Oscillator

- Describe the basic concept of an oscillator
- Discuss the basic principles of operation of an oscillator
- Analyze the operation of RC and LC oscillators
- Describe the operation of the basic relaxation oscillator circuits

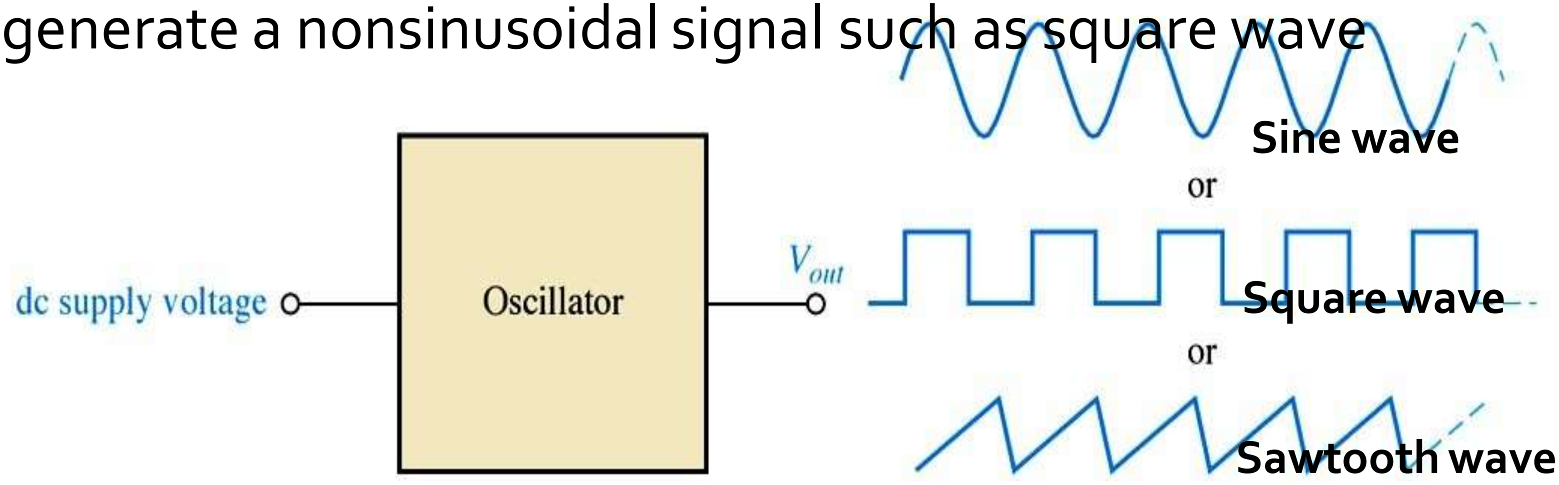
- **Oscillator** is an electronic circuit that generates a periodic waveform on its output without an external signal source. It is used to convert dc to ac.

- Oscillators are circuits that produce a continuous signal of some type without the need of an input.

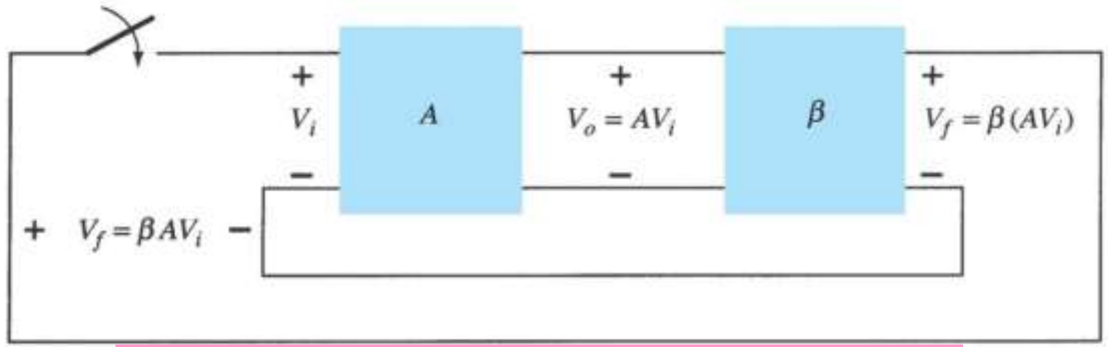
- These signals serve a variety of purposes.

- Communications systems,
- digital systems (including computers), and
- test equipment make use of oscillators

- An oscillator is a circuit that produces a repetitive signal from a dc voltage.
- 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



1. **RC oscillators**
   - Wien Bridge
   - Phase-Shift
1. **LC oscillators**
   - Hartley
   - Colpitts
   - Crystal
1. **Unijunction / relaxation oscillators**



Feedback circuit used as an oscillator

- **When switch at the amplifier input is open, no oscillation occurs.**
- **Consider V_i, results in $V_o = AV_i$ (after amplifier stage) and $V_f = \beta(AV_i)$ (after feedback stage)**
- **Feedback voltage $V_f = \beta(AV_i)$ where βA is called loop gain.**
- **In order to maintain $V_f = V_i$, βA must be in the correct magnitude and phase.**
- **When the switch is closed and V_i is removed, the circuit will continue operating since the feedback voltage is sufficient to drive the amplifier and feedback circuit, resulting in proper input voltage to sustain the loop**

- An oscillator is an amplifier with positive feedback.

V_e V_o

V_s A

V_f β

$$V_e = V_s + V_f \quad (1)$$

$$V_f = \beta V_o \quad (2)$$

$$V_o = AV_e = A\left(V_s + V_f\right) = A\left(V_s + \beta V_o\right) \quad (3)$$

$$V_o = AV_e = A\left(V_s + V_f\right) = A\left(V_s + \beta V_o\right)$$

$$V_o = AV_s + A\beta V_o$$

$$\left(1 - A\beta\right)V_o = AV_s$$

- The closed loop gain is:

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{\left(1 - A\beta\right)}$$

- In general A and β are functions of frequency and thus may be written as;

$$A_f(s) = \frac{V_o}{V_s}(s) = \frac{A(s)}{1 - A(s)\beta(s)}$$

$A(s)\beta(s)$ is known as **loop gain**

- Writing $T(s) = A(s)\beta(s)$ the loop gain becomes;

$$A_f(s) = \frac{A(s)}{1 - T(s)}$$

- Replacing s with $j\omega$

$$A_f(j\omega) = \frac{A(j\omega)}{1 - T(j\omega)}$$

- and $T(j\omega) = A(j\omega)\,\beta(j\omega)$

- At a specific frequency f_0

$$T(j\omega_0) = A(j\omega_0)\beta(j\omega_0) = 1$$

- At this frequency, the closed loop gain;

$$A_f(j\omega_0) = \frac{A(j\omega_0)}{1 - A(j\omega_0)\beta(j\omega_0)}$$

will be infinite, i.e. the circuit will have finite output for zero input signal - oscillation

- Thus, the condition for sinusoidal oscillation of frequency f_0 is;

$$A(j\omega_0)\beta(j\omega_0) = 1$$

- This is known as **Barkhausen criterion**.

- The frequency of oscillation is solely determined by the phase characteristic of the feedback loop – the loop oscillates at the frequency for which the phase is zero.

- The feedback oscillator is widely used for generation of sine wave signals.
- The positive (in phase) feedback arrangement maintains the oscillations.
- The feedback gain must be kept to unity to keep the output from distorting.

In phase

V_f

A_v

V_o

Noninverting amplifier

Feedback circuit

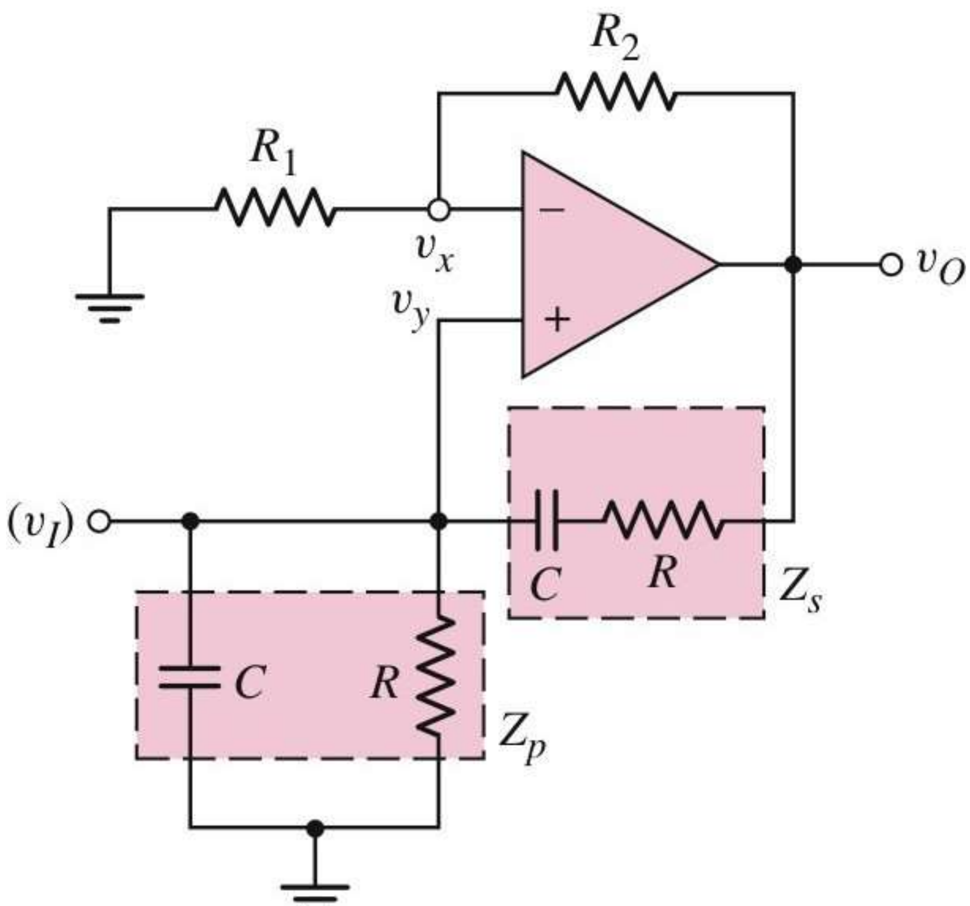
1. The magnitude of the loop gain must be unity or slightly larger

   $$\left|A\beta\right| = 1$$ – Barkhaussen criterion

2. Total phase shift, ϕ of the loop gain mus t be 0 ° or 360°

- 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**

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



Working of Wein bridge Oscillator

The feedback signal in this oscillator circuit is connected to the non-inverting input terminal so that the op-amp works as a non-inverting amplifier.

The condition of zero phase shift around the circuit is achieved by balancing the bridge, zero phase shift is essential for sustained oscillations.

The frequency of oscillation is the resonant frequency of the balanced bridge and is given by the expression **$f_o = 1/2\pi RC$**

At resonant frequency (f_o), the inverting and non-inverting input voltages will be equal and “in-phase” so that the negative feedback signal will be cancelled out by the positive feedback causing the circuit to oscillate.

From the analysis of the circuit, it can be seen that the feedback factor $\beta = 1/3$ at the frequency of oscillation. Therefore for sustained oscillation, the amplifier must have a gain of 3 so that the loop gain becomes unity.

For an inverting amplifier the gain is set by the feedback resistor network R_f and R_i and is given as the ratio $-R_f/R_i$.

- The loop gain for the oscillator is;

$$T(s) = A(s)\beta(s) = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{Z_p}{Z_p + Z_s}\right)$$

- where;

$$Z_p = \frac{R}{1 + sRC}$$

- and;

$$Z_s = \frac{1 + sRC}{sC}$$

- Hence;

$$\boldsymbol{T(s)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+sRC+\left(1/sRC\right)}\right]}$$

- Substituting for *s*;

$$T(j\omega)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+j\omega RC+\left(1/j\omega RC\right)}\right]$$

- For oscillation frequency f_0;

$$T(j\omega_0)=\left(1+\frac{R_2}{R_1}\right)\left[\frac{1}{3+j\omega_0 RC+\left(1/j\omega_0 RC\right)}\right]$$

- Since at the frequency of oscillation, $T(j\omega)$ must be real (for zero phase condition), the imaginary component must be zero;

$$j\omega_0 RC + \frac{1}{j\omega_0 RC} = 0$$

- Which gives us;

$$\omega_0 = \frac{1}{RC}$$

- From the previous equation;

$$T(j\omega_0) = \left(1 + \frac{R_2}{R_1}\right)\left[\frac{1}{3 + j\omega_0 RC + (1/j\omega_0 RC)}\right]$$

- the magnitude condition is;

$$1 = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{1}{3}\right) \quad \text{or} \quad \frac{R_2}{R_1} = 2$$

To ensure oscillation, the ratio R_2/R_1 must be slightly greater than 2.

- With the ratio;

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

- then;

$$K \equiv 1 + \frac{R_2}{R_1} = 3$$

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

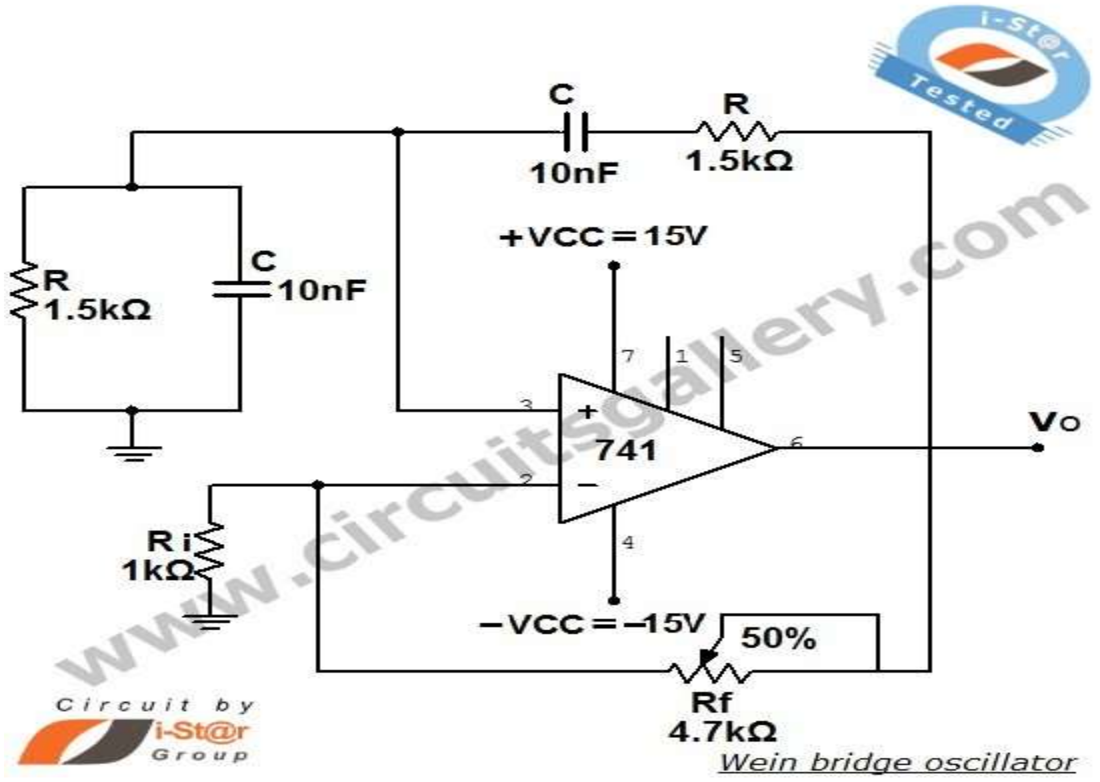
- $K > 3$: growing oscillations
- $K < 3$: decreasing oscillations

Design

The required frequency of oscillation
fo=1kHz
we have,

Take **C=0.01µF**, then **R=**1.6kΩ (Use **1.5kΩ** standard)
Gain of the amplifier section is given by,

Take **Ri=1kΩ**, then **Rf**=2.2kΩ
(Use **4.7kΩ Potentio meter** for fine corrections)



Phase-Shift Oscillator

R_f

$-$

0 V C C C V_o

R

$+$

R R

Phase-shift oscillator

- The phase shift oscillator utilizes **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 frequency for this type is similar to any RC circuit oscillator:

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

where $\beta = 1/29$ and the phase-shift is 180^o

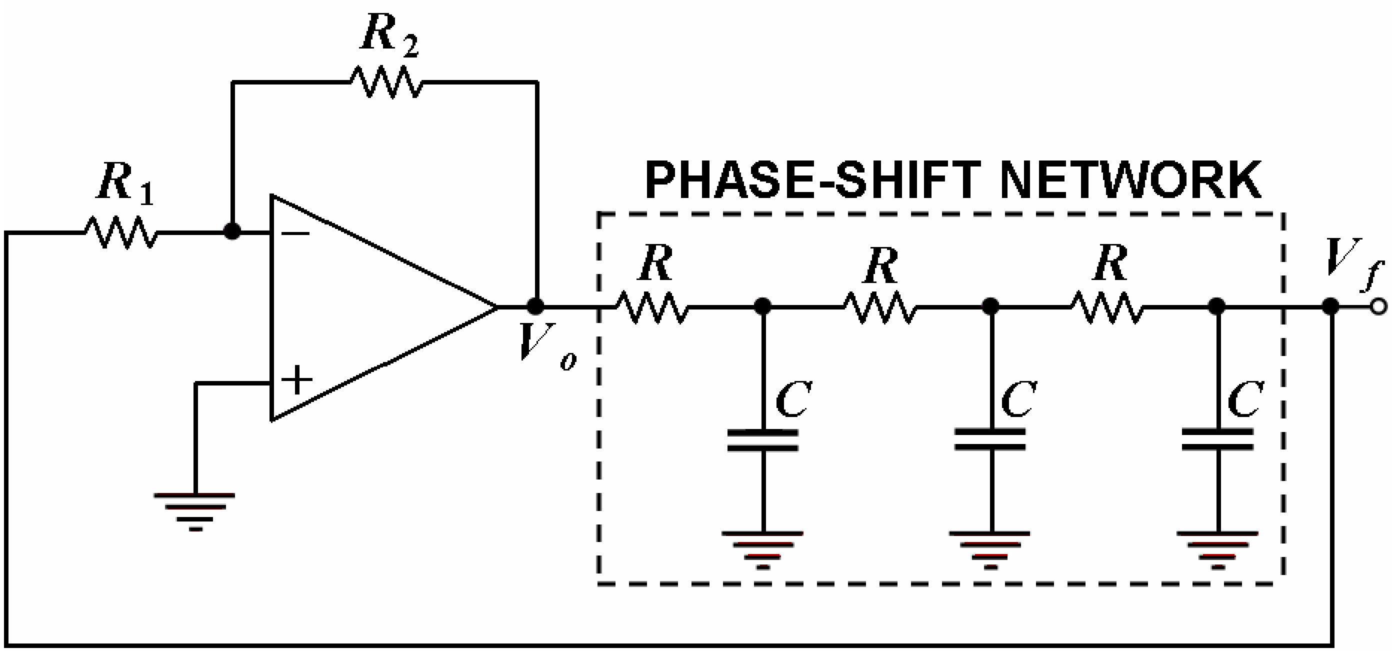
- For the loop gain βA to be greater than unity, the gain of the amplifier stage must be greater than 29.

- If we measure the phase-shift per RC section, each section would not provide the same phase shift (although the overall phase shift is 180^o).

- In order to obtain exactly 60^o phase shift for each of three stages, emitter follower stages would be needed for each RC section.

The gain must be at least 29 to maintain the oscillation

Phase-Shift Oscillator



The transfer function of the RC network is

$$\mathrm{TF} = \frac{\mathrm{Vin}}{\mathrm{Vo}} = \frac{1}{(\mathrm{SRC})^3 + 5(\mathrm{SRC})^2 + 6(\mathrm{SRC}) + 1}$$

Phase-Shift Oscillator

If the gain around the loop equals 1, the circuit oscillates at this frequency. Thus for the oscillations we want,

$$K\,(TF) = 1$$

or $$(SRC)^3 + 5(SRC)^2 + 6(SRC) + 1 - K = 0$$

Putting s=jω and equating the real parts and imaginary parts, we obtain

$$-j\omega^3 (RC)^3 + 6\, j\omega\, RC = 0 \quad \ldots..\ (1) \qquad \text{(Imaginary Part)}$$

$$-5\, \omega^2 (RC)^2 + 1 - K = 0 \quad \ldots..\ (2) \qquad \text{(Real Part)}$$

Phase-Shift Oscillator

From equation (1) ;

$$-\omega^2 (RC)^2 + 6 = 0$$

$$\omega = \frac{\sqrt{6}}{(RC)}$$

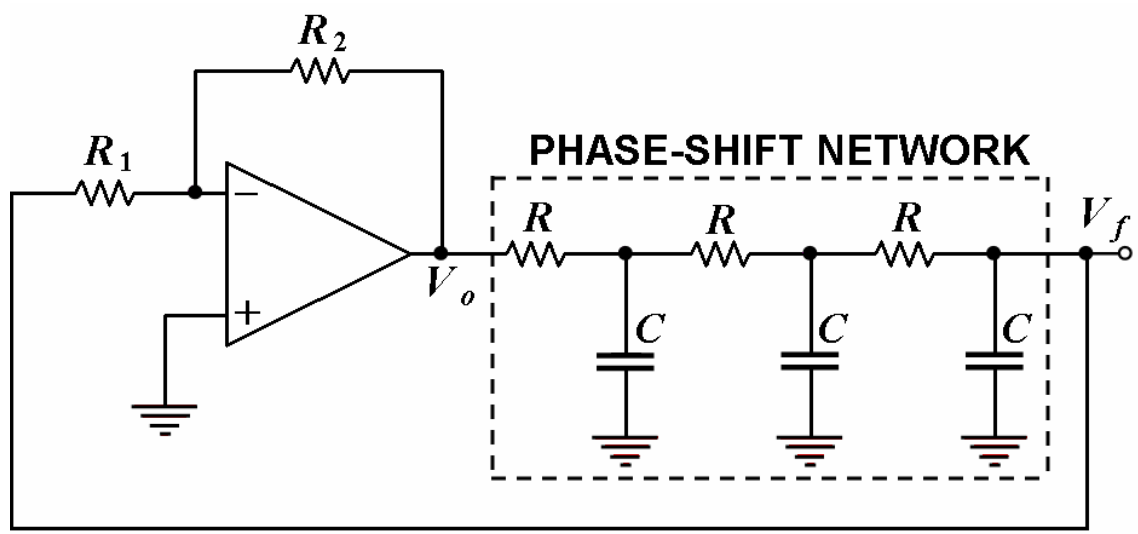
Substituting into equation (2) ;

$$-5\left[\frac{6}{(RC)^2}\right](RC)^2 + 1 = K$$

$$\Rightarrow \quad K = -29$$

The gain must be at least 29 to maintain the oscillations.

Phase Shift Oscillator – Practical



$$f_r = \frac{\sqrt{6}}{2\pi RC}$$

$$K = \frac{R_2}{R_1} = 29$$

Phase Shift Oscillator – Practical

Design

Frequency of oscillation (F):

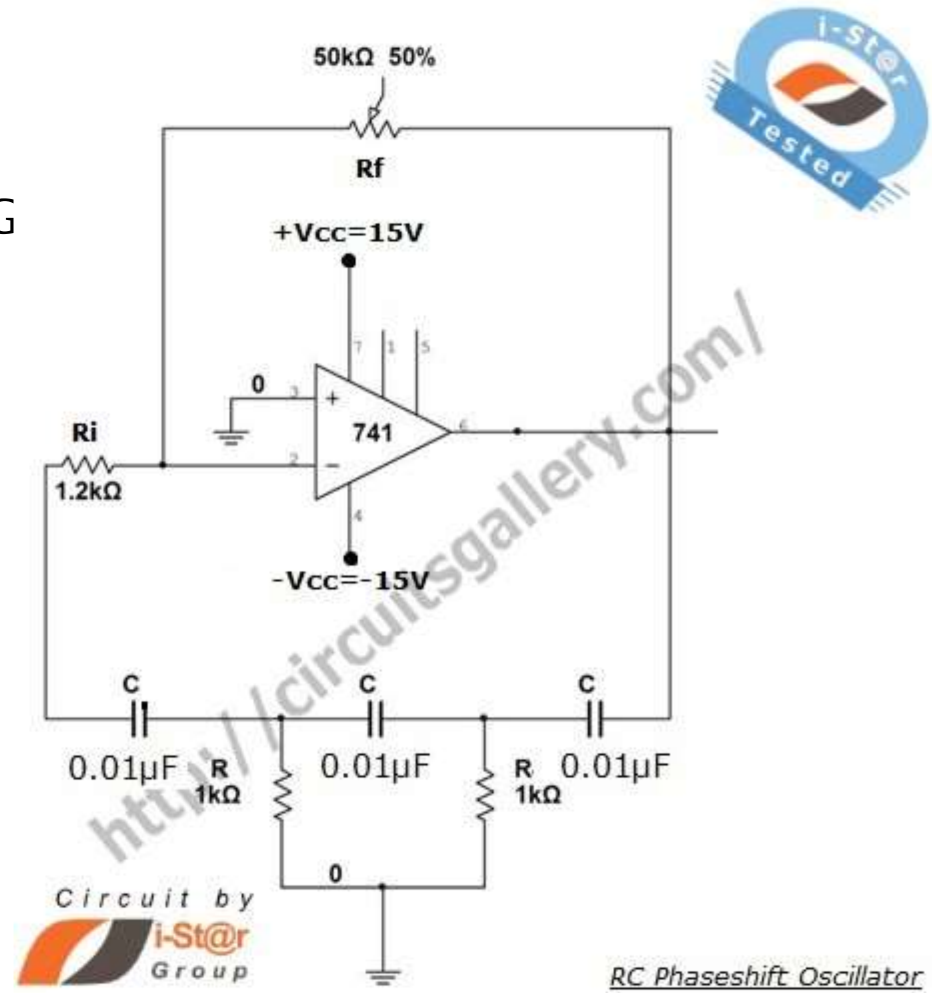
Gain of the Op Amp inverting amplifier (G

Attenuation offered by the feedback RC network is 1/29, so the gain of inverting amplifier should be 29

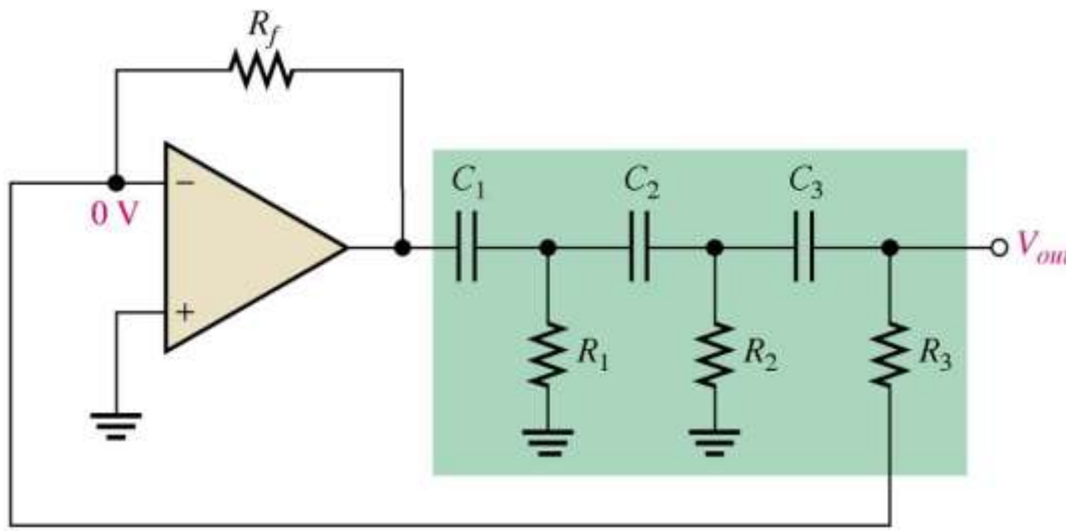
Use R_i=1.2 KΩ

So, R_f=35KΩ

Use 50KΩ potentiometer and adjust its value to obtain output on CRO



Phase Shift Oscillator – Practical

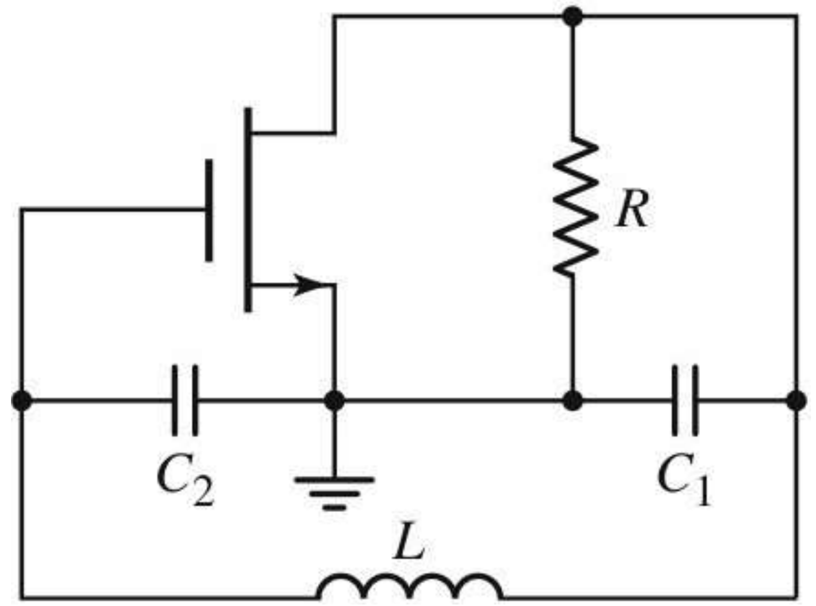


The last R has been incorporated into the summing resistors at the input of the inverting op-amp.

$$f_r = \frac{1}{2\pi\sqrt{6}RC} \qquad K = \frac{-R_f}{R_3} = -29$$

- 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.

- 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.

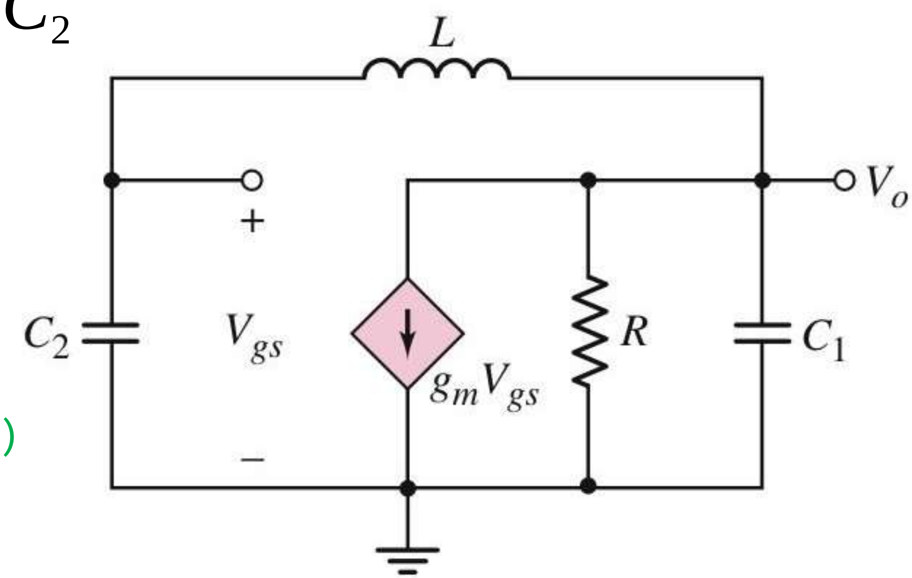


- KCL at the output node:

$$\frac{V_o}{\frac{1}{sC_1}} + \frac{V_o}{R} + g_m V_{gs} + \frac{V_o}{sL + \frac{1}{sC_2}} = 0 \qquad \text{- Eq (1)}$$

- voltage divider produces:

$$V_{gs} = \left(\frac{\frac{1}{sC_2}}{\frac{1}{sC_2} + sL} \right) \bullet V_o \qquad \text{- Eq (2)}$$



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

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

- Assume that oscillation has started, then Vo≠o

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

- Let s=jω

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

- 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)

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

$$\frac{\omega^2 L C_2}{R} = g_m + \frac{1}{R}$$ - Eq (4)

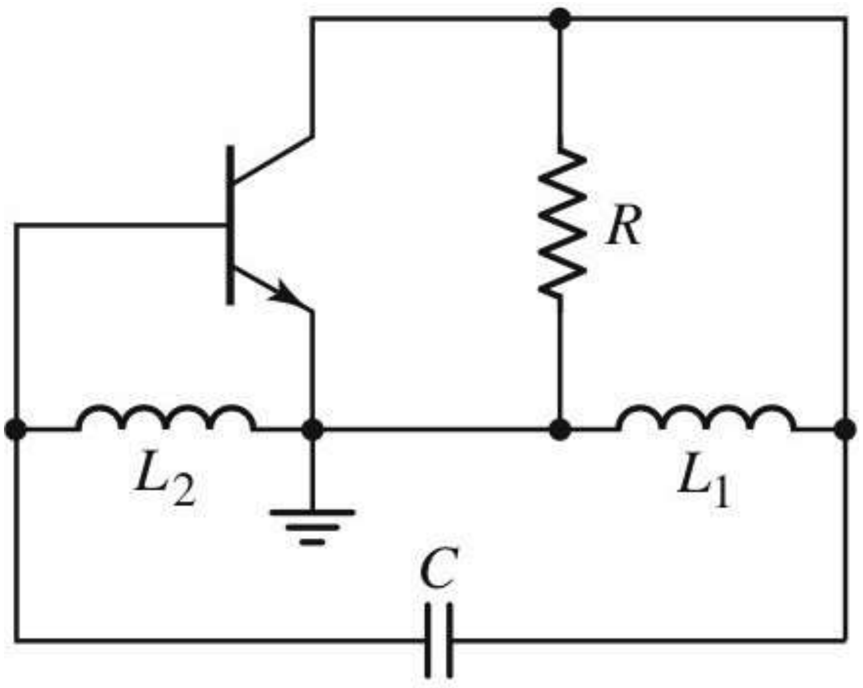
- Combining Eq(3) and Eq(4):

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

- to initiate oscillations spontaneously:

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

- 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*.

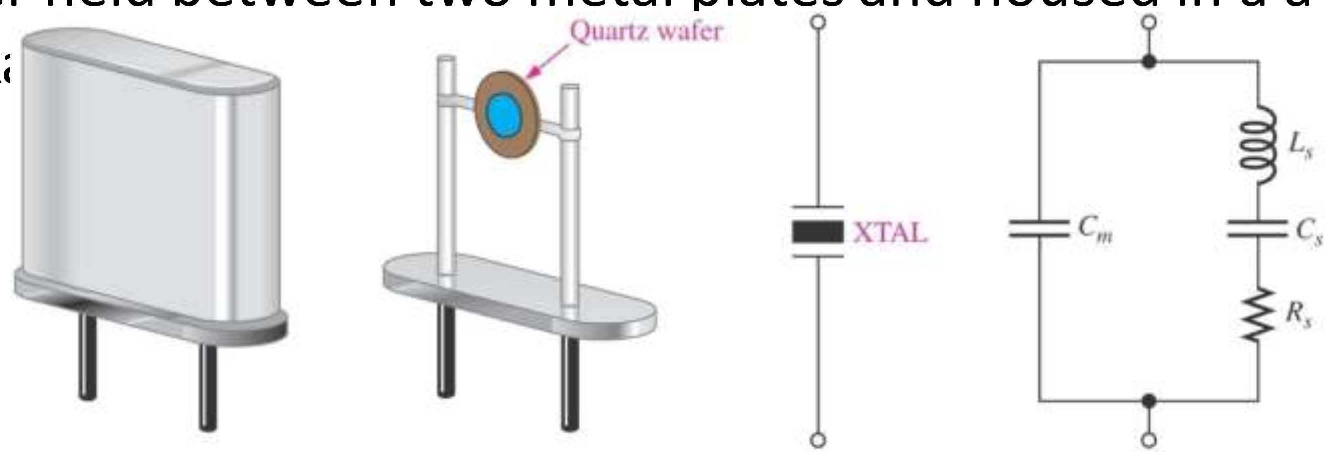


- the analysis of Hartley oscillator is identical to that Colpitts oscillator.
- the frequency of oscillation:

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

- υ 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.

- υCrystals used in electronic applications consist of a quartz wafer held between two metal plates and housed in a a pack

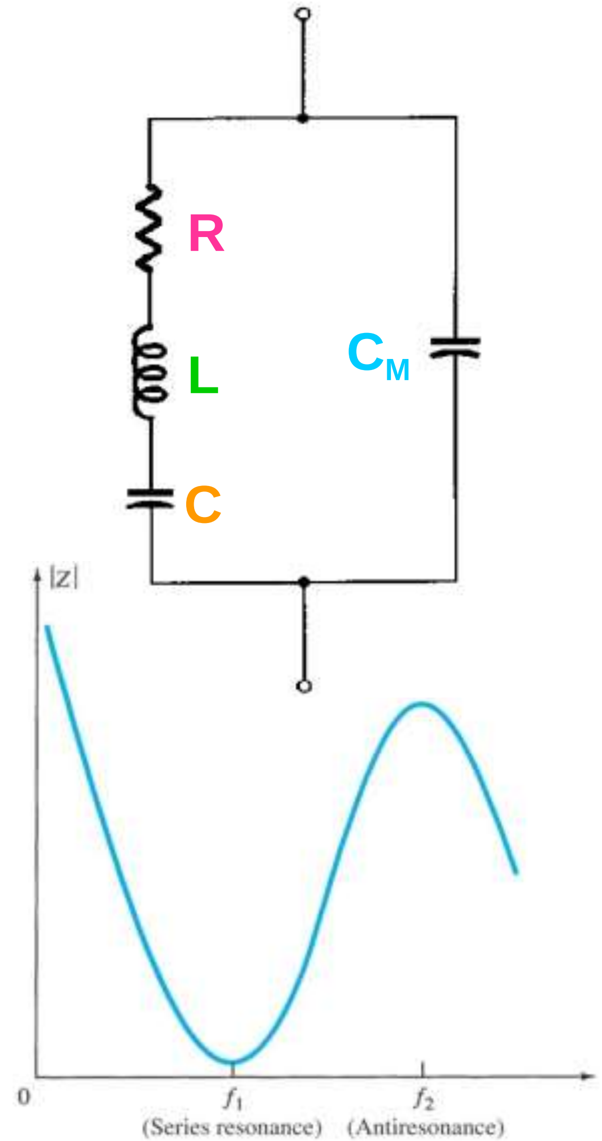


(a) Typical packaged crystal (b) Basic construction (without case) (c) Symbol (d) Electrical equivalent

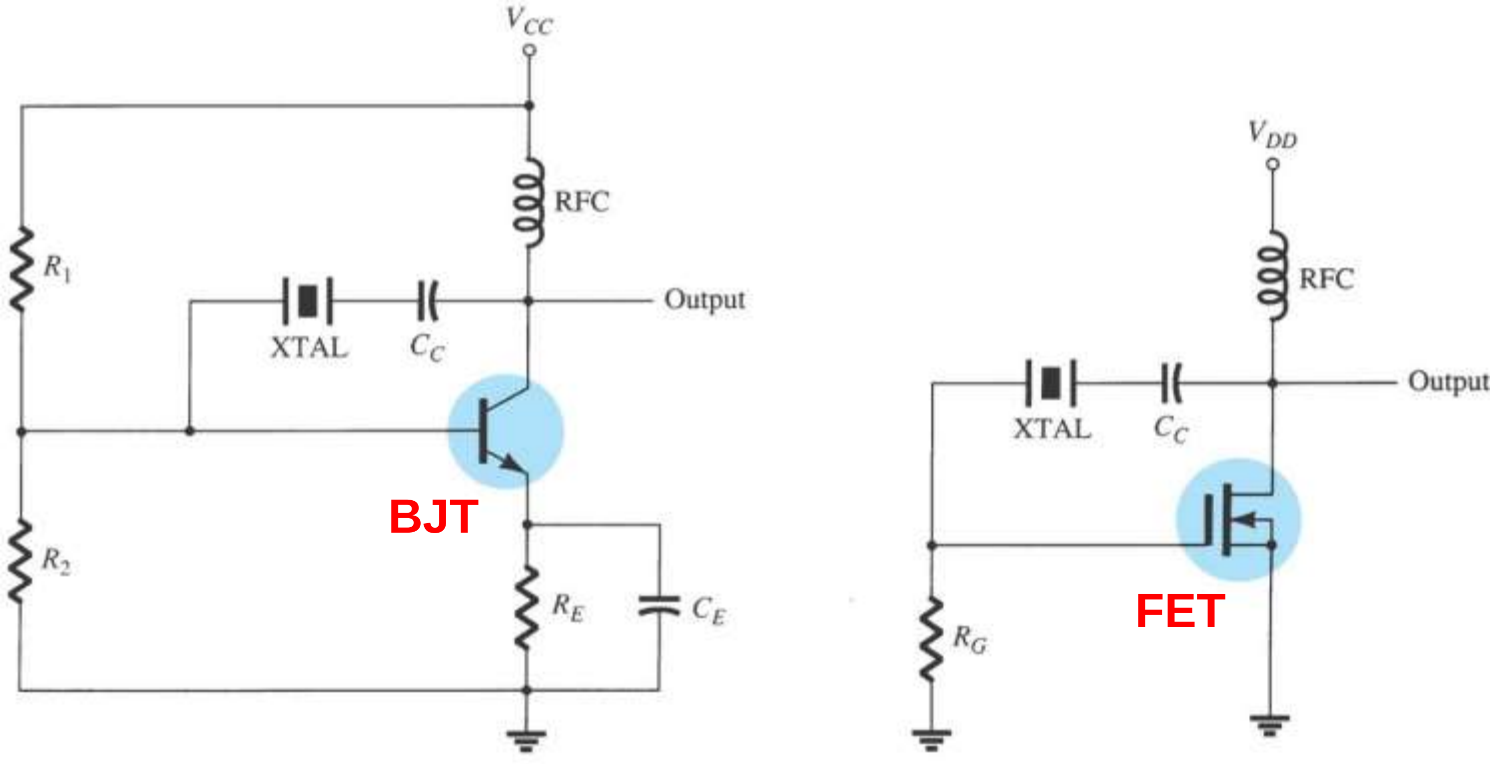
- Piezoelectric Effect
  - The quartz crystal is made of silicon oxide (SiO_2) and exhibits a property called the *piezoelectric*
  - When a changing an alternating voltage is applied across the crystal, it vibrates at the frequency of the applied voltage. In the other word, the frequency of the applied 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.

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 antiresonance) 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



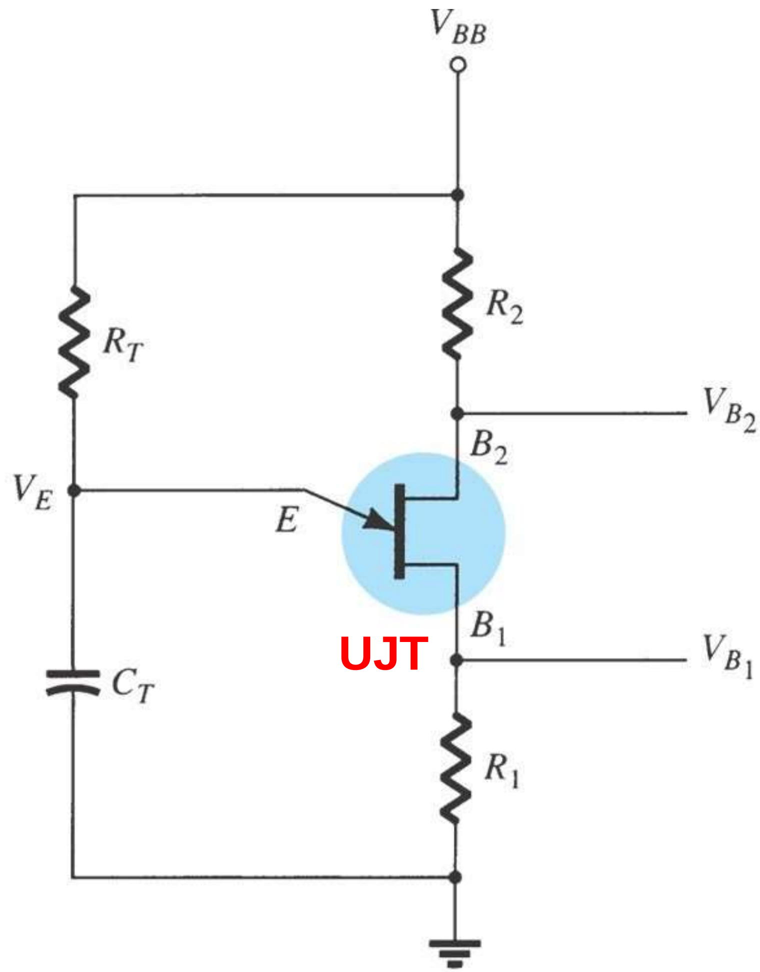
- The crystal is connected as a series element in the feedback path from collector to the base so that it is excited in the series-resonance mode



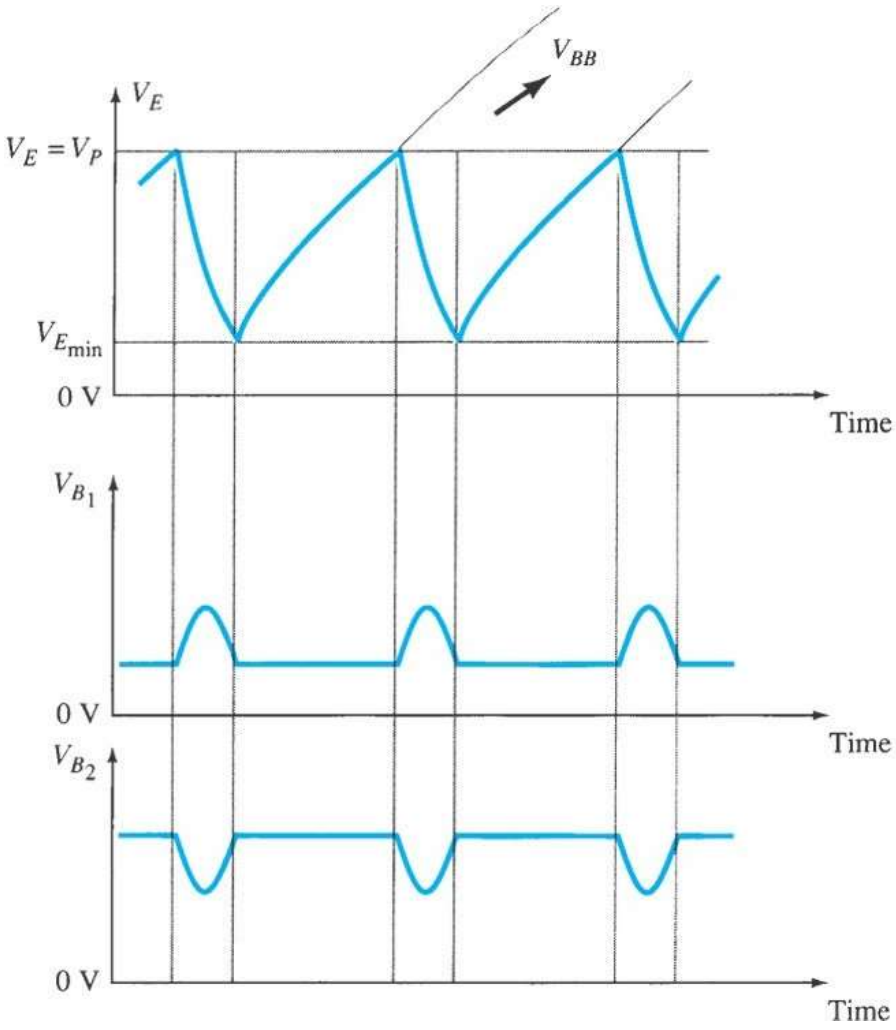
(a) (b)

- 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: $f_o = \dfrac{1}{2\pi\sqrt{LC_C}}$

- 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



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



- The oscillating frequency is calculated as follows:

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

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