IFI5481: RF Circuits, Theory and Design

Lecturer: Prof. Tor A. Fjeldly, UiO og NTNU/UNIK [torfj@unik.no]

Assistant: Malihe Zarre Dooghabadi [malihezd@ifi.uio.no]

Syllabus: Lectured material and examples, Kap. 1-5
www.unik.no/~torfj/INF-RFD/course_INF-RFD.htm

Problems/Projects:

- Problemsolving by Malihe each week
- Mandatory homework problems after each chapter
- Two design projects using the RF simulator ADS

Literature: R. Ludwig, G. Bogdanov, *RF Circuit Design, Theory and Applications*, 2nd Ed., Pearson/Prentice Hall, 2008

Syllabus

- *Ch. 1 Introduction*
- *Ch. 2 Transmission Line Analysis*
- *Ch. 3 The Smith Chart*
- *Ch. 4 Single- and Multiport Networks*
- *Ch. 5 An Overview of RF Filter Design*

Importance of RF design

- Wireless communications (explosive growth of cell phones, WLAN, etc., 900 MHz and up)
- Global positioning systems (GPS, 1.2 – 1.6 GHz)
- Satellite communications (C band broadcast, 4 GHz uplink, 6 GHz downlink)

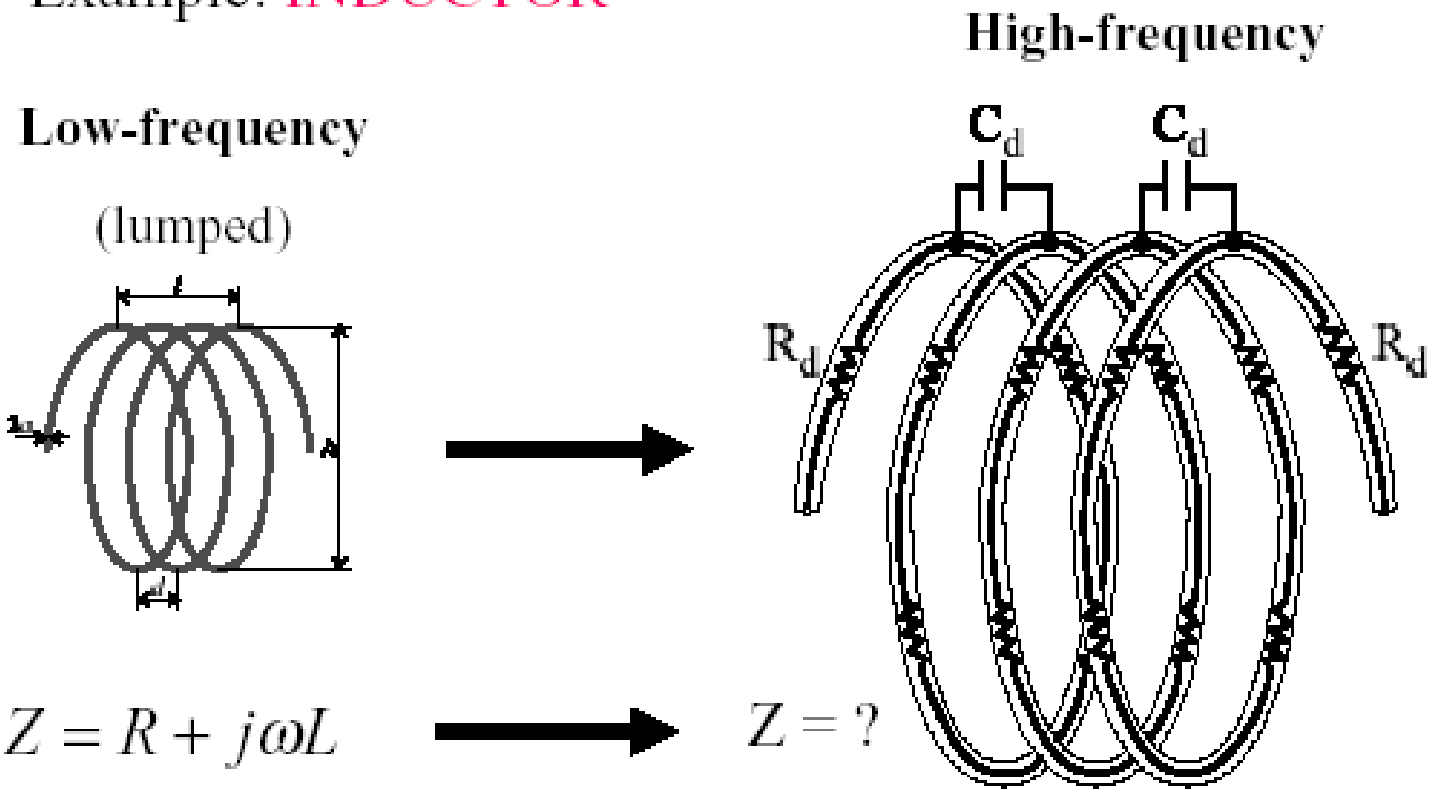
Why separate RF courses?

- lumped circuit representation no longer applies!!

- have to consider wave nature of signals

How to make a distributed theory?

- Example: INDUCTOR



$Z = R + j\omega L$ → $Z = ?$

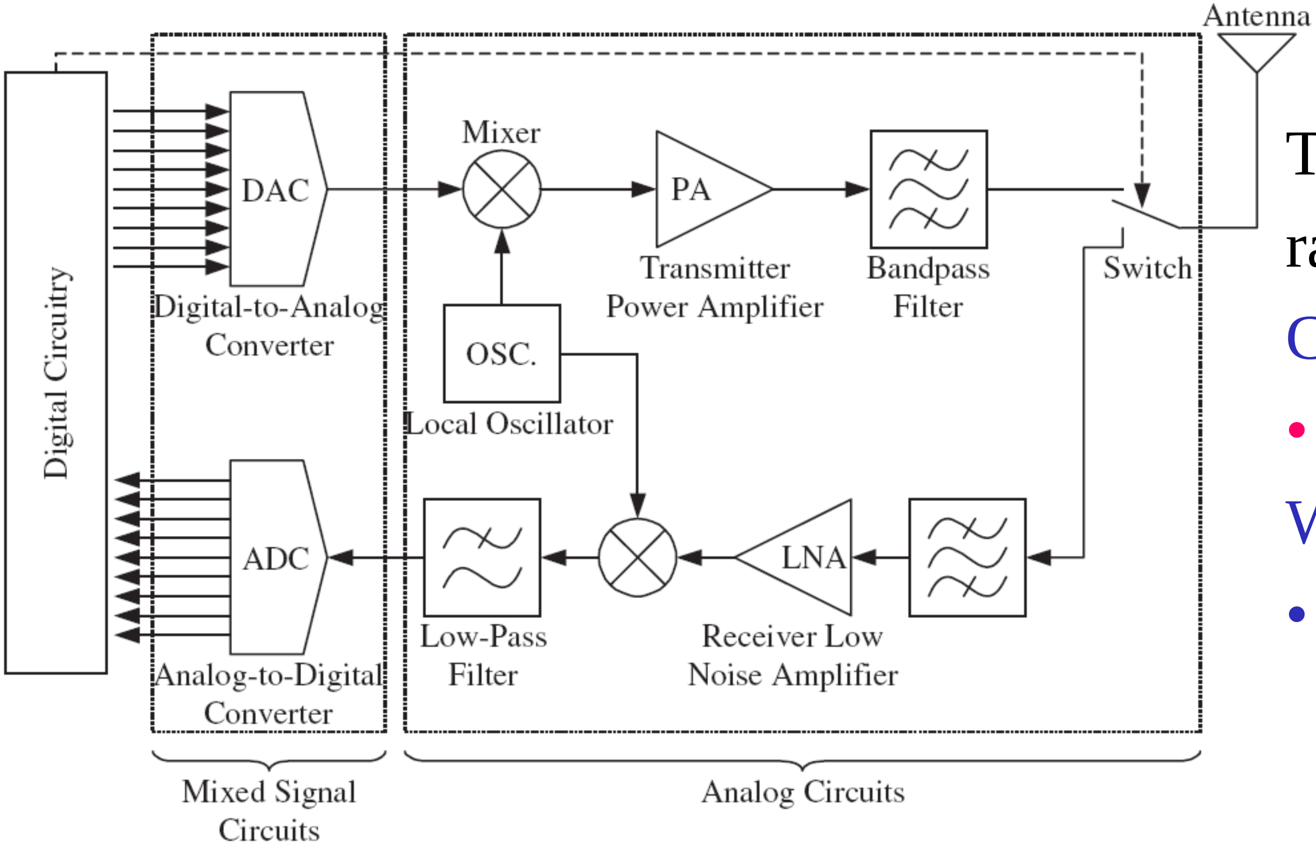
Relevant questions

- Where does conventional AC analysis fail?
- Which characteristica make RF behavior different from low-frequency behavior?
- What kind of 'new' circuit theory must be used?
- How is this theory applied in practical design of RF circuits?

Frequency spectrum

- RadioFrequency (RF)
  - TV, wireless phones, GPS
  - 300 MHz … 3 GHz operational frequency
  - 1 m … 10 cm wavelength in **air**
- MicroWave (MW)
  - RADAR, remote sensing
  - 8 GHz … 40 GHz operational frequency
  - 3.75 cm …7.5 mm wavelength in **air**

Design example: Generic RF tranceiver circuit (cell phone, WLAN, ..)



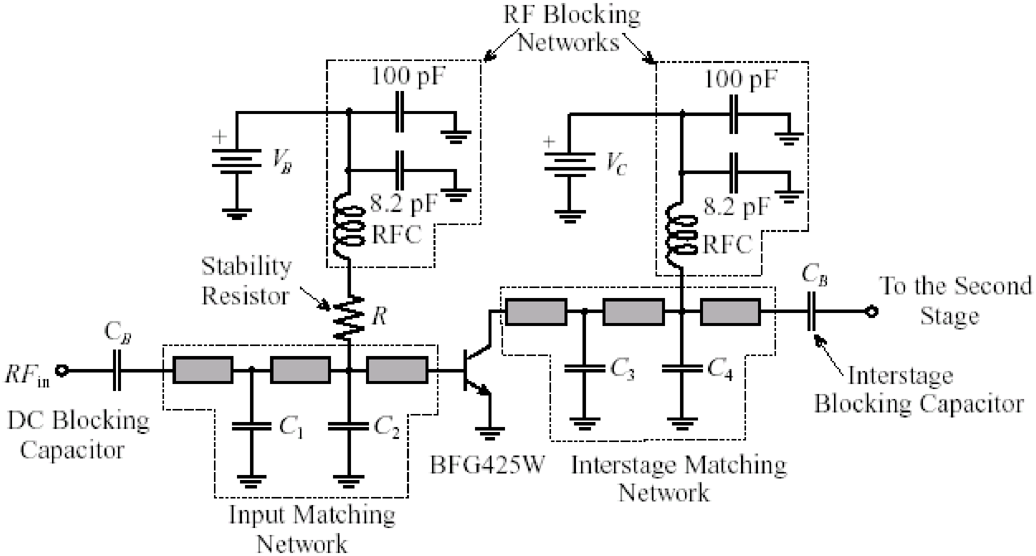
Typical frequency range:

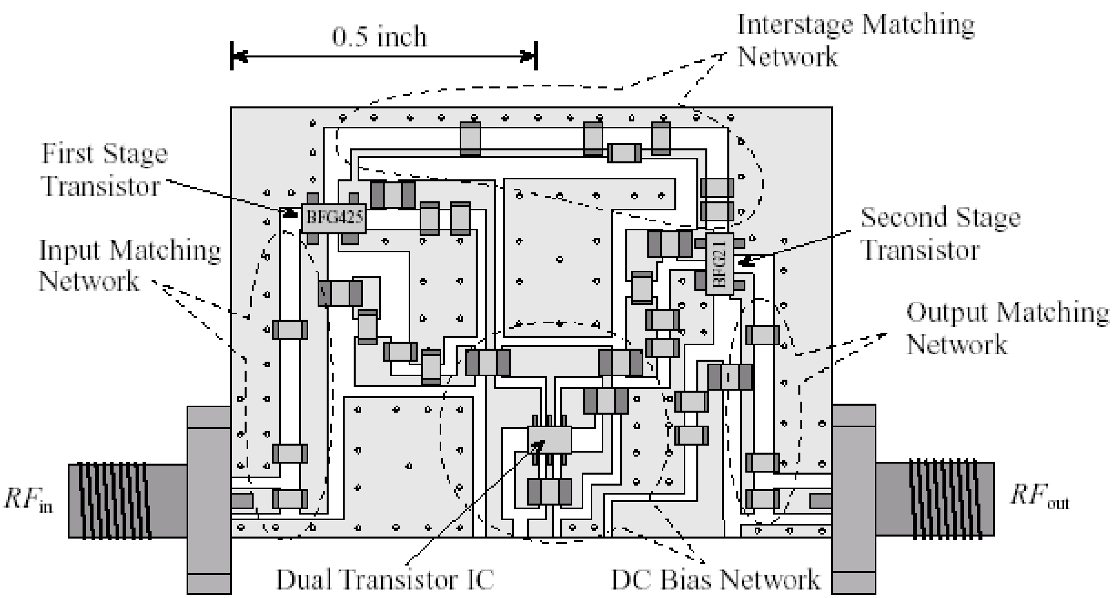
Cell phone

- 950 MHz, 1.9 GHz

WLAN

- 2.4 GHz, 5 GHz



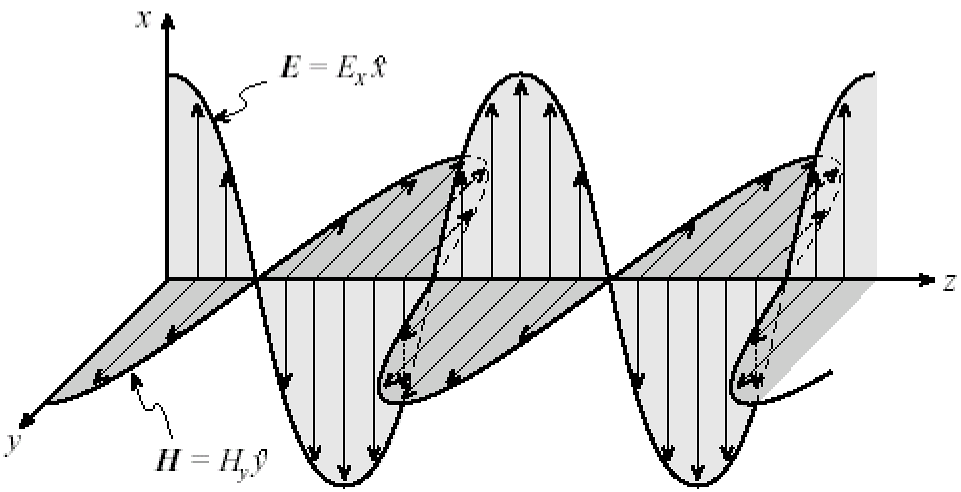


Implementation of power amplifier

- matching networks
- BJT/FET active devices
- biasing circuits

- printed circuit board
- mircostripline realization
- surface mount technology

Electromagnetic wave propagation



TEM mode

Basics:

$$E_x = E_{0x}\cos(\omega t - \beta z)$$

$$H_y = H_{0y}\cos(\omega t - \beta z)$$

Intrinsic impedance:

$$Z_0 = E_x / H_y = \sqrt{\mu/\varepsilon} =$$

$$\sqrt{\mu_0\mu_r/\varepsilon_0\varepsilon_r} = 377\Omega\sqrt{\mu_r/\varepsilon_r}$$

Phase velocity:

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}}$$

IEEE frequency spectrum

Frequency	Band Frequency	Wavelength
ELF (Extreme Low Frequency)	30–300 Hz	10,000–1000 km
VF (Voice Frequency)	300–3000 Hz	1000–100 km
VLF (Very Low Frequency)	3–30 kHz	100–10 km
LF (Low Frequency)	30–300 kHz	10–1 km
MF (Medium Frequency)	300–3000 kHz	1–0.1 km
HF (High Frequency)	3–30 MHz	100–10 m
VHF (Very High Frequency)	30–300 MHz	10–1 m
UHF (Ultrahigh Frequency)	300–3000 MHz	100–10 cm
SHF (Superhigh Frequency)	3–30 GHz	10–1 cm
EHF (Extreme High Frequency)	30–300 GHz	1–0.1 cm
Decimillimeter	300–3000 GHz	1–0.1 mm
P Band	0.23–1 GHz	130–30 cm
L Band	1–2 GHz	30–15 cm
S Band	2–4 GHz	15–7.5 cm
C Band	4–8 GHz	7.5–3.75 cm
X Band	8–12.5 GHz	3.75–2.4 cm
Ku Band	12.5–18 GHz	2.4–1.67 cm
K Band	18–26.5 GHz	1.67–1.13 cm
Ka Band	26.5–40 GHz	1.13–0.75 cm
Millimeter wave	40–300 GHz	7.5–1 mm
Submillimeter wave	300–3000 GHz	1–0.1 mm

RF behavior of passive components

Conventional circuit analysis:

– *R* taken to be frequency independent

– Ideal capacitor: $X_C = -1/\omega C$

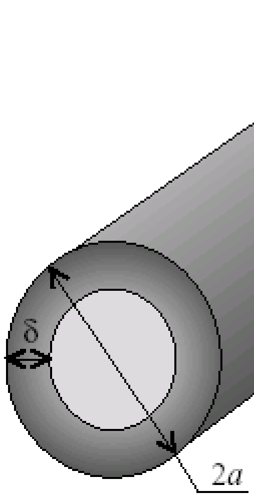
– Ideal inductor : $X_L = \omega L$

In reality:

– *R*, *L*, *C* are made from wires, plates, coils

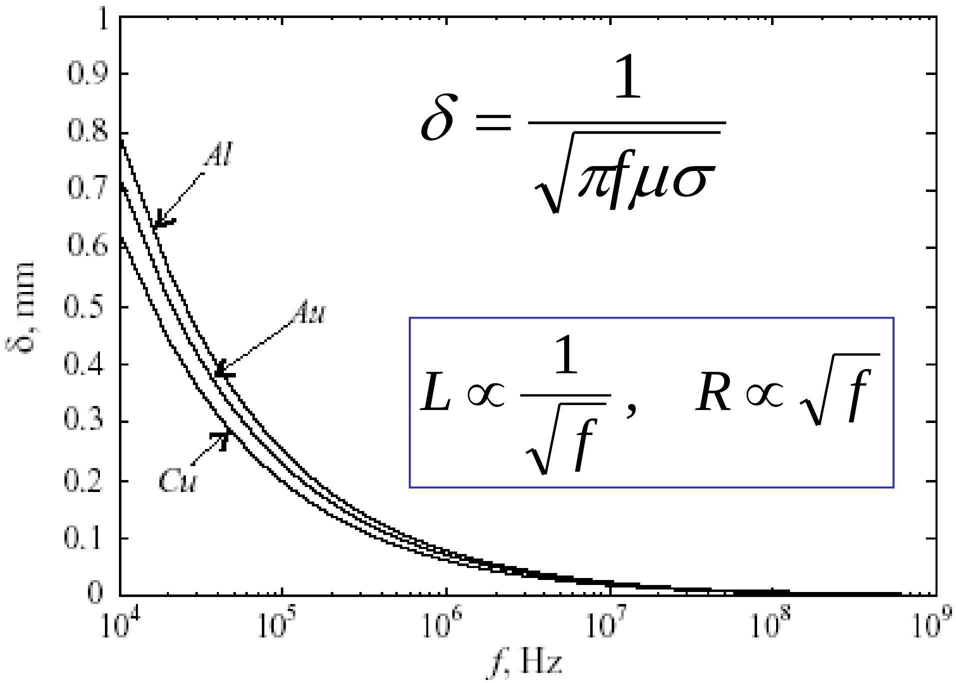
– Each possesses resistive, inductive and capacitive behavior

Example: Skin effect in wire resistor



$$R/R_{DC} \cong \frac{a}{2\delta} \cong \omega L/R_{DC} \qquad R_{DC} = \frac{1}{\pi a^2 \sigma}$$

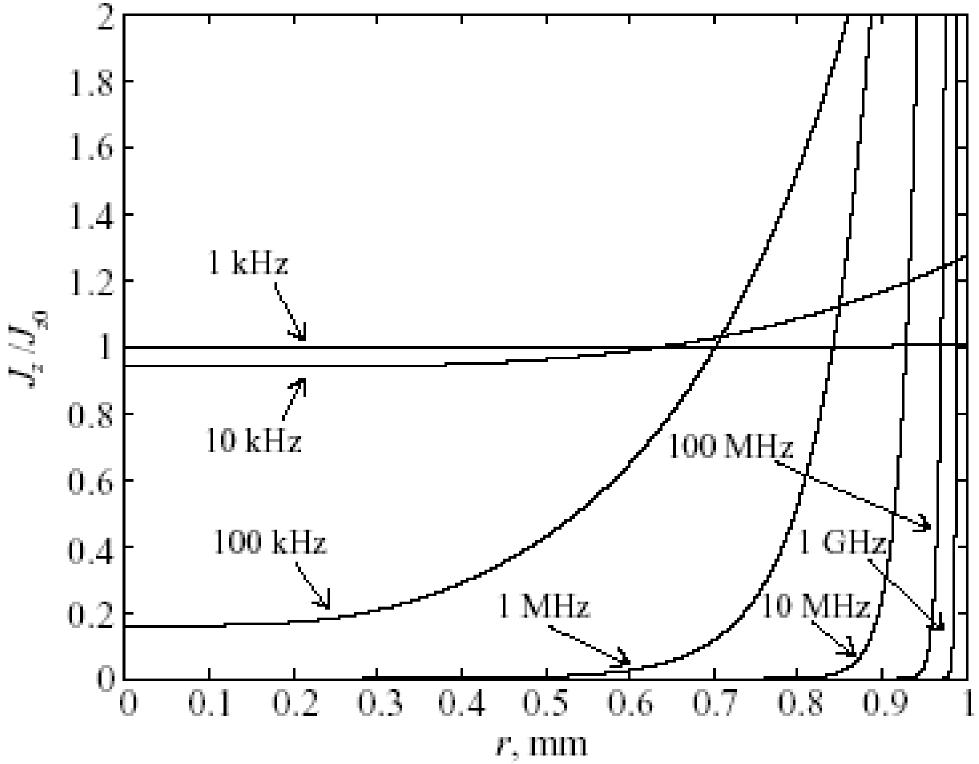
High frequency results in skin effect whereby current flow is pushed to the outside by the magnetic field.



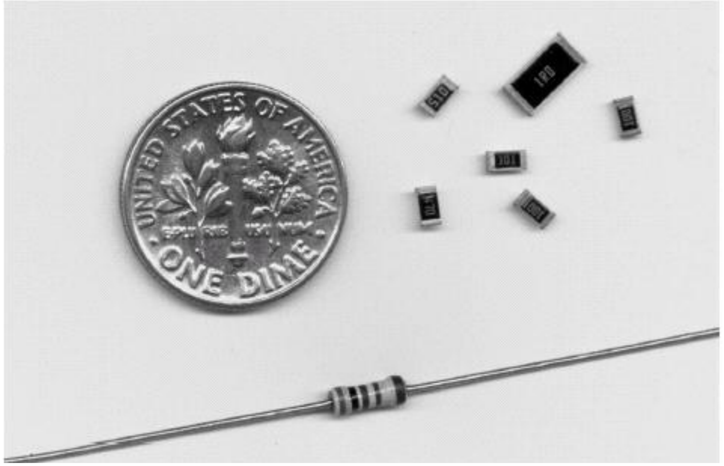
$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

$$L \propto \frac{1}{\sqrt{f}}, \quad R \propto \sqrt{f}$$

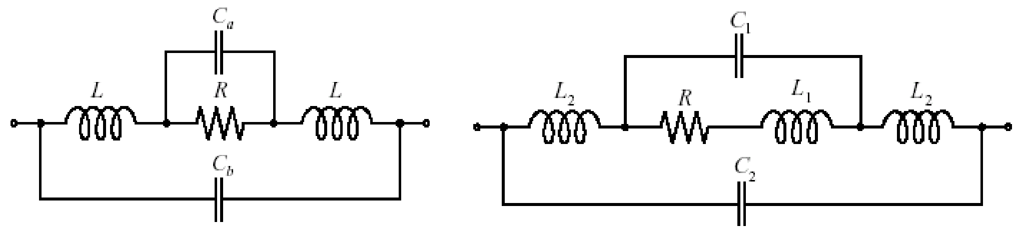
Current distribution in the wire

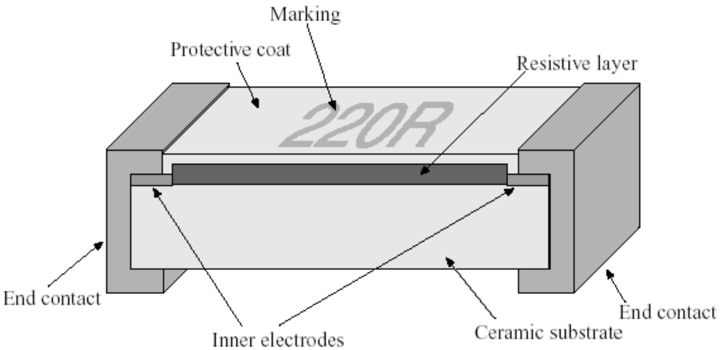


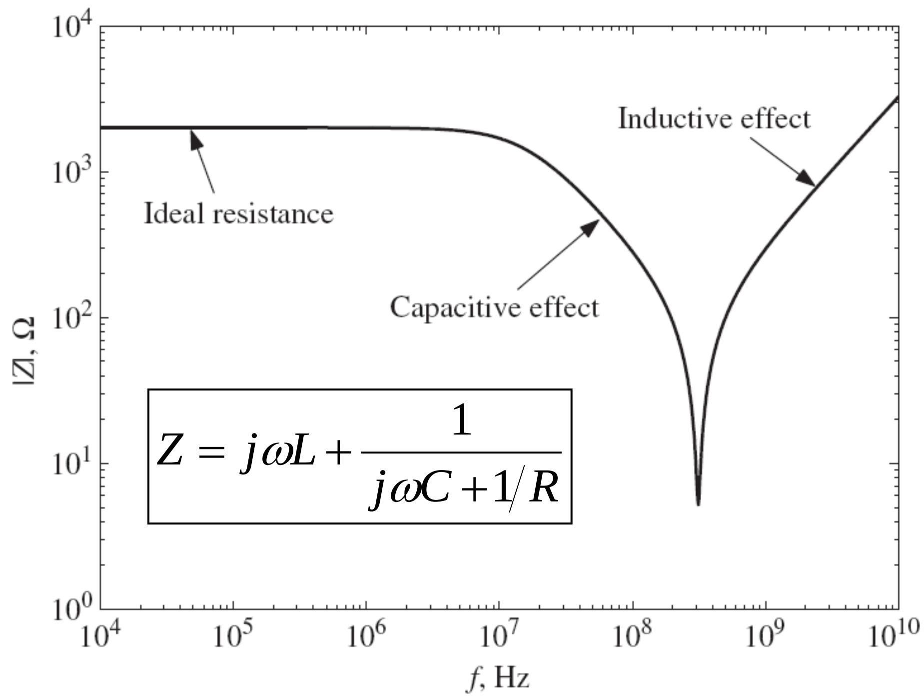
- Low frequency gives a uniform current distribution
- Medium to high frequency pushes current to the outside
- At RF the current is completely restricted to the surface



High-frequency resistors

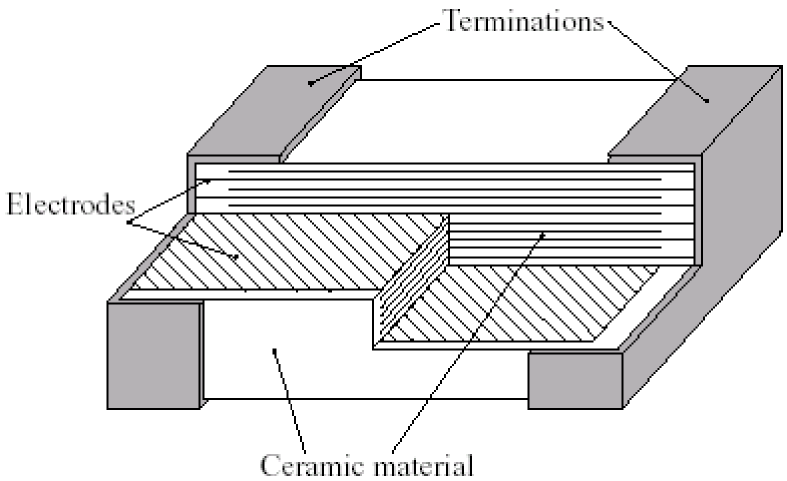


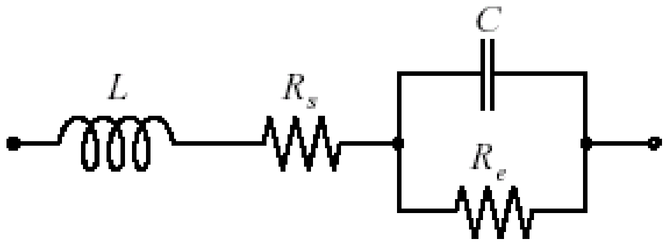


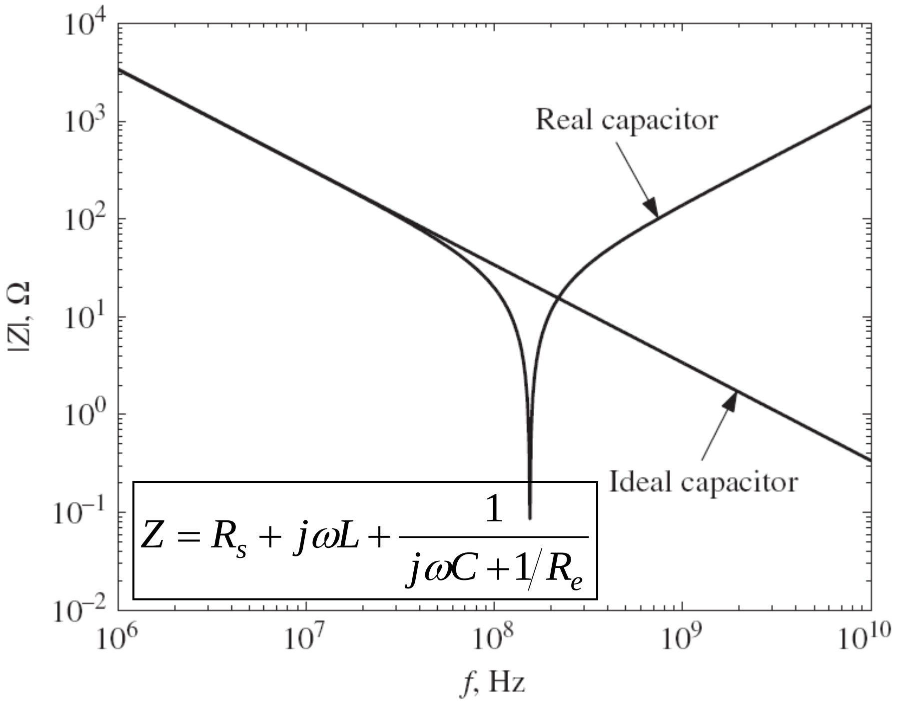


- Surface mounted thin-film chip resistors for RF applications
- Lumped electrical equivalents
- RF impedance response of metal film resistor

High-frequency capacitors

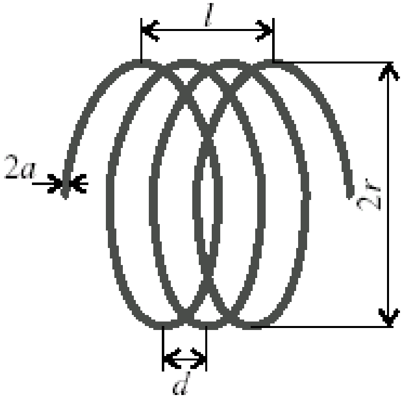


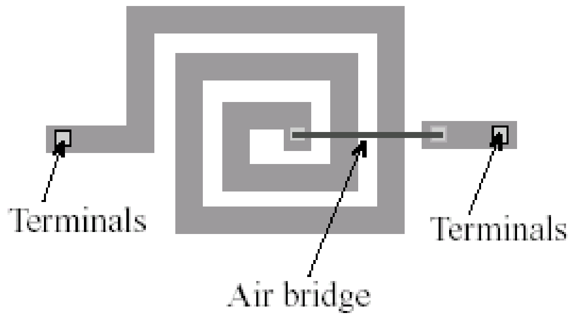


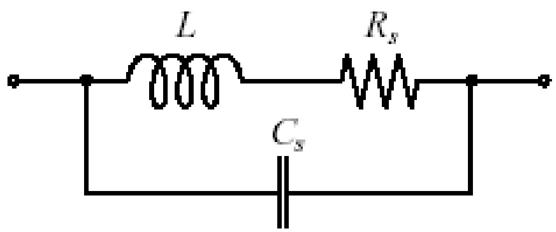


- Surface mounted thin-film chip capacitor for RF applications
- Lumped electrical equivalent
- RF impedance response of chip capacitor.
- Loss tangent: $\tan(\Delta_p) = \left|\frac{\mathrm{Re}\{Y_p\}}{\mathrm{Im}\{Y_p\}}\right| = \frac{1}{\omega C R_e}$

High-frequency inductors







- Surface mounted inductors: wire-wound coil or flat coil
- Lumped electrical equivalent
- RF impedance response of inductor.
- Quality factor: $Q = X/R_s$