Lecture 2

of

EEE307

Electronics for Communications

Department of Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University (XJTLU)

Wednesday, 11th September 2019

(make-up class for Mid-Autumn Festival on Friday, 13/9)

- ❑ **carrier frequencies**
  - ➢ applications & lumped circuit consideration
- ❑ RF Signals in dBm
- ❑ **RF Passive Components**
  - ➢ behaviour of resistors, inductors & capacitors

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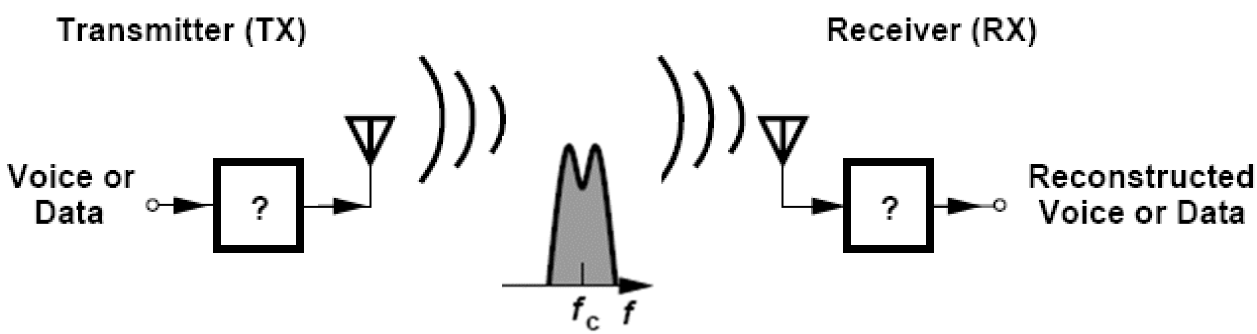
Wireless Communication Systems
(carrier frequency)

- In wireless communications using **radio waves**, various frequencies are used for transmitting information. From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.



- The frequency of the information-carrying **electromagnetic (EM) waves** propagating in air (or in space) is usually called the **carrier frequency**, denoted by f_c.

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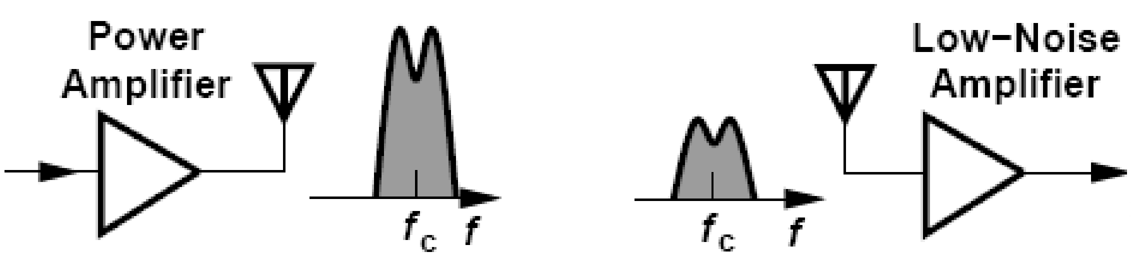
Wireless Communication Systems
(carrier frequency)

- The **carrier frequency** obviously is an important consideration in the design of electronic circuits for wireless communications (and also optical fibre communications).
  - It means the **antennas** operate at the carrier frequency and the circuits (both the **passive circuits** and **solid-state electronic circuits**) connected to the antennas operate at the same frequency.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

  - PA, LNA, front-end RF filters, mixers, VCO, PLLs

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Optical Fibre Communication

(LEDs & photodetector as antenna counterparts)

- In optical fibre communications, the counterparts of the antennas are:
  - a light source which can be turned on and off at high speed; typically it is a **light-emitting diode** (**LED**) or in high data rate transmission, a **laser diode**;
  - a **photodetector** which produces a very weak electric current in response to the optical signal at very high frequencies; typically it is a photodiode.
  - topics taught in EEE314 in detail

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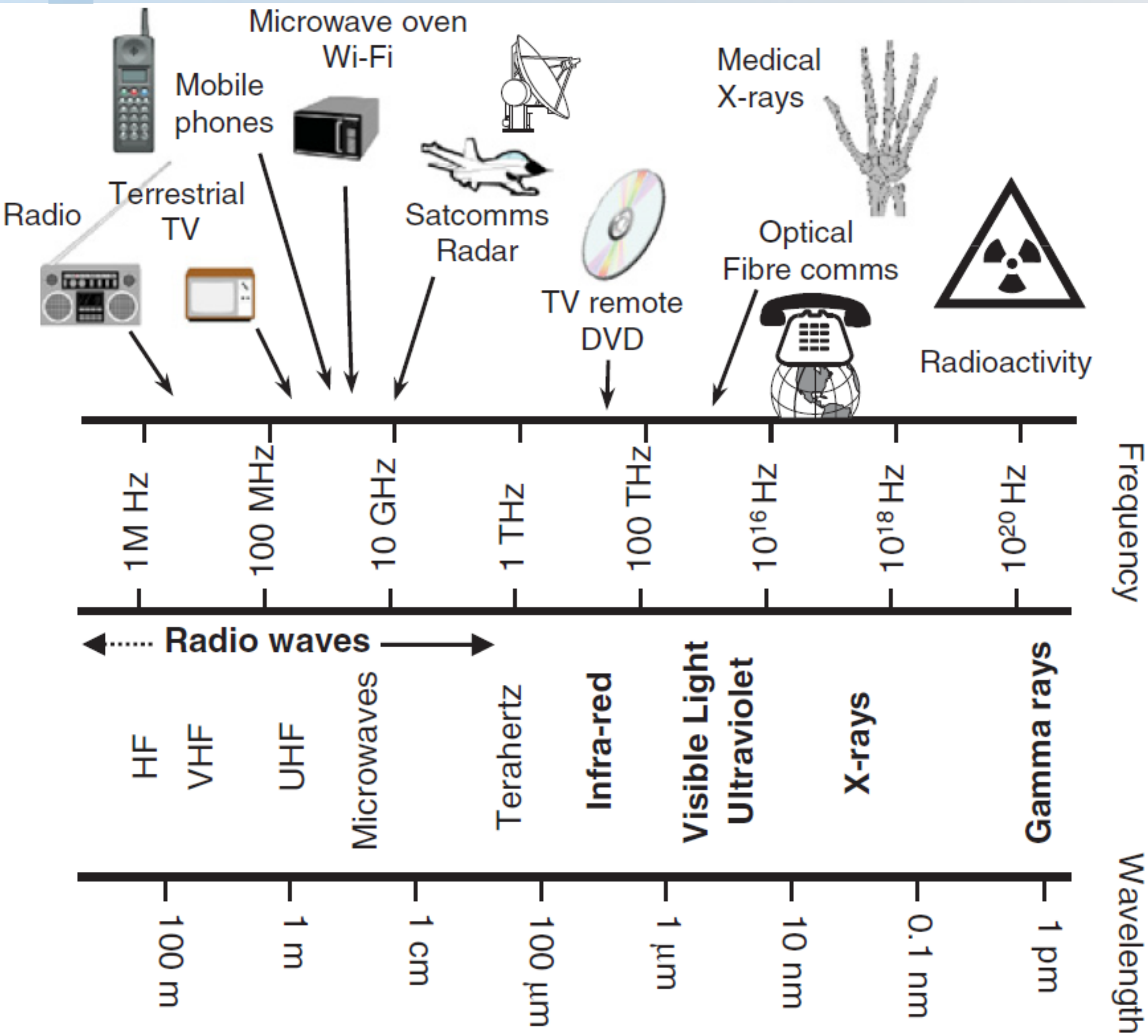
Wireless Communication

(applications)



- Depending on the specific applications of wireless communications, the **carrier frequency** varies very broadly, spanning a wide range in the **electromagnetic spectrum**.

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Frequencies of Applications

(radio waves & optical waves)

- Some applications are common in our daily life.

Frequency	Application
0.5 to 2.6 MHz	Medium wave AM radio band
220 MHz	Digital audio broadcasting
500–850 MHz	UHF TV band
850, 900 MHz and 1.8, 1.9 GHz	GSM mobile (cell) phones
2.2 GHz	3G mobile phones
2.45 GHz	Microwave ovens, Bluetooth, 802.11b/g/n wireless LANs
10 GHz	Military radar
11–12 GHz	European satellite TV
60 GHz	802.11ad gigabit wireless LANs
77 GHz	Cruise control in some cars
198 THz	Long-distance fibre communications
333 THz	TV infra-red remote control
430 THz	Red light
1 million THz	X-rays in hospital

- Note 198 THz for long-distance fibre communications (λ =1.5 μm).

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Various Applications

(radio waves)

- There are other applications using radio waves but not for communication among people:
  - radio-frequency identification (RFID), used in management of logistics (e.g. luggage at airport, items in supermarkets)
  - near-field communications (NFC), used in contactless payment (e.g. VISA wave)
  - internet of things (IoT); wireless sensor network
  - detection of leaking water pipes
  - remote sensing

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Radio Frequencies

(wireless applications)

- Sometimes it is helpful to remember the frequencies of common wireless applications.

AM broadcast band	535–1605 kHz
Short wave radio band	3–30 MHz
FM broadcast band	88–108 MHz
VHF TV (2–4)	54–72 MHz
VHF TV (5–6)	76–88 MHz
UHF TV (7–13)	174–216 MHz
UHF TV (14–83)	470–890 MHz
US cellular telephone	824–849 MHz
	869–894 MHz
European GSM cellular	880–915 MHz
	925–960 MHz
GPS	1575.42 MHz
	1227.60 MHz
Microwave ovens	2.45 GHz
US DBS	11.7–12.5 GHz
US ISM bands	902–928 MHz
	2.400–2.484 GHz
	5.725–5.850 GHz
US UWB radio	3.1–10.6 GHz

- It can be convenient to communicate with people in the field or outside the field.
- You may easily impress them by showing that you know something about electronics for wireless communications.
- Examples: 1.5 GHz for GPS; 12 GHz for direct broadcast satellite.

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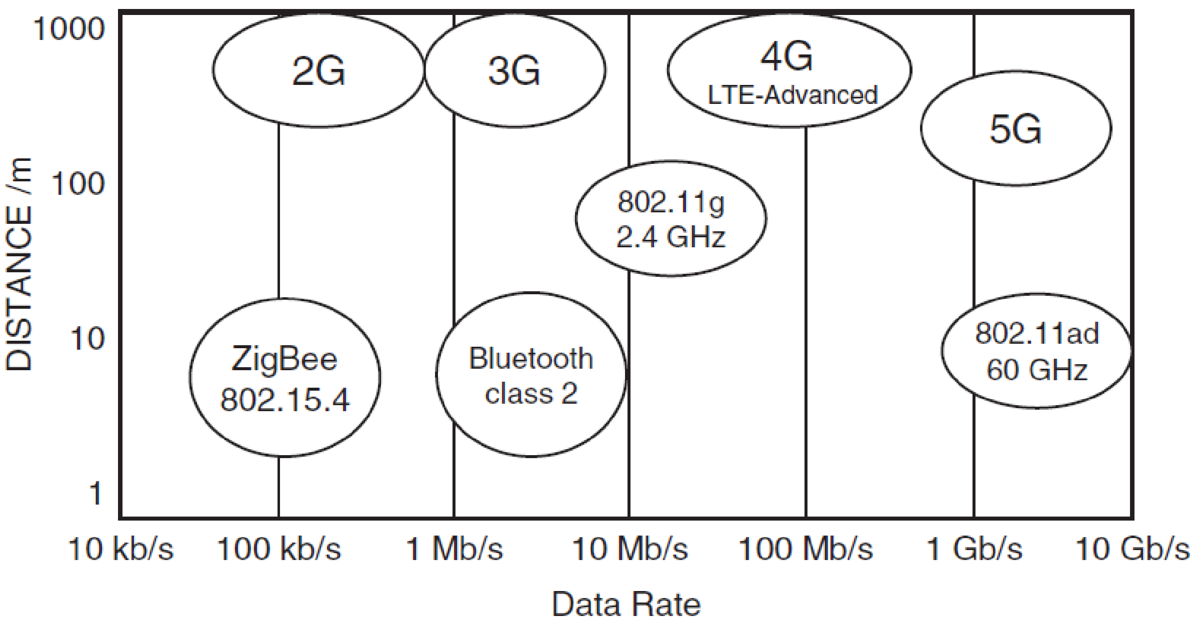
Wireless Communication Systems

(carrier frequency)

- The general trend is that the higher is the carrier frequency, the faster is the speed in data transmission.

From: Ian Robertson et al., Microwave and Millimetre-Wave Design for Wireless Communications. © 2016 John Wiley & Sons, USA.

- The trade-off is the distance of data transmission.



- Note the **millimeter-wave communications** for the multi-Gbps WiFi at **60 GHz** but in a short range.

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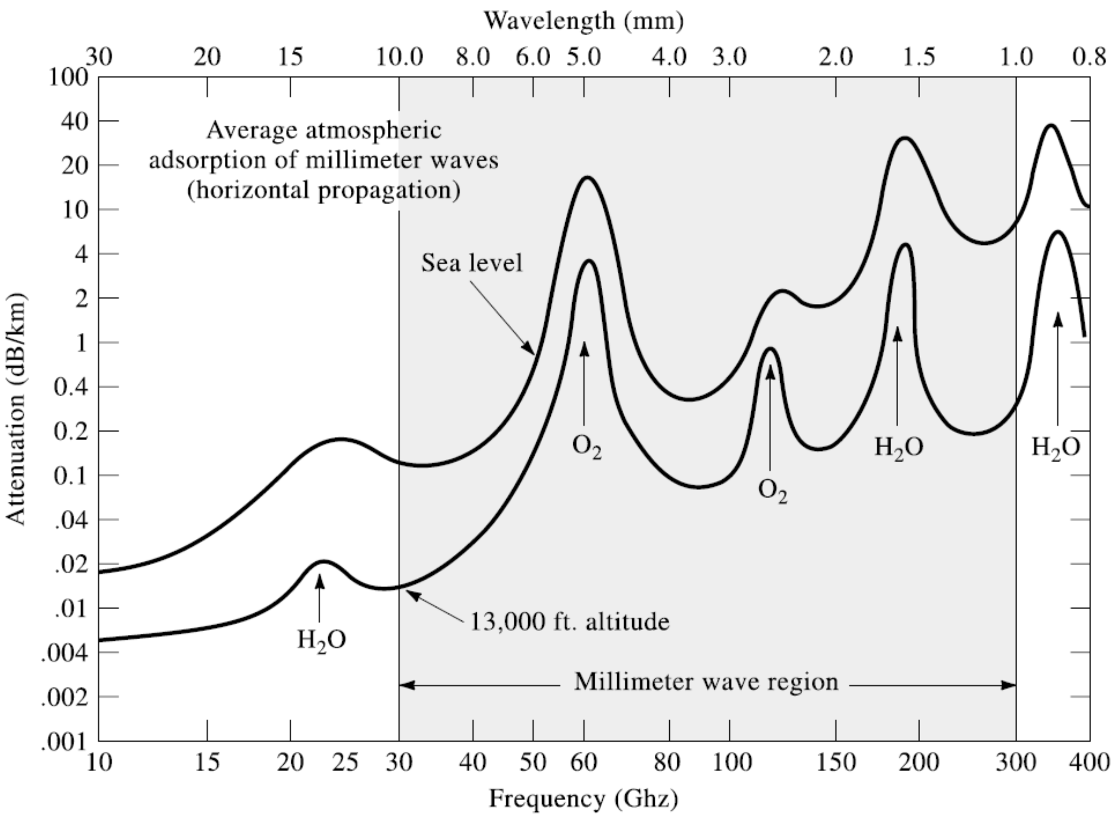
Wireless Communication

(atmospheric absorption)

- In the wireless communications, the **propagation loss** of the EM waves need to be considered.



From: David M. Pozar, *Microwave Engineering*, 4e. © 2012 John Wiley & Sons, USA.

- The choice of the **carrier frequency** for certain wireless applications also depends on the **atmospheric absorption** of the EM waves at certain frequencies.

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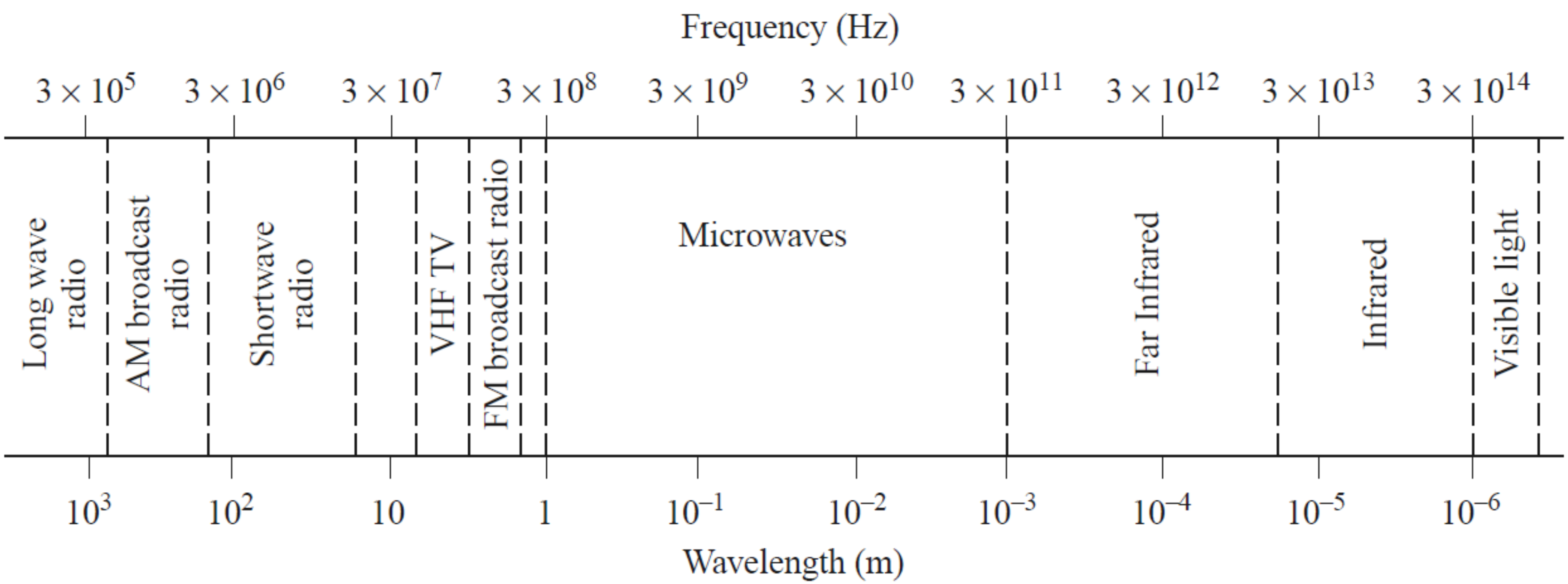
Frequency Spectrum
(different naming)

- In referring to the range of **carrier frequencies** used in wireless communications, it happens that the terminology varies.



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Frequency Spectrum
(different naming)

<u>Approximate Band Designations</u>

Medium frequency	300 kHz–3 MHz
High frequency (HF)	3 MHz–30 MHz
Very high frequency (VHF)	30 MHz–300 MHz
Ultra high frequency (UHF)	300 MHz–3 GHz
L band	1–2 GHz
S band	2–4 GHz
C band	4–8 GHz
X band	8–12 GHz
Ku band	12–18 GHz
K band	18–26 GHz
Ka band	26–40 GHz
U band	40–60 GHz
V band	50–75 GHz
E band	60–90 GHz
W band	75–110 GHz
F band	90–140 GHz

- Some people may prefer using slightly different terms in referring to certain parts of the frequency spectrum.
  - confusion or convenience?

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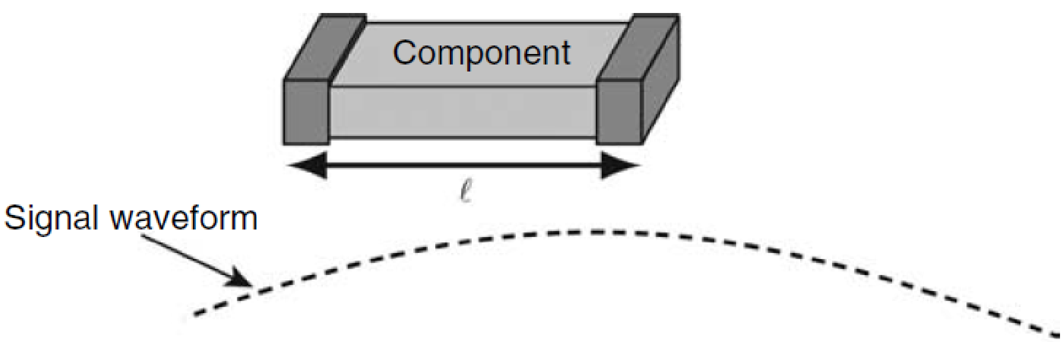
Frequency & Circuit Size

(signal wavelength & lumped circuits)

- When electronic circuits operate at certain frequencies, the electrical signals propagate in the circuits with corresponding wavelengths.
- When the frequency gets higher, the wavelength becomes shorter. This has significant implications in the implementation of electronic circuits operating at radio frequencies.

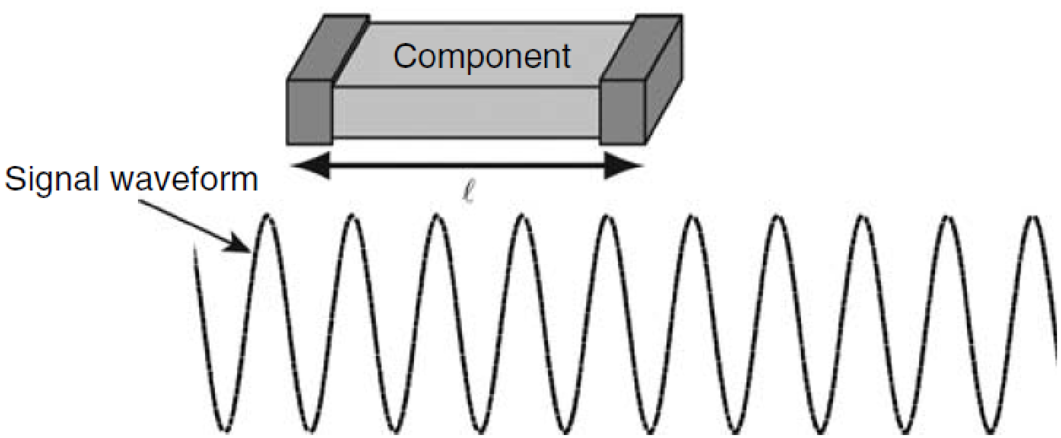


  - lumped circuit analysis at low frequencies.

Frequency & Circuit Size

(distributed circuits & $\lambda/10$)

- When the wavelength of the electrical signals is comparable to the component or circuit size, **lumped circuit analysis** will no longer be valid.
  - The components & circuits needed to treated as **distributed circuits**.
- The rule of thumb is one tenth of the wavelength.
  - If the component of circuit size is < **$\lambda/10$**, distributed circuit effects can be ignored.



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RF Signal Power

(dBm)

- Apart from the frequency and wavelength, the power level of an RF signal is also an important consideration in circuits for communications.
  - Why do we consider the power rather than voltage or current in RF circuits?
- It is common in the field that the power level of RF signals are expressed in **dBm** defined as follows:
  - 0 dBm means 1 mW in the linear scale power; 10 dBm means 10 mW; -3dBm = 0.5 mW; -20dBm = 0.01 mW

$$P_{sig}\big|_{\mathrm{dBm}} = 10\log\left(\frac{P_{sig}}{1\ \mathrm{mW}}\right)$$

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RF Signal Power

(power gain & voltage gain)

- With the power RF signals described in dBm, the signal gain/loss can be determined easily in dB, even without using calculators.

$$A_P|_{\text{dB}} = 10\log\frac{P_{out}}{P_{in}} \qquad A_V|_{\text{dB}} = 20\log\frac{V_{out}}{V_{in}}$$

  - Note the difference between signal gains $A_P|_{\text{dB}}$ and $A_V|_{\text{dB}}$.

$$\begin{aligned} A_P|_{\text{dB}} &= 10\log\frac{\frac{V_{out}^2}{R_0}}{\frac{V_{in}^2}{R_0}} \\ &= 20\log\frac{V_{out}}{V_{in}} \\ &= A_V|_{\text{dB}}, \end{aligned}$$

  - The **power gain** can be related to the **voltage gain** as shown here, if the input and output impedance are equal (e.g. 50 Ω).

From: Behzad Razavi, *RF Microelectronics*,

RF Passive Components

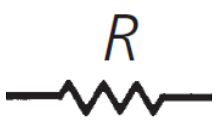
(parasitic circuit elements)

- ❑ In the design and construction of RF circuits for communications, passive components (e.g. resistors, capacitors and inductors) are also used as in the low frequency situations.
- ❑ However, the passive components behave somewhat differently at radio frequencies.
- ❑ This is because of the ***parasitic*** **circuit elements** associated with these components (including the wire connections).
  - ➢ At low frequencies (e.g. 50 kHz), their effects on the electronic circuits are negligible.

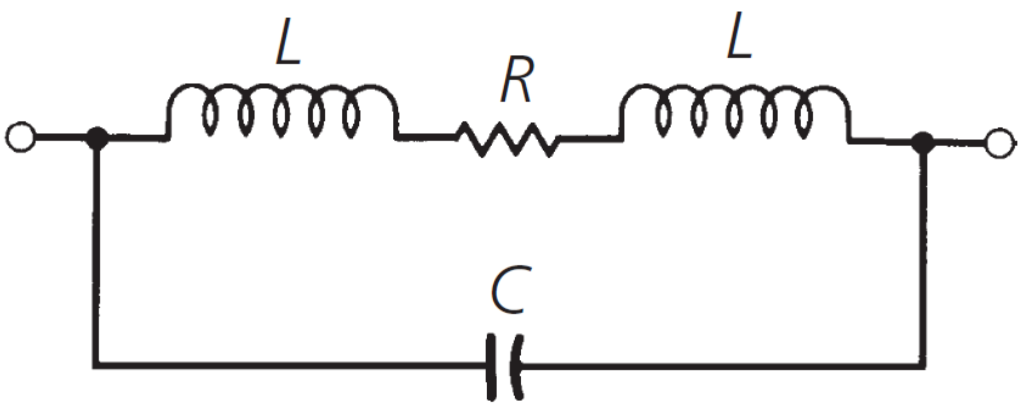
Resistors at Radio Frequencies

(equivalent circuit)

- At low frequencies where **lumped circuit analysis** is applicable, a resistor can be regarded as a pure resistor, represented simply as:



- At radio frequencies, the **equivalent circuit** of a resistor contains parasitic inductors & capacitors.



  - These parasitic circuit elements are obvious in discrete components.

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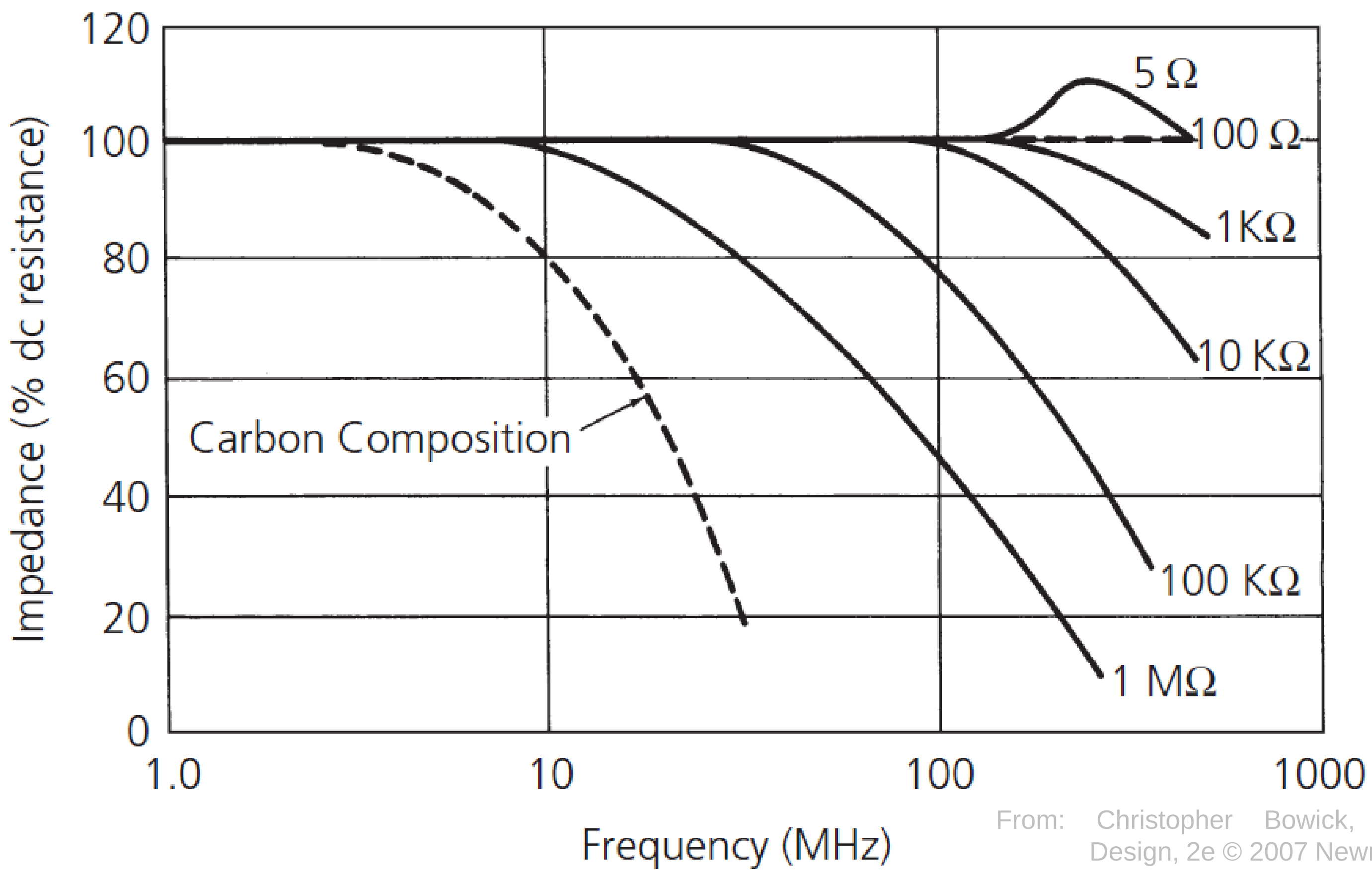
Resistors at Radio Frequencies

(impedance behavior)



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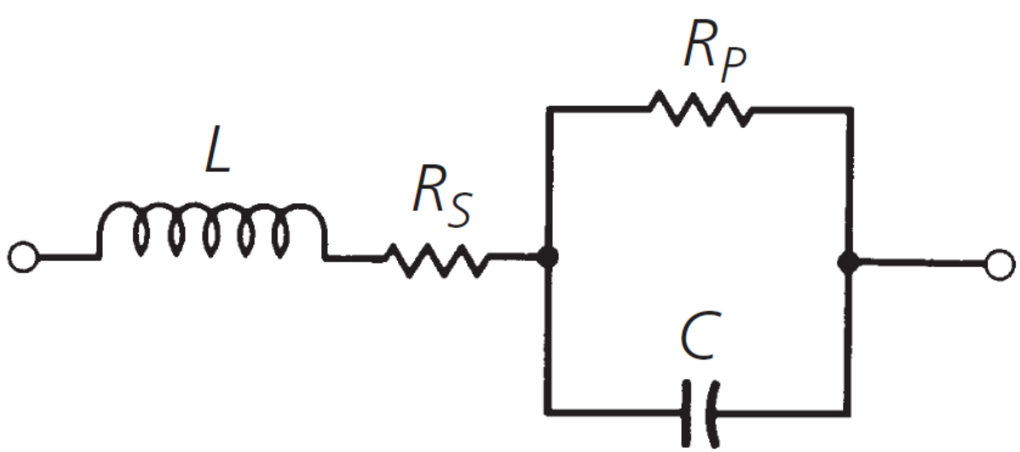
- Note the maximum frequencies for the resistors.

Capacitors at Radio Frequencies
(equivalent circuit)

- Similarly, at radio frequencies, a capacitor can no longer be regarded as a pure capacitor.
- The **equivalent circuit** of a capacitor contains parasitic inductors and resistors.



> What causes the parasitic circuit elements $\boldsymbol{R_s}$ and $\boldsymbol{R_p}$?

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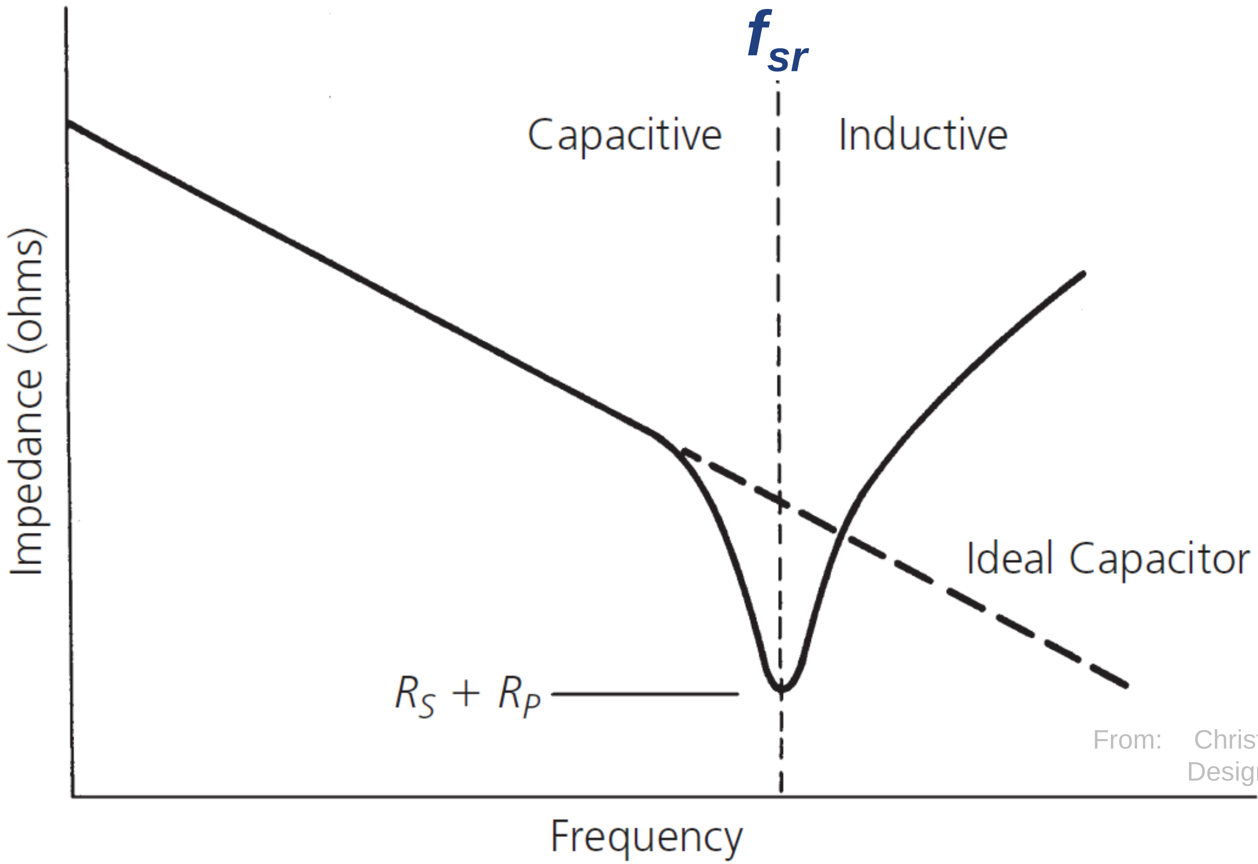
Capacitors at Radio Frequencies

(impedance of a capacitor)



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- Note the **self-resonance frequency** f_{sr}.

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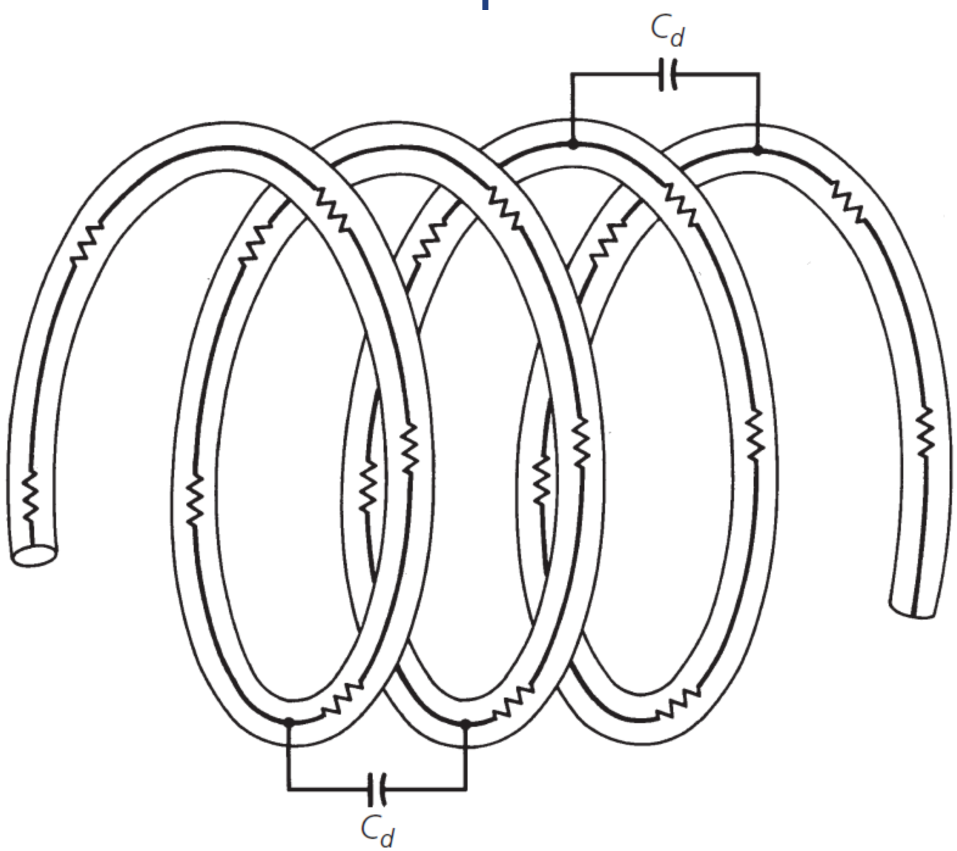
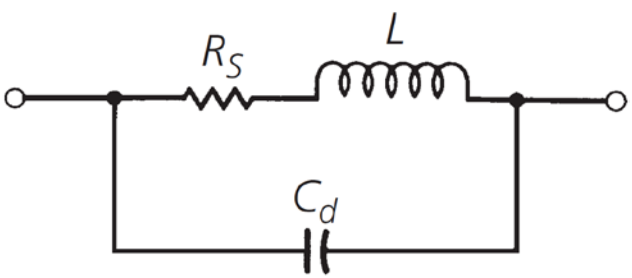
Inductors at Radio Frequencies

(equivalent circuit)

- As for inductors, a coil inductor contains distributed capacitance and series resistance.





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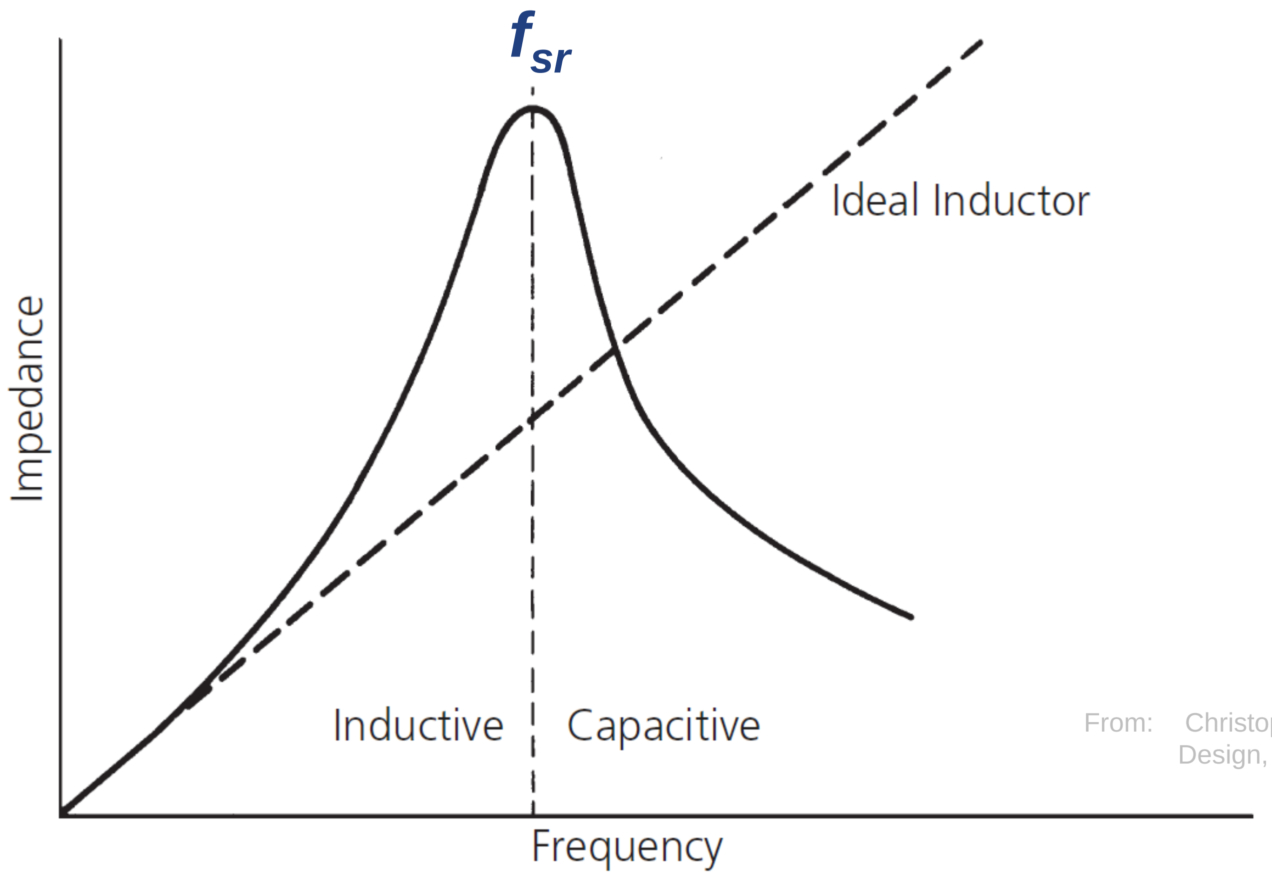
Inductors at Radio Frequencies

(impedance of inductor)



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- Note the **self-resonance frequency** f_{sr}.

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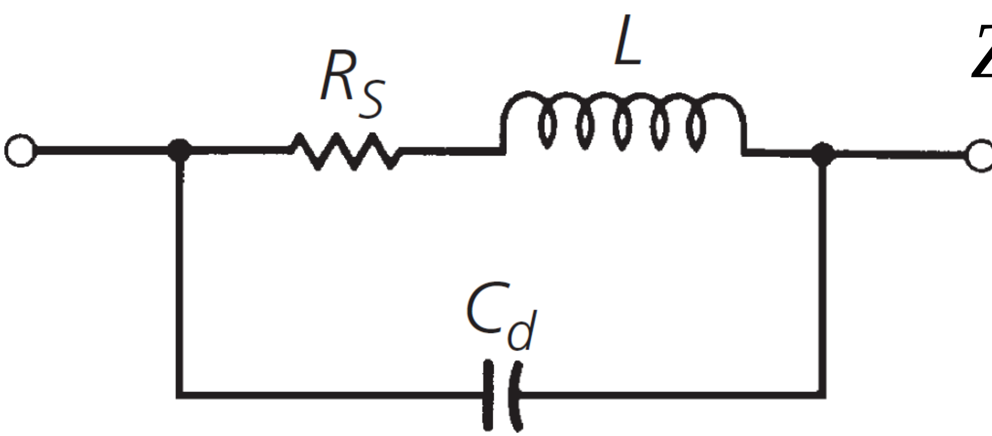
RF Passive Components

(impedance measurements)

- In principle, the **impedance** of RF passive components can be determined by measuring the voltage and current (with both the **magnitude** & **phase**) of the two-terminal components.
  - Impedance analysers can be used for such measurements up to a few gigahertz (e.g. 3 GHz or even 5 GHz).
  - More often, the impedance can be determined indirectly by **S-parameter** measurements using a **vector network analyser** (VNA), with the data then converted to impedance (using matrix conversion).
  - It requires only one-port S-parameter measurements for RF passive components.

Impedance Determination
(from equivalent circuits)

- When the equivalent circuits are given, the impedance of RF passive components can be determined using basic circuit analysis techniques.
- The **impedance** *Z* consisting of the real part ***R*** and imaginary part ***X***: $Z = R + jX$
  - ***R***: equivalent resistance; ***X***: equivalent **reactance**



$$Z_{eqL} = \left(R_S + X_L\right) // X_C$$

$$X_L = j\omega L \qquad X_C = \frac{1}{j\omega C}$$

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Impedance Determination

(admittance as inverse of impedance)

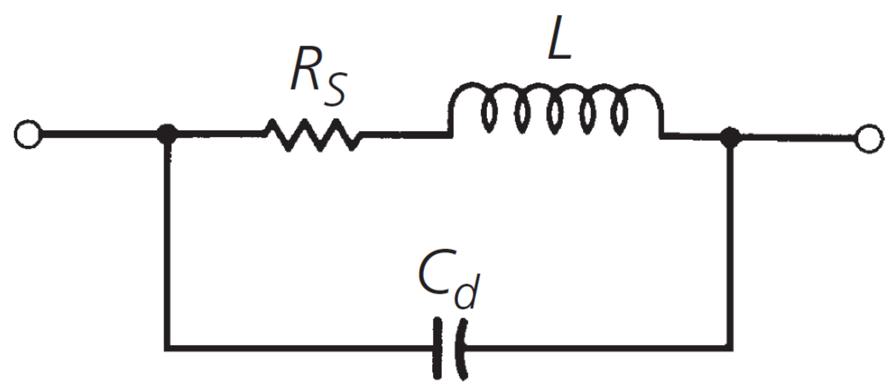
- Sometimes in circuits with parallel connections, it is convenient to use **admittance** Y which is the inverse of impedance: $Y = 1/Z = Z^{-1}$

$$Z_{eqL} = Y_{eqL}^{-1}$$

$$Y_{eqL} = \frac{1}{R_S + X_L} + \frac{1}{X_C}$$

$$= \frac{1}{R_S + j\omega L} + j\omega C_d$$

$$= \frac{1 + j\omega C_d R_S - \omega^2 L C_d}{R_S + j\omega L}$$



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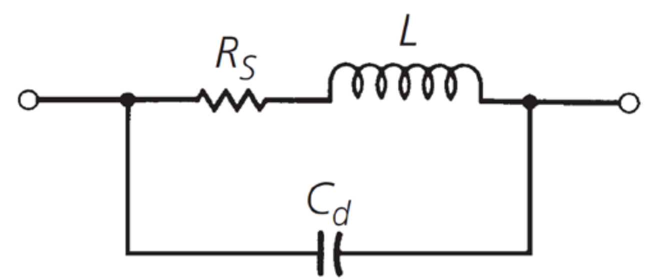
Impedance Determination

(impedance from admittance inversed)

$$Z_{eqL} = Y_{eqL}{}^{-1} = \left[\frac{1 + j\omega C_d R_S - \omega^2 L C_d}{R_S + j\omega L}\right]^{-1}$$

$$= \frac{R_S + j\omega L}{(1-\omega^2 LC) + j\omega C_d R_S}$$



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$$Z_{eqL} = \frac{(R_S + j\omega L)\left[(1-\omega^2 LC) + j\omega C_d R_S\right]}{(1-\omega^2 LC)^2 + (\omega C_d R_S)^2}$$

$$= \frac{\left[R_S(1-\omega^2 LC) - \omega^2 LCR_S\right] + j\omega\left[(1-\omega^2 LC)L + C_d R_S{}^2\right]}{(1-\omega^2 LC)^2 + (\omega C_d R_S)^2}$$

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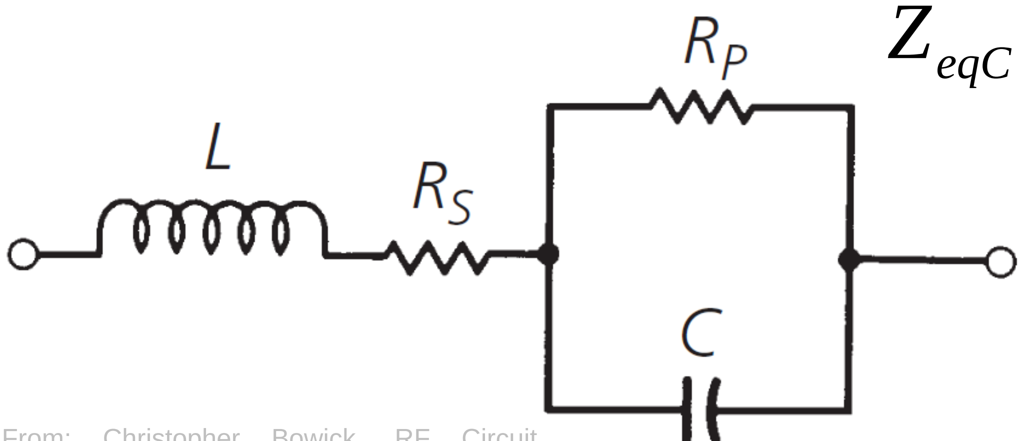
Real & Imaginary Parts of *Z*

(for calculating quality factor)

- The **impedance** *Z* expressed in terms of the real part ***R*** and the imaginary part ***X*** would be useful for determination of a figure of merit for RF passive components, namely **quality factor *Q***.
  - The **quality factor** is an important parameter for inductors (& resonant circuits) but usually not capacitors.



$$Z_{eqC} = X_L + R_S + \frac{1}{\dfrac{1}{R_P} + \dfrac{1}{X_C}}$$

From: Christopher Bowick, RF Circuit Design, 2e © 2007 Newnes, USA.

RF Capacitor Equivalent Circuit

(impedance determination)

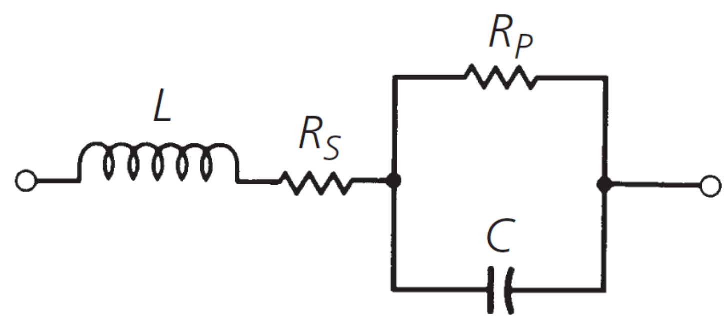
- From the simplified expression, the real and imaginary parts of the impedance become clear.

$$Z_{eqC} = X_L + R_S + \frac{1}{\frac{1}{R_P} + j\omega C}$$

$$= j\omega L + R_S + \left(\frac{R_P}{1 + j\omega C R_P} \right)$$

$$= j\omega L + R_S + \left[R_P \left(1 - j\omega C R_P \right) \right]$$

$$= \left(R_S + R_P \right) + j\omega \left(L - C R_P^{\ 2} \right)$$



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Quality Factor Q

(definition in terms of energy)

- The **quality factor Q** has its most fundamental definition using the energy concept:

$$Q = 2\pi\left(\frac{energy\ stored}{energy\ loss\ in\ a\ cycle}\right)$$

$$= \omega\left(\frac{energy\ stored}{average\ power\ loss}\right)$$

$$\boxed{\begin{aligned} \omega &= \frac{2\pi}{T} \\ f &= \frac{1}{T} \\ \omega &= 2\pi f \end{aligned}}$$

- The **Q** value indicates how many cycles the total stored energy can sustain.
  - ***Q*** = 2π × (number of cycles)

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Quality Factor Q

(***Q*** determined from ***Z***)

- Remember that ideal reactive components (either inductors or capacitors) store energy; resistive components dissipate energy.
  - In the impedance of RF passive components (in general any 1-port network), the imaginary part *X* is related to the energy stored and the real part *R* is related to the energy dissipated.
  - Deriving from the energy definition, *Q* can be determined from the impedance:

$$E_{storedC} = \frac{1}{2} C V^2; \quad E_{storedL} = \frac{1}{2} L I^2$$

$$\boxed{Q = \frac{|X|}{R} = \frac{|\mathrm{Im}(Z)|}{\mathrm{Re}(Z)}}$$

$$P_{avg} = \frac{1}{2} I R^2 = \frac{V^2}{2R}$$

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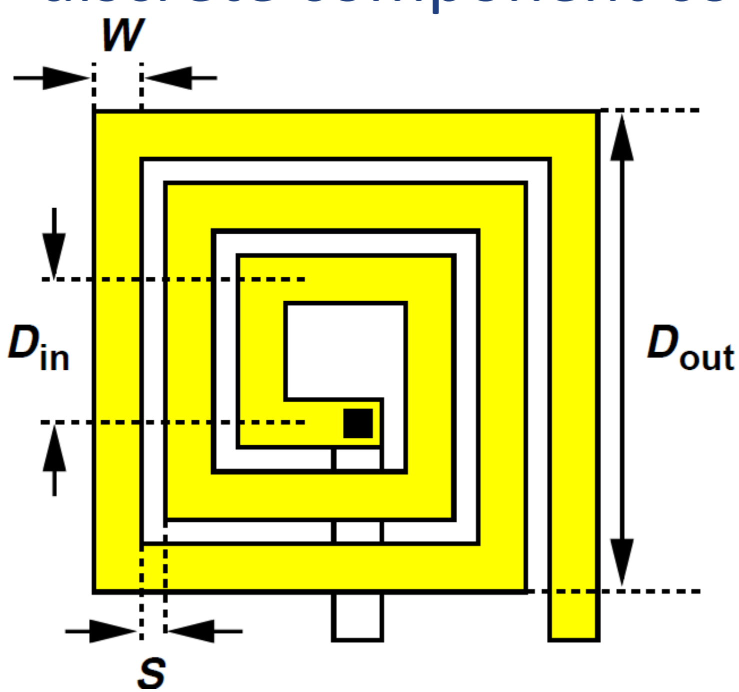
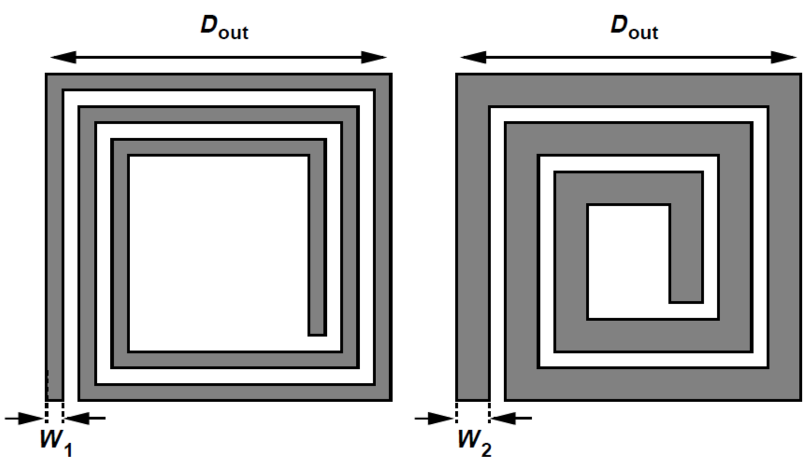
RFIC Passive Components

(planar spiral inductor)

- In integrated circuit (IC) design, passive components are also used for RFICs. Their implementation are however different from the discrete component counterparts.





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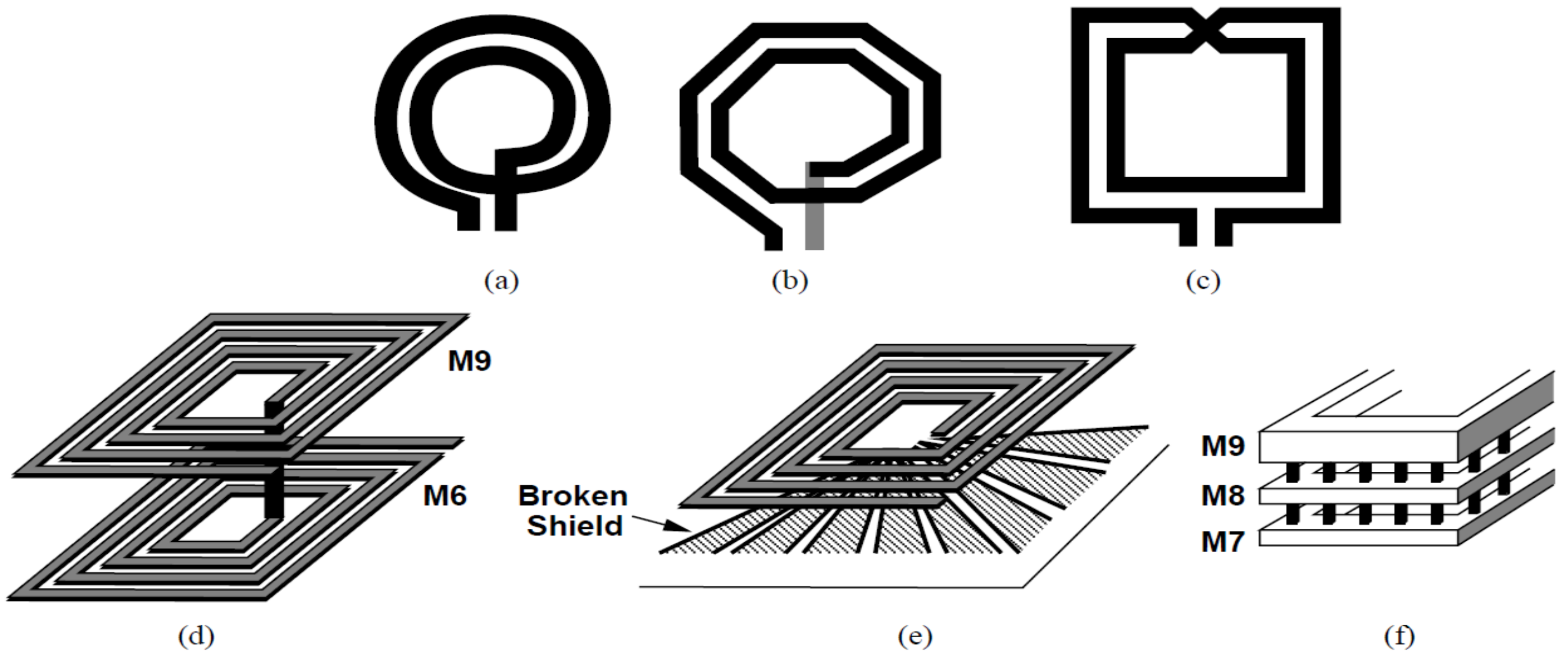
RFIC Passive Components

(planar spiral inductor)

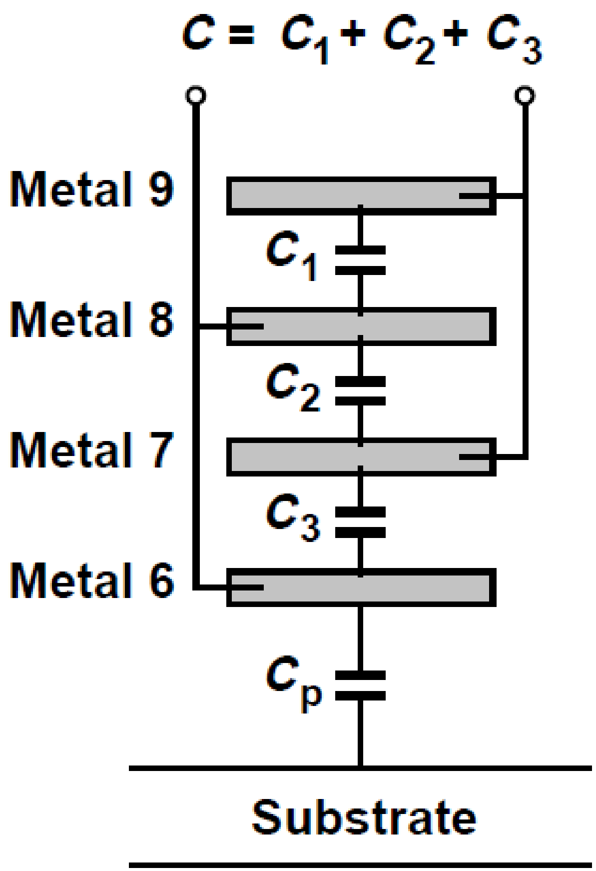
- There can be various designs of planar spiral inductors in RFIC design to minimise the parasitics.



From: Behzad Razavi, *RF Microelectronics*,

RFIC Passive Components

(parallel-plate capacitor)



- In the case of capacitors in RFIC design, the multiple metal layers are used for making parallel-plate capacitors.
- The MOS capacitor structure is also used sometimes because of its thin gate oxide and the voltage controllability.

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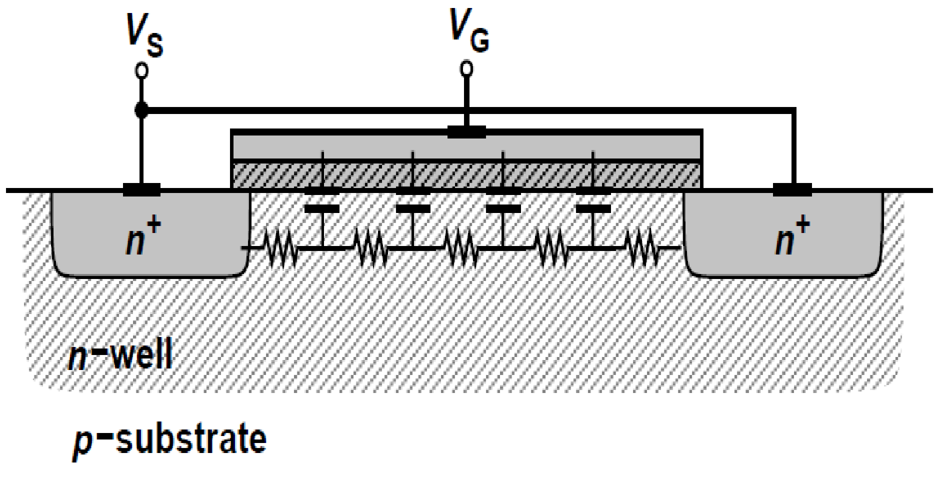
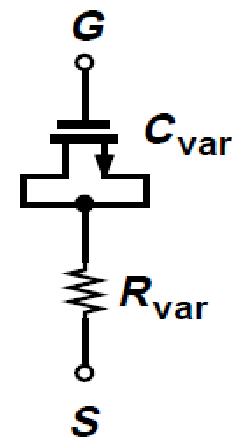
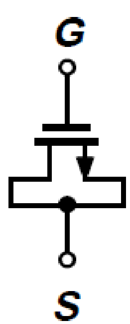
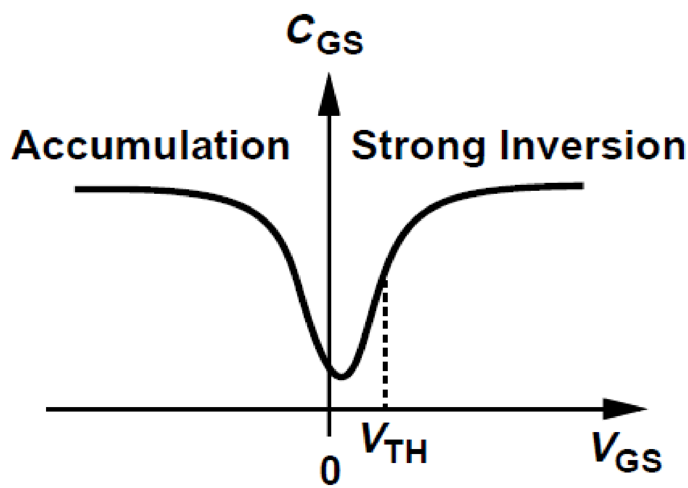
RFIC Passive Components

(MOS variable capacitor - varactor)









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