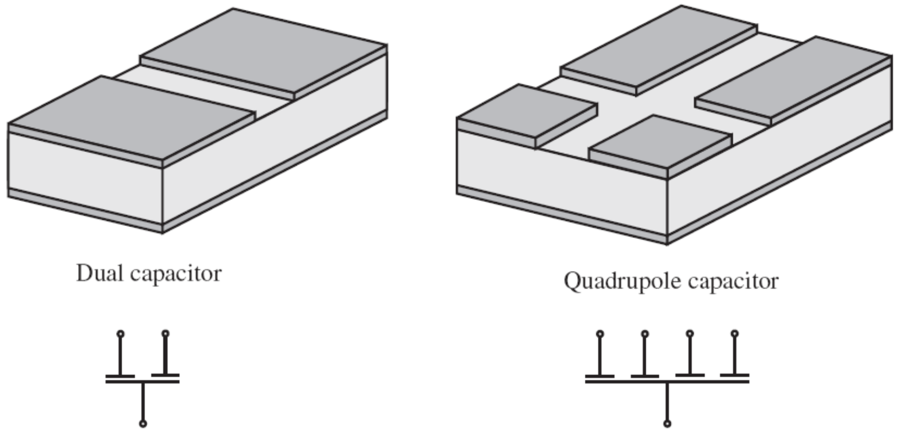
- Above F_r, the capacitor behaves as an inductor.
- In general, larger-value capacitors tend to exhibit more internal inductance than smaller-value capacitors.
- Therefore, it may happen that a $0.1\mu F$ may not be as a good as a $300pF$ capacitor in a bypass application at $250\ MHz$.
- The issue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

Capacitors at High Frequencies (contd.)

Chip Capacitors

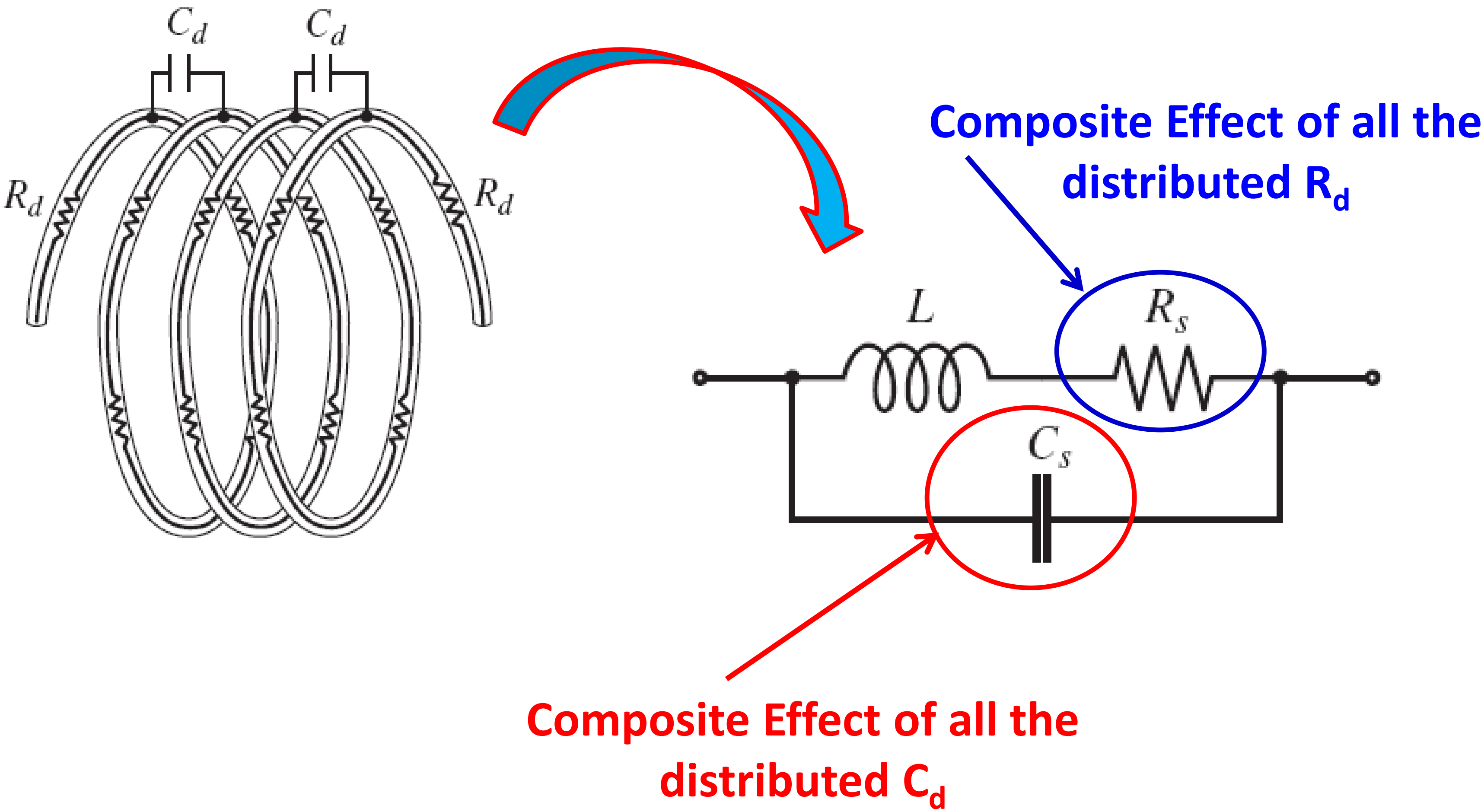


Cross-section of a single-plate capacitor connected to the board



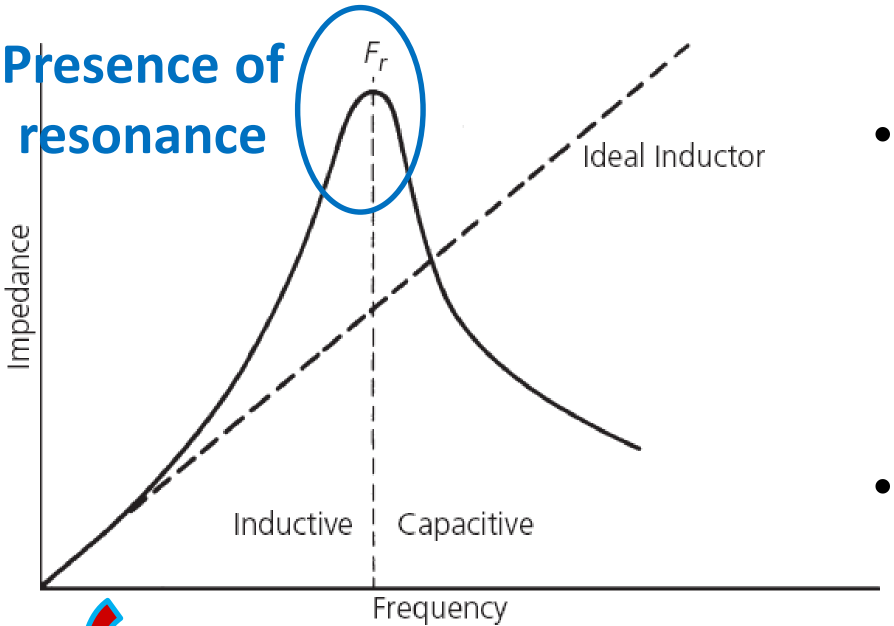
Inductors at High Frequencies

Equivalent Circuit Representation of an Inductor → coil type



Inductors at High Frequencies (contd.)

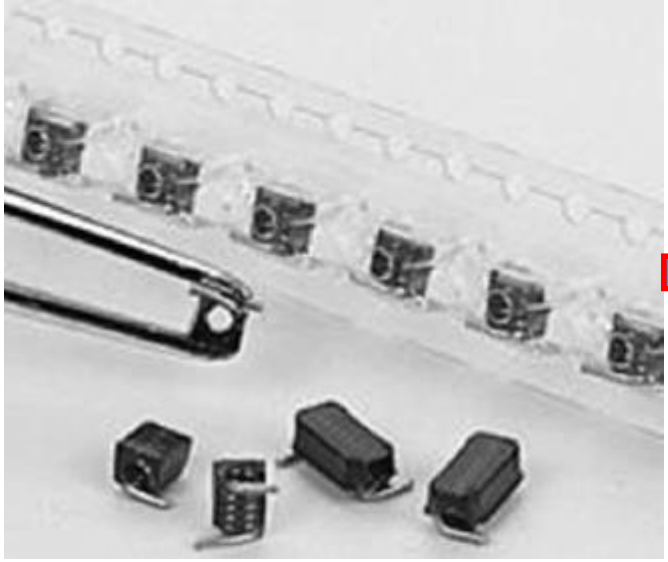
Presence of resonance



- 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