Oscillator

CM

Objectives

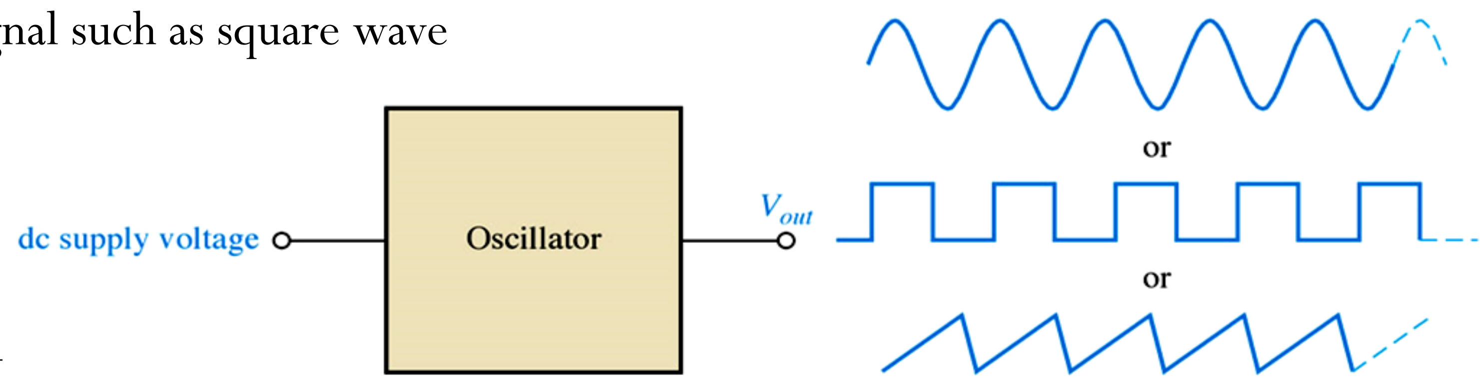
- Describe the basic concept of an oscillator
- Discuss the basic principles of operation of an oscillator
- Analyze the operation LC and RC sine wave oscillators
- Analyze the operation of crystal oscillators

Application of Oscillators

- Oscillators are used to generate signals, e.g.
  - Used as a local oscillator to transform the RF signals to IF signals in a receiver;
  - Used to generate RF carrier in a transmitter
  - Used to generate clocks in digital systems;
  - Used as sweep circuits in TV sets and CRO.

Introduction

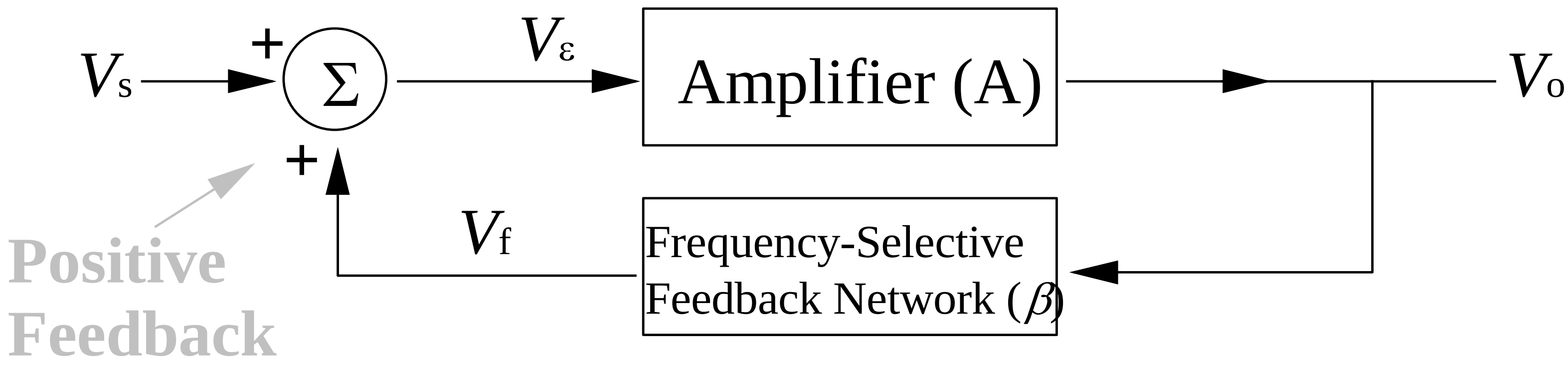
- An oscillator is a circuit that produces a repetitive signal from a dc voltage.
- (Function is opposite to that of a rectifier)
- The output wave shape may be sinusoidal, triangular, pulse, or some other shape.
- Two broad categories:
  - fixed frequency
    - absolute accuracy and freedom from drift are of prime importance
  - variable frequency
    - ease of tuning and repeatability are usually important.
- The feedback oscillator relies on a positive feedback of the output to maintain the oscillations.
- The relaxation oscillator makes use of an RC timing circuit to generate a nonsinusoidal signal such as square wave



Types of oscillators

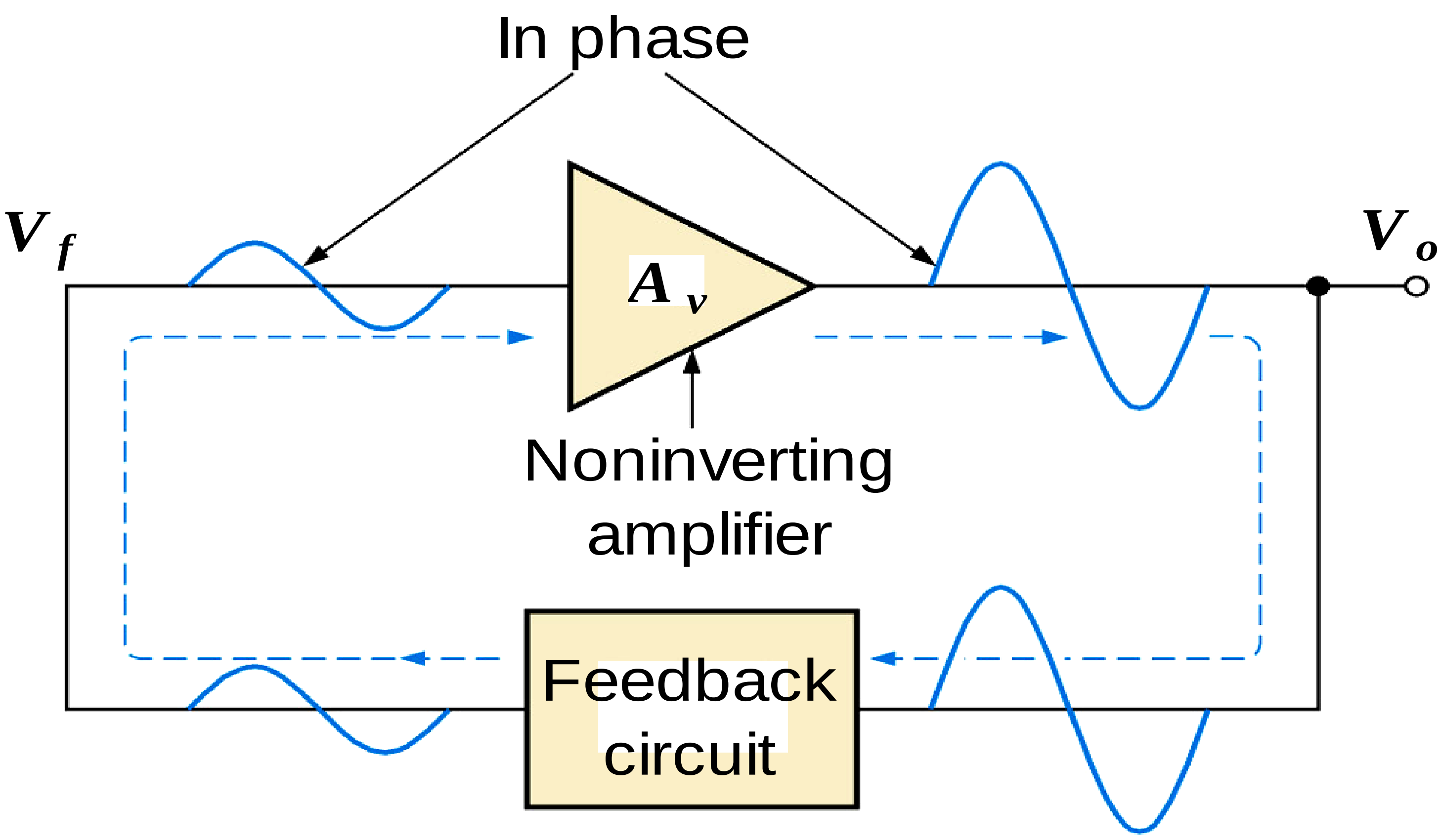
1. RC oscillators
   - Wien Bridge
   - Phase-Shift
2. LC oscillators
   - Hartley
   - Colpitts
   - Clapp
   - Crystal
3. Relaxation oscillators

Oscillators

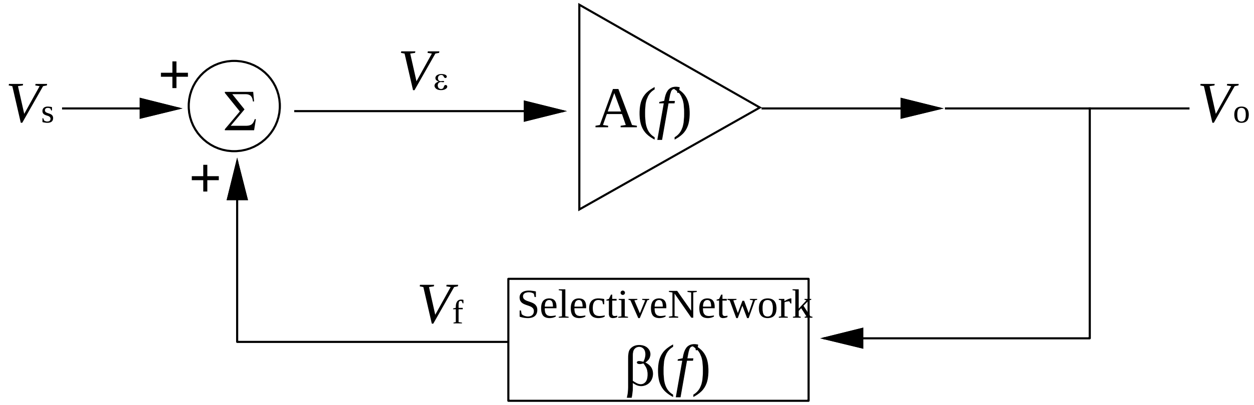


A linear oscillator contains:
- a frequency selection feedback network
- an amplifier to maintain the loop gain at **unity**

Basic principles for oscillation



Basic Linear Oscillator



$$V_o = AV_\varepsilon = A(V_s + V_f) \quad \text{and} \quad V_f = \beta V_o$$

$$\Rightarrow \frac{V_o}{V_s} = \frac{A}{1 - A\beta}$$

If $V_s = 0$, the only way that V_o can be nonzero is that loop gain $A\beta=1$ which implies that

$$|A\beta| = 1$$

$$\angle A\beta = 0$$

(Barkhausen Criterion)

How does the oscillation get started?

- Noise signals and the transients associated with the circuit turning on provide the initial source signal that initiate the oscillation

Practical Design Considerations

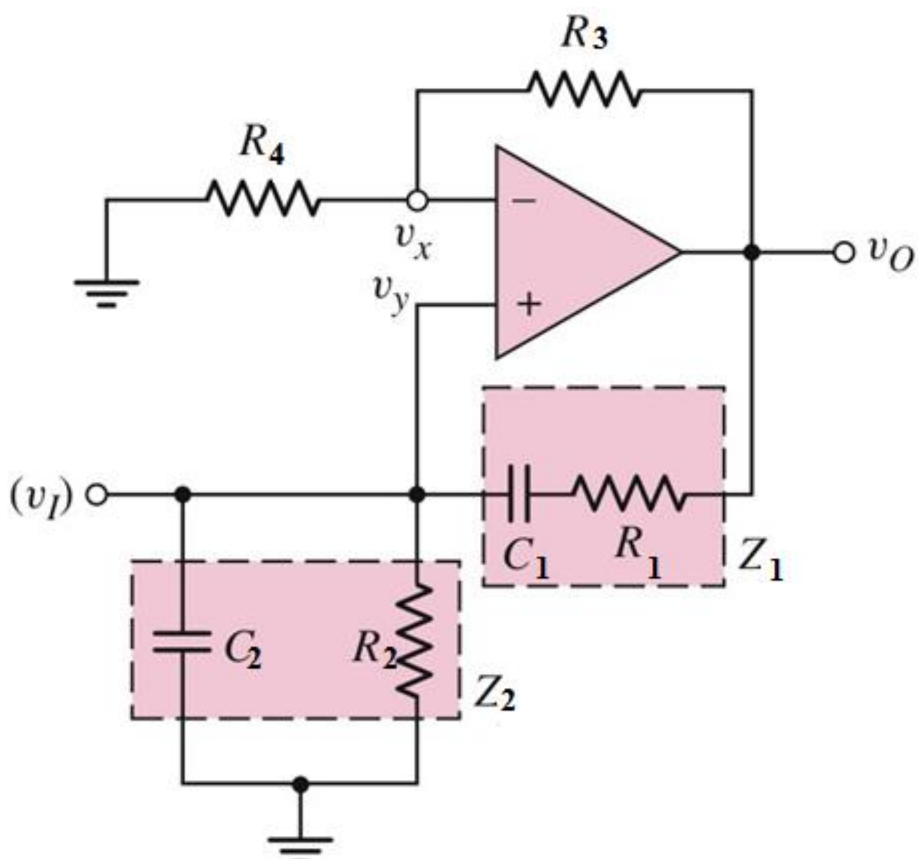
- Usually, oscillators are designed so that the loop gain magnitude is slightly higher than unity at the desired frequency of oscillation
- This is done because if we designed for unity loop gain magnitude a slight reduction in gain would result in oscillations that die to zero
- The drawback is that the oscillation will be slightly distorted (the higher gain results in oscillation that grows up to the point that will be clipped)

RC Oscillators

- RC feedback oscillators are generally limited to frequencies of 1 MHz or less.
- The types of RC oscillators that we will discuss are the Wien-bridge and the phase-shift

Wien-bridge Oscillator

- It is a low frequency oscillator which ranges from a few kHz to 1 MHz.



Wien Bridge Oscillator

Let $X_{C1} = \dfrac{1}{\omega C_1}$ and $X_{C2} = \dfrac{1}{\omega C_2}$

$$Z_1 = R_1 - jX_{C1}$$

$$Z_2 = \left[\frac{1}{R_2} + \frac{1}{-jX_{C2}}\right]^{-1} = \frac{-jR_2X_{C2}}{R_2 - jX_{C2}}$$

Therefore, the feedback factor,

$$\beta = \frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2} = \frac{(-jR_2X_{C2} / R_2 - jX_{C2})}{(R_1 - jX_{C1}) + (-jR_2X_{C2} / R_2 - jX_{C2})}$$

$$\beta = \frac{-jR_2X_{C2}}{(R_1 - jX_{C1})(R_2 - jX_{C2}) - jR_2X_{C2}}$$

β can be rewritten as:

$$\beta = \frac{R_2 X_{C2}}{R_1 X_{C2} + R_2 X_{C1} + R_2 X_{C2} + j(R_1 R_2 - X_{C1} X_{C2})}$$

For ***Barkhausen Criterion***, imaginary part = 0, i.e.,

$$R_1 R_2 - X_{C1} X_{C2} = 0$$

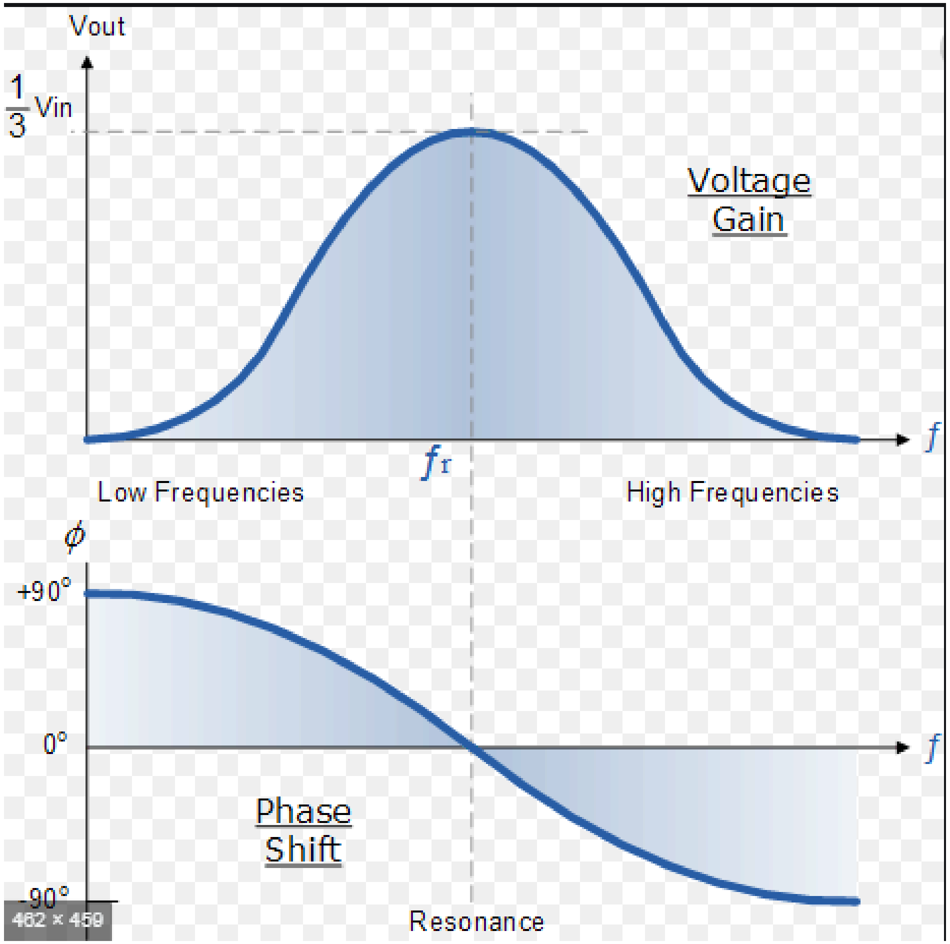
$$\text{or} \quad R_1 R_2 = \frac{1}{\omega C_1} \frac{1}{\omega C_2}$$

$$\Rightarrow \omega_0 = 1/\sqrt{R_1 R_2 C_1 C_2}$$

Supposing,

R_1=R_2=R and X_{C1}= X_{C2}=X_C,

$$\beta = \frac{R X_C}{3 R X_C + j(R^2 - X_C^2)} = \left(\frac{1}{3}\right)$$



Wien-bridge Oscillator

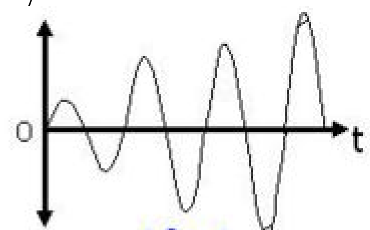
$$A\beta = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{3}\right) = 1$$

- then;

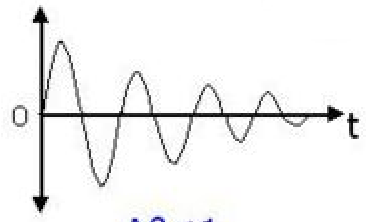
$$\frac{R_2}{R_1} = 2$$

$A = 3$ ensures the loop gain of unity – oscillation

- $A > 3$: growing oscillations



- $A < 3$: decreasing oscillations



Example

By setting $\omega = \frac{1}{R'C}$ we get

Imaginary part = 0 and $\beta = \frac{1}{3}$

Due to ***Barkhausen Criterion***,

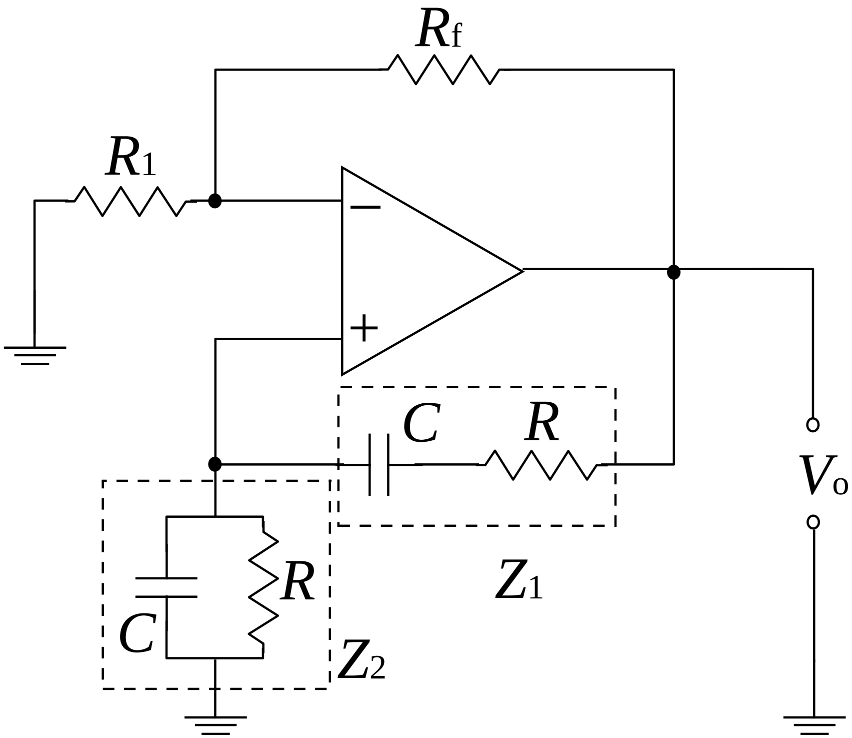
Loop gain $A_v\beta$=1

where

A_v : Gain of the amplifier

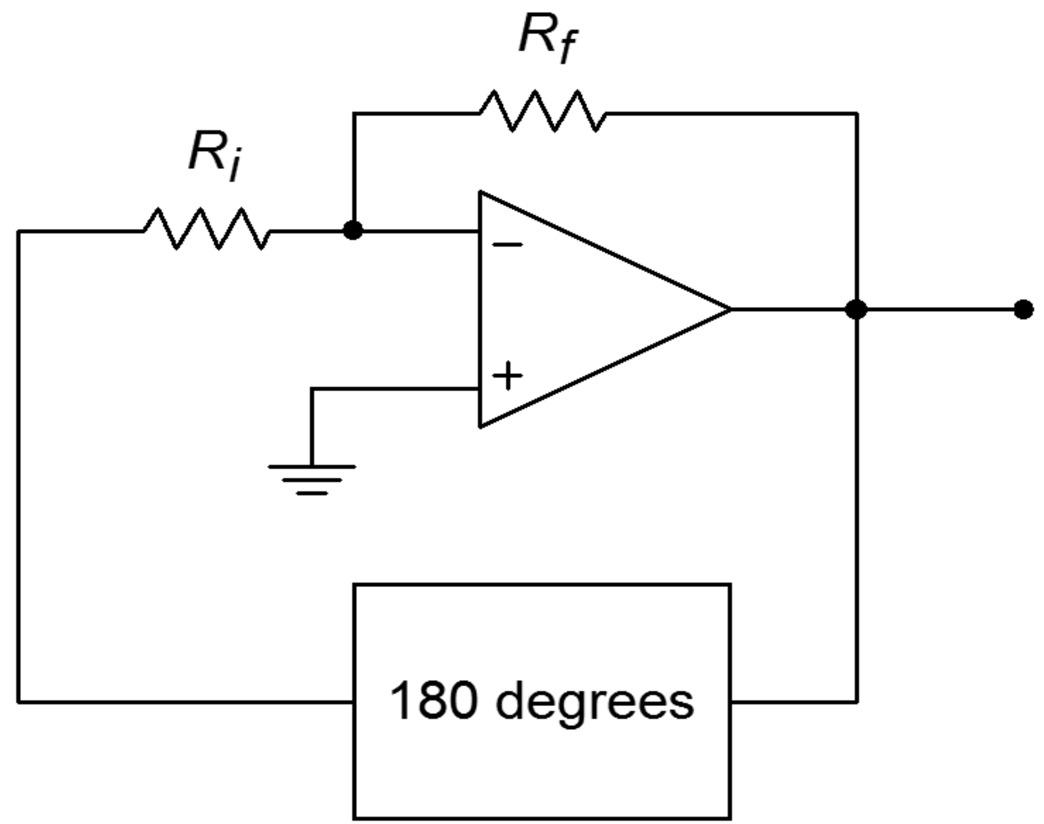
$$A_v\beta = 1 \Rightarrow A_v = 3 = 1 + \frac{R_f}{R_1}$$

Therefore, $\frac{R_f}{R_1} = 2$



Wien Bridge Oscillator

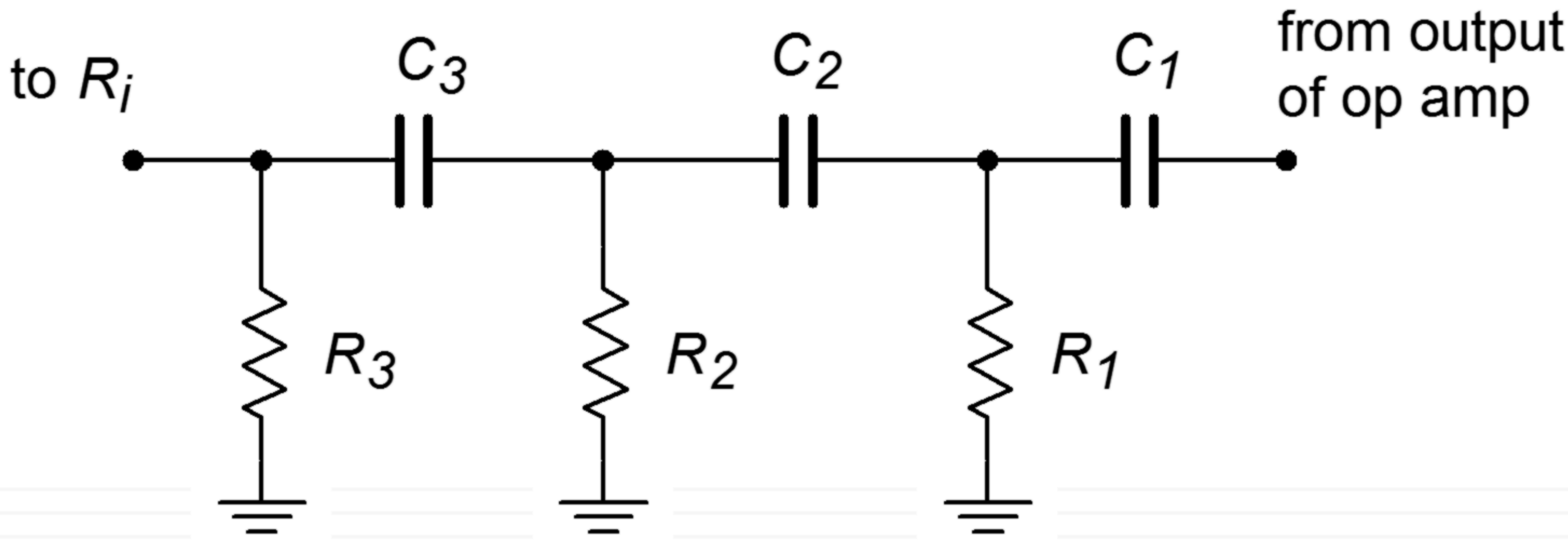
Phase-Shift Oscillator

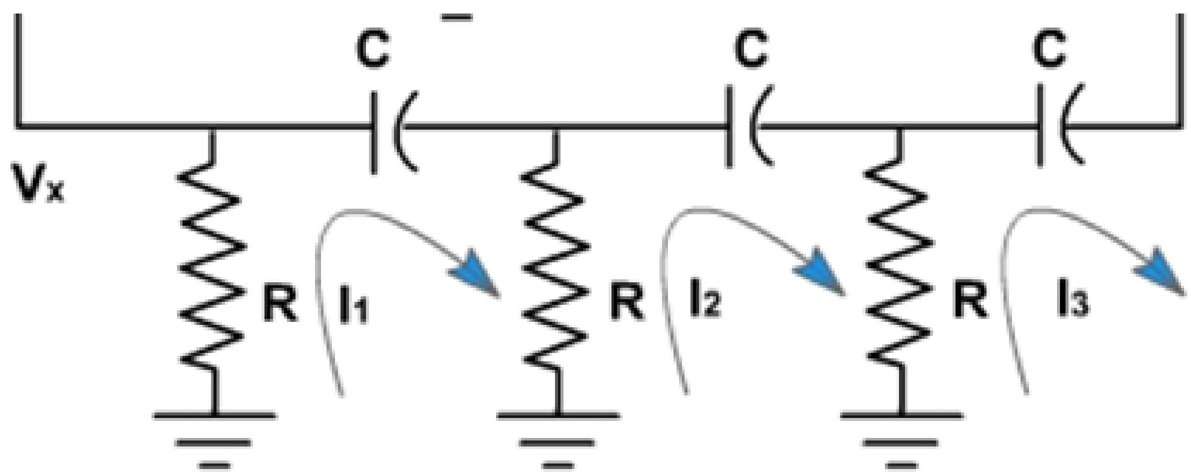


Phase-Shift Oscillator

- The phase shift oscillator utilizes at least three RC circuits to provide 180º phase shift that when coupled with the 180º of the op-amp itself provides the necessary feedback to sustain oscillations.
- The gain must be at least 29 to maintain the oscillations.
- The frequency of resonance for the this type is similar to any RC circuit oscillator:

$$f_r = \frac{1}{2\pi\sqrt{2N}RC}$$


to R_i
C_3
C_2
C_1
from output of op amp
R_3
R_2
R_1


C
C
C
Vx
R
I1
R
I2
R
I3

$$V_x = -I_1 R$$

$$X_C = \frac{1}{\omega c}$$

$$I_1 R - jI_1 X_C + (I_1 - I_2)R = 0$$

$$(I_2 - I_1)R - jI_2 X_C + (I_2 - I_3)R = 0$$

$$(I3 - I_2)R - jI_3 X_C + V_0 = 0$$

$$I_1 = -\frac{V_x}{R}$$

$$I_2 = \frac{I_1}{R}(2R - jX_C) = -\frac{V_x}{R^2}(2R - jX_C)$$

$$I_3 = \frac{1}{R}\left\{(2R - jXC)^2\left(-\frac{V_x}{R^2}\right) + VX\right\}$$

$$= -\left\{\frac{3R^2 - XC^2 - j4RX_C}{R^2}\right\}VX$$

$$-V_0 = -(R - jX_C)\left\{\frac{3R^2 - X_C^2 j4RXC}{R^2}\right\}V_x + \frac{V_x}{R}(2R - jX_C)$$

$$-V_0 = VX\left\{\frac{(3R^3 - R X_C^2 - j4R^2Xc - j3R^2X_C^3 - 4RX_C^2) + 2R^3 - jR^2XC}{R^3}\right\}$$

$$\frac{V_x}{V_0} = \frac{R^3}{R^3 - 5RX_C^2 - 6jR^2X_C + jX_C^3}$$

putting $X_C = \frac{1}{\omega C}$, we get

$$\frac{V_x}{V_0} = \frac{R^3}{R^3 - \frac{5R}{\omega^2 C^2} - \frac{6jR^2}{\omega C} + \frac{j}{\omega^3 C^3}}$$

to 180o between V_x and V_O, imaginary term of V_x / V_O must be zero.

$$\frac{j}{\omega^3 C^3} - \frac{6jR^2}{\omega C} = 0$$

$$\omega^2 C^2 = \frac{1}{6R^2}$$

$$\omega = \frac{1}{RC\sqrt{6}}$$

$$f = \frac{1}{2\pi RC\sqrt{6}}$$

This is the frequency of oscillation. Substituting this frequency in V_x / V_O expression.

$$\frac{R^3}{R^3 - 5R.6R^2} = -\frac{1}{29} = \beta$$

at 180° phase shift from Vo to Vx can be obtained if

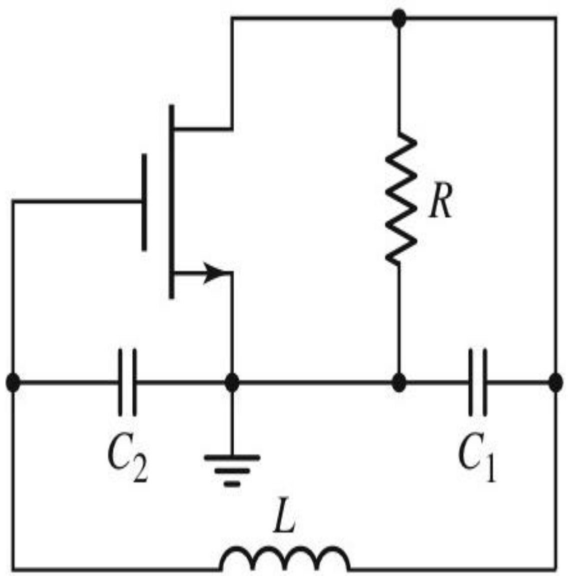
$$\frac{1}{2\pi RC\sqrt{6}}$$

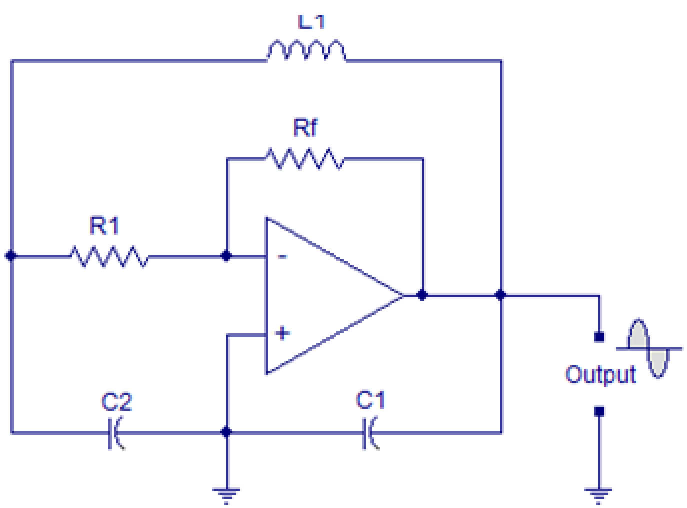
f it feedback circuit becomes $1/29$.

LC Oscillators

- Use transistors and LC tuned circuits or crystals in their feedback network.
- For hundreds of kHz to hundreds of MHz frequency range.
- Examine Colpitts, Hartley and crystal oscillator.

Colpitts Oscillator





- The Colpitts oscillator is a type of oscillator that uses an LC circuit in the feed-back loop.
- The feedback network is made up of a pair of *tapped capacitors (C_1 and C_2)* and *an inductor L* to produce a feedback necessary for oscillations.
- The output voltage is developed across C_1.
- The feedback voltage is developed across C_2.

Colpitts Oscillator Applications

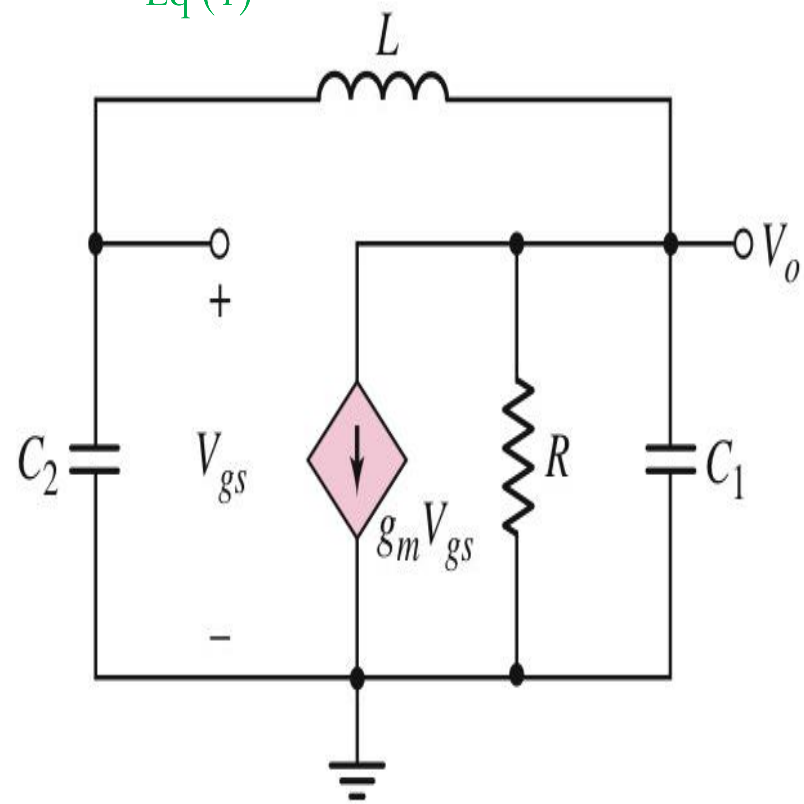
- Applicable to obtain periodic output signals of high frequency.
- Colpitts Oscillator using surface acoustic wave devices can be used to produce useful sensors like temperature sensors and audio sensors.
- Applicable in circuits where a large frequency range is used.
- Finds vast applications in mobile communications and radio forecasting.

Colpitts Oscillator

- KCL at the output node:

$$\frac{V_o}{\frac{1}{sC_1}} + \frac{V_o}{R} + g_m V_{gs} + \frac{V_o}{sL + \frac{1}{sC_2}} = 0$$

- Eq (1)



- voltage divider produces:

$$V_{gs} = \left(\frac{\frac{1}{sC_2}}{\frac{1}{sC_2} + sL} \right) \bullet V_o$$

- Eq (2)

- substitute eq(2) into eq(1):

$$V_o \left[g_m + sC_2 + \left(1 + s^2 LC_2\right)\left(\frac{1}{R} + sC_1\right) \right] = 0$$

Colpitts Oscillator

- Assume that oscillation has started, then Vo≠0

$$s^3LC_1C_2+\frac{s^2LC_2}{R}+s\left(C_1+C_2\right)+\left(g_m+\frac{1}{R}\right)=0$$

- Let s=jω

$$\left(g_m+\frac{1}{R}-\frac{\omega^2LC_2}{R}\right)+j\omega\left[\left(C_1+C_2\right)-\omega^2LC_1C_2\right]=0$$

- both real & imaginary component must be zero
  - Imaginary component:

$$\omega_o=\frac{1}{\sqrt{L\left(\frac{C_1C_2}{C_1+C_2}\right)}}$$

- Eq (3)

Colpitts Oscillator

- both real & imaginary component must be zero
  - Real component: $$\frac{\omega^2 LC_2}{R} = g_m + \frac{1}{R}$$ - Eq (4)
- Combining Eq(3) and Eq(4):

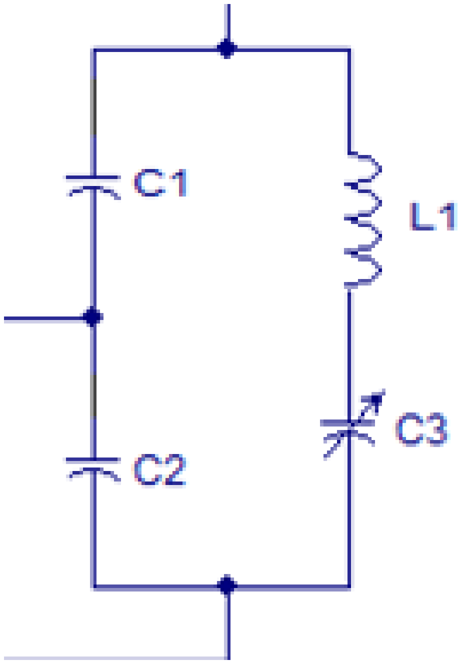
$$\frac{C_2}{C_1} = g_m R$$

- to initiate oscillations spontaneously:

$$g_m R > \left(\frac{C_2}{C_1} \right)$$

Clapp oscillator

- modification of Colpitts oscillator.
- The only difference is that there is one additional capacitor connected in series to the inductor in the tank circuit.



Clapp oscillator

- C3 is to improve the frequency stability.
- prevents the stray capacitances and other parameters of the transistor from affecting C1 and C2
- C1, C2 fixed and C3 is made variable. (modify the eqn)
- Frequency of oscillation

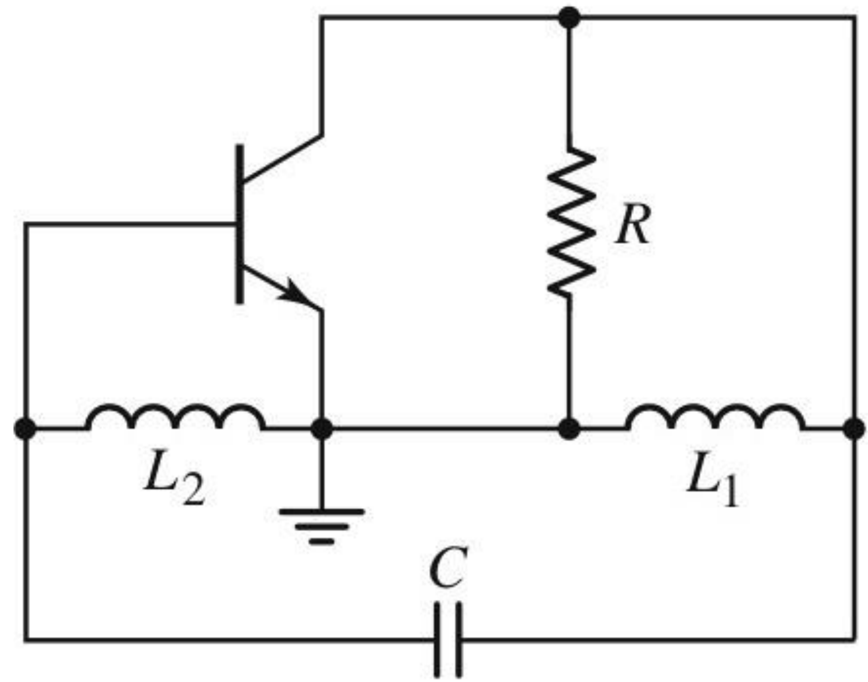
$$F = \frac{1}{2\pi\sqrt{L(\frac{1}{C1}+\frac{1}{C2}+\frac{1}{C3})}}$$

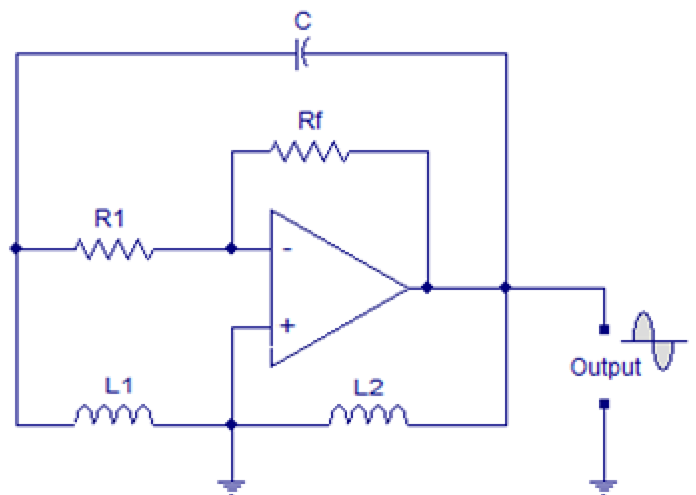
- C3<<C1,C2

$$F = \frac{1}{2\pi\sqrt{LC3}}$$

Hartley Oscillator

- The Hartley oscillator is almost identical to the Colpitts oscillator.
- The primary difference is that the feedback network of the Hartley oscillator uses *tapped inductors (L_1 and L_2)* and *a single capacitor C*.





Hartley Oscillator

- the analysis of Hartley oscillator is identical to that Colpitts oscillator.
- the frequency of oscillation:

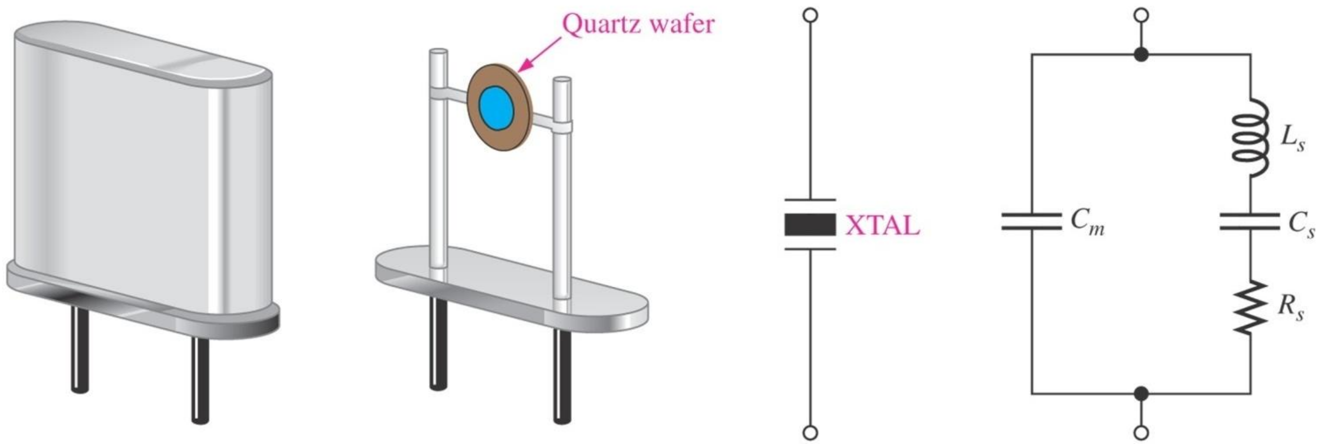
$$\omega_o = \frac{1}{\sqrt{(L_1 + L_2)C}}$$

- Prove it (HW)

Crystal Oscillator

- Most communications and digital applications require the use of oscillators with extremely stable output. Crystal oscillators are invented to overcome the output fluctuation experienced by conventional oscillators.

- Crystals used in electronic applications consist of a quartz wafer held between two metal plates and housed in a package as shown



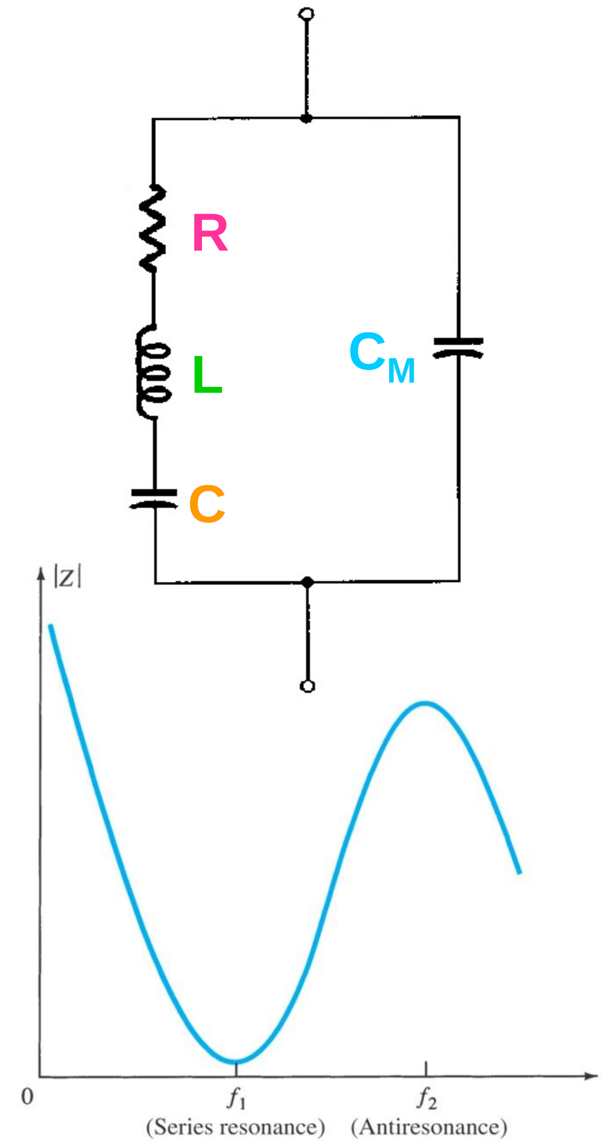
(a) Typical packaged crystal (b) Basic construction (without case) (c) Symbol (d) Electrical equivalent

Crystal Oscillator

- Piezoelectric Effect
  - The quartz crystal is made of silicon oxide (SiO_2) and exhibits a property called the *piezoelectric*
  - When a changing an alternating voltage is applied across the crystal, it vibrates at the frequency of the applied ac voltage. In the other word, the frequency of the applied ac voltage is equal to the natural resonant frequency of the crystal.
  - The thinner the crystal, higher its frequency of vibration. This phenomenon is called piezoelectric effect.

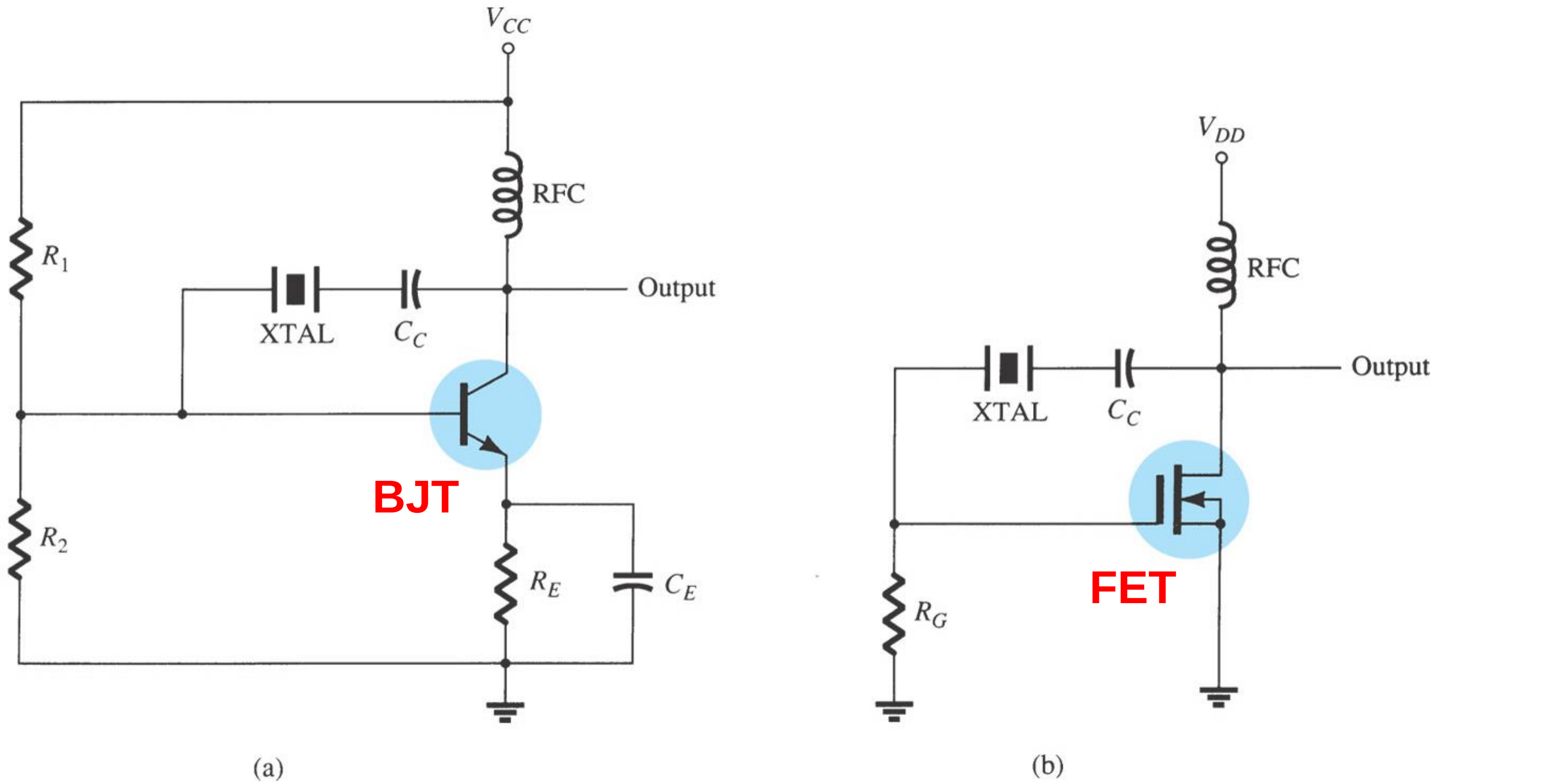
Crystal Oscillator

- Characteristic of Quartz Crystal
  - The crystal can have two resonant frequencies;
  - One is the series resonance frequency f_1 which occurs when $X_L = X_C$. At this frequency, crystal offers a very low impedance to the external circuit where $Z = R$.
  - The other is the parallel resonance (or anti resonance) frequency f_2 which occurs when reactance of the series leg equals the reactance of C_M. At this frequency, crystal offers a very high impedance to the external circuit



Crystal Oscillator

- The crystal is connected as a series element in the feedback path from collector to the base so that it is excited in the series-resonance mode



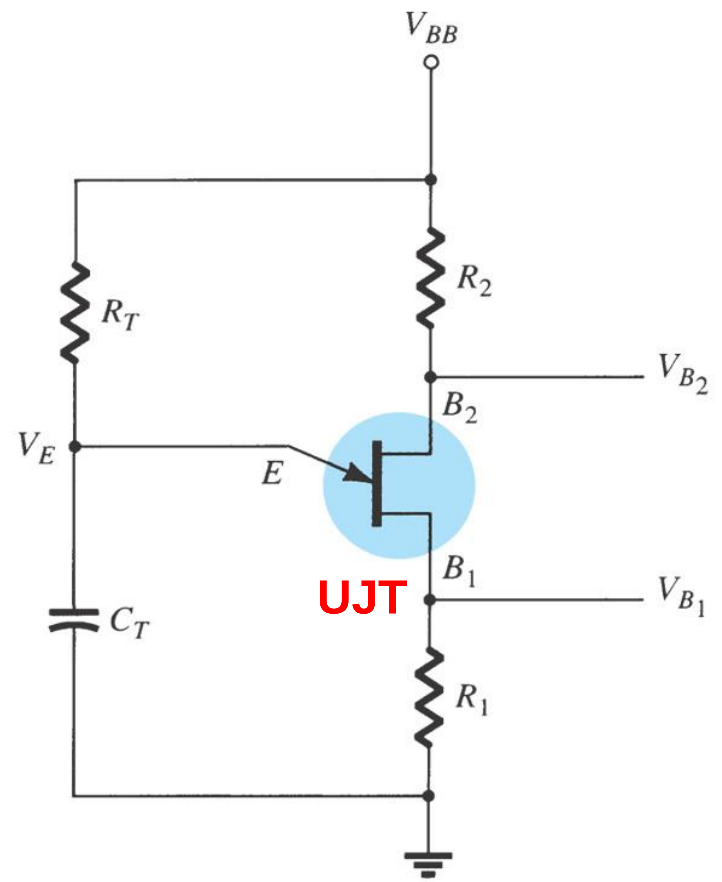
Crystal Oscillator

- Since, in series resonance, crystal impedance is the smallest that causes the crystal provides the largest positive feedback.
- Resistors R_1, R_2, and R_E provide a voltage-divider stabilized dc bias circuit. Capacitor C_E provides ac bypass of the emitter resistor, R_E to avoid degeneration.
- The RFC coil provides dc collector load and also prevents any ac signal from entering the dc supply.
- The coupling capacitor C_C has negligible reactance at circuit operating frequency but blocks any dc flow between collector and base.
- The oscillation frequency equals the series-resonance frequency of the crystal and is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC_C}}$$

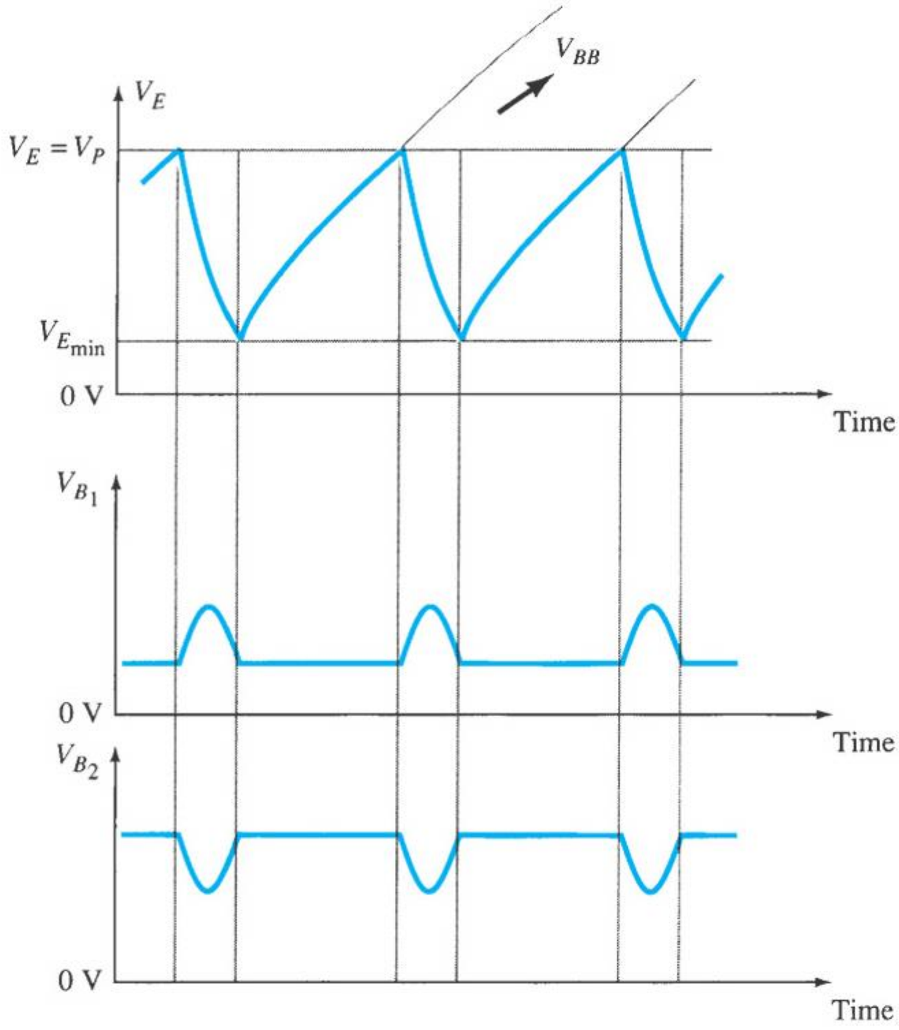
Unijunction Oscillator

- The unijunction transistor can be used in what is called a *relaxation oscillator* as shown by basic circuit as follow.
- The unijunction oscillator provides a pulse signal suitable for digital-circuit applications.
- Resistor R_T and capacitor C_T are the timing components that set the circuit oscillating rate



Unijunction Oscillator

- Sawtooth wave appears at the emitter of the transistor.
- This wave shows the gradual increase of capacitor voltage



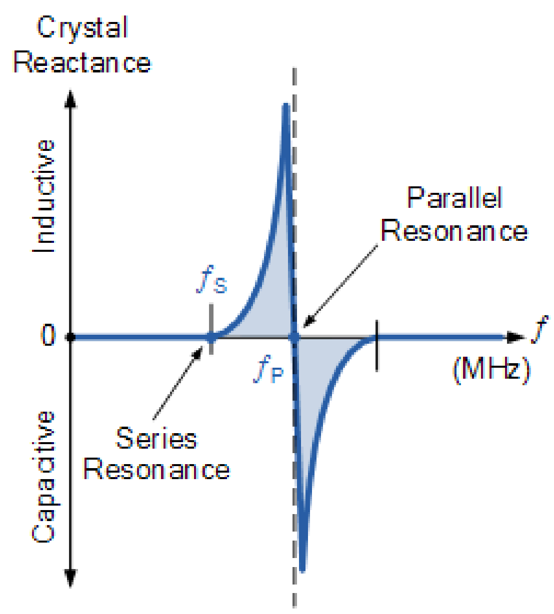
Unijunction Oscillator

- The oscillating frequency is calculated as follows:

$$f_o \cong \frac{1}{R_T C_T \ln\left[1/(1-\eta)\right]}$$

- where, η = the unijunction transistor intrinsic stand- off ratio
- Typically, a unijunction transistor has a stand-off ratio from 0.4 to 0.6

Crystal Reactance against Frequency



$$X_S = R^2 + \left(X_{LS} - X_{CS}\right)^2$$

$$X_{CP} = \frac{-1}{2\pi f C_P}$$

$$X_P = \frac{X_S \times X_{CP}}{X_S + X_{CP}}$$

Series Resonant Frequency

$$f_S = \frac{1}{2\pi\sqrt{L_S C_S}}$$

The parallel resonance frequency, *ƒ*p occurs when the reactance of the series LC leg equals the reactance of the parallel capacitor, Cp and is given as:

Parallel Resonant Frequency

$$f_P = \frac{1}{2\pi\sqrt{L_S\left(\frac{C_P C_S}{C_P + C_S}\right)}}$$

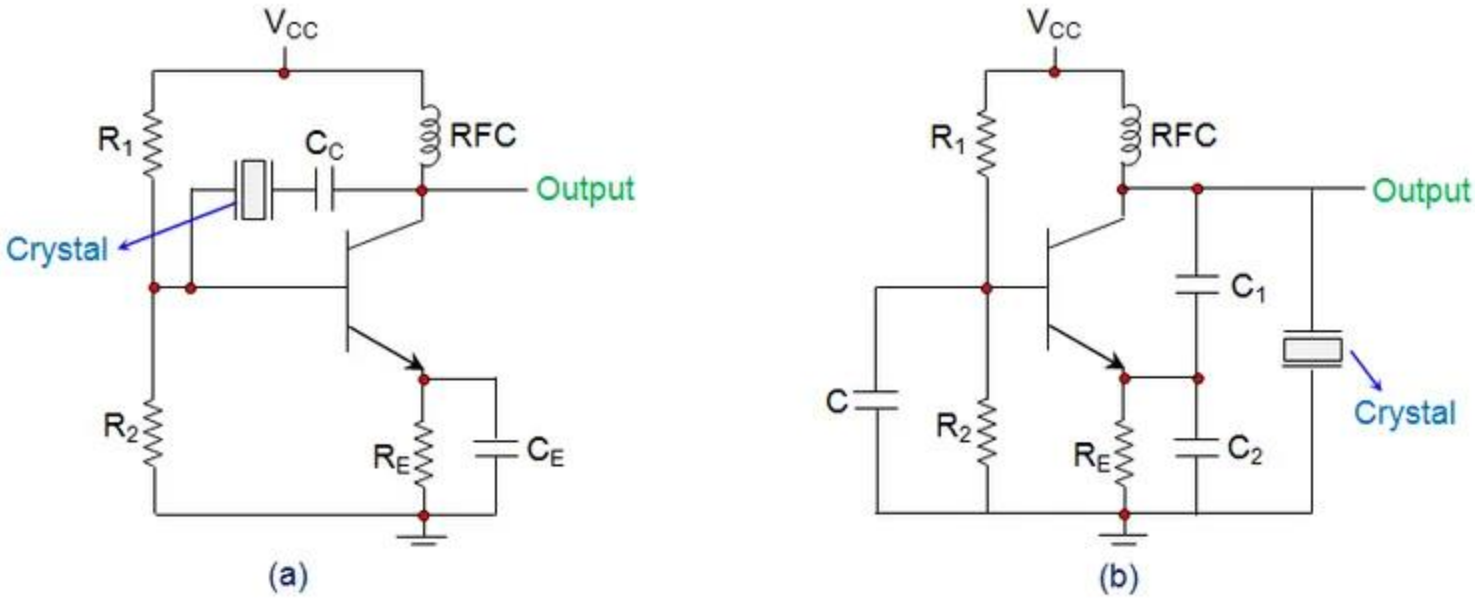


Figure 2 Crystal Oscillator Operating in (a) Series Resonance (b) Parallel Resonance

$$fp = (1/(2\pi\sqrt{(LCeq)})$$

$$Ceq = C_M C / C_M + C$$