Lecture 12: Antennas & Antenna Matching

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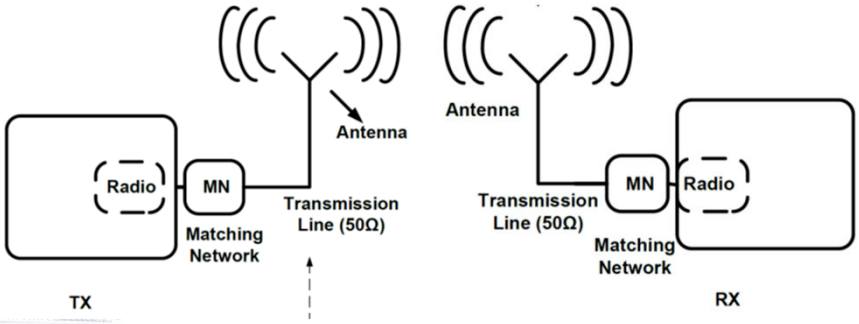
Antenna for Wireless Transmission



Antenna Types & Length

- Wire Antenna
- PCB Antenna or Microstrip Antenna
- Panel Antenna
- Patch Antenna
- Phased Array Antenna
- Chip Antenna
- Antenna length is related to transmitted signal wavelength λ

$$\lambda = \frac{c}{f}$$

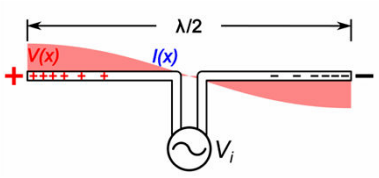
Radio Spectrum Frequencies

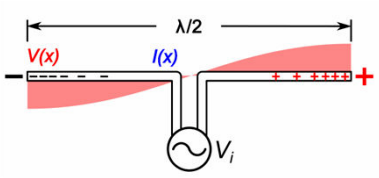
Frequency range	ITU designation	IEEE bands	Wavelength range
…	ELF, SLF, ULF, VLF, LF	—	
30 – 300 kHz	**LF** (Low frequency)	—	1 km – 10 km
300 kHz – 3 MHz	**MF** (Medium frequency)	—	100 m – 1 km
3 – 30 MHz	**HF** (High frequency)	HF	10 m – 100 m
30 – 300 MHz	**VHF** (Very high frequency)	VHF	1 m – 10 m
300 MHz – 3 GHz	**UHF** (Ultra high frequency)	UHF, L, S	10 cm – 1 m
3 – 30 GHz	**SHF** (Super high frequency)	S, C, X, Ku, K, Ka	1 cm – 10 cm
…	EHF, THF	Ka, V, W, mm	

Examples: AM radio ~ 1 MHz, FM radio ~ 100 MHz, Terrestrial TV ~ VHF&UHF, Cellular ~ 850 MHz, 900 MHz, 1800 MHz, 1900 MHz, 2200 MHz, 2300 MHz, etc, Wi-Fi ~ 2.4 GHz, 5 GHz, 6 GHz.

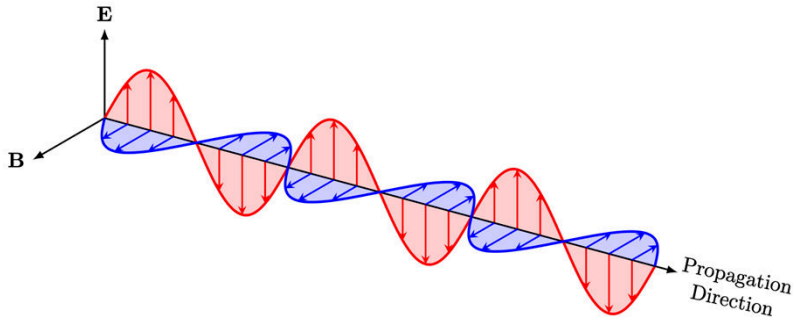
Dipole Antenna

- Consists of two identical conductive elements.
- Each side of the transmitter feedline is connected to one of the conductors.
- Build variable electric field from potential difference.



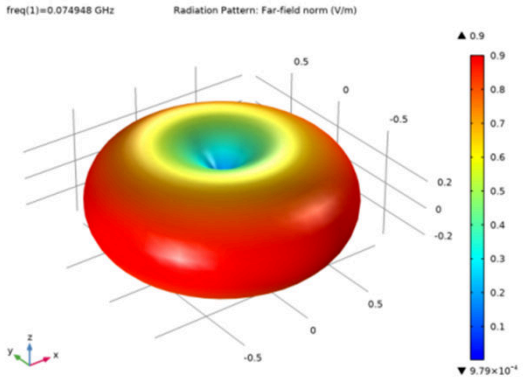


EM Signal Propagation



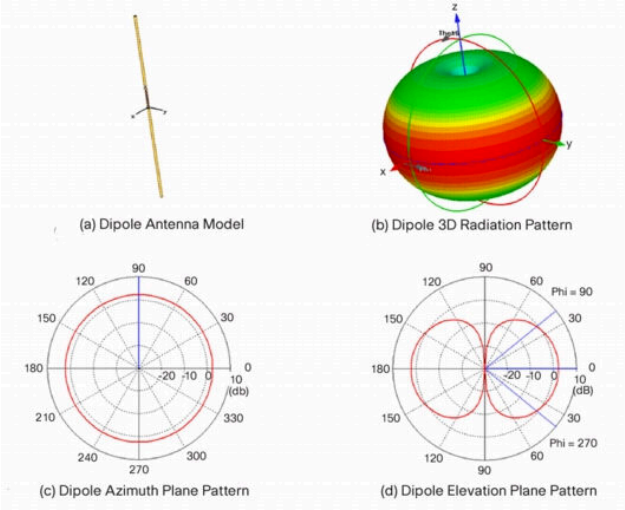
- Variable electric field induces magnetic field, which induces electric field, thus building a propagating EM signal.

Radiation Pattern



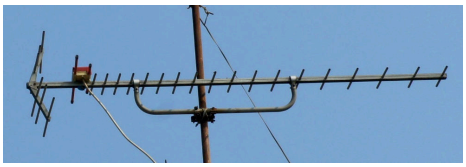
- Radiation pattern shows the directional (angular) dependence of the strength of the radio waves from the antenna.

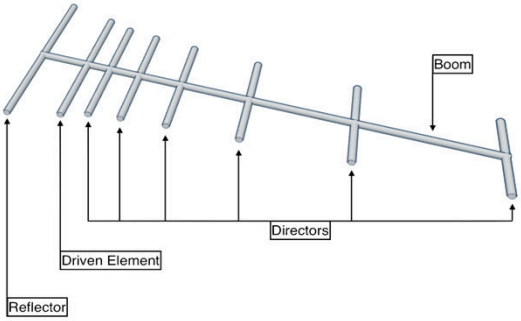
Radiation Pattern Views



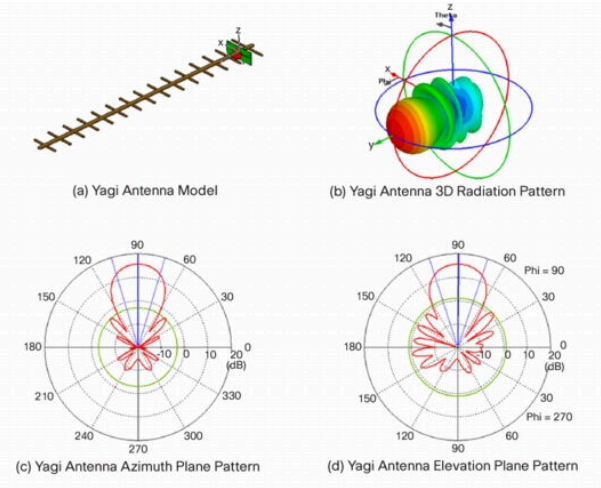
Example: UHF TV RX Antenna

- **Yagi–Uda** antenna uses a dipole for its driven element.
- Used to receive terrestrial TV transmission in UHF range.
- UHF (Ultra High Frequency): 300 MHz to 3 GHz.
- Directional antenna.





Radiation Pattern



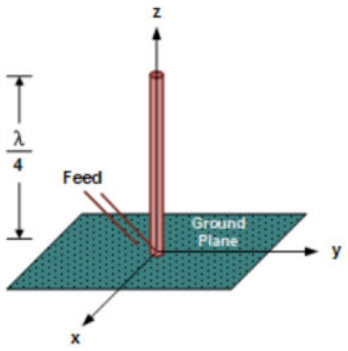
Example: VHF TV RX Antenna

- For VHF range, which requires a longer dipole, many Yagi–Uda antennas use a folded dipole design for the driven element.
- VHF (Very High Frequency): 30 MHz to 300 MHz.
- But *not* always: see Rabbit Ears TV Antenna.

Also for HF & FM Radio TX (VHF)

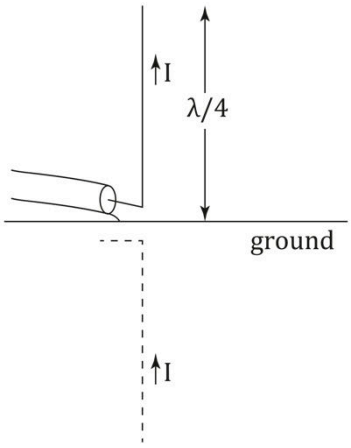
Monopole Antenna

- Straight conductor mounted perpendicularly over conductive surface (ground plane).
- The driving signal from the transmitter goes through a feedline.
- One side of the feedline is attached to the lower end of the monopole, and the other side is attached to the ground plane (consisting of cables buried under Earth).



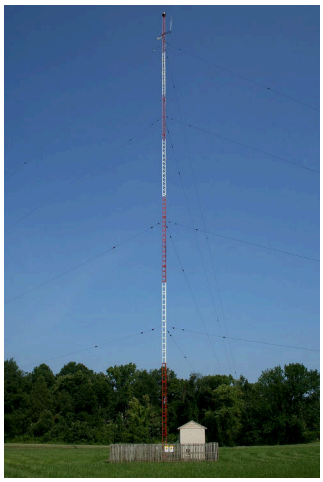
Ground Provides Mirror Image

- A λ /4 monopole antenna and its ground image combined form a λ /2 dipole that radiates only in the upper half of space.

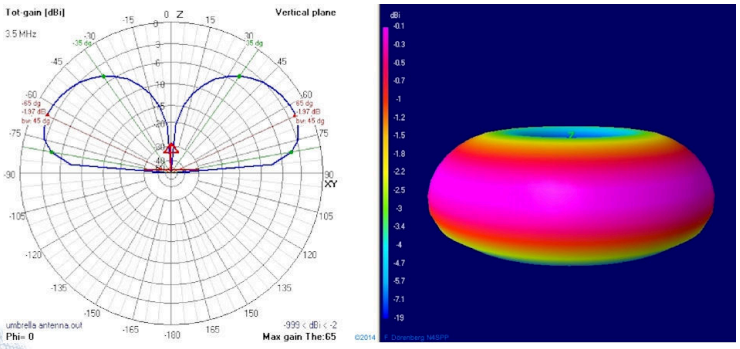


Example: AM Radio TX

- AM radio station mast radiator monopole antenna.
- The mast itself is connected to the transmitter and radiates the radio waves.
- It is mounted on a ceramic insulator to isolate it from the ground.

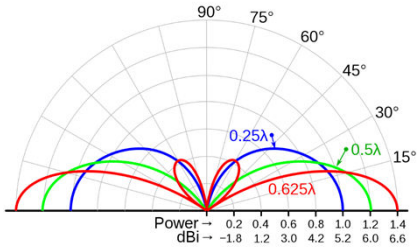


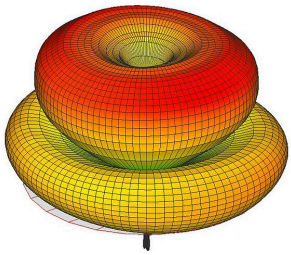
Radiation Pattern



- Vertical radiation pattern of ideal monopole antenna over a perfect infinite ground.

Variation on Radiation Pattern

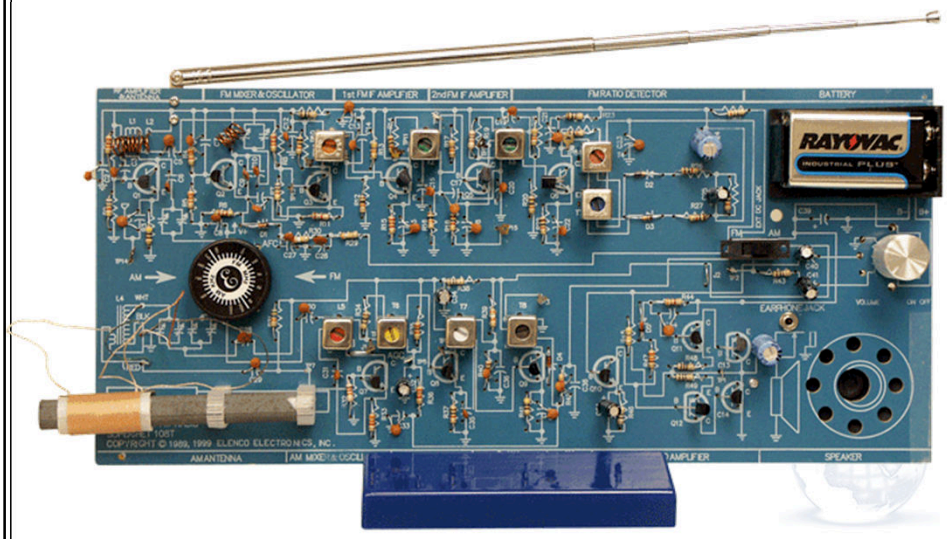




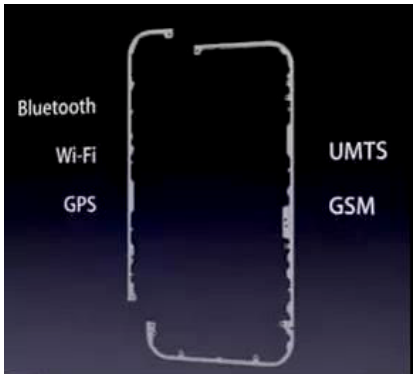
- Vertical radiation patterns of monopole antennas with different lengths.
- Multi-lobed radiation pattern for 0.625λ monopole.

Examples: Car, FM Radio, WiFi AP

AM vs. FM RX Antenna



Examples: Phone, iPhone 4s



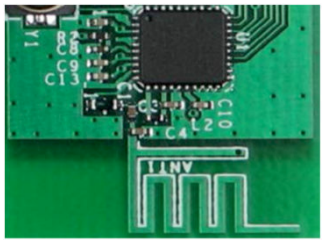
Dish Antenna

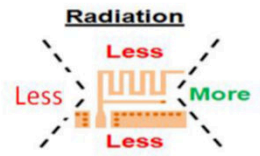
- The dish itself is just a concentrator or reflector.
- E.g.: Satellite TV RX.
- The signal is highly attenuated.

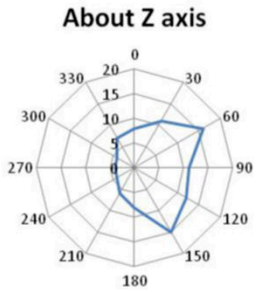
PCB Antenna

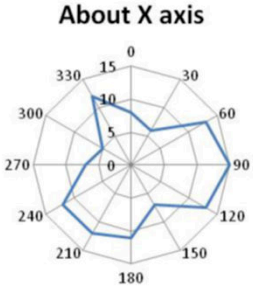
- Trace drawn on the PCB.
- Can be a straight trace, inverted F-type trace, meandered trace, circular trace, or a curve with wiggles depending on the antenna type and space constraints.
- PCB antenna requires more PCB area, has a lower efficiency than the wire antenna, but is cheaper and easier to manufacture.
- Acceptable for low-range applications, e.g. Bluetooth.

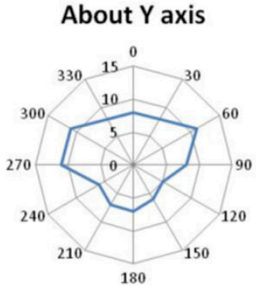
PCB Antenna



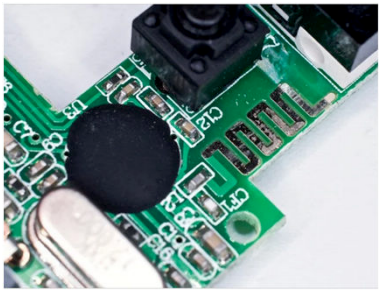


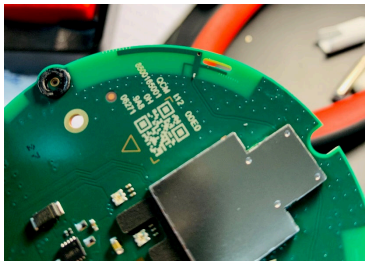


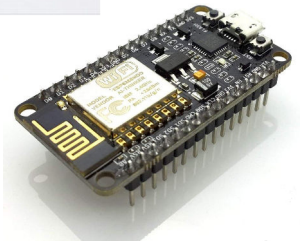




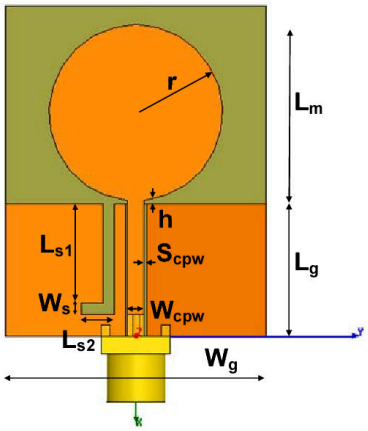
Example: Mouse, Keyboard, Sensor



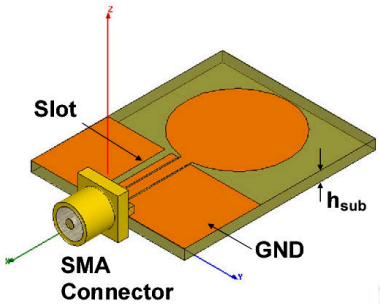




Different Shapes Possible



(a)

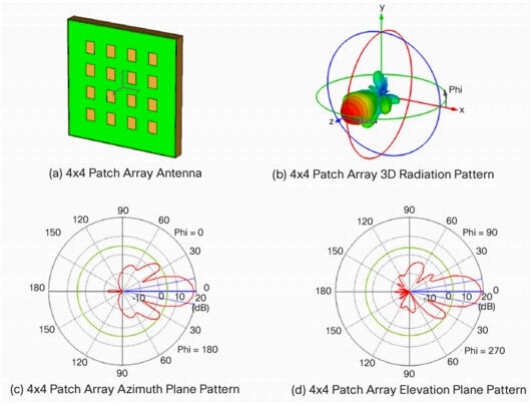


(b)

Panel Antennas

Cellular Telephony & TV UHF TX

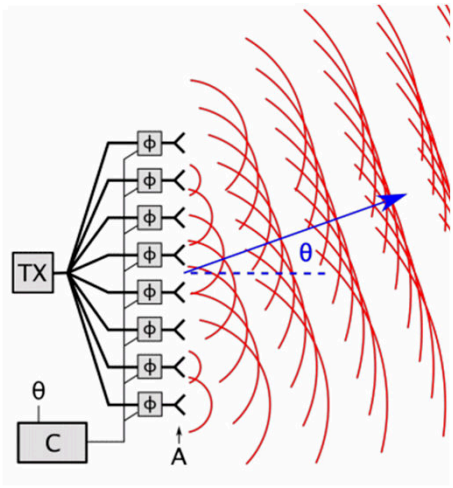
Patch Antennas (*Antenna Array*)



Phased Array Antenna

- Computer-controlled array of antennas to build a beam of radio waves that can be electronically steered to point in different directions without moving the antennas.
- Transmitted signal is fed to individual antenna elements with proper phase for each so output from the separate elements combine (superpose) to increase power radiated in desired directions and suppress radiation in undesired directions.
- Examples: Starlink satellite system (from SpaceX), 5G MIMO for cell phones.

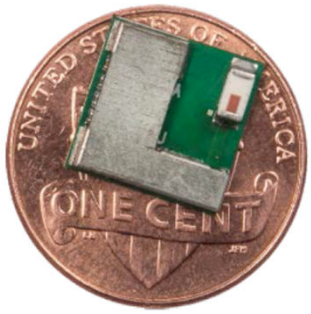
Computer Controls Phase Shifters

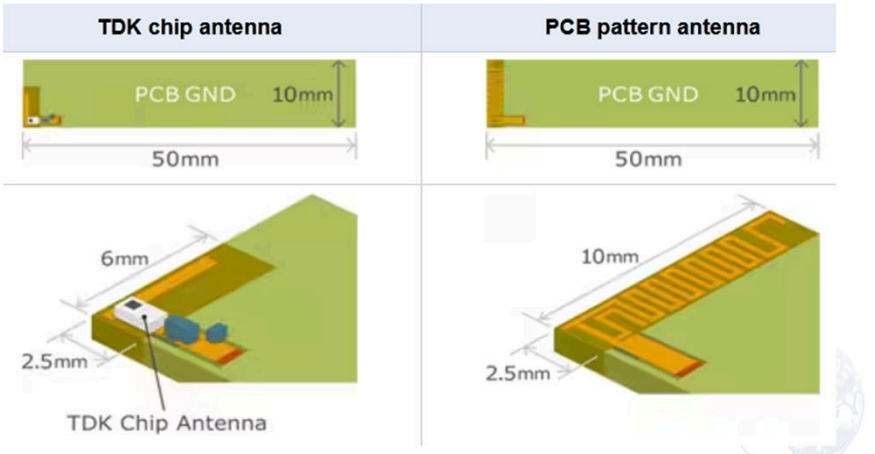


Starlink Dish

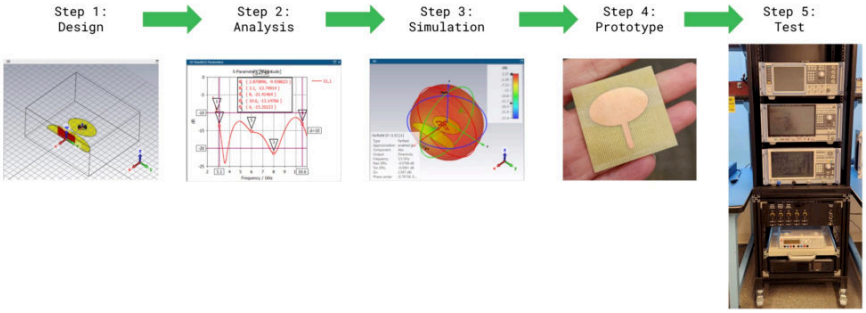
Chip Antennas

- Antenna inside the IC itself, with a conductor packed inside.
- Useful when there is limited space to print a PCB antenna or support a 3D wire antenna.

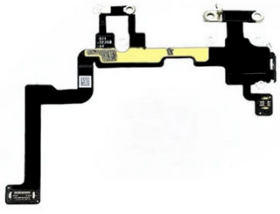




Antenna Design



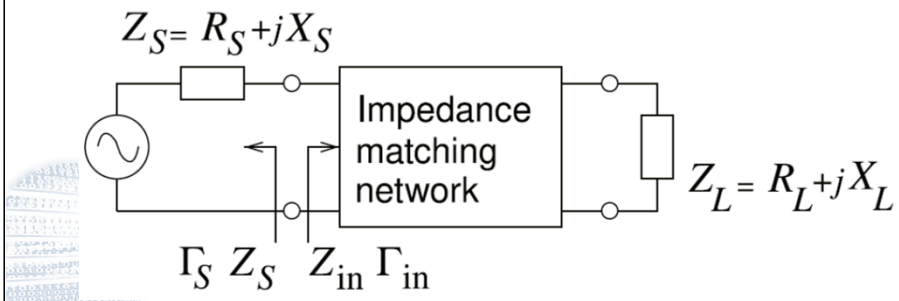
Many Antennas: Samsung, iPhone 11 FlexCable



Antenna Matching

- For maximum power transfer, we need:

$$\boldsymbol{Z_{in} = Z_S^*}$$



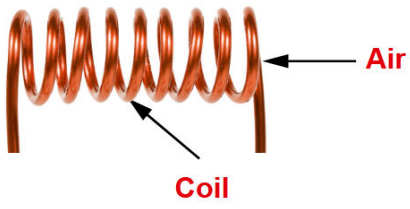
Matching Network

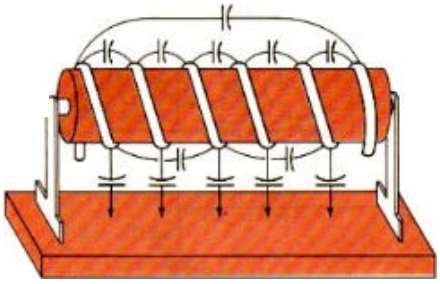
- If load has non-zero real part (i.e., can dissipate power), a matching network can always be found.
- Design of matching network is called impedance matching.
- Matching networks are constructed using lossless elements, such as lumped capacitors, lumped inductors, transmission lines, microstrips, etc. So, ideally, there is no extra power loss in the circuit.

Elements for Matching Networks

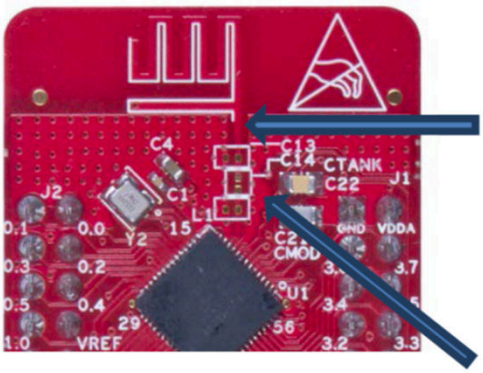
- Up to few GHz, lumped inductors and lumped capacitors can be used.
- Above a few GHz, lumped inductors are not recommended, due to high loss (wire resistance) and high parasitic capacitances (inter-winding capacitance).
- Lumped inductors can be replaced with segments of transmission lines or stubs (they suffer smaller loss and have smaller parasitics).
- Lumped capacitors can still be used at higher frequencies compared to lumped inductors.
- Transmission lines cannot be used at lower frequencies because they need to be longer due to the longer signal wavelength λ.

Lumped Inductors





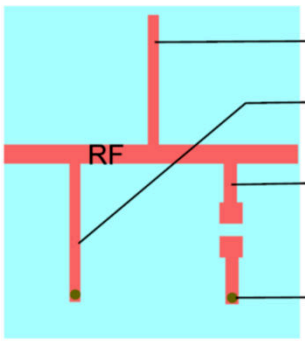
Matching Network



Only 3 mm trace to Antenna. Transmission line width is not critical

Matching Network

Examples for Stubs



Open circuited stub

Short circuited stub

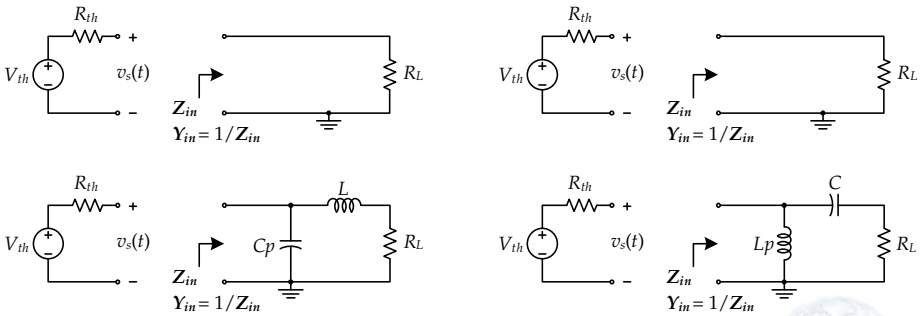
Unintentional stub in a shunt component

Unintentional stub to ground

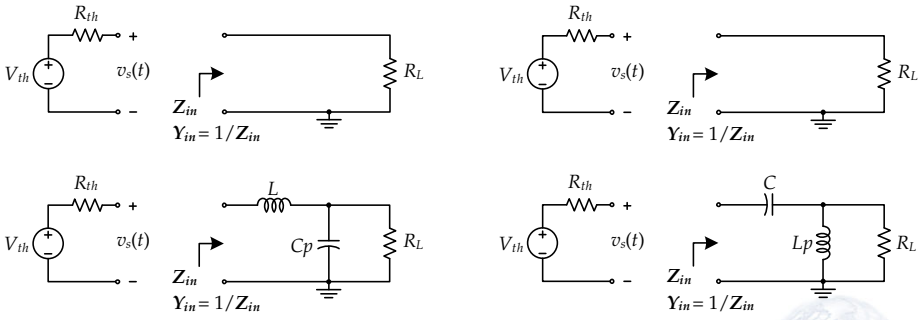
Matching Network Design

- Two Element Matching
  - L-shaped circuit.
  - Use an inductor and a capacitor.
  - Transform R_L into larger resistance R_p
    - Use series active element first.
  - Transform R_L into smaller resistance R_s
    - Use shunt active element first.
- Three Element Matching
  - T-network or Pi-network.

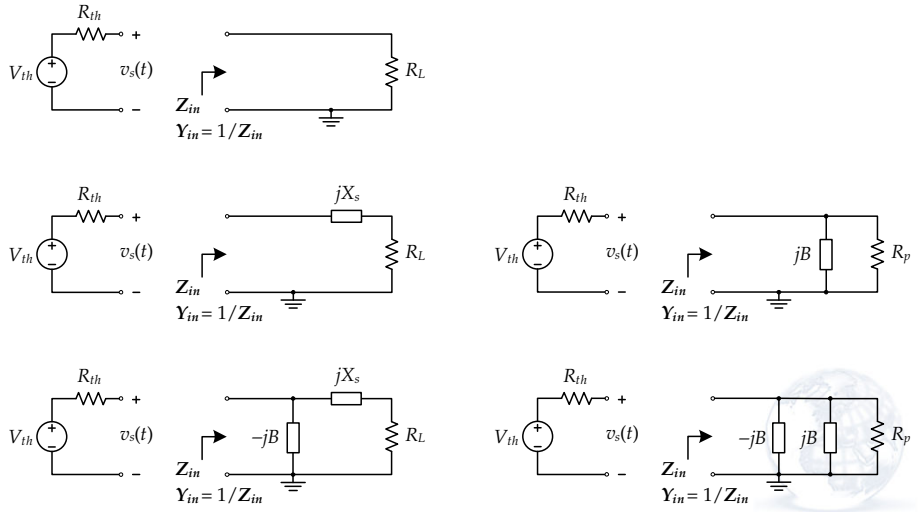
Series L-Network



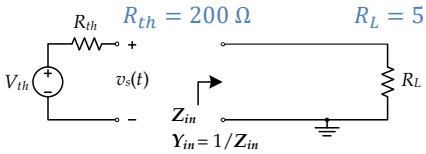
Shunt (Parallel) L-Network



Analysis of Series L-Network



Numerical Example

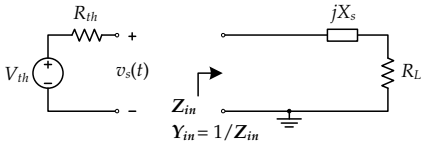


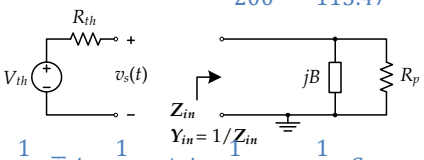
$R_{th} = 200\ \Omega$ $\quad R_L = 50\ \Omega$

$$Y_{in} = \frac{1}{Z_{in}} = \frac{1}{50 \pm j86.6\ \Omega} = 0.005 \mp j0.00866\ \text{S}$$

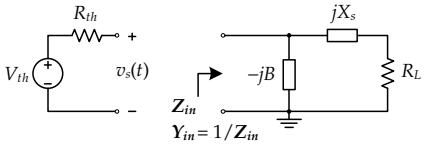
$$Z_{in} = R_L + jX_s = 50 \pm j86.6\ \Omega$$

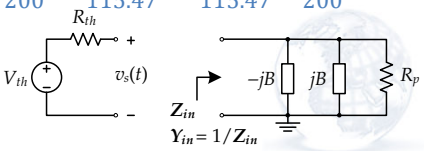
$$Y_{in} = 0.005 \mp j0.00866\ \text{S} = \frac{1}{200} \mp j\frac{1}{115.47}\ \text{S}$$



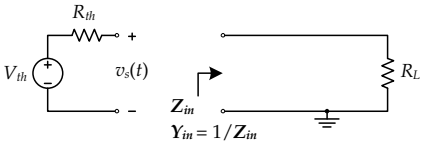


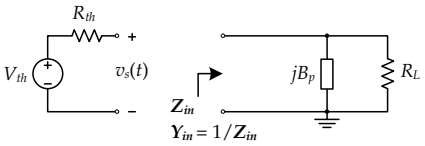
$$Y_{in} = \frac{1}{200} \mp j\frac{1}{115.47} \pm j\frac{1}{115.47} = \frac{1}{200}\ \text{S}$$

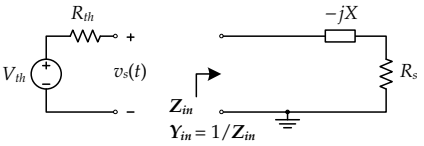


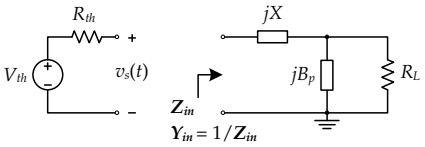


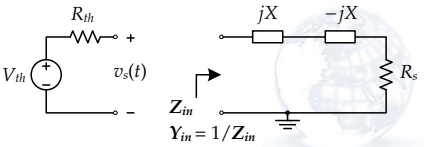
Homework: Shunt L-Network







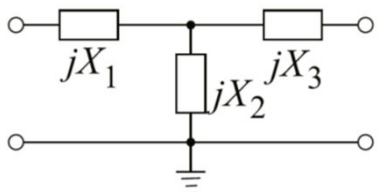




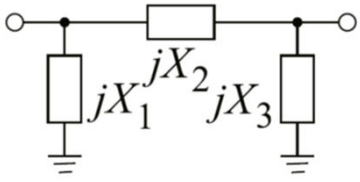
Controlling Q factor

- With L network (i.e., two-element matching), the circuit Q is fixed once source and load resistances, R_S and R_L, are fixed.
- Introducing a third element in the matching network provides an extra degree of freedom in the design for adjusting Q, and hence bandwidth.
- Popular three-element matching networks are the T network and the Pi network.

Three-Element Matching



(a) T network



(b) Pi network

Matching Via Smith Chart