Contents

Oscillators

How the feedback circuit provides operation as an oscillator is obtained by noting the denominator in the basic **negative feedback** equation,

$$A_f(\omega) = \frac{A(\omega)}{1 + \beta(\omega)A(\omega)}.$$

When $\beta(\omega)A(\omega) = -1$ or magnitude 1 at a phase angle of $180°$, the denominator becomes 0 and the gain with feedback, $A_f(\omega)$, becomes infinite. Thus, an infinitesimal signal (noise voltage) can provide a measurable output voltage, and the circuit will be unstable and have oscillations. So, this criterion

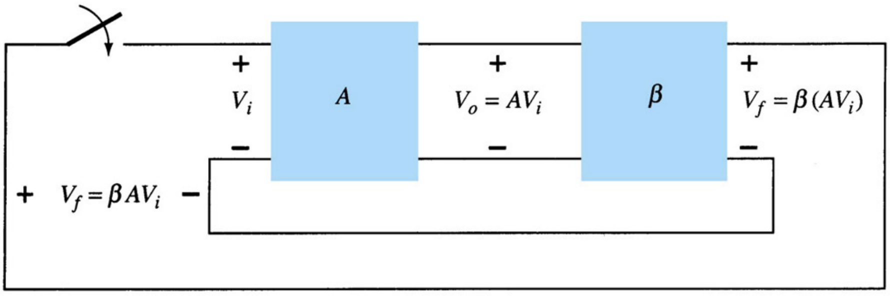
$$\beta(\omega)A(\omega) = -1$$

is known as the **Barkhausen criterion** for oscillation.
If we have the negative feedback loop-gain βA to be -1 only at a single frequency, i.e.,

$$\boxed{\beta(\omega_0)A(\omega_0) = -1,}$$

then we will have oscillations only at $\omega = \omega_0$.Thus, this circuit will act as an oscillator even without an input signal (noise in the circuit acts as an input signal), will be called an **oscillator circuit** where it produces a signal only at the frequency of $\omega = \omega_0$.

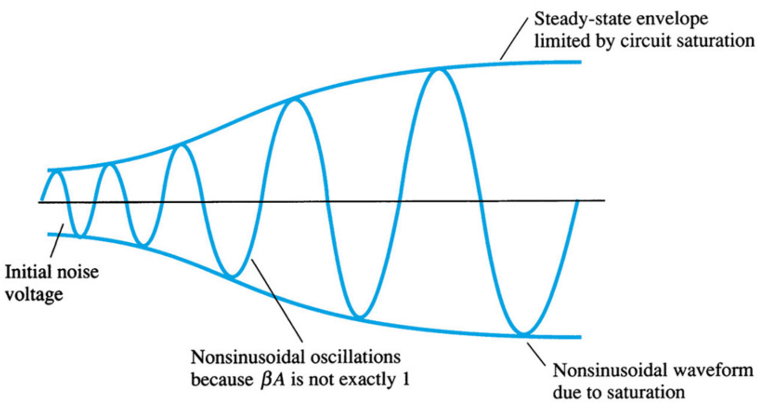
To understand how a feedback circuit performs as an oscillator, consider the **positive feedback** circuit below.



Consider that we have a fictitious voltage at the amplifier input, v_i. Thus, we have a feedback voltage $v_f = \beta A v_i$, where βA is referred to as the **loop-gain**. If the circuits of the base amplifier and feedback network provide βA of a correct magnitude and phase, v_f can be made equal to v_i. Then, when the switch is closed and fictitious voltage v_i is removed, the circuit will continue operating since the feedback voltage is sufficient to drive the amplifier and feedback circuits resulting in a proper input voltage to sustain the loop operation. The output waveform will still exist after the switch is closed if the condition $\beta A = 1$ is met.

In reality, no input signal is needed to start the oscillator going. Only the condition $\beta A = 1$ must be satisfied for self-sustained oscillations to result. In practice, βA is made greater than 1 and the system is started oscillating by amplifying **noise voltage**, which is always present. Saturation factors in the practical circuit provide an average value of $\beta A = 1$. The resulting waveforms are never exactly sinusoidal. However, the closer the value βA is to exactly 1, the more nearly sinusoidal is the waveform.

The figure below shows how the noise signal results in a buildup of a steady-state oscillation condition.

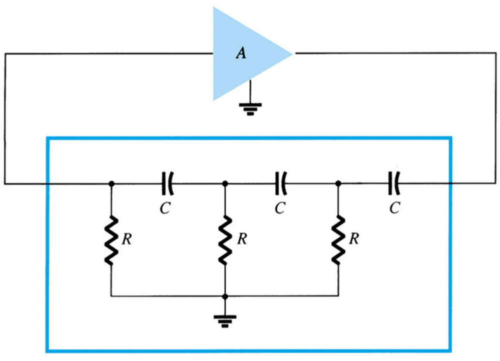


Types of Oscillator Circuits

Main classes of oscillator circuits are given below

1. Phase-Shift Oscillator
2. Wien-Bridge Oscillator
3. Tuned Oscillator Circuits
4. Crystal Oscillator
5. Unijunction Oscillator

Phase-Shift Oscillator

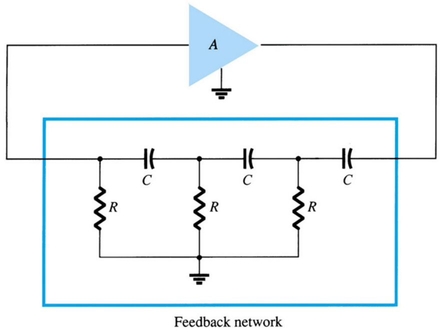


- In this configuration (where A is **negative**), feedback gain is given by

$$\beta(\omega) = \frac{1}{1 - 5\alpha^2 - j\,(6\alpha - \alpha^3)}$$

where $\alpha = 1/(\omega RC)$. The oscillation occurs at a frequency ω_0 where $\angle\beta(\omega_0) = 180°$. Thus, the oscillation frequency f_0 which cancels the imaginary part is given by

$$\boxed{f_0 = \frac{1}{2\pi RC\sqrt{6}}}$$



$$\beta(\omega) = \frac{1}{1 - 5\alpha^2 - j\left(6\alpha - \alpha^3\right)}$$

- As $\alpha|_{\omega_0} = \sqrt{6}$, feedback gain at the oscillation frequency is given by

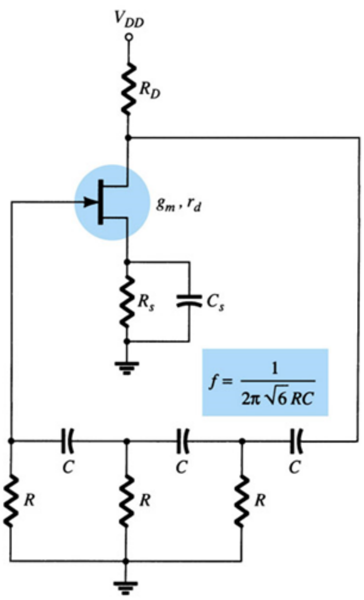
$$\beta(\omega_0) = -\frac{1}{29}$$

The amplifier must supply enough gain to compensate for losses. The overall gain must be unity. Thus, the absolute gain of the amplifier stage must be greater than $|1/\beta(\omega_0)|$, i.e.,

$$\boxed{|A| > 29.}$$

- The RC networks provide the necessary phase shift for a positive feedback. They also determine the frequency of oscillation.

FET Phase-Shift Oscillator



Example 1: It is desired to design phase-shift oscillator (as in the previous slide) using an FET having $g_m = 5\,\text{mS}$, $r_{ds} = 40\,\text{k}\Omega$, and feedback circuit resistor value of $R = 10\,\text{k}\Omega$. Select the value of C for oscillator operation at $1\,\text{kHz}$ and R_D for $A > 29$ to ensure oscillator operation.

Solution: Since $f_0 = \frac{1}{2\pi RC\sqrt{6}}$, we can solve for C as follows

$$C = \frac{1}{2\pi f_0 R\sqrt{6}} = \frac{1}{2\pi(1k)(10k)\sqrt{6}} = 6.5\,\text{nF}.$$

Next, we solve for R'_D where $R'_D = r_{ds}||R_D$ to provide a gain of $A = 40$ (this allows for some loading between R'_D and the feedback network input impedance):

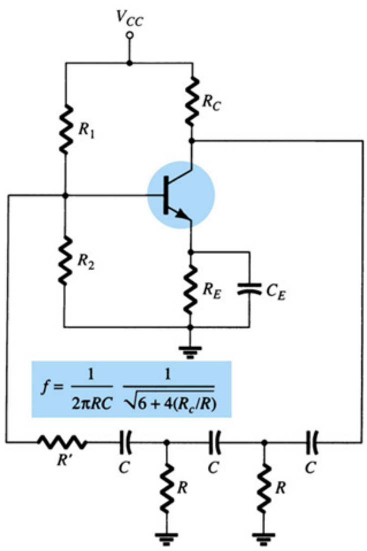
$$|A| = g_m R'_D = 40$$

$$R'_D = \frac{|A|}{g_m} = \frac{40}{5 \times 10^{-3}} = 8\,\text{k}\Omega.$$

Finally, we solve for R_D to be

$$R_D = \frac{r_{ds}R'_D}{r_{ds} - R'_D} = 10\,\text{k}\Omega.$$

BJT Phase-Shift Oscillator

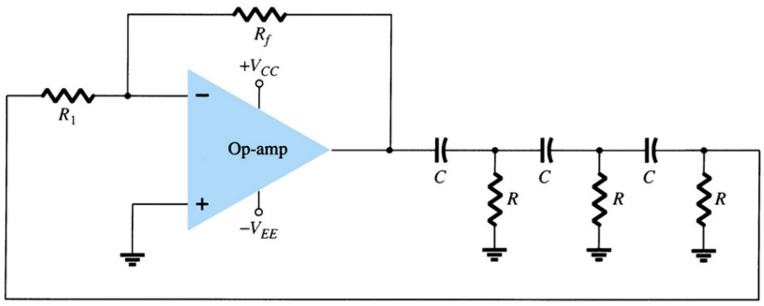


In the figure above: $R' = R - R_i = R - R_1||R_2||h_{ie}$.

For the loop-gain to be greater than unity, the requirement on the current gain of the transistor is found to be

$$h_{fe} > 23 + 29\frac{R}{R_C} + 4\frac{R_C}{R}.$$

Opamp Phase-Shift Oscillator

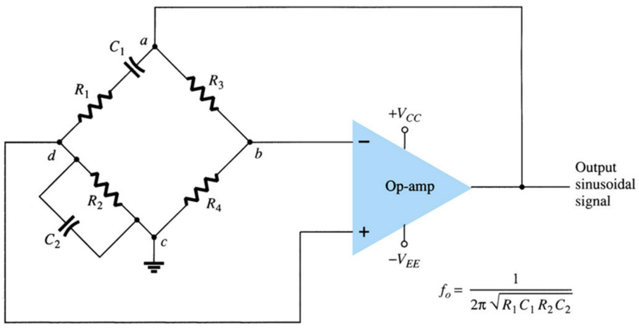


In the figure above, in order to sustain oscillation, i.e., $\beta(\omega_0)A(\omega_0) \geq 1$ we need to have

$$\frac{R_f}{R_1} \geq 29$$

.

Wien-Bridge Oscillator



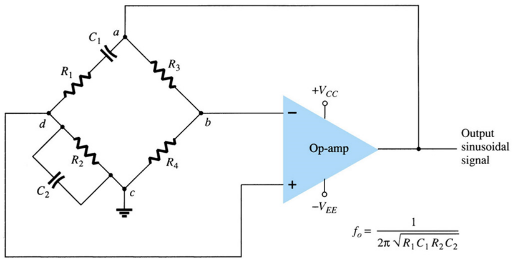
Let us first define $Z_1 = R_1 + Z_{C_1}$ and $Z_2 = R_2||Z_{C_2}$.

- Then, the positive feedback loop-gain is given as

$$\beta(\omega)A(\omega) = \underbrace{\frac{Z_2}{Z_1+Z_2}}_{\beta(\omega)} \underbrace{\left(1+\frac{R_3}{R_4}\right)}_{A(\omega)} = \frac{1}{1+Z_1/Z_2}\left(1+\frac{R_3}{R_4}\right)$$

In order to have the loop-gain to be 1, the Z_1/Z_2 needs to have **zero phase**, i.e., imaginary part needs to be zero. Thus, the oscillation frequency f_0 is found to be

$$\boxed{f_0 = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}}$$



- Hence, the positive feedback loop-gain at the oscillation frequency f_0 becomes

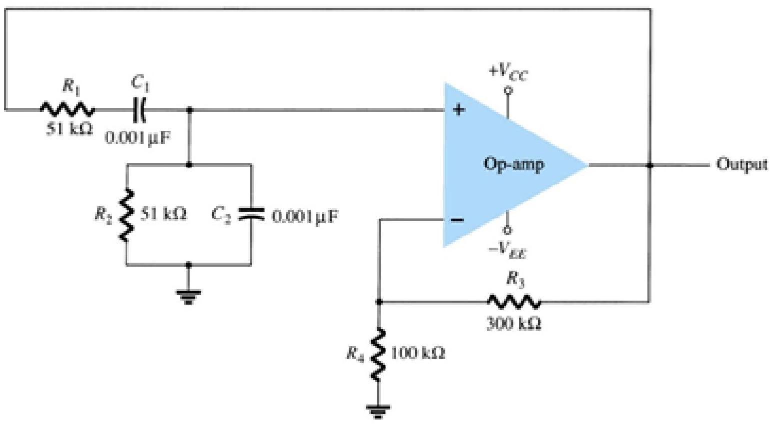
$$\beta(\omega_0)A(\omega_0) = \frac{1}{1+\left(\frac{R_1}{R_2}+\frac{C_2}{C_1}\right)}\left(1+\frac{R_3}{R_4}\right)$$

In order to sustain the oscillation, i.e., $\beta(\omega_0)A(\omega_0) \geq 1$,

$$\boxed{\frac{R_3}{R_4} \geq \frac{R_1}{R_2}+\frac{C_2}{C_1}}$$

- Thus, when $R_1 = R_2 = R$ and $C_1 = C_2 = C$, then

$$f_0 = \frac{1}{2\pi RC}$$
$$\frac{R_3}{R_4} \geq 2.$$



Example 2: Calculate the resonant frequency of the Wien bridge oscillator shown above.

Solution: Oscillation frequency is given by

$$f_0 = \frac{1}{2\pi RC} = \frac{1}{2\pi(51k)(1n)} = 3120.7\,\text{Hz}.$$

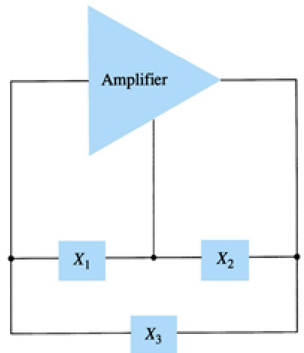
Example 3: Design the RC elements of a Wien bridge oscillator for operation at $f_0 = 10\,$kHz.

Solution: Using equal values of R and C, we can select $R = 100\,\text{k}\Omega$ and calculate the required value of C as

$$C = \frac{1}{2\pi f_0 R} = \frac{1}{2\pi(10k)(100k)} = 159\,\text{pF}.$$

We can use $R_3 = 300\,\text{k}\Omega$ and $R_4 = 100\,\text{k}\Omega$ to provide a ratio R_3/R_4 greater than 2 for oscillation to take place.

Tuned Oscillator Circuits



	Reactance Element		
Oscillator Type	X_1	X_2	X_3
Colpitts oscillator	C	C	L
Hartley oscillator	L	L	C
Tuned input, tuned output	LC	LC	—

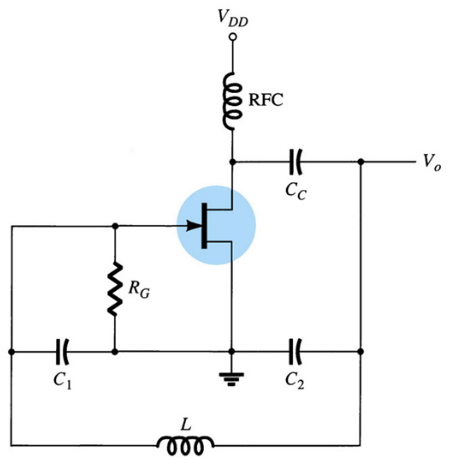
Tuned Oscillators use a parallel LC resonant circuit (LC-tank) to provide the oscillations.

There are two common types:

- **Colpitts:** The resonant circuit is an inductor and two capacitors.
- **Hartley:** The resonant circuit is a tapped inductor or two inductors and one capacitor.

Colpitts Oscillator Circuits

FET Colpitts Oscillator

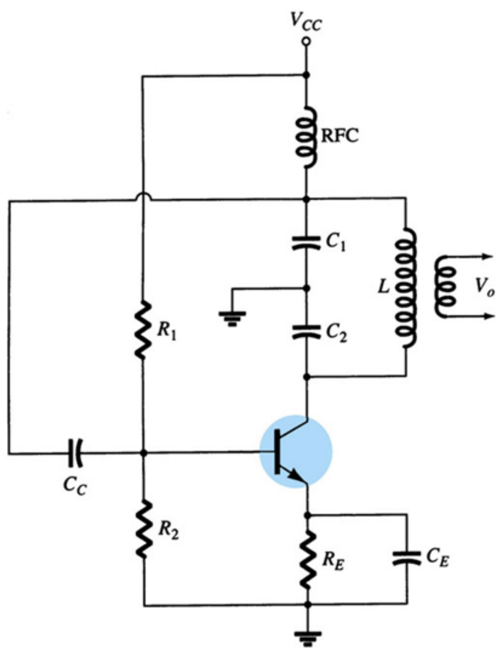


Oscillator frequency

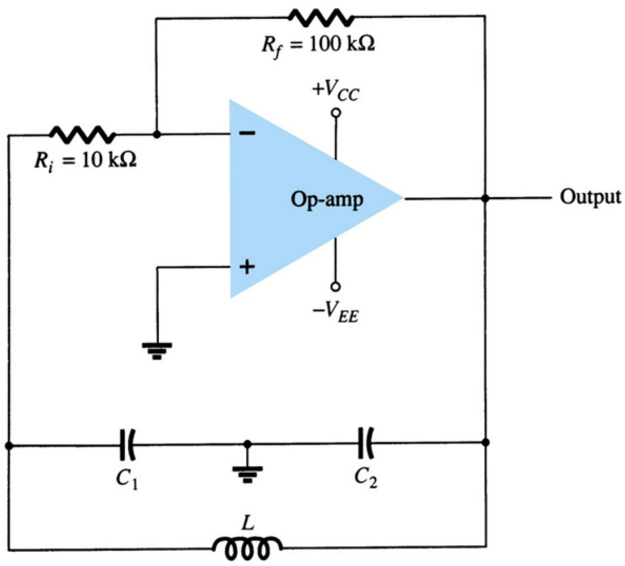
$$f_0 = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

where $C_{eq} = \dfrac{C_1C_2}{C_1 + C_2}$.

BJT Colpitts Oscillator

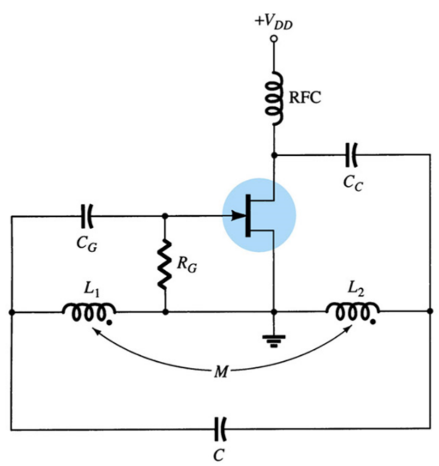


Opamp Colpitts Oscillator



Hartley Oscillator Circuits

FET Hartley Oscillator

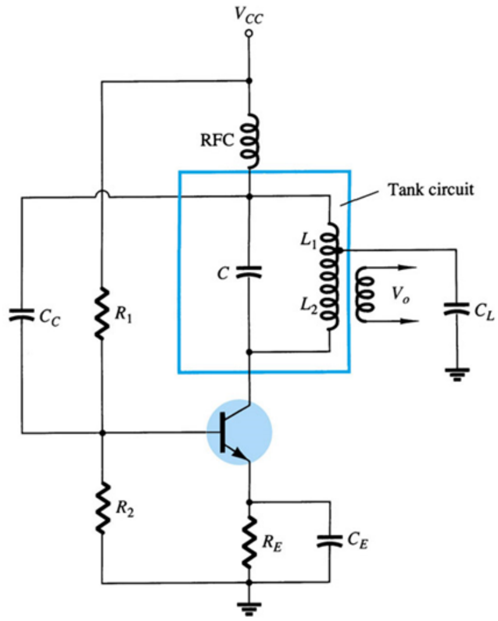


Oscillator frequency

$$f_0 = \frac{1}{2\pi\sqrt{L_{eq}C}}$$

where $L_{eq} = L_1 + L_2 + 2M$ with M denoting the mutual inductance.

BJT Hartley Oscillator



Crystal Oscillator

A crystal oscillator is basically a tuned-circuit oscillator using a piezoelectric crystal as a resonant tank circuit. The crystal (usually quartz) has a greater stability in holding constant at whatever frequency the crystal is originally cut to operate. Crystal oscillators are used whenever great stability is required, such as in communication transmitters and receivers.

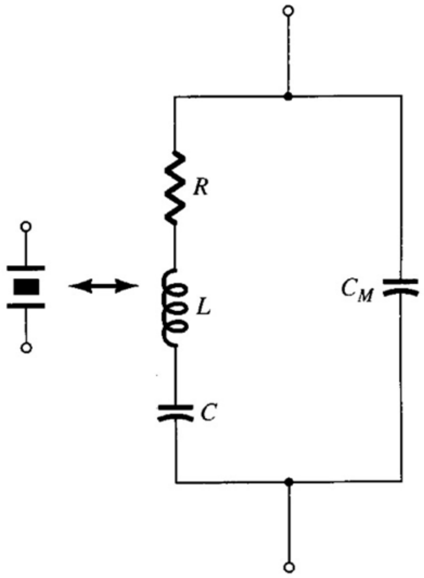
A **quartz** crystal (one of a number of crystal types) exhibits the property that when mechanical stress is applied across the faces of the crystal, a difference of potential develops across opposite faces of the crystal. This property of a crystal is called the **piezoelectric effect**. Similarly, a voltage applied across one set of faces of the crystal causes mechanical distortion in the crystal shape.

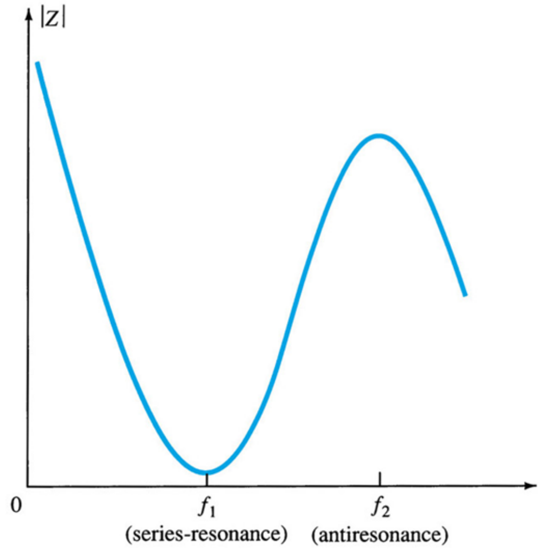
When alternating voltage is applied to a crystal, mechanical vibrations are set up. These vibrations having a natural resonant frequency dependent on the crystal. Although the crystal has electromechanical resonance, we can represent the crystal action by an equivalent **electrical resonant circuit**.

The crystal has two resonant frequencies as shown below:

- **Series resonant:** RLC determine the resonant frequency. The crystal has a low impedance.
- **Parallel resonant:** RL and C_M determine the resonant frequency. The crystal has a high impedance.

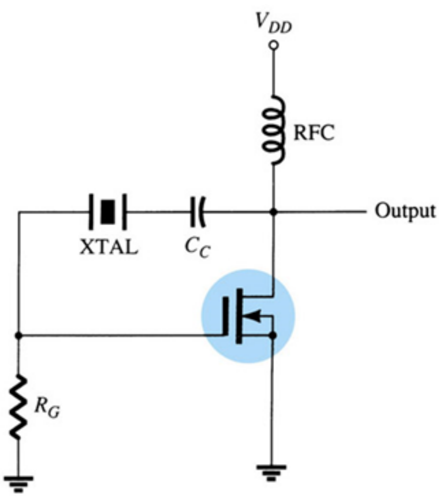
The series and parallel resonant frequencies are very close, within 1% of each other.



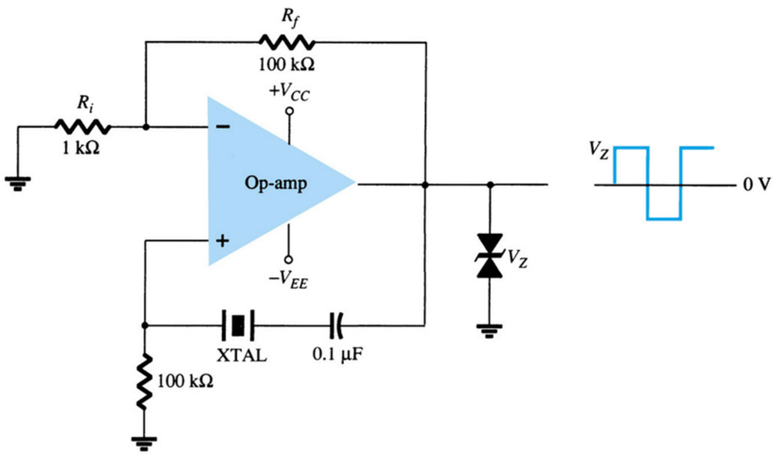


Series-Resonant Crystal Oscillator

Series-Resonant Crystal FET Oscillator

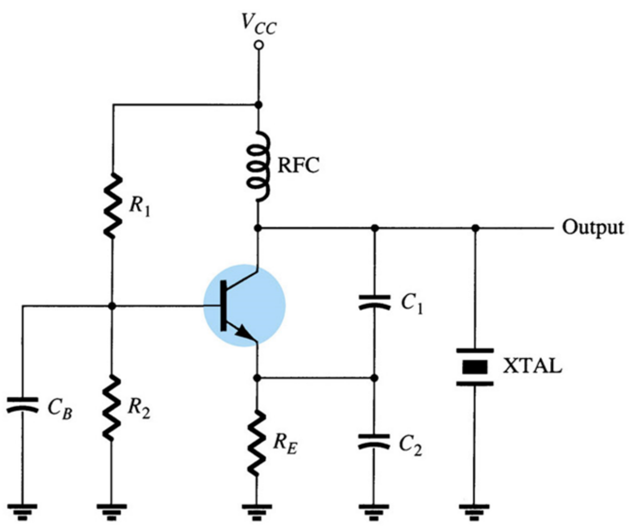


Series-Resonant Crystal Opamp Oscillator

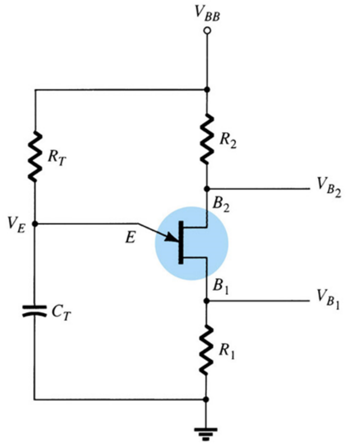


Parallel-Resonant Crystal Oscillator

Parallel-Resonant Crystal BJT Oscillator



Unijunction Oscillator



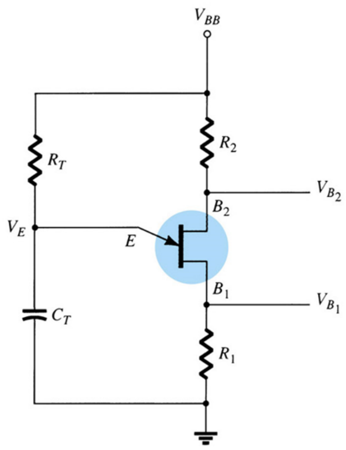
Unijunction transistor (UJT) can be used in a single-stage oscillator circuit to provide a **pulse signal** suitable for digital-circuit applications.

The unijunction transistor can be used in what is called a **relaxation oscillator** as shown by the basic circuit above. Resistor R_T and capacitor C_T are the timing components that set the circuit oscillating rate.

The oscillating frequency may be calculated as

$$f_0 = \frac{1}{R_T C_T \ln\left(\frac{1}{1-\eta}\right)}$$

where η is the unijunction transistor intrinsic stand-off ratio.



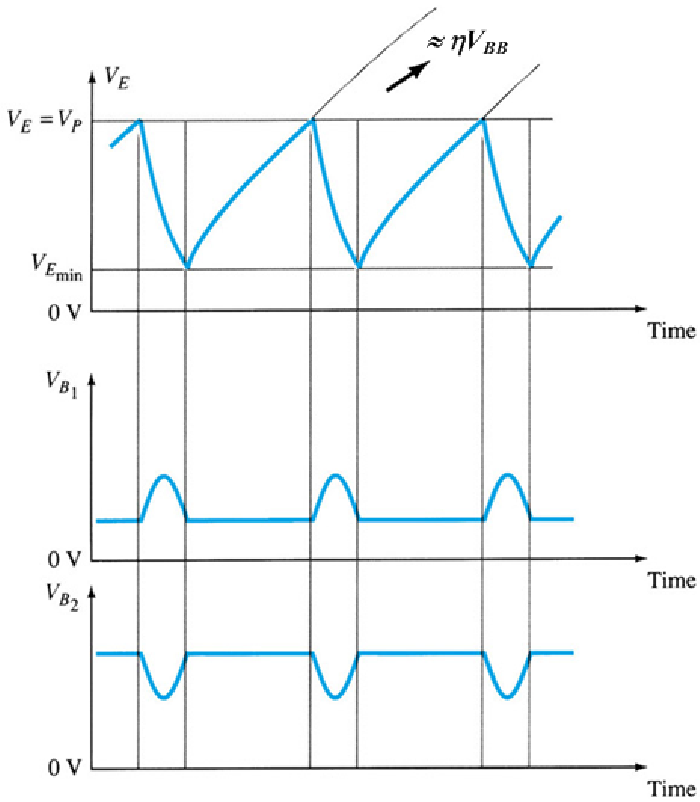
Typically, a unijunction transistor has a stand-off ratio from 0.4 to 0.6, i.e., $0.4 \leq \eta \leq 0.6$. Using a value of $\eta = 0.5$ gives us

$$f_0 \cong \frac{1.5}{R_T C_T}$$

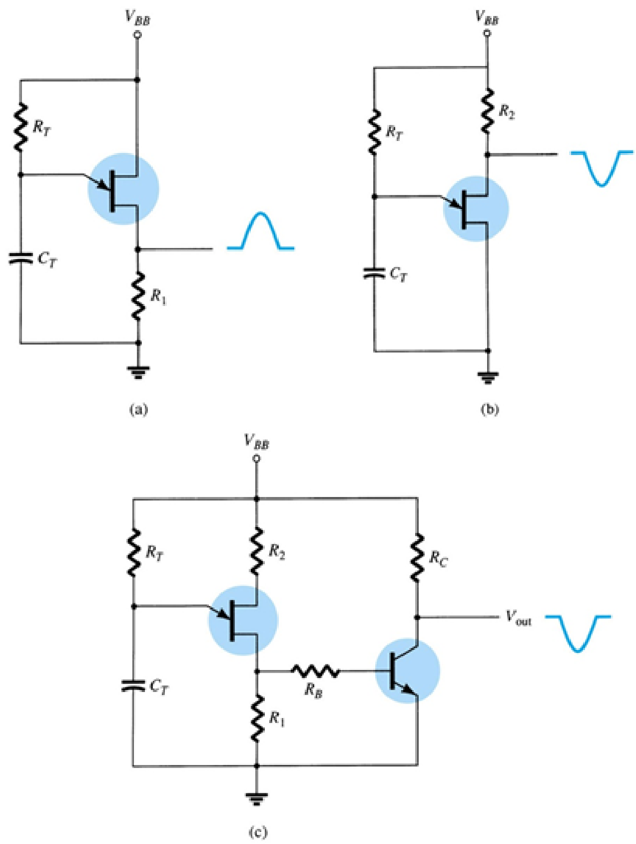
Capacitor C_T is charged through resistor R_T toward supply voltage V_{BB}. As long as the capacitor voltage V_E is below a stand-off voltage (V_P) given by

$$V_P = \eta\left(V_{B_2} - V_{B_1}\right) + V_{B_1} + V_{D(ON)} \cong \eta V_{BB} + V_{D(ON)}$$

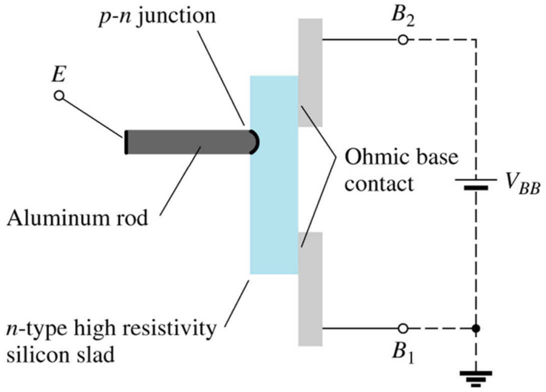
the unijunction emitter lead appears as an open circuit. When the emitter voltage across capacitor C_T exceeds this value (V_P), the unijunction circuit fires, discharging the capacitor, after which a new charge cycle begins.

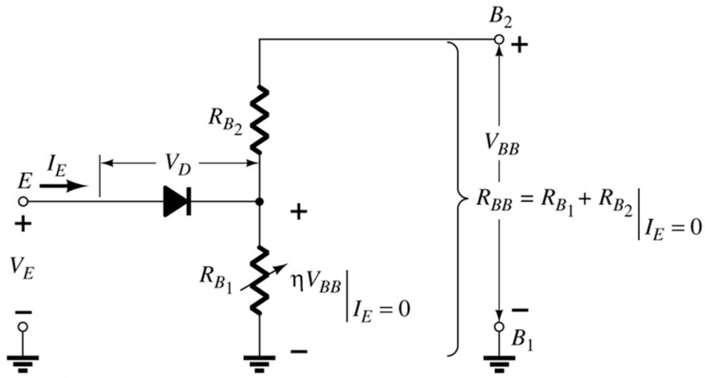


When the unijunction fires, a voltage rise is developed across R_1 and a voltage drop is developed across R_2 as shown above. The signal at the emitter is a **sawtooth voltage** waveform that at B_1 is a **positive-going pulse** and at B_2 is a **negative-going pulse**.



A few circuit variations of the unijunction oscillator are provided in the figure above.





Basic construction and equivalent circuit representation of the UJT is given in the figure above.