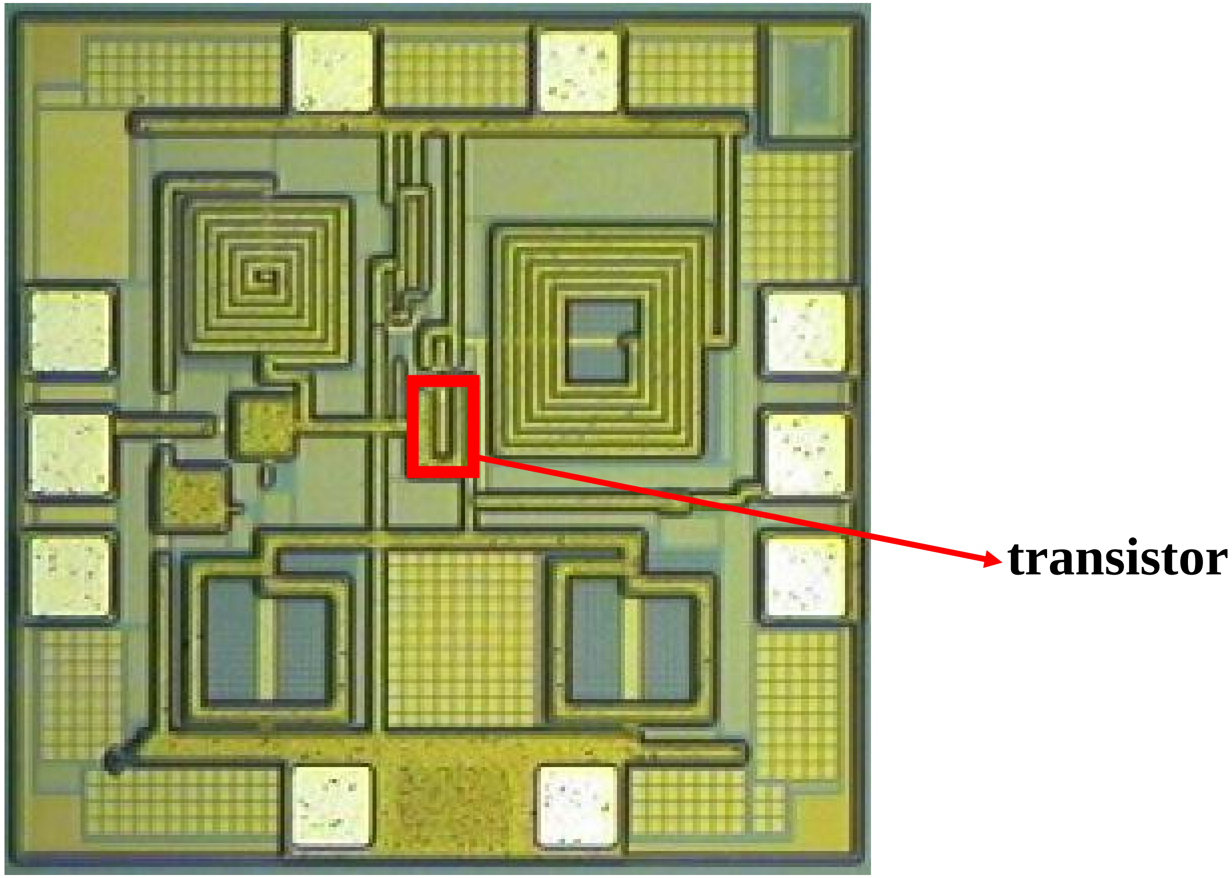
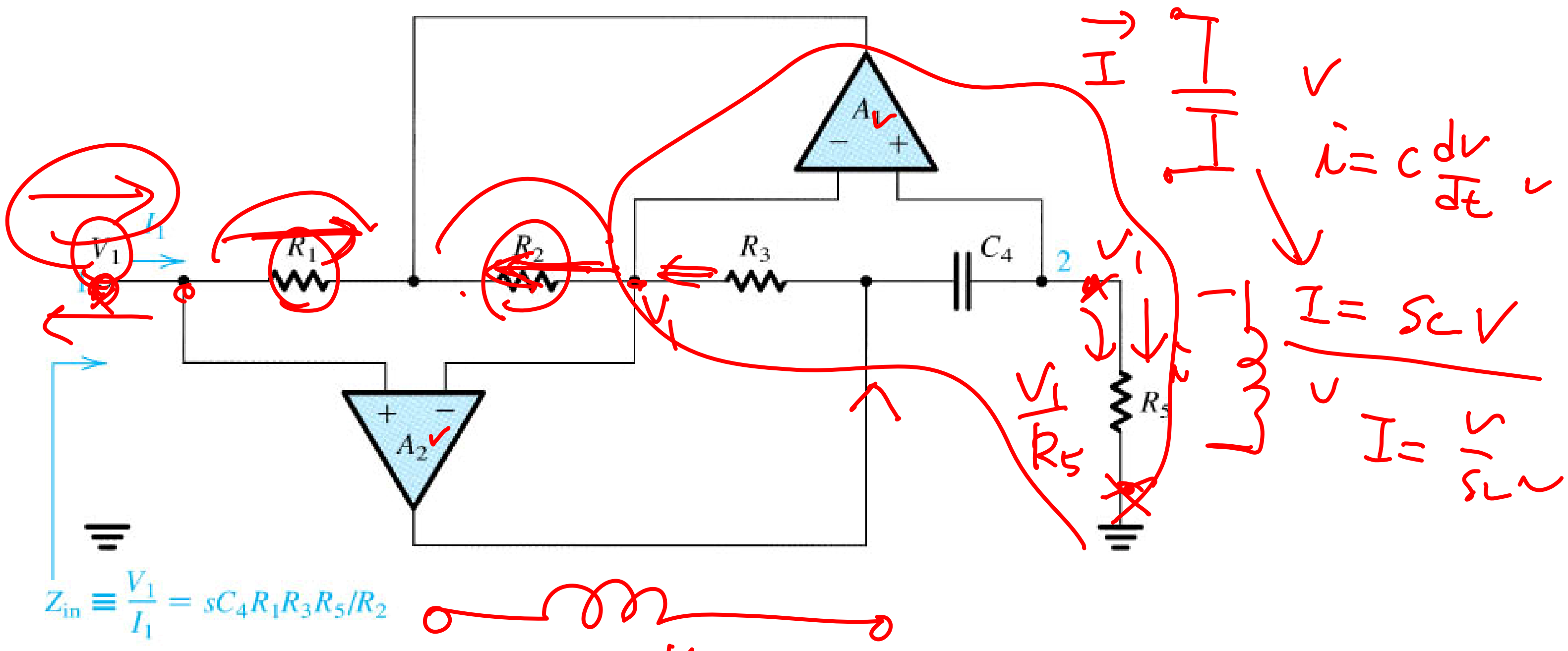
Second-Order Active Filters Based on Inductor Replacement

- Obtained by replacing the inductor *L* in the *LCR* resonator with an op amp-*RC* circuit that has an inductive input impedance.



2GHz LNA

The Antoniou Inductance-Simulation Circuit

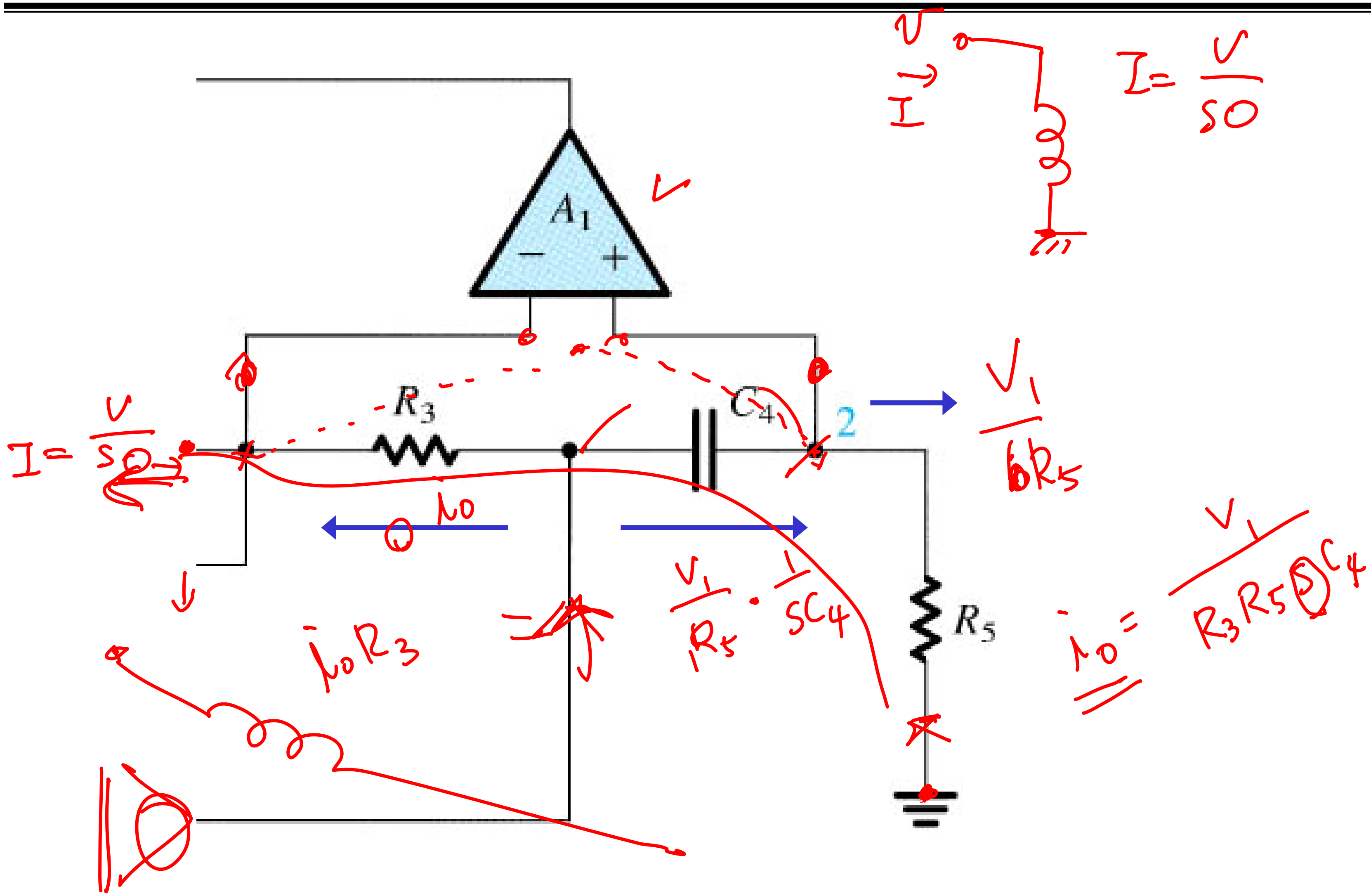


(a)

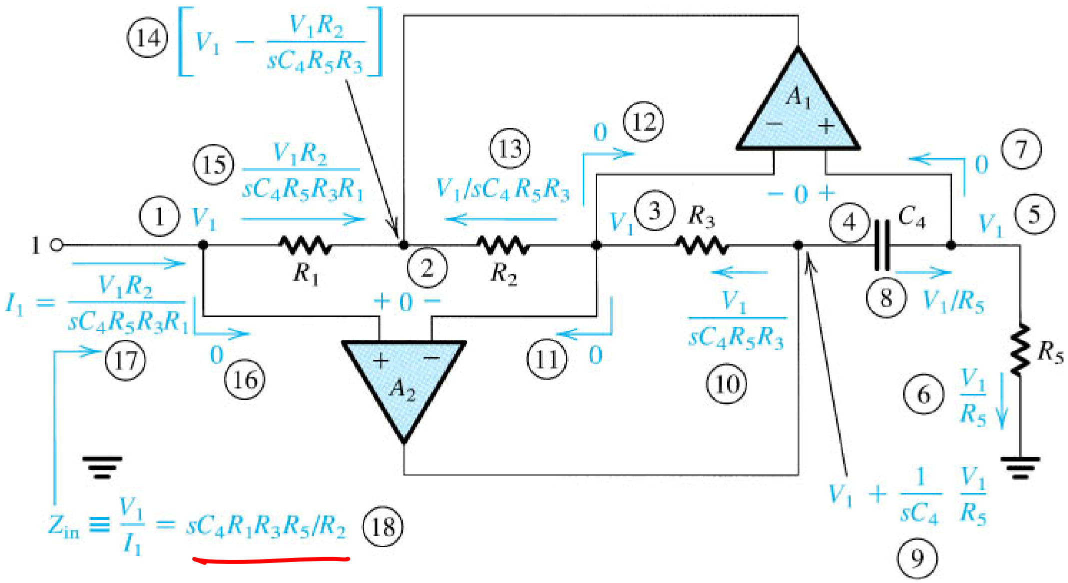
- Invented by A. Antoniou.
- If the circuit is fed at its input (node 1) with a voltage source V_1 and the input current is denoted I_1, (for ideal op amps)

$$Z_{in} \equiv \frac{V_1}{I_1} = \frac{sC_4R_1R_3R_5}{R_2} \qquad L = \frac{C_4R_1R_3R_5}{R_2}$$

$i = v / sa$



The Antoniou Inductance-Simulation Circuit



① Assuming ideal op amps.

② Analysis begins at node 1, which is assumed to be fed by a voltage source V1.

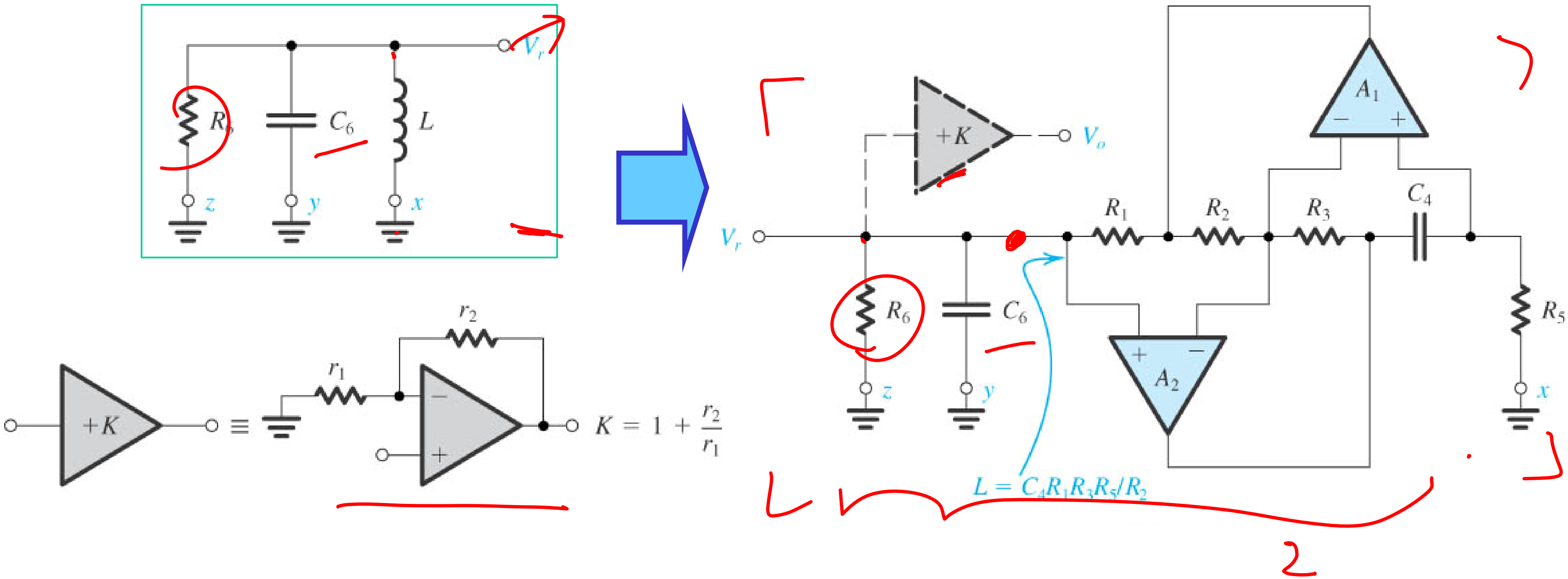
③ Analysis proceeds step by step, with the order of the steps indicated by the circled numbers.

- The design of this circuit is usually based on selecting

$$R_1=R_2=R_3=R_5=R \text{ and } C4=C \rightarrow L=CR^2$$

- Convenient values are selected for C and R to yield the desired inductance value L.

The Op Amp-RC Resonator



- Replacing the inductor L with a simulated inductance realized by the Antoniou circuit → Second-order resonator.
- Pole frequency

$$\omega_o = \frac{1}{\sqrt{LC_6}} = \frac{1}{\sqrt{C_4C_6R_1R_3R_5/R_2}}$$

The Op Amp-RC Resonator

- Pole Q factor

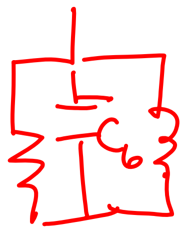
$$Q = \omega_o C_6 R_6 = R_6 \sqrt{\frac{C_6}{C_4} \frac{R_2}{R_1 R_3 R_5}}$$

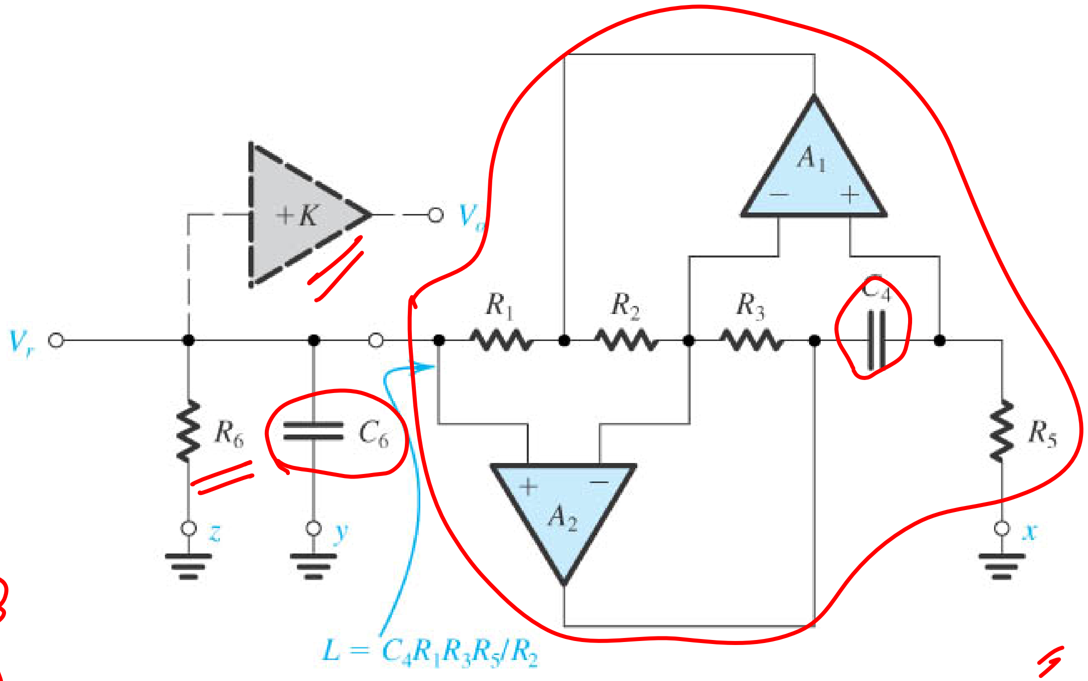
- Usually selects $C_4 = C_6 = C$ and $R_1 = R_2 = R_3 = R_5 = R$, which results in

$\omega_o =$

$$\omega_o = \frac{1}{CR}$$

$$Q = \frac{R_6}{R}$$

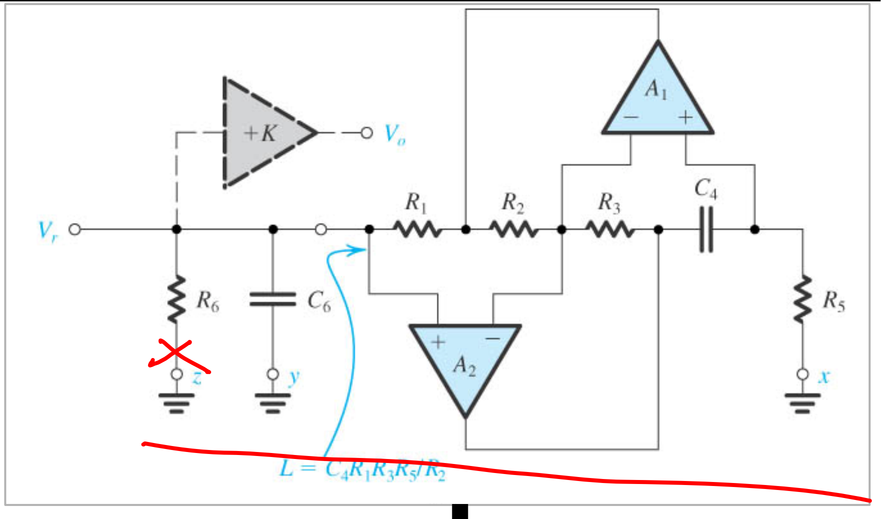


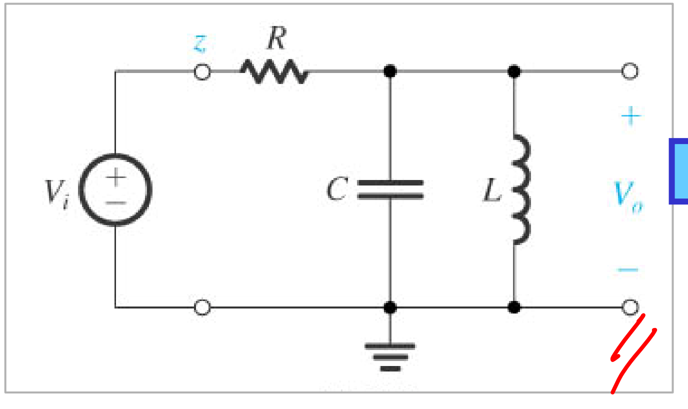


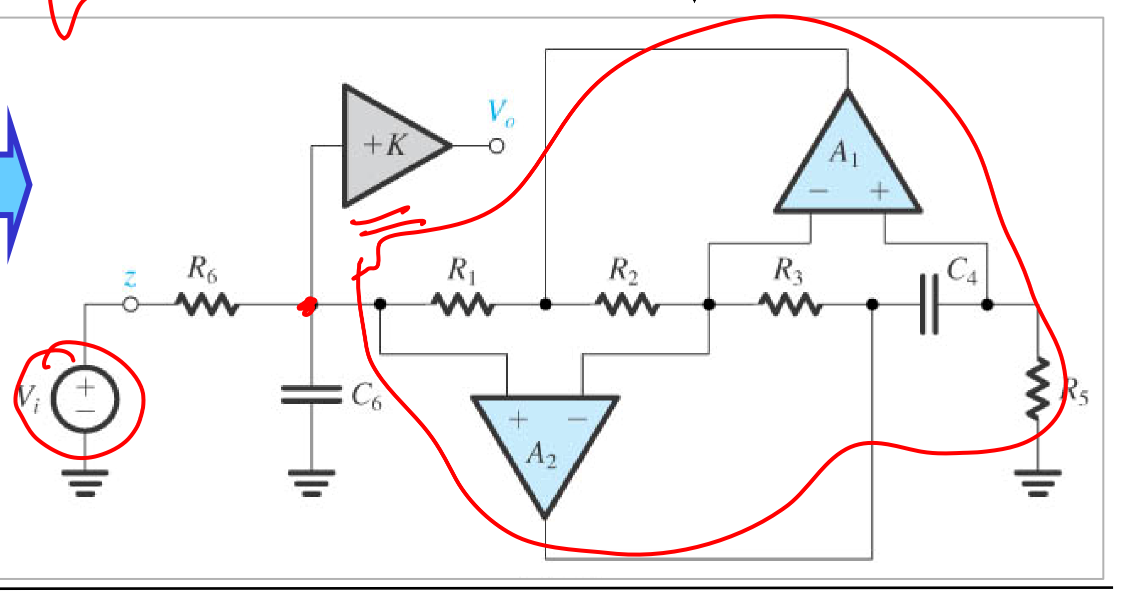
- Select a practically convenient value for C
  → Determine the value of R to realize a given ω_o
  → Determine the value of R_6 to realize a given Q
- Op-amp buffer amplifier is used at the output to eliminate loading effect.

Realization of the Various Filter Types

- Bandpass function.
  → disconnect node z from ground
  and connect it to the signal source V_i

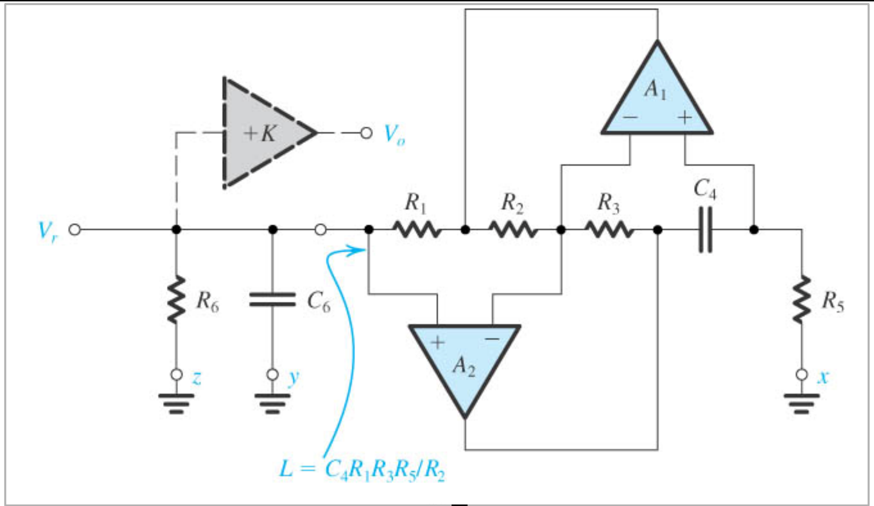


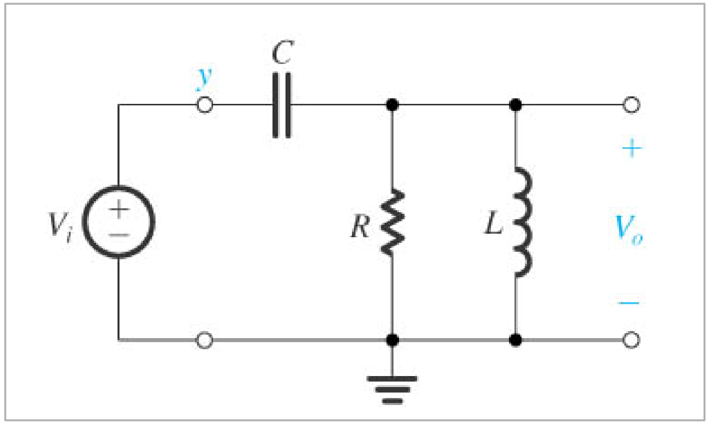


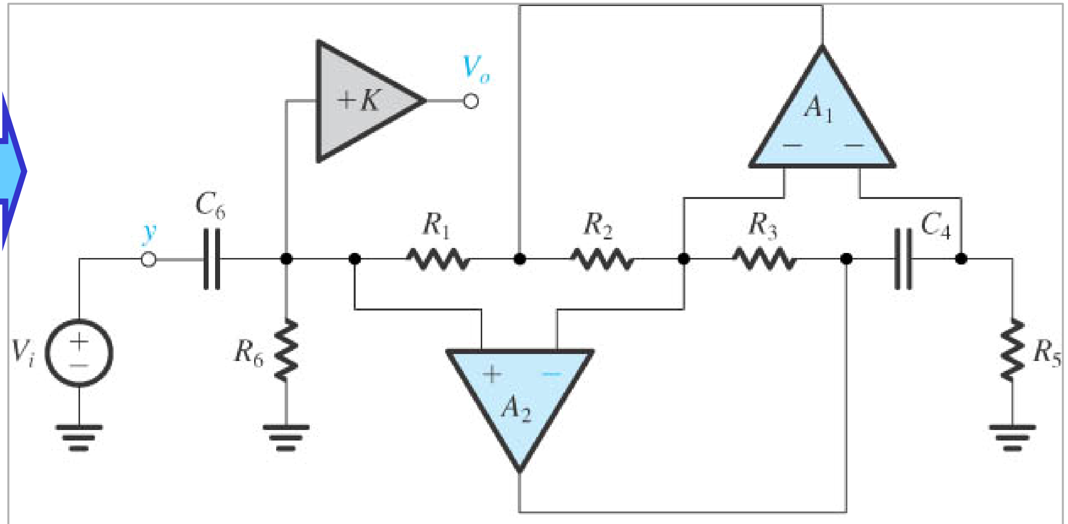


Realization of the Various Filter Types

- High-pass function
  → inject V_i to node y



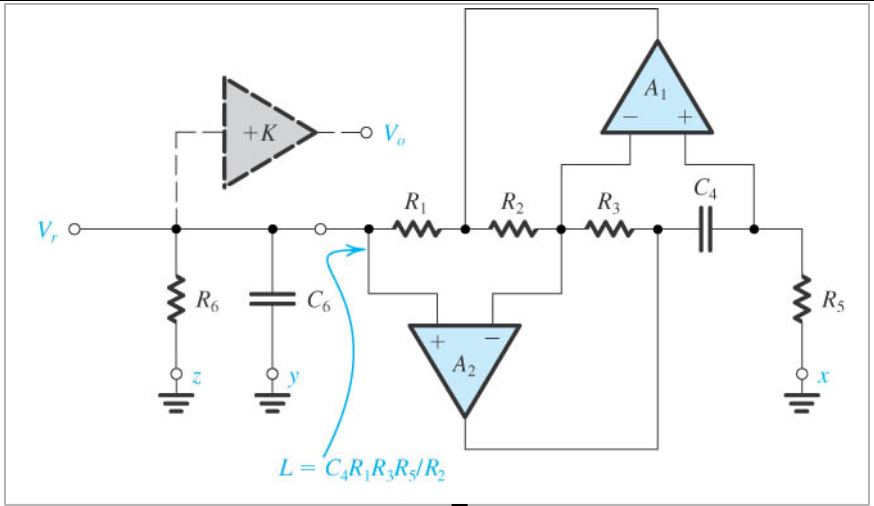


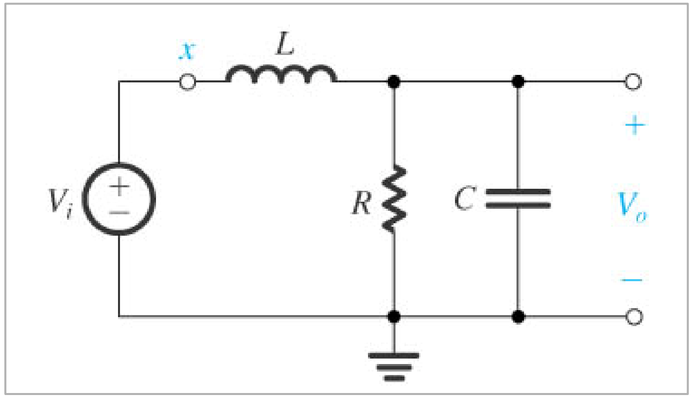


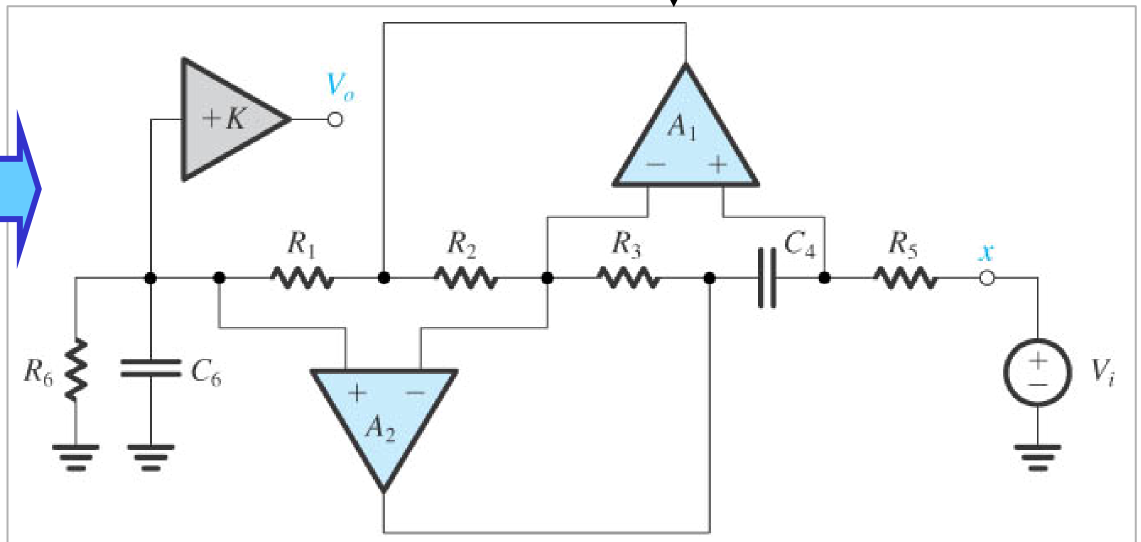
(b) HP

Realization of the Various Filter Types

- Low-pass function
  → inject V_i to node x



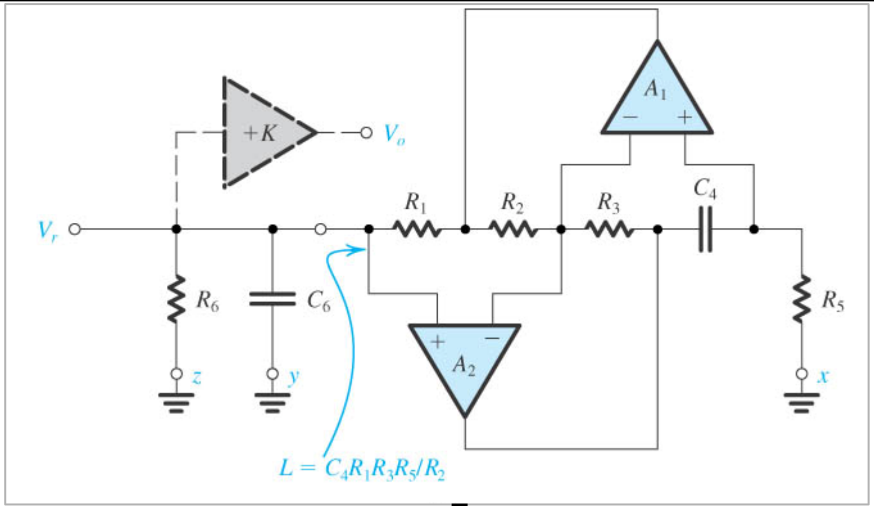


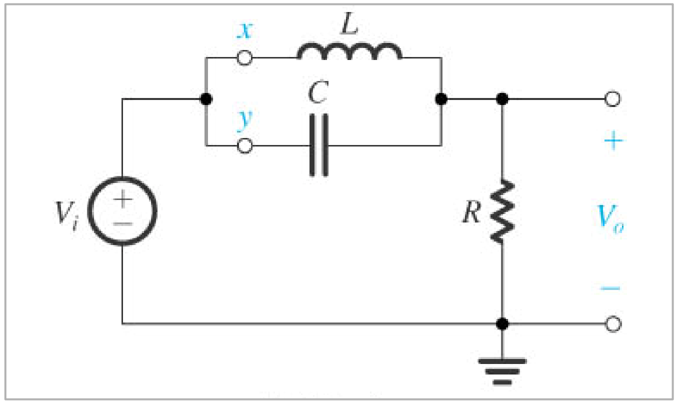


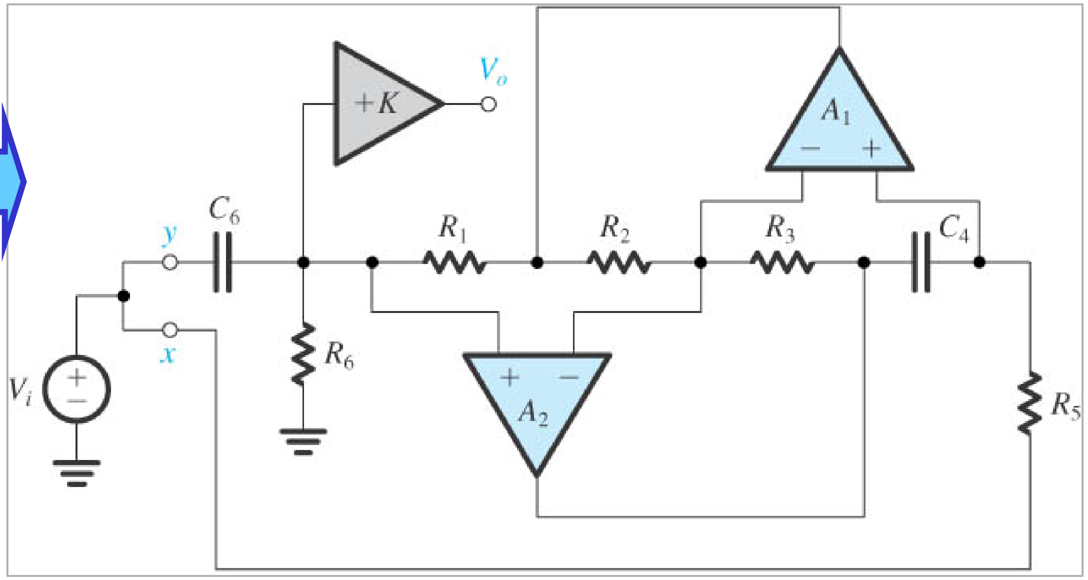
(a) LP

Realization of the Various Filter Types

- Regular Notch function ($\omega_n = \omega_o$).
  → Feed V_i to node *x* and *y*







The All – Pass Circuit

- An all-pass function with a flat gain of unity

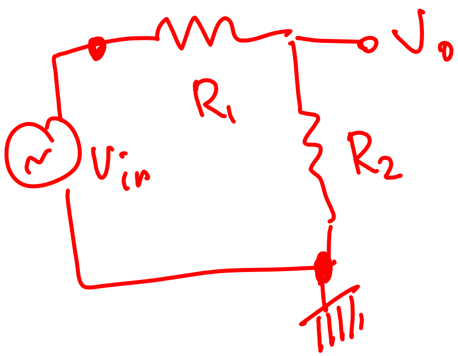
  AP = 1 − (BP with a center-frequency gain of 2) → **complementary**

  $T' = 1 - T$

- All-pass circuit with unity flat gain is the **complement** of the bandpass circuit with a center-frequency gain of 2.

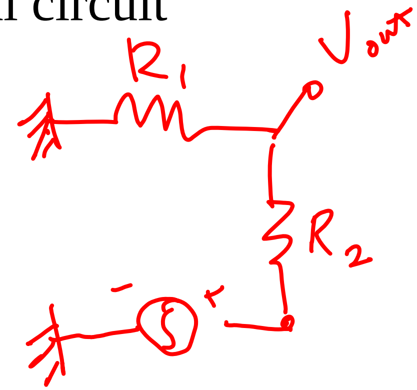
- A simple procedure for obtaining the complement of a given linear circuit.

  : Interchanging input and ground in a linear circuit generates a circuit whose transfer function is the complement of that of the original circuit



$V_o = \frac{R_2}{R_1+R_2} V_{in}$ $\quad T = \frac{R_2}{R_1+R_2}$

$T = 1 - \frac{R_2}{R_1+R_2} = \frac{R_1}{R_1+R_2}$



The All – Pass Circuit

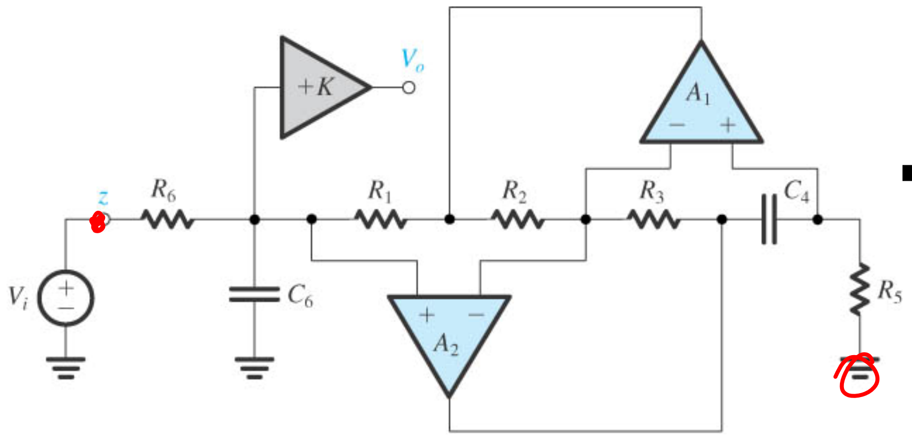


Fig. 12.22(c) Band-Pass 2

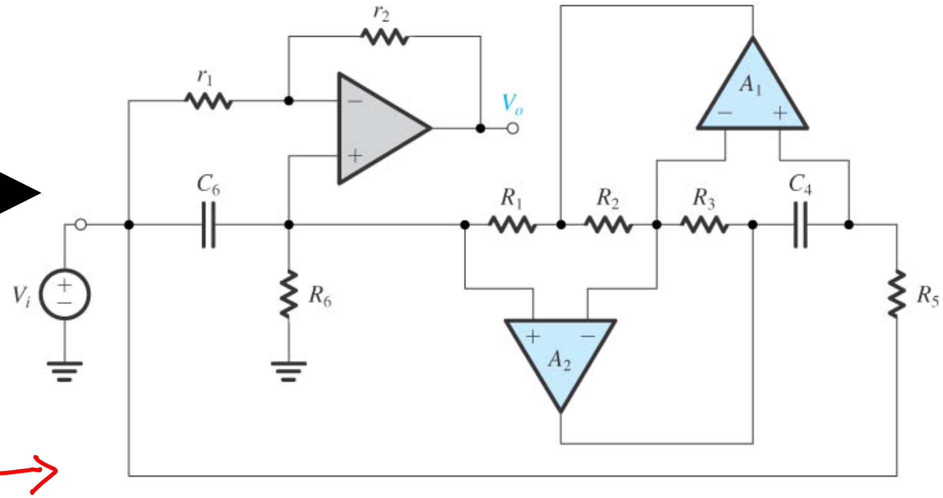


Fig. 12.22(g) All-Pass

- All pass filter implementation.
  - ① Use the circuit of Fig. 12.22(c) to realize a BP with a gain of 2 by simply selecting $K = 2$ and implementing the buffer amplifier with the circuit of Fig.12.21(c) with $r_1 = r_2$.
  - ② Then interchange input and ground and thus obtain the all-pass circuit of Fig.12.22(g)

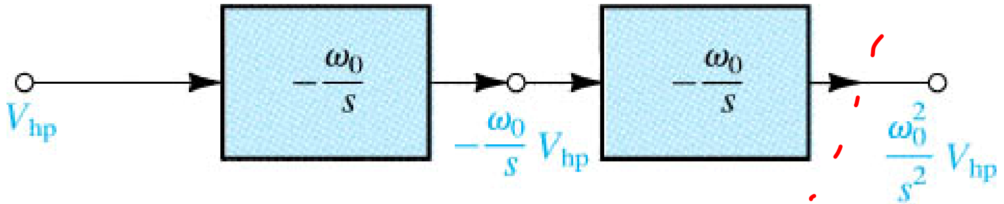
Derivation of the Two-Integrator-Loop Biquad

- To derive the two-integrator-loop biquadratic circuit, start from the second-order high-pass transfer function HP

$$\frac{V_{hp}}{V_i} = \frac{Ks^2}{s^2 + s(\omega_o/Q) + \omega_o^2}$$

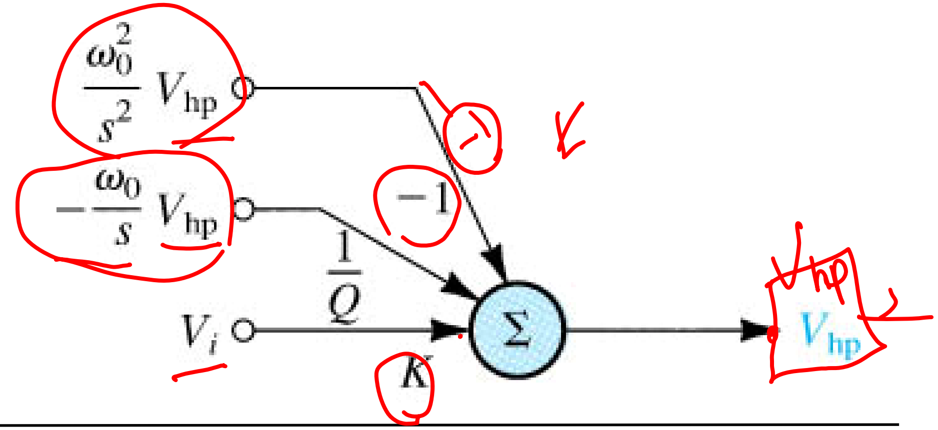
, K is the high-frequency gain

$$V_{hp} + \frac{1}{Q}\left(\frac{\omega_o}{s}V_{hp}\right) + \left(\frac{\omega_o^2}{s^2}V_{hp}\right) = KV_i$$



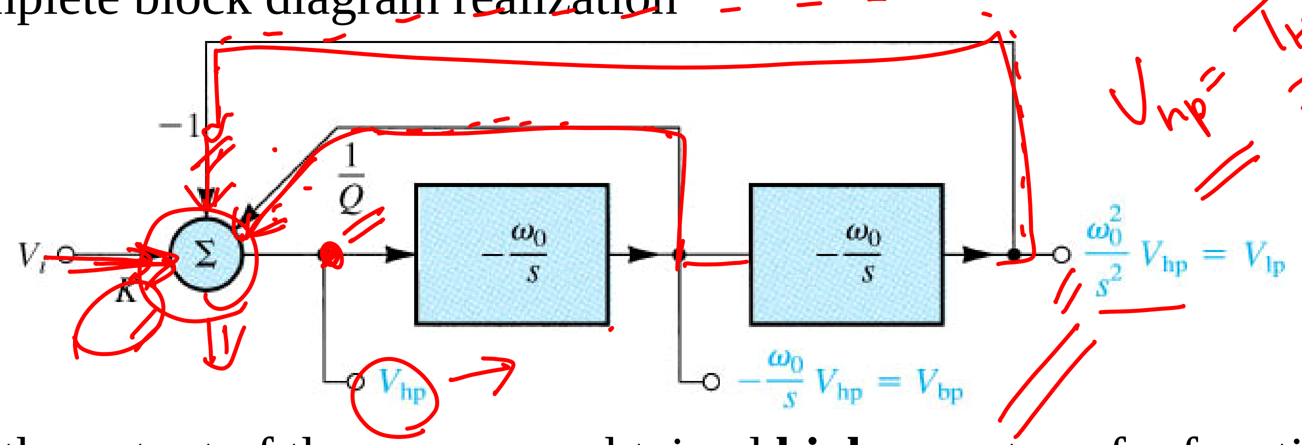
- To express V_{hp},

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_o}{s}V_{hp} - \frac{\omega_o^2}{s^2}V_{hp}$$



Derivation of the Two-Integrator-Loop Biquad

- A complete block diagram realization



- From the output of the **summer**, obtained **high-pass** transfer function

$$T_{hp} \equiv \frac{V_{hp}}{V_i}$$

$$\frac{cs^2}{s^2+as+b} \leftarrow HP \times -\frac{\omega_0}{s} =$$

- From the output of the **first integrator**, obtained **bandpass** function

$$T_{bp}(s) \equiv \frac{(-\omega_o/s)V_{hp}}{V_i} = \frac{K\omega_o s}{s^2 + s(\omega_o/Q) + \omega_o^2} \times \left(-\frac{\omega_0}{s}\right) \leftarrow BP$$

- From the output of the **second integrator**, obtained **lowpass** function

$$T_{lp}(s) \equiv \frac{(\omega_o^2/s^2)V_{hp}}{V_i} = \frac{K\omega_o^2}{s^2 + s(\omega_o/Q) + \omega_o^2} \rightarrow LP$$

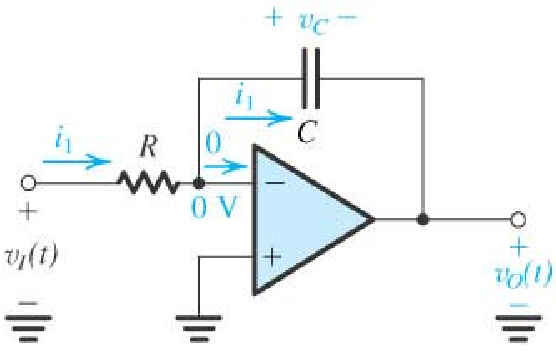
Simultaneously
→Universal
active filter

Circuit Implementation using OP-AMP (Miller Integrator)

$ax + by$

$ax - by$

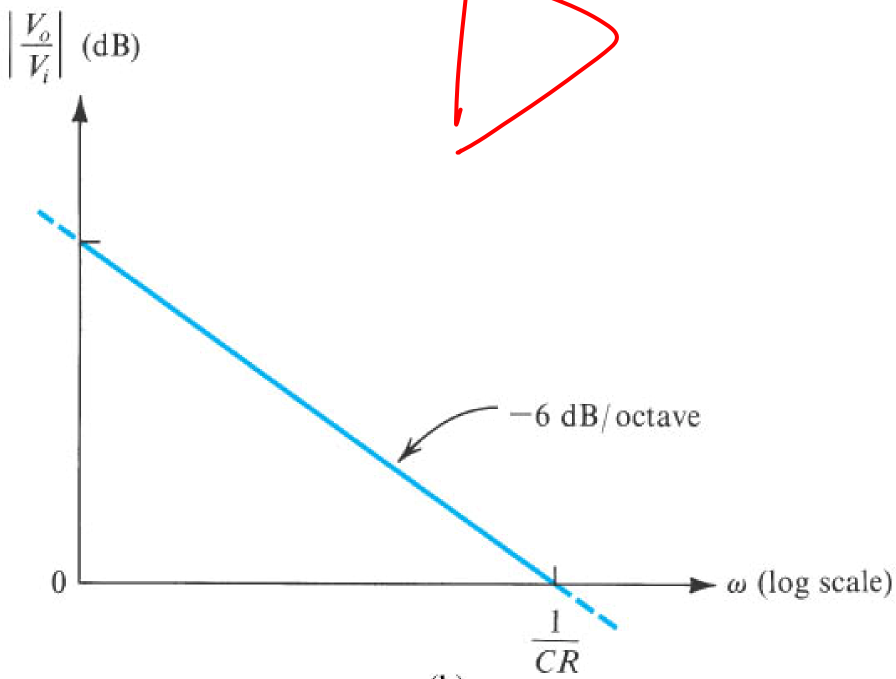
$-\frac{1}{sCR}$



$$v_O(t) = -\frac{1}{CR}\int_0^t v_I(t)\,dt$$

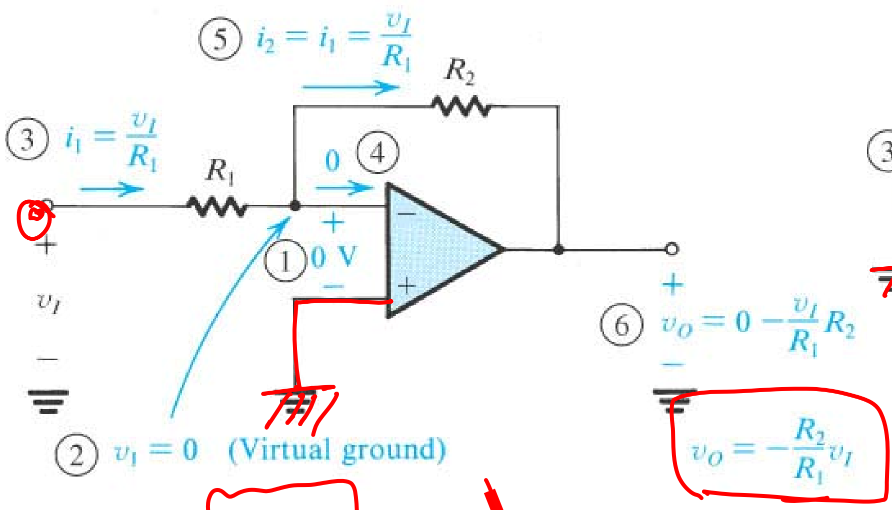
$$\frac{V_o}{V_i} = -\frac{1}{sCR}$$

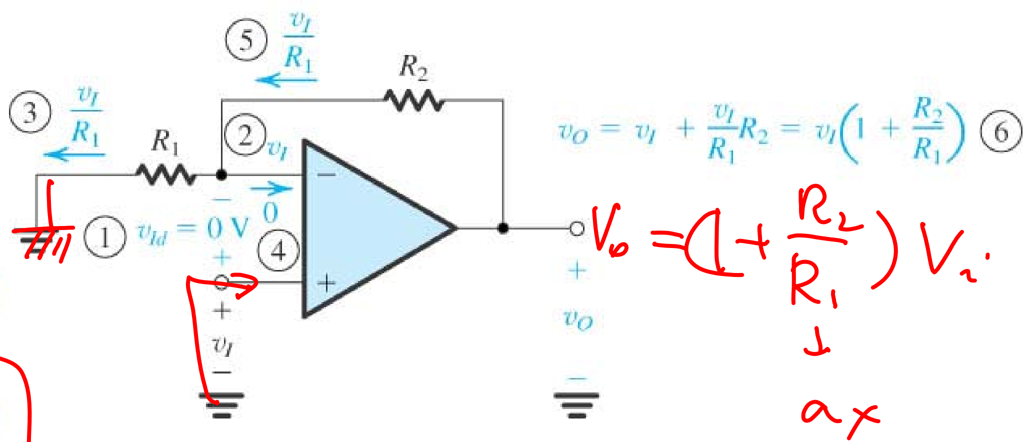
(a)



(b)

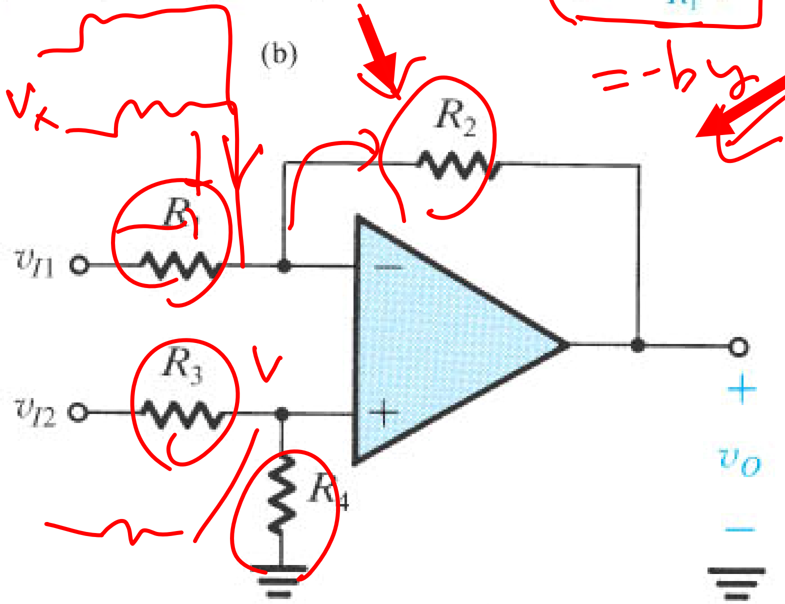
Circuit Implementation using OP-AMP (Basic)



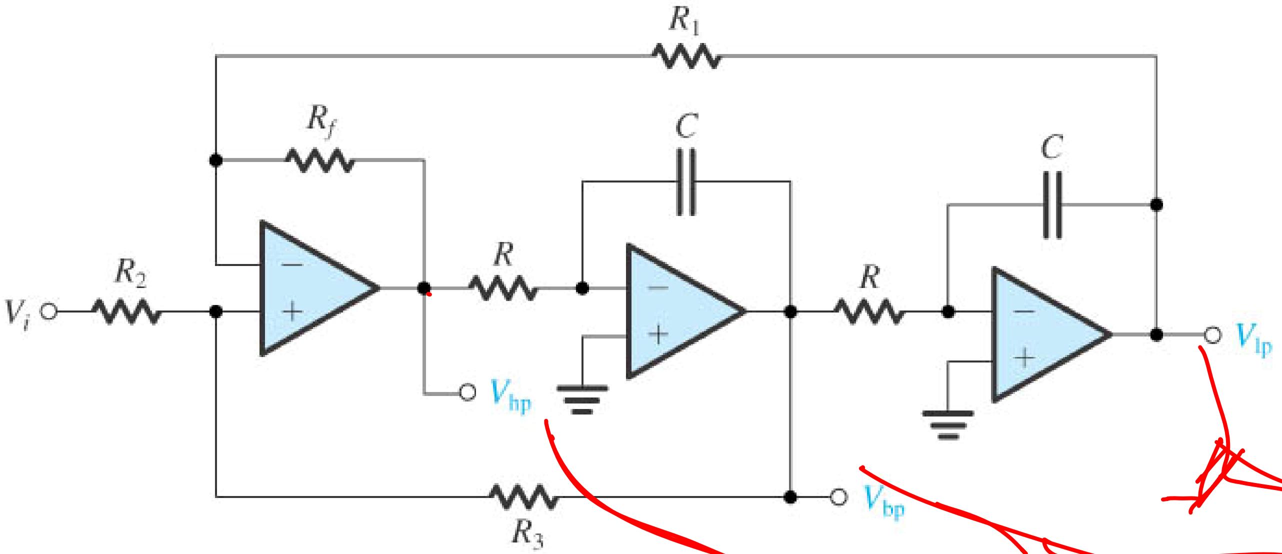


ax − by + cz

(b)



Circuit Implementation



- The Kerwin-Huelsman-Newcomb circuit(KHN biquad)
  – integrator → Miller integrator circuit having $CR=1/\omega_0$.
  – summer → op-amp summing circuit
- Design the circuit
  ① Select suitable C and R for $CR=1/\omega_0$.
  ② Determine the values of the resistors associated with the summer

$$V_{hp} = \frac{R_3}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)V_i + \frac{R_2}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)\left(-\frac{\omega_o}{s}V_{hp}\right) - \frac{R_f}{R_1}\left(\frac{\omega_o^2}{s^2}V_{hp}\right)$$

Circuit Implementation - Coefficients

- $$V_{hp} = \frac{R_3}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)V_i + \frac{R_2}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)\left(-\frac{\omega_o}{s}V_{hp}\right) - \frac{R_f}{R_1}\left(\frac{\omega_o^2}{s^2}V_{hp}\right)$$

$\boxed{\omega_o}$

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_o}{s}V_{hp} - \frac{\omega_o^2}{s^2}V_{hp}$$

→ $\dfrac{R_f}{R_1} = 1$

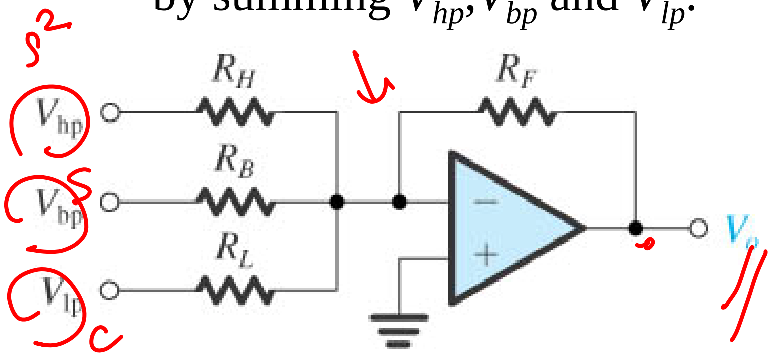
→ $\dfrac{R_3}{R_2} = 2Q-1 \quad (\because R_f = R_1)$

→ $K = 2 - \dfrac{1}{Q} \quad (\because R_f = R_1, \dfrac{R_3}{R_2} = 2Q-1)$

$R_1\ R_2\ R_3$

➔ the gain is fixed to this value

- Realizing notch and all-pass functions by summing V_{hp}, V_{bp} and V_{lp}.



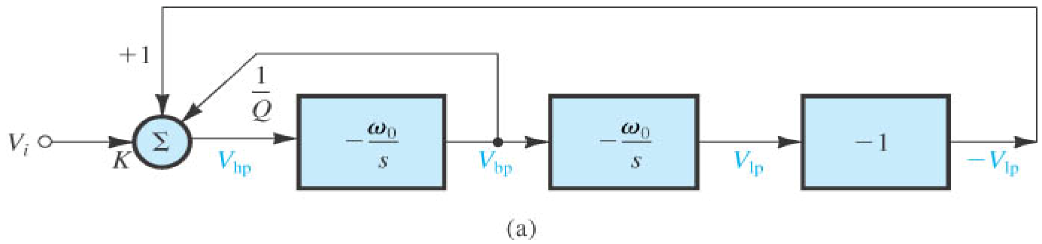
$$V_o = -\left(\frac{R_F}{R_H}V_{hp} + \frac{R_F}{R_B}V_{bp} + \frac{R_F}{R_L}V_{lp}\right)$$

$$= -V_i\left(\frac{R_F}{R_H}T_{hp} + \frac{R_F}{R_B}T_{bp} + \frac{R_F}{R_L}T_{lp}\right)$$

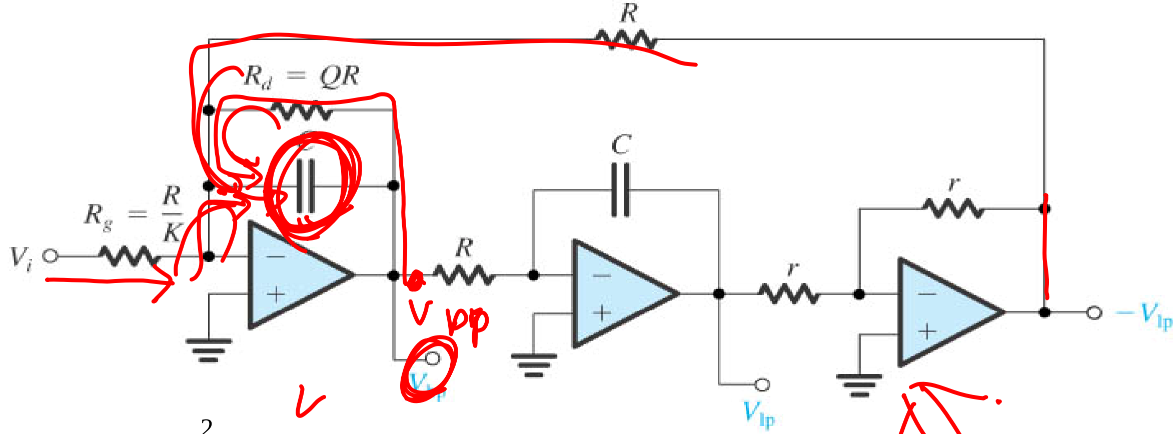
$$\frac{V_o}{V_i} = -K\frac{(R_F/R_H)s^2 - s(R_F/R_B)\omega_o + (R_F/R_L)\omega_o^2}{s^2 + s(\omega_o/Q) + \omega_o^2}$$

- Different zeros can be obtained by the appropriate selection of the values of the summing resistors

An Alternative Two-Integrator-Loop Biquad Circuit



(a)



(b)

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_o}{s}V_{hp} - \frac{\omega_o^2}{s^2}V_{hp}$$

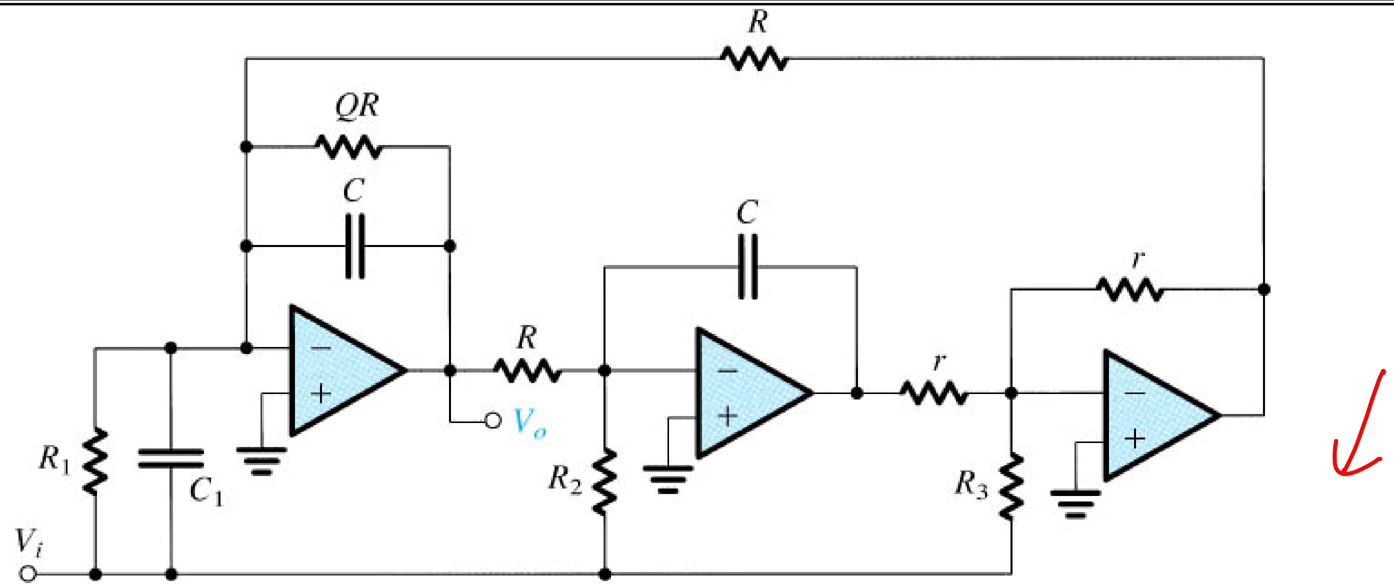
V hp

$$-\frac{\omega_o}{s}V_{hp} = -\frac{\omega_o}{s}KV_i - \frac{\omega_o}{s}\frac{1}{Q}V_{bp} + \frac{\omega_o}{s}V_{lp}$$

$$V_{bp} = -\frac{\omega_o}{s}KV_i - \frac{\omega_o}{s}\frac{1}{Q}V_{bp} - \left(-\frac{\omega_o}{s}V_{lp}\right) = -\frac{\omega_o}{s}\left\{KV_i + \frac{1}{Q}V_{bp} + (-V_{lp})\right\}$$

▪ **Tow-Thomas Biquad** Circuit : all in single-ended mode with the same sign → no HP

An Alternative Two-Integrator-Loop Biquad Circuit

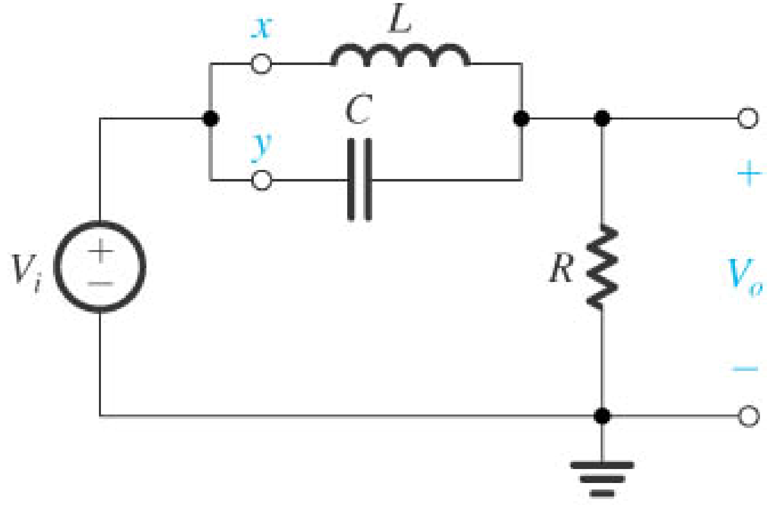


- Feedforward scheme is employed to realize the finite transmission zeros required for the notch and all-pass functions.
- The virtual grounds at the input of each of three amps permits the input signal to be fed to all the op functions.
- Transfer function is (Derive it)

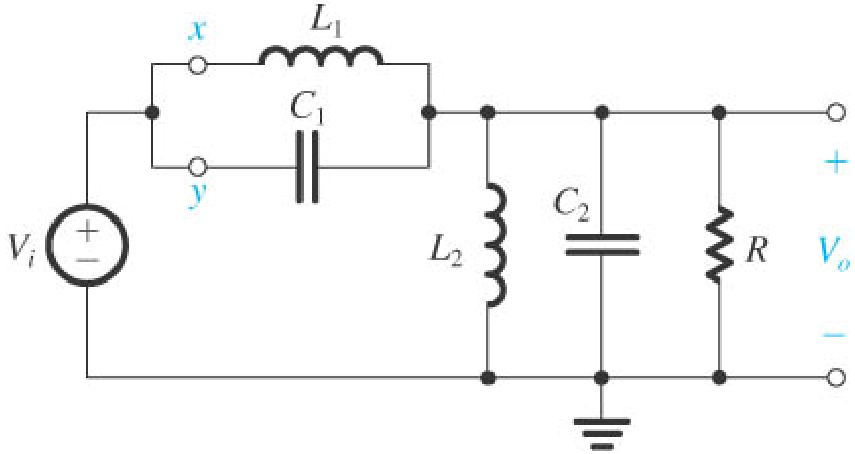
$$\frac{V_o}{V_i} = -\frac{s^2\left(\frac{C_1}{C}\right) + s\frac{1}{C}\left(\frac{1}{R} - \frac{r}{RR_3}\right) + \frac{1}{C^2RR_2}}{s^2 + s\frac{1}{QCR} + \frac{1}{C^2R^2}}$$

Additional Slides

Realization of the Notch Functions



(e) Notch at ω_0



(f) General notch

- The impedance of the LC circuit becomes infinite at $\omega_0 = 1/\sqrt{LC}$
  → zero transmission
- The resistor does not introduce zeros.

$$T(s) = a_2 \frac{s^2 + \omega_0{}^2}{s^2 + s(\omega_0 / Q) + \omega_0{}^2}$$

- To obtain arbitrary ω_n

$$L_1 C_1 = \frac{1}{\omega_n{}^2}$$

- L_1C_1 tank will introduce a pair of zeros at $\pm j\omega_n$, provided the L_2C_2 tank is not resonant at ω_n.
- The natural modes have not been altered,

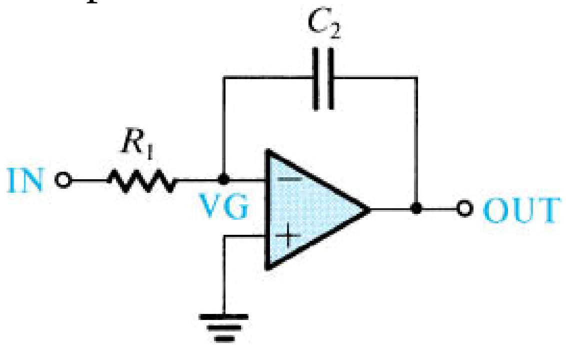
$$C_1 + C_2 = C \quad ; \quad L_1 \| L_2 = L$$

- It is obtained from the original LCR resonator by lifting part of L and part of C off ground

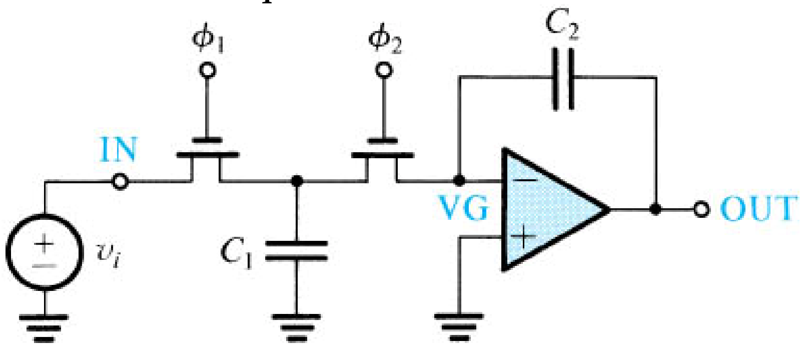
Switched-Capacitor Filters

❑ The Basic Principle

- A capacitor switched between two circuit nodes is equivalent to a resistor

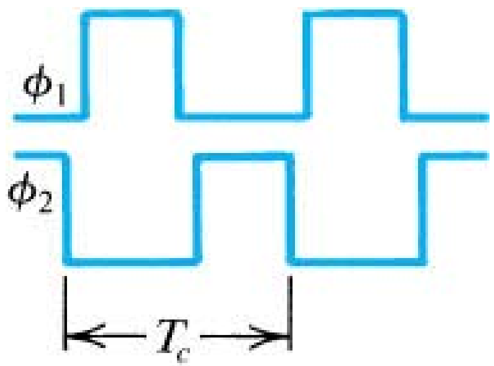


(a)



(b)

- The two MOS switches are driven by a non-overlapping two-phase clock



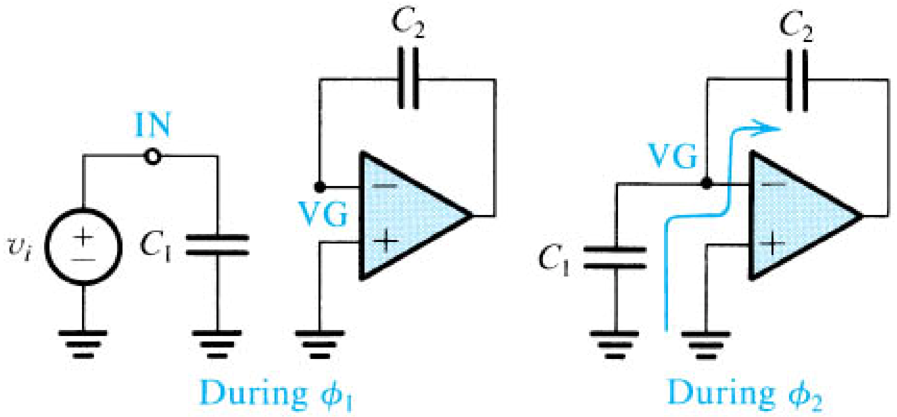
(c)

- During ϕ_1, C_1 charges up to v_i

$$q_{C1} = C_1 v_i$$

During ϕ_2, C_1 is connected to the input of the op amp

Switched-Capacitor Filters



(d)

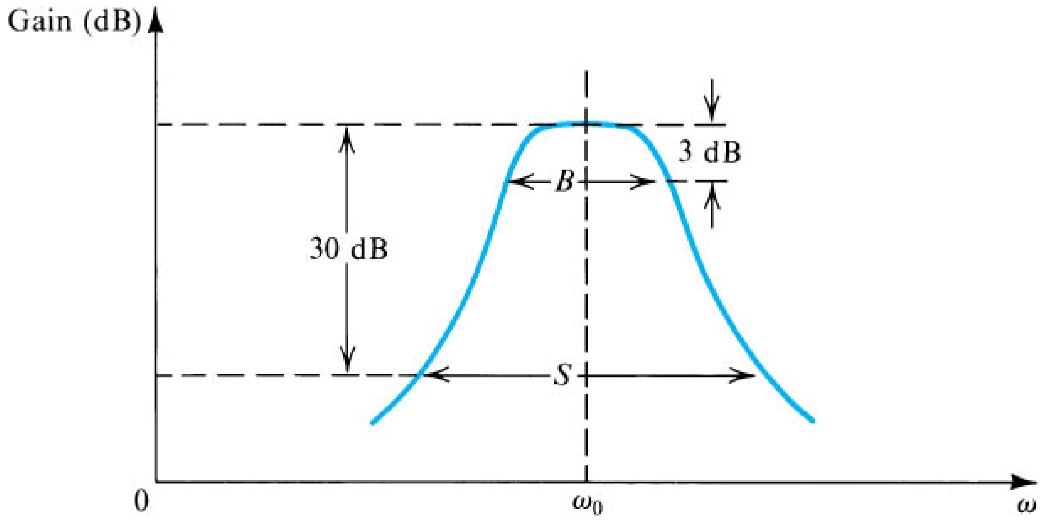
- During each T_c, $q_{C1} = C_1 v_i$ is extracted from the input source and supplied to C_2

$$i_{av} = \frac{C_1 v_i}{T_c}$$

$$R_{eq} \equiv \frac{v_i}{i_{av}} = \frac{T_c}{C_1}$$

$$\text{Time constant} = C_2 R_{eq} = T_c \frac{C_2}{C_1}$$

Tuned Amplifiers



- ω_o=center frequency
- B=3-dB bandwidth
- Skirt selectivity=S/B
- In many applications, B < 5% of ω_o → narrow-band
  → certain approximations

Tuned Amplifiers

❑ The Basic Principle

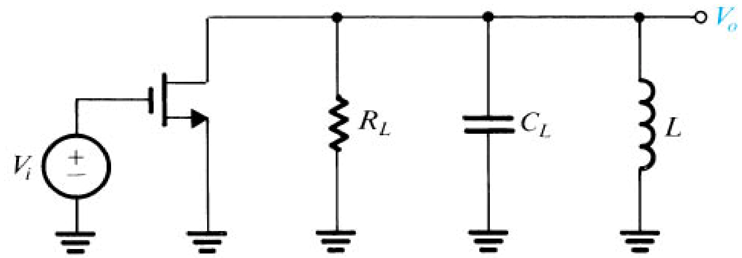
- The use of a parallel LCR circuit as the load or at the input
- Single-tuned amplifier
- $R = R_L \parallel r_o$
- $C = C_L$ + FET output capacitance (usually very small)
- $V_o = -\dfrac{g_m V_i}{Y_L} = -\dfrac{g_m V_i}{sC + 1/R + 1/sL}$

$$\frac{V_o}{V_i} = -\frac{g_m}{C}\frac{s}{s^2 + s(1/CR) + 1/LC}$$

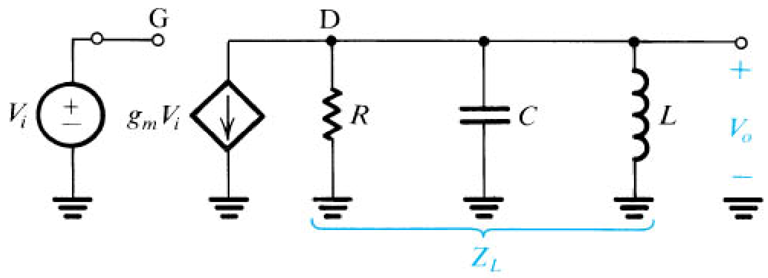
$$\omega_o = 1/\sqrt{LC}, \qquad B = 1/CR$$

$$Q \equiv \frac{\omega_o}{B} = \omega_o CR$$

$$\frac{V_o(j\omega_o)}{V_i(j\omega_o)} = -g_m R$$



(a)



(b)

- At resonance the reactance of *L* & *C* cancel out and the impedance of the parallel *LCR* circuit reduces to *R*

Tuned Amplifiers

- **Inductor Losses**

$$Q_o \equiv \frac{\omega_o L}{r_s} : 50 \sim 200$$

  - The analysis of a tuned amplifier is greatly simplified by representing the inductor loss by a parallel resistance R_p
  - $Y(j\omega_o) = 1/(r_s + j\omega_o L)$

$$= \frac{1}{j\omega_o L}\frac{1}{1 - j(1/Q_o)} = \frac{1}{j\omega_o L}\frac{1 + j(1/Q_o)}{1 + (1/Q_o{}^2)}$$

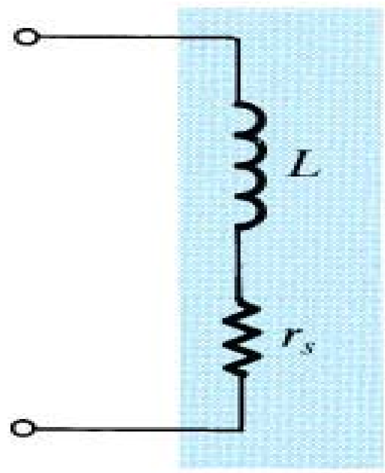
$$Q_o >> 1$$

$$Y(j\omega_0) \cong (1/\, j\omega_o L)\big(1 + j(1/Q_o)\big)$$

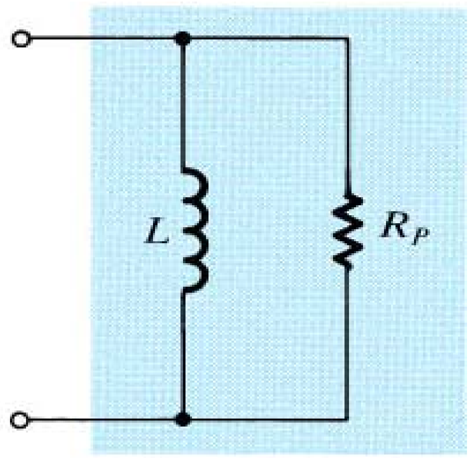
$$Q_o = \frac{R_P}{\omega_o L}$$

$$R_P = \omega_o L Q_o = r_s Q_o{}^2$$

  - The coil Q factor poses an upper limit on the value of Q achieved by the tuned circuit



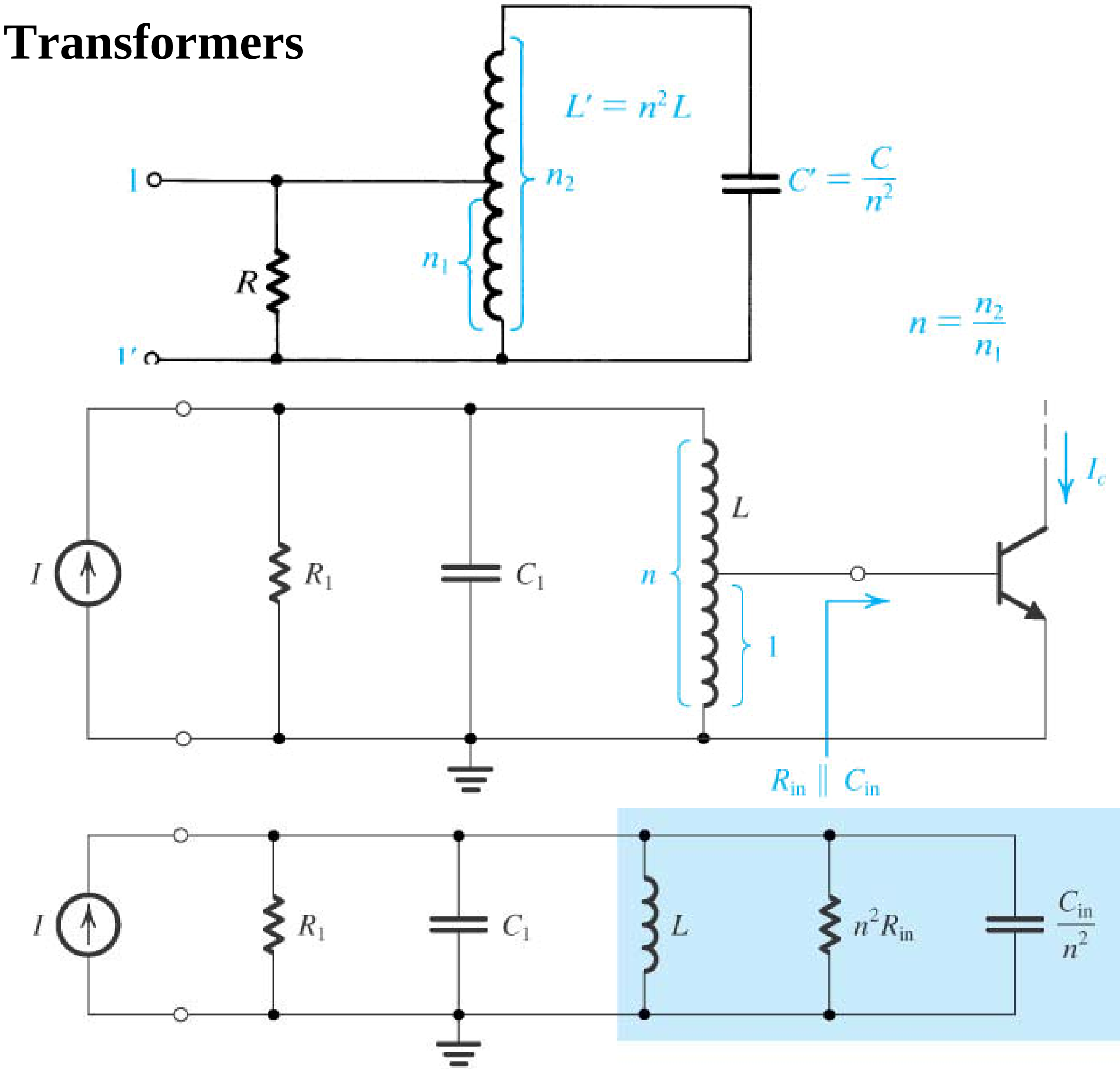
(a)



(b)

Tuned Amplifiers

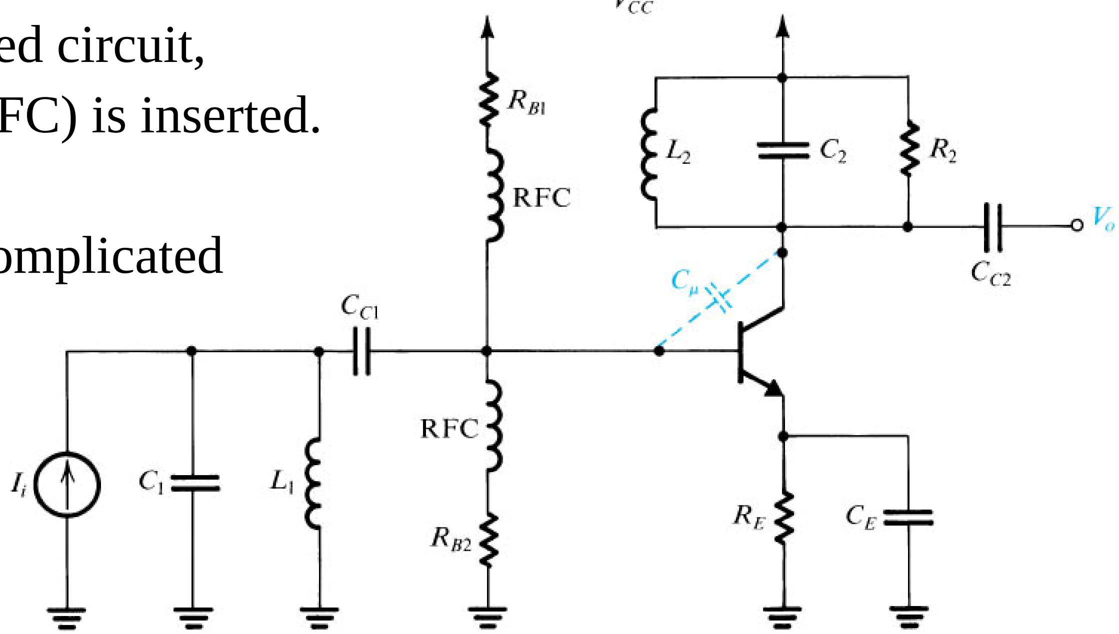
❑ Use of Transformers



Tuned Amplifiers

❑ Amplifiers with Multiple Tuned Circuits

- To avoid the loading effect of R_{B1} and R_{B2} on the input tuned circuit, a radio-frequency choke (RFC) is inserted.



- The analysis and design is complicated by the Miller effect due to C_μ. The reflected impedance will cause detuning response of the input circuit.

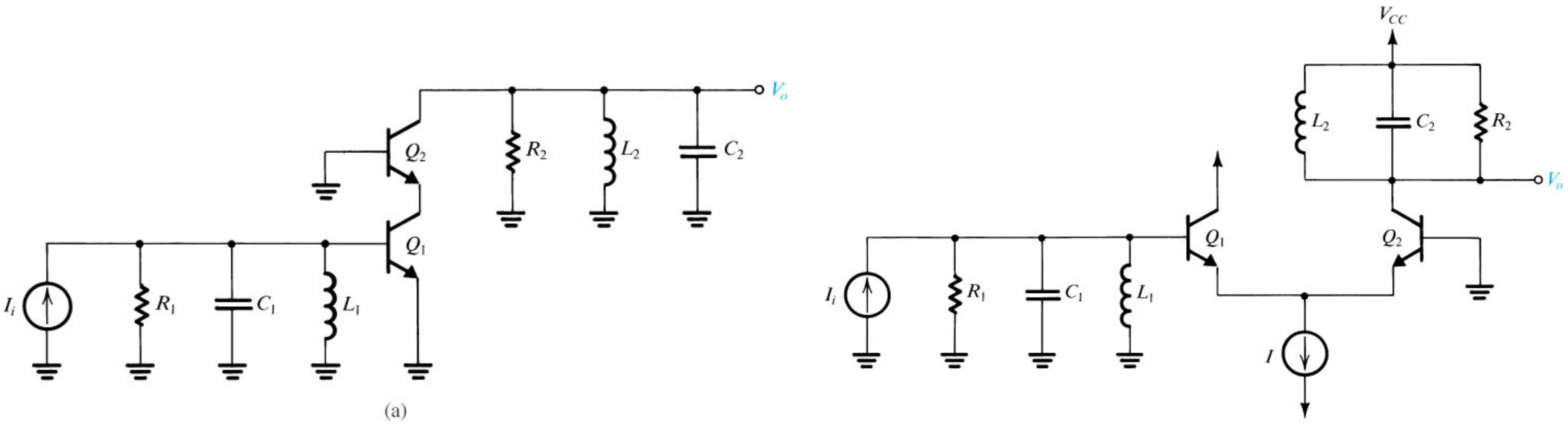
- Method1: Neutralizing by using additional circuits arranged to feed back a current equal and opposite to that through C_μ.

- Method2: Using circuits that do not suffer from Miller effect.

Tuned Amplifiers

❑ The Cascode and the CC-CB Cascade

- No Miller effect: cascode and the common-collector, common-base cascade

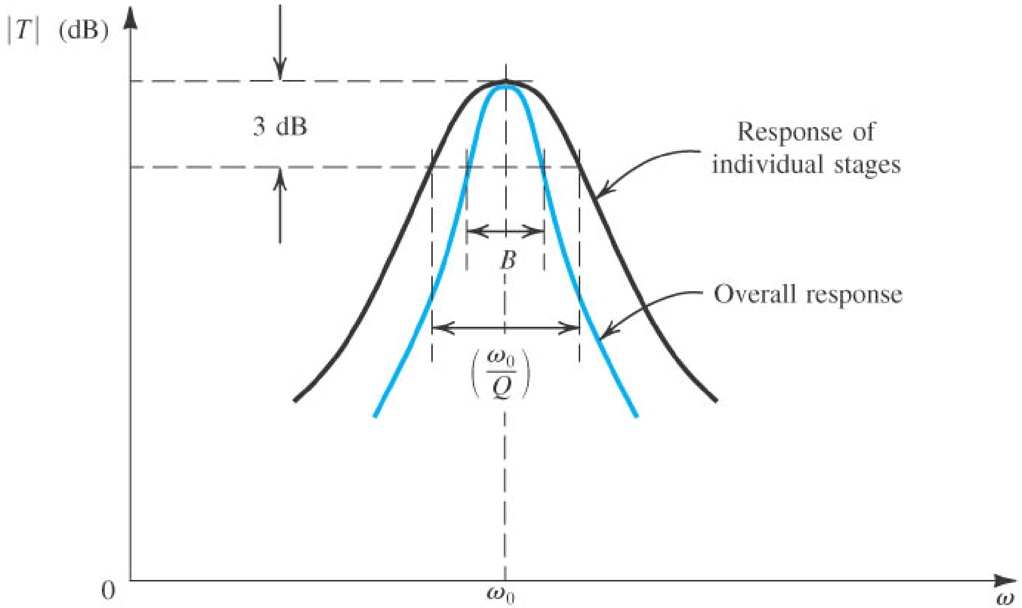


(b)

Tuned Amplifiers

❑ Synchronous Tuning

- A tuned amplifier with multiple tuned circuits
- Assuming the overall response is the product of the individual responses
- N identical resonant circuits : synchronously tuned case



$$B = \frac{w_0}{Q}\sqrt{2^{1/N} - 1}$$

Bandwidth-shrinkage factor