EE230-02 RFIC II
Fall 2018

Lecture 4: Impedance Matching

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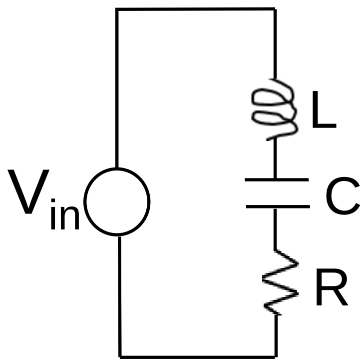
ENG-259

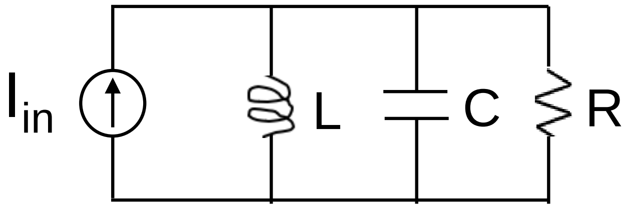
Series & Parallel Resonance



$$Z(\omega_0) = R$$

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$$

$$|V_L| = |V_C| = Q \cdot |V_{in}|$$



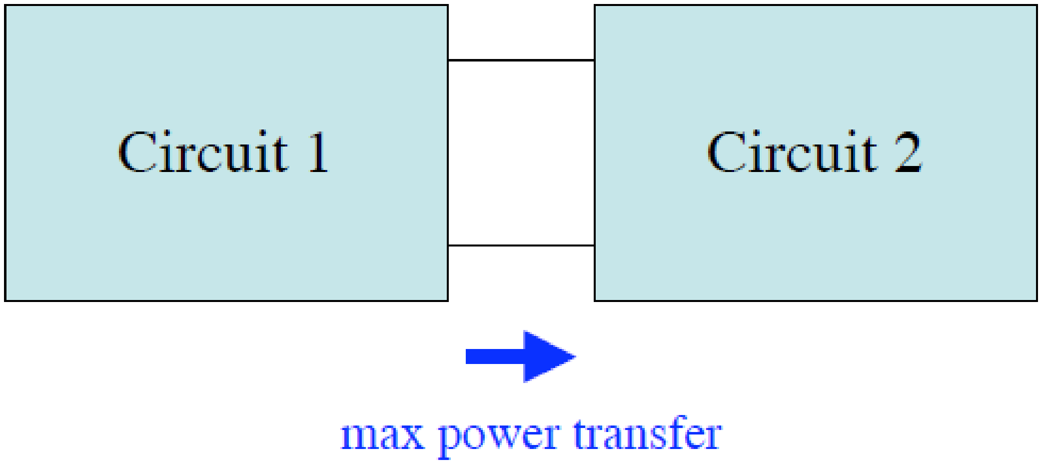
$$Q = \frac{R}{\omega_0 L} = \omega_0 RC$$

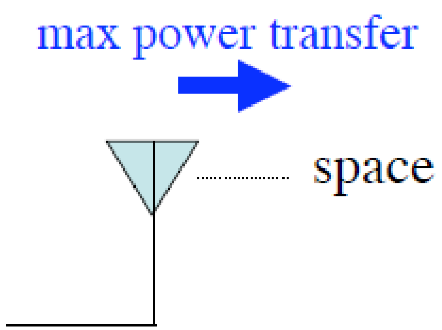
$$|I_L| = |I_C| = Q \cdot |I_{in}|$$

Impedance Matching

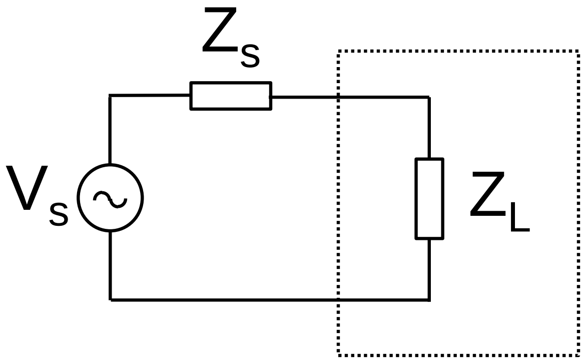
- Impedance matching is a major problem in high-frequency circuit design.

- It is concerned with matching one part of a circuit to another in order to achieve *maximum power transfer* between the two parts.





Maximum Power Transfer Theorem



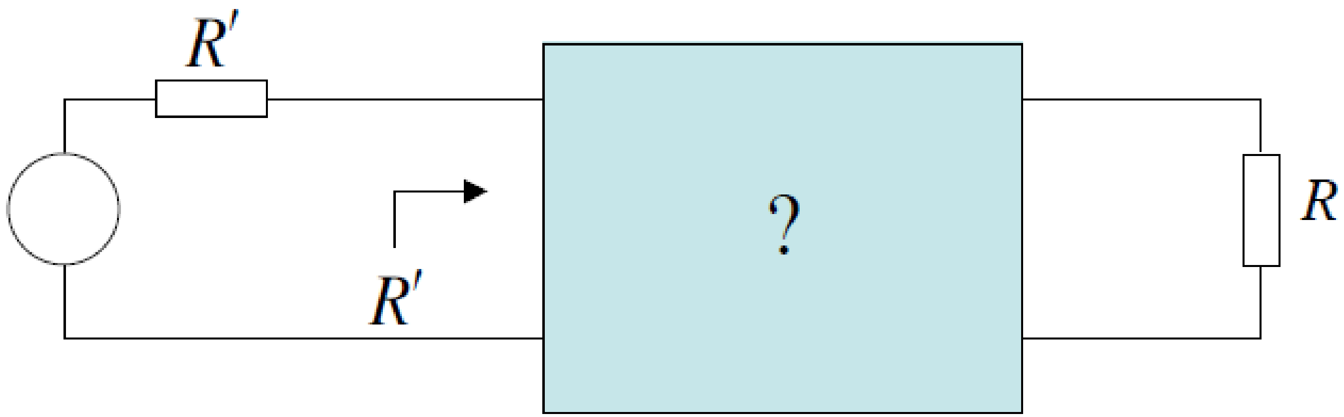
$$Z_s = R_s + jX_s$$

$$Z_L = R_L + jX_L$$

$$Maximum\ power\ is\ delivered\ when\ R_L = R_s\ \ \&\ \ X_L = -X_s$$

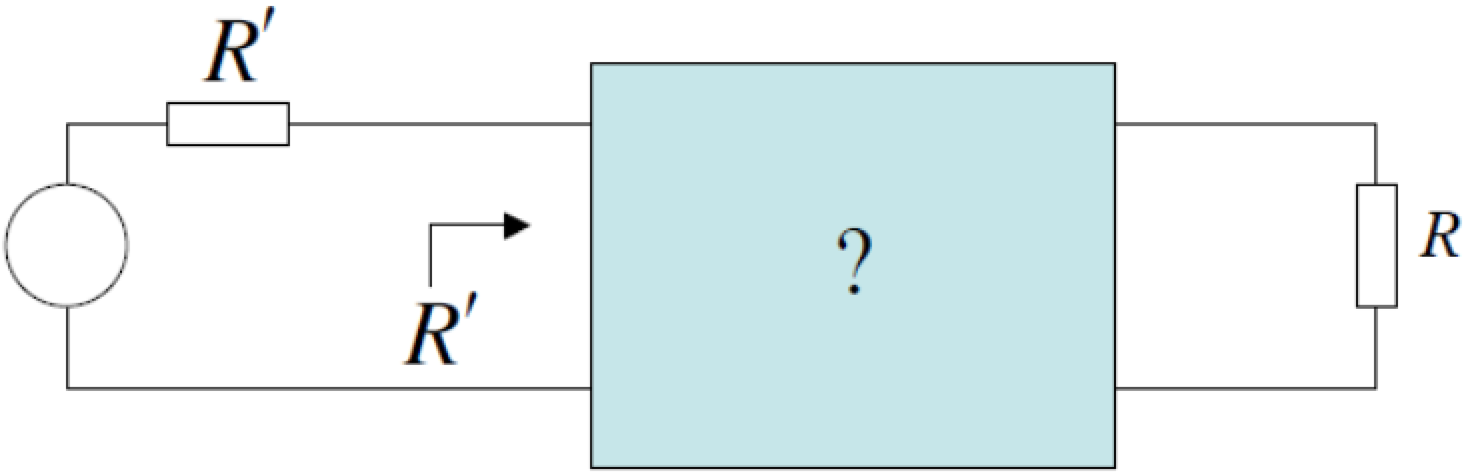
The Problem

Given a load R, find a circuit that can match the driving resistance R' at frequency ω_0.



Obviously, the matching circuit must contain L and C in order to specify the matching frequency.

Simple Matching



L matching circuit (single LC section)
π matching circuit
T matching circuit

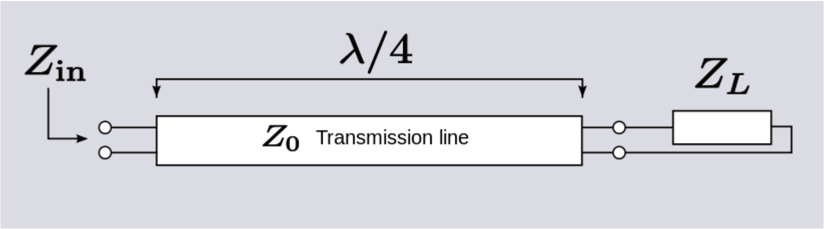
Impedance Transformation

- RF input and output impedances are standardized at 50 Ω (75 Ω for TV)
- 50 Ω is approximate tradeoff between max. power handling capability and min. loss
- On-chip : don’t use 50 Ω impedances as large power is needed to drive 50 Ω
- Match at LNA input and PA output

Impedance Matching

Traditional microwave techniques:

- λ/4 transformer

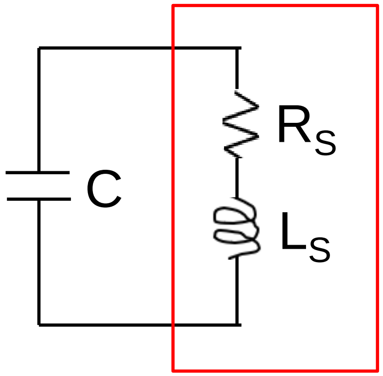


$$Z_{in} = \frac{Z_o^2}{Z_L}$$

- Stub matching
  Use open and short T-lines to obtain the desired Z_{in}

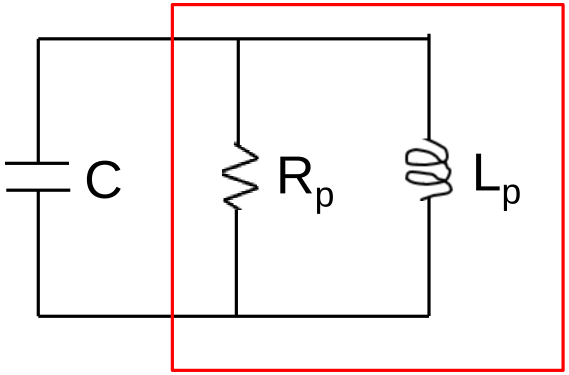
In RFIC, we use L-matching with lumped components

Series-Parallel Transformation



Neither series nor parallel

Make series-parallel conversion at resonance.



$$R_s + j\omega_0 L_s = \frac{R_p \cdot j\omega L_p}{R_p + j\omega L_p}$$

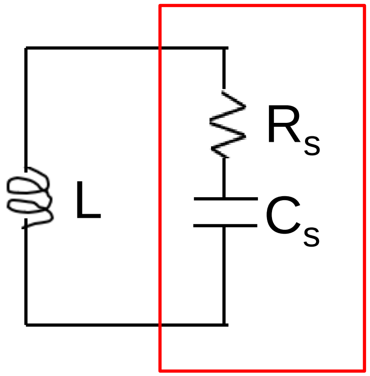
$$Q_p = \frac{R_p}{\omega_0 L_p} \qquad Q_s = \frac{\omega_0 L_s}{R_s}$$

$$Q_p = Q_s = Q$$

Remember this!

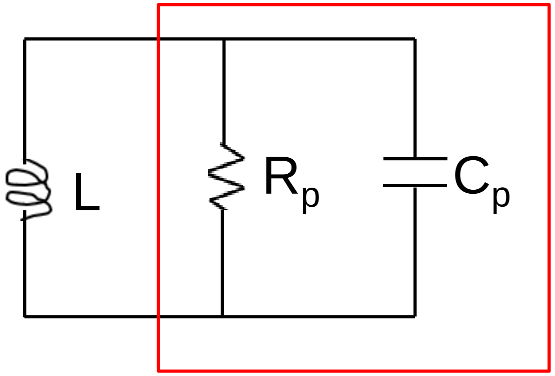
$$\boxed{R_p = R_s(1+Q^2) \qquad L_p = L_s \frac{1+Q^2}{Q^2}}$$

Series-Parallel Transformation



Neither series nor parallel

Make series-parallel conversion at resonance.



$$R_p = R_s(1 + Q^2)$$

$$C_p = \frac{C_s \cdot Q^2}{1 + Q^2}$$

Series-Parallel Transformation

R_p is always larger than R_s

$$R_p = R_s(1 + Q^2)$$

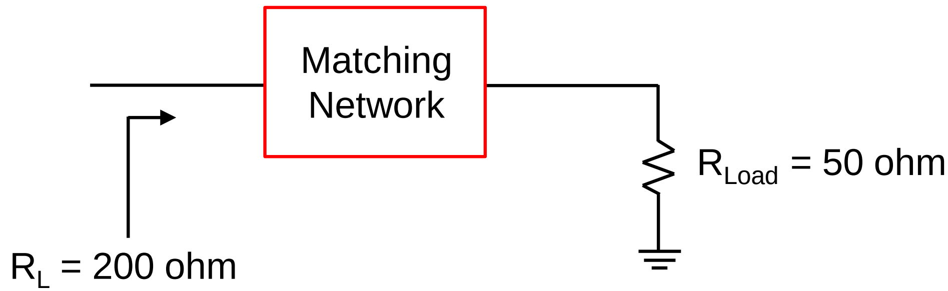
$$X_p = X_s \frac{1 + Q^2}{Q^2}$$

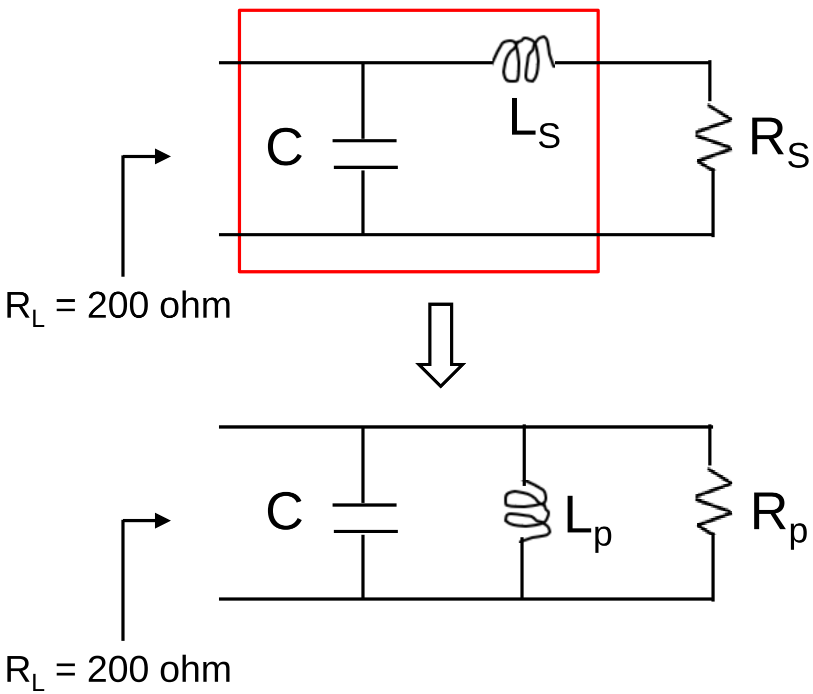
$$L_p = L_s \frac{1 + Q^2}{Q^2}$$

$$C_p = C_s \frac{Q^2}{1 + Q^2}$$

L-Match: Upward Impedance Transform

Low-pass L-match





$$R_p = R_s(1 + Q^2)$$

$$L_p = L_s \frac{1 + Q^2}{Q^2}$$

L-Match: Upward Impedance Transform

Transform Equations

$$R_p = R_s(1+Q^2) \Longrightarrow Q = \sqrt{\frac{R_p}{R_s} - 1}$$

$$Q = \frac{R_p}{\omega_0 L_p} \Longrightarrow L_p = \frac{R_p}{\omega_0 Q}$$

$$L_s = L_p \frac{Q^2}{1+Q^2}$$

$$C = \frac{1}{L_p \omega_o^2}$$

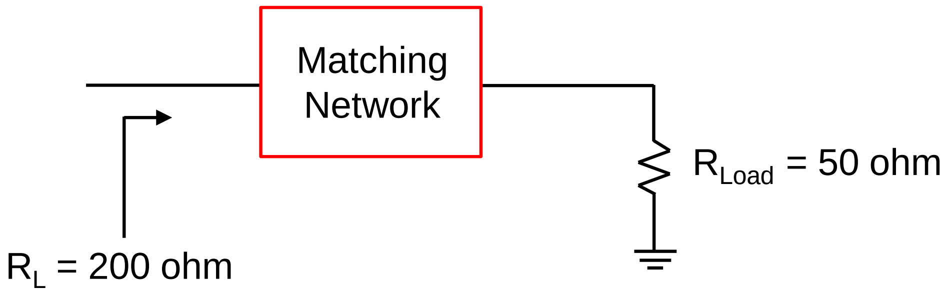
Example:

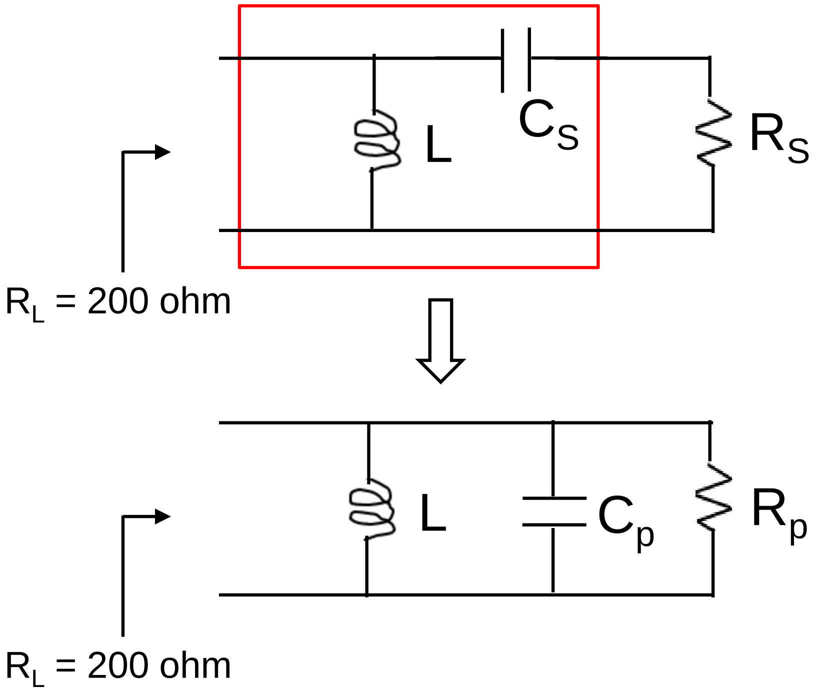
Match 50 Ω to 200 Ω at 2.4GHz

$$R_s = 50\ \Omega$$
$$R_p = 200\ \Omega$$
$$\omega_0 = 2\pi \cdot\ 2.4GHz$$
$$Q = \sqrt{\frac{200}{50} - 1} = \sqrt{3} = 1.73$$
$$L_p = \frac{200}{2\pi \cdot\ 2.4GHz \cdot 1.73} = 7.67\ nH$$
$$L_s = 7.67\,\frac{1.73^2}{1+1.73^2} = 5.75\ nH$$
$$C = \frac{1}{7.67\omega_o^2} = 0.573\ \mathrm{pF}$$

L-Match: Upward Impedance Transform

High-pass L-match





$$R_p = R_s(1 + Q^2)$$

$$C_p = C_s \frac{Q^2}{1 + Q^2}$$

L-Match: Upward Impedance Transform

Transform Equations

$$R_p = R_s(1 + Q^2) \implies Q = \sqrt{\frac{R_p}{R_s} - 1}$$

$$Q = \omega_0 C_p R_p \implies C_p = \frac{Q}{\omega_0 R_p}$$

$$C_s = C_p \frac{1 + Q^2}{Q^2}$$

$$L = \frac{1}{C_p \omega_o^2}$$

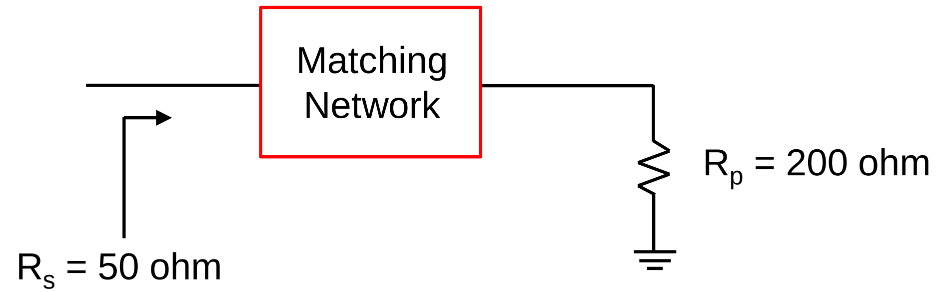
Example:

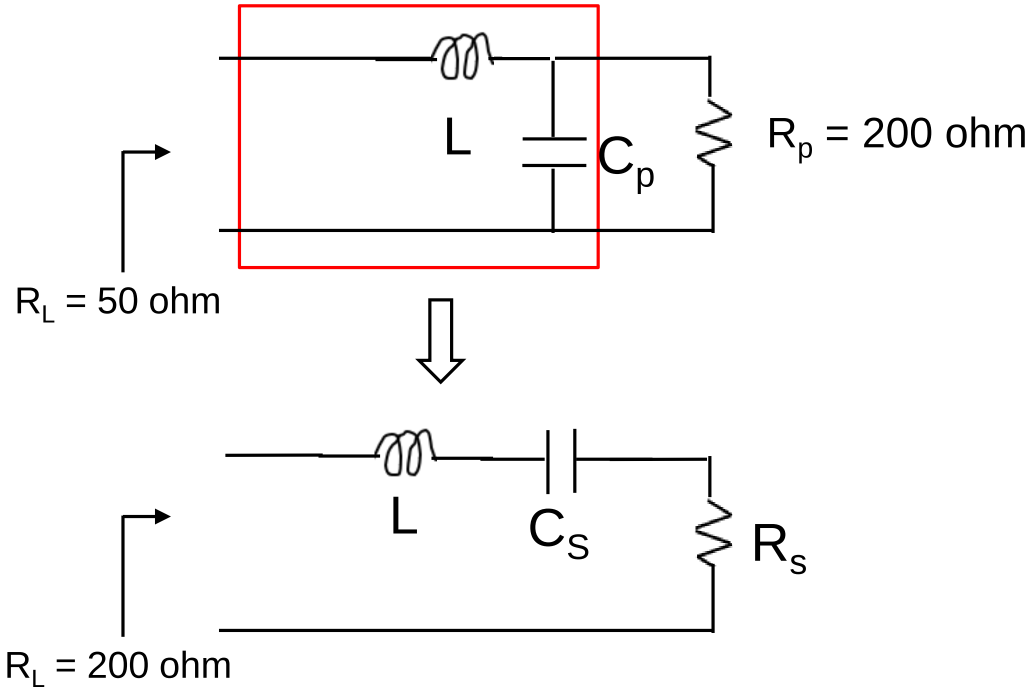
Match 50 Ω to 200 Ω at 2.4GHz

$$R_s = 50\ \Omega$$
$$R_p = 200\ \Omega$$
$$\omega_0 = 2\pi \cdot\ 2.4GHz$$
$$Q = \sqrt{\frac{200}{50} - 1} = \sqrt{3} = 1.73$$
$$C_p = \frac{1.73}{2\pi \cdot 2.4GHz \cdot 200} = 0.574\ pF$$
$$C_s = 0.574\, \frac{1 + 1.73^2}{1.73^2} = 0.765\ pF$$
$$C = \frac{1}{0.574pF \cdot \omega_o^2} = 7.66\ \mathrm{nH}$$

L-Match: Downward Impedance Transform

Low-pass L-match





$$R_p = R_s(1 + Q^2)$$

$$C_p = C_s \frac{Q^2}{1 + Q^2}$$

L-Match: Downward Impedance Transform

Example:

Match 200 Ω to 50 Ω at 2.4GHz

$R_s = 50\ \Omega$

$R_p = 200\ \Omega$

$\omega_0 = 2\pi \cdot\ 2.4GHz$

$$Q = \sqrt{\frac{R_p}{R_s} - 1} = \sqrt{\frac{200}{50} - 1} = \sqrt{3} = 1.73$$

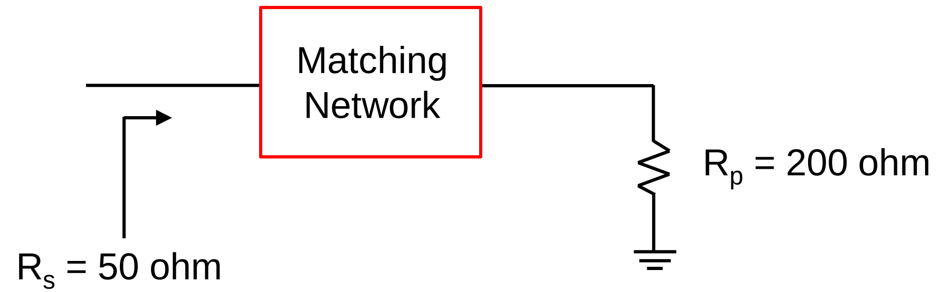
$$Q = \frac{1}{\omega_0 R_s C_s} \Longrightarrow C_s = \frac{1}{\omega_0 R_s Q} = \frac{1}{2\pi\cdot\ 2.4GHz\cdot 50\cdot 1.73} = 0.329\ pF$$

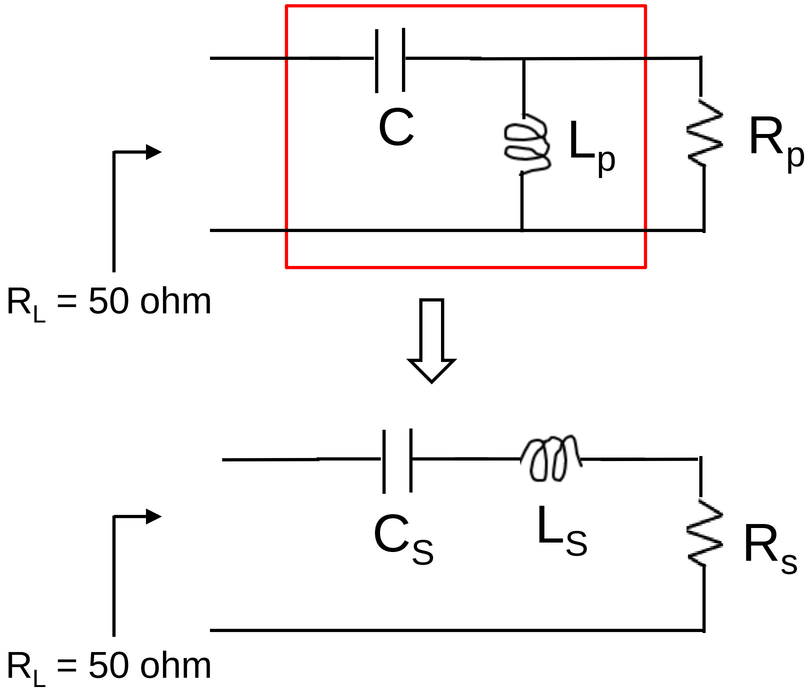
$$C_p = C_s \frac{Q^2}{1+Q^2} = 0.246\ pF$$

$$L = \frac{1}{C_s \omega_o^2} = \frac{1}{0.246pF\cdot\omega_o^2} = 2.46\ \mathrm{nH}$$

L-Match: Downward Impedance Transform

High-pass L-match





$$R_p = R_s(1 + Q^2)$$

$$L_p = L_s \frac{Q^2 + 1}{Q^2}$$

L-Match: Downward Impedance Transform

Example:

Match 200 Ω to 50 Ω at 5.6GHz

$R_s = 50\ \Omega$

$R_p = 200\ \Omega$

$\omega_0 = 2\pi \cdot 5.6GHz$

$$Q = \sqrt{\frac{R_p}{R_s} - 1} = \sqrt{\frac{200}{50} - 1} = \sqrt{3} = 1.73$$

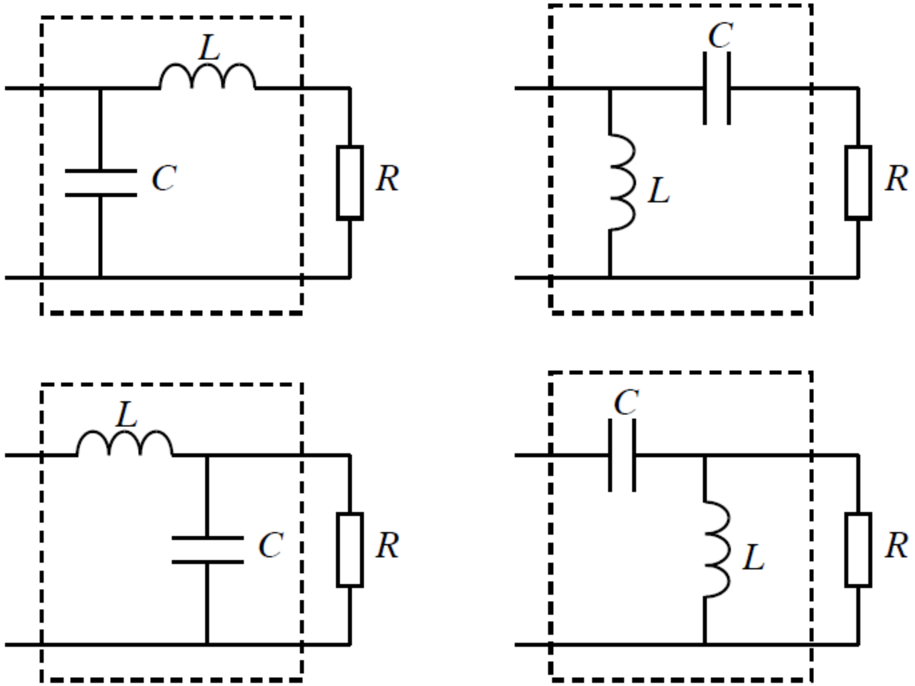
$$Q = \frac{\omega_0 L_s}{R_s} \Longrightarrow L_s = \frac{QR_s}{\omega_0} = \frac{1.73x50}{2\pi \cdot 5.6GHz} = 2.46\ nH$$

$$L_p = L_s \frac{Q^2+1}{Q^2} = 2.46nH\, \frac{1.73^2+1}{1.73} = 3.28nH$$

$$C = \frac{1}{L_s \omega_o^2} = 0.328\ \mathrm{pF}$$

L-Match Summary

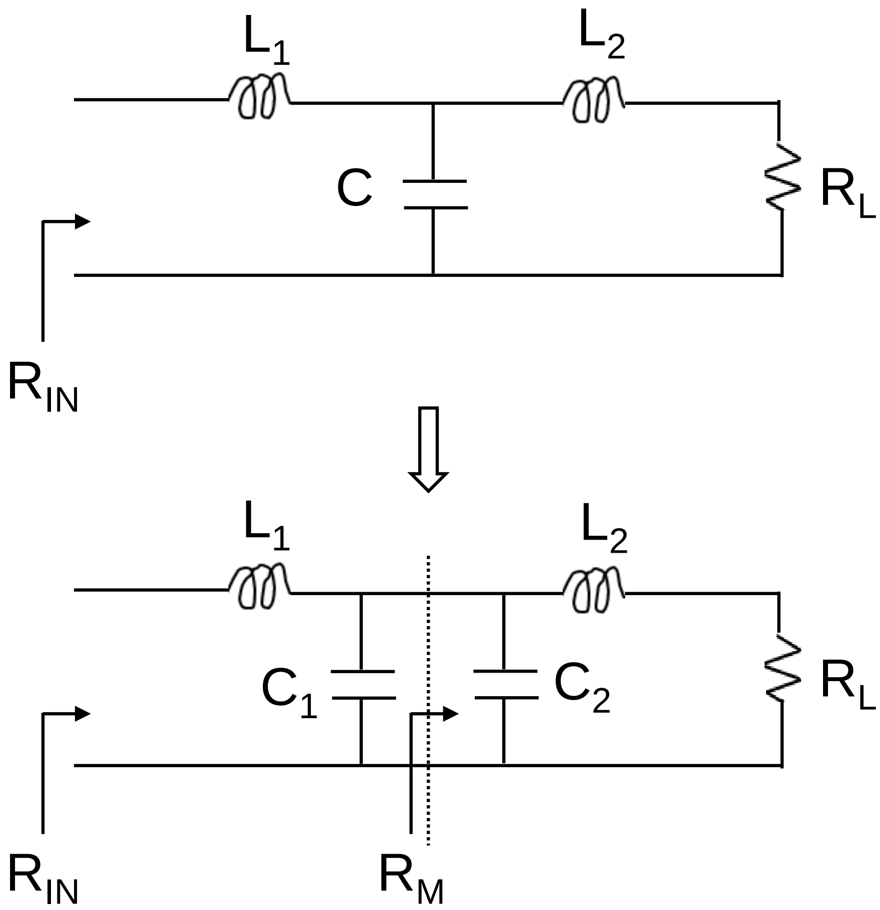
4-types of L-match



$$Once \quad R_s,\ R_p,\ \omega_0 \quad is\ known \quad \Longrightarrow \quad Q = \sqrt{\frac{R_p}{R_s} - 1} \quad is\ fixed$$

T-Match

To design for a different Q, i.e. different Bandwidth for a given ω_0
We need another degree of freedom



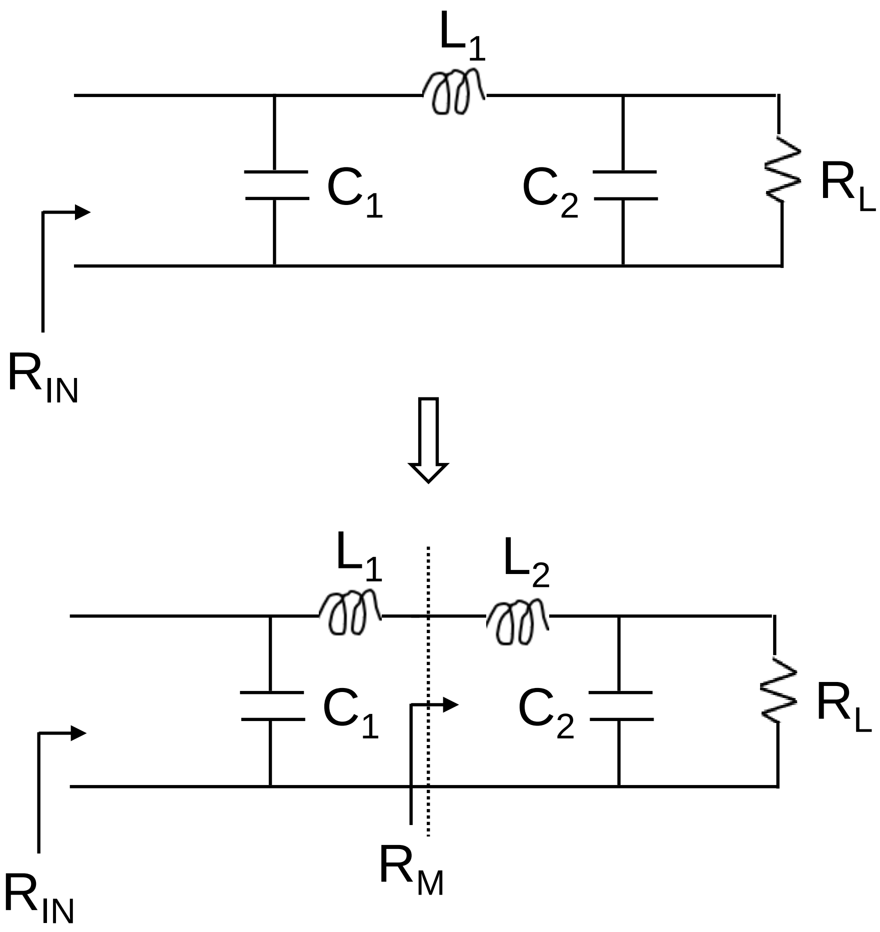
$$Q = Q_L + Q_R$$

$$= \sqrt{\frac{R_M}{R_{IN}} - 1} + \sqrt{\frac{R_M}{R_L} - 1}$$

$R_M > R_L$

$R_M > R_{IN}$

π-Match



$$Q = Q_L + Q_R$$

$$= \sqrt{\frac{R_{IN}}{R_M} - 1} + \sqrt{\frac{R_L}{R_M} - 1}$$

$R_M < R_L$

$R_M < R_{IN}$

Criteria in choosing Matching networks

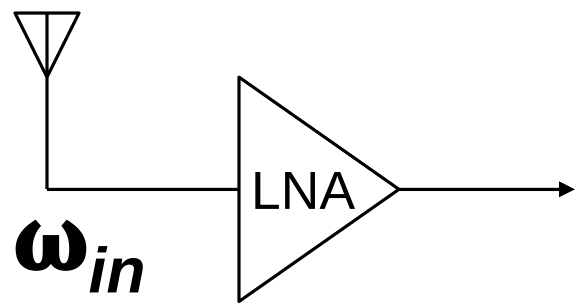
1. Q - choose between L-match and T- or π-match
2. Lowpass or Highpass
3. Area
   - Number of components
   - Number of inductors
   - Values of L's and C's

Basic Receiver

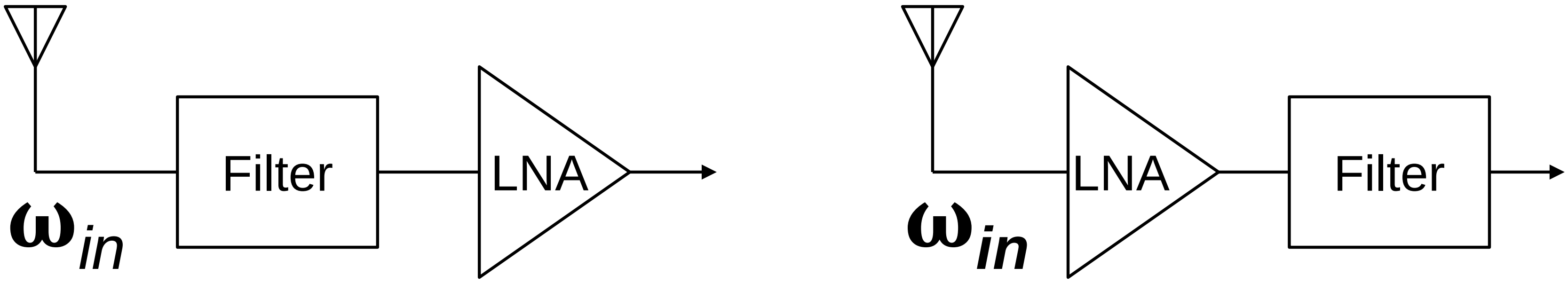
Challenges for Receiver

- Amplify weak desired signals
- Remove unwanted signals (interferers)
- Maximize Signal-to-Noise ratio (Minimize noise)

Low Noise Amplifier: increase signal amplitude



Basic Receiver



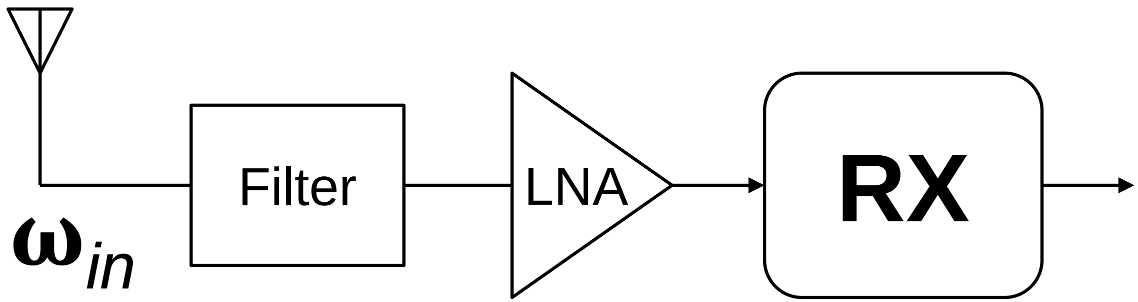
Filter before LNA

- Reduce interferers & noise for Rx
- Attenuate signal due to insertion loss

Filter after LNA

- LNA must deal with all inputs (signal, noise, interferers)

Basic Receiver Types



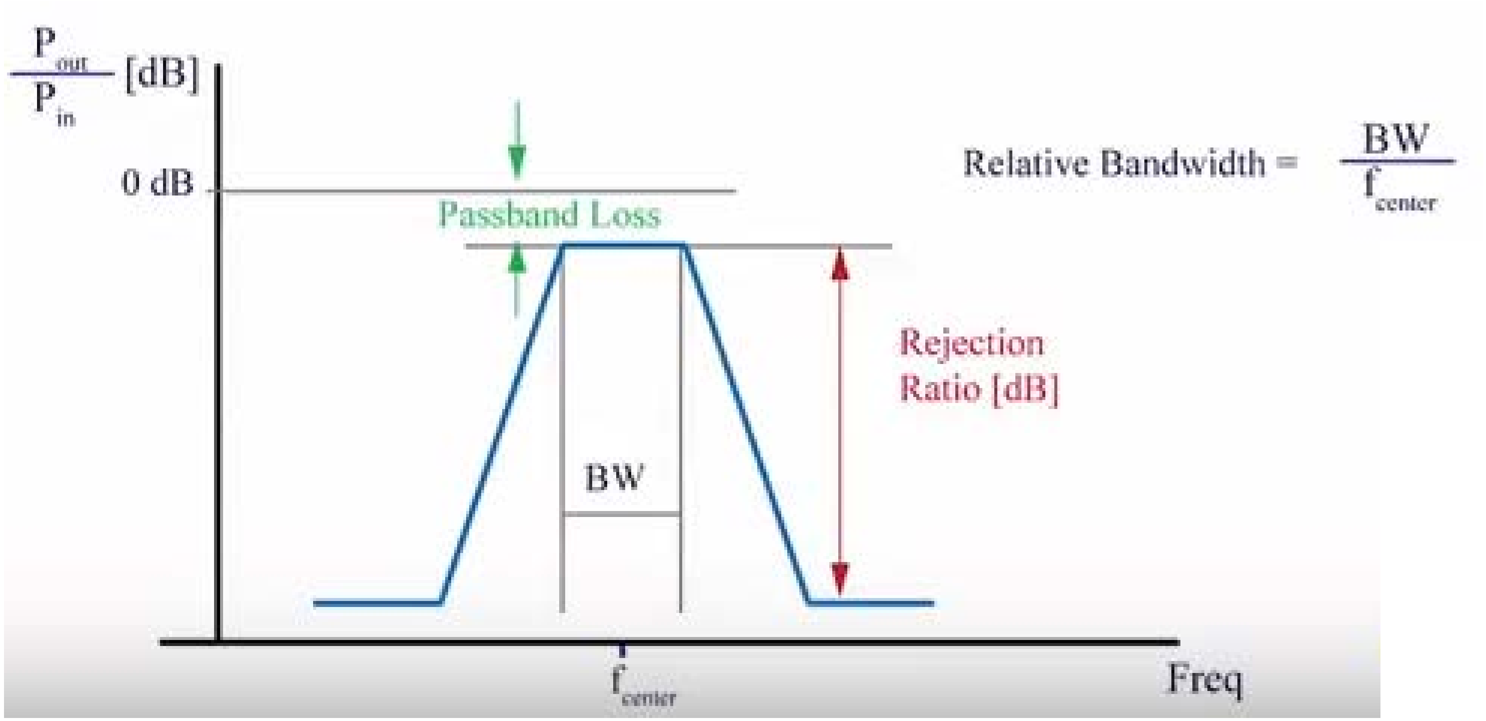
- Direct conversion (homodyne or Zero IF)
- Intermediate-conversion (heterodyne)
- Two-stage conversion (super-heterodyne)

Filters

- Insertion loss
  - Attenuation in the passband
- Selectivity
  - How well can they select a single channel
  - Measured by quality factor of the filter
- The quality factor is inversely proportional to the fractional bandwidth of the filter
  - Fractional bandwidth is $\Delta f = \frac{BW}{f_c}$ where f_c is the center frequency
  - In order to have a small BW at high f_c, a very high Q filter is needed

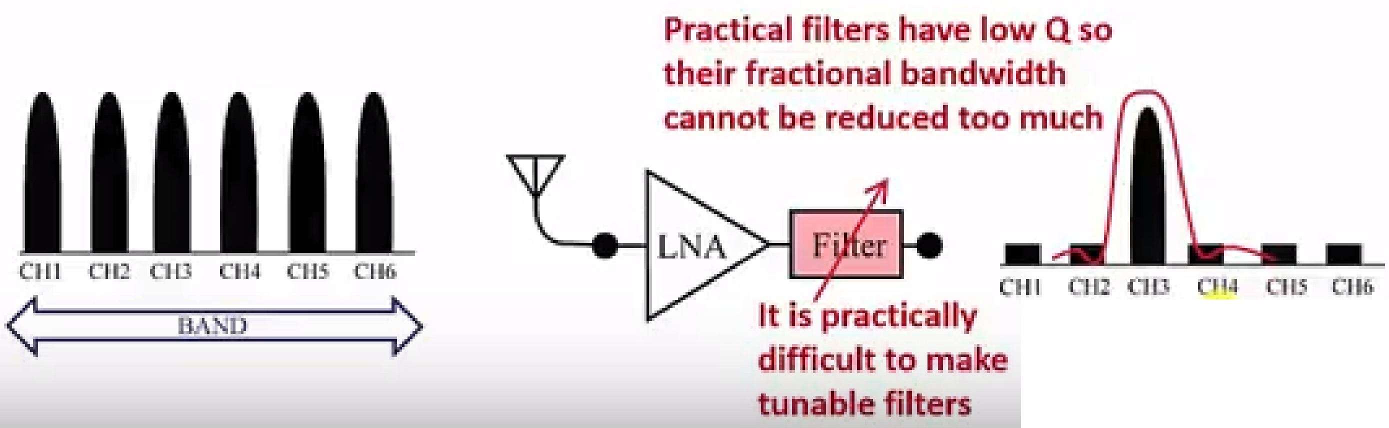
Filter Bandwidth

- Filters have a fractional BW
  - Doesn't change with f_{center} for a given filter type
- The absolute BW *does* change
- Lower f_{center} results in a narrower absolute BW



Channel Selection

- We have learnt that most communication systems divide the frequency band into several narrower channels
- The receiver should select each channel for detection
  - Need for very sharp filter response (high quality filter)
  - Need for variable filter (Tunnable filter)



RX – Frequency Conversion

- Frequency of a signal can be shifted by multiplying it with another sinusoidal signal

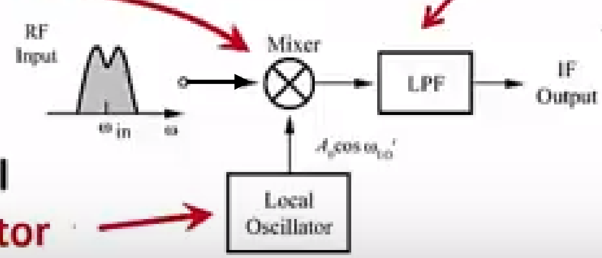
$$x(t) = A\ cos\ \omega_{in} t$$

$$s(t) = \cos\ \omega_{LO}\ t$$

$$x(t) \times s(t) = \frac{A}{2}\cos(\omega_{in} - \omega_{LO})t + \frac{A}{2}\cos(\omega_{in} + \omega_{LO})t$$

multiplication is performed by a mixer

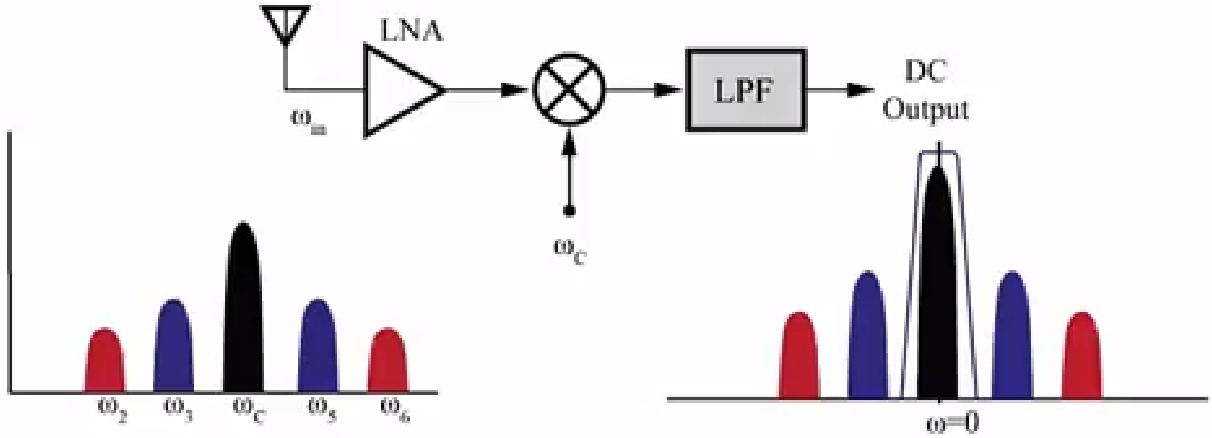
Low Pass Filter to remove the high frequency signal



the other sinusoidal signal comes from a local oscillator

Homodyne Receiver (Zero IF)

- Uses same carrier as Tx to down convert signal
- Provide coherent detection
- Translates spectrum around carrier to *DC*



Homodyne Receiver

- Benefits:
  - Reduced system complexity
  - Baseband signal is readily available
  - High-selectivity
- Disadvantages
  - LO leakage causes self mixing that leads to large DC offset
  - Need to generate a precise coherent LO
- Most practical today due to software radios
  - Baseband is sampled by ADC and mixing, filtering done digitally