L - 9: Quartz Crystal Oscillators

1. Introduction

Crystals are naturally occurring or synthetically manufactured compounds exhibiting **piezoelectric effects.**

Meaning of Piezoelectric Effect

- A phenomenon by which under the influence of mechanical pressure, a voltage gets generated across the opposite faces of the crystal and vice versa.
  i.e.

  - If a mechanical force is applied so as to force the crystal to vibrate, an $a.c.$ voltage gets generated across it, or conversely,
  - If a crystal is subjected to $a.c.$ voltage it vibrates.

Every crystal (depending on the cut) has its own resonating frequency, so under mechanical vibrations a crystal generates an electric signal of constant frequency. A crystal has greater stability in holding the constant frequency

Types of crystals exhibiting piezoelectric effect;

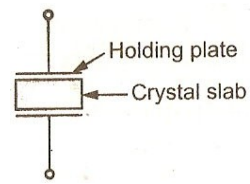
Types of crystal	Piezoelectric activities	Mechanical strength	Cost	Area of application
Rochelle Salts	Greatest	Weakest and can easily break	Intermediate	Microphones Headsets Loudspeakers
Quartz	Intermediate	Intermediate	Inexpensive	Transmitters Receivers RF oscillators RF Filters Watches
Tourmaline	Least	Strongest	Expensive	Rare in practice

- Rochelle Salts have the greatest piezoelectric activity, i.e. for a given $a.c.$ voltage they vibrate more than Quartz or Tourmaline
- Quartz is inexpensive and easily available in nature and hence very commonly used in crystal oscillators

A crystal oscillator is a tuned circuit oscillator using a piezoelectric crystal as its resonant tank circuit.

2. Constructional details

A quartz crystal is naturally hexagonal prism, but for its practical use it is cut to a rectangular slab. The slab is then mounted between two metal plates.



Construction

$A.C.$ Equivalent Circuit

- When the crystal is not vibrating, is equivalent to the capacitance due to the mechanical mounting of the crystal – mounting capacitance C_M
- When it is vibrating it experiences internal frictional losses – resistance R , while the mass of the crystal indicating its inertia being represented by an inductance L . In vibrating condition, it is having some stiffness, which can be represented by a capacitor C .

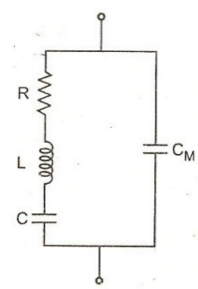
Let C_M - Mounting capacitance

The capacitance existing due to metal separation by dielectric-like crystal slab in shunt

R - Internal frictional losses due to vibrations,

L - Inertia due to the mass of the vibrating crystal,

C - Capacitance indicating stiffness in vibrating conditions.



Equivalent Circuit

R L C forms a resonating circuit

$$f_r = \frac{1}{2\pi\sqrt{LC}}\sqrt{\frac{Q^2}{1+Q^2}}\ ;\ Where\ \ Q = \frac{\omega L}{R}\ \text{- quality factor of crystal}$$

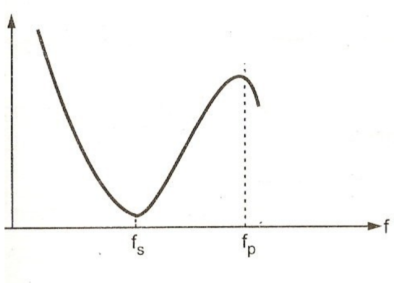
Since the quality factor of a crystal is very high $\sqrt{\frac{Q^2}{1+Q^2}} \approx 1$, hence $f_r = \frac{1}{2\pi\sqrt{LC}}$

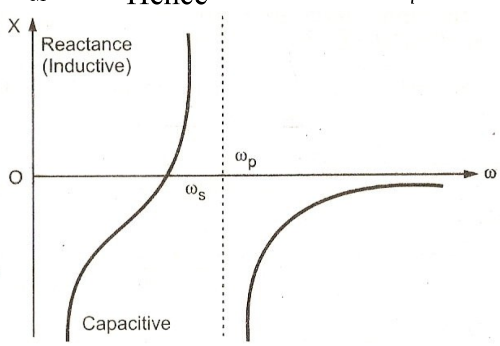
The crystal frequency is inversely proportional to the thickness of the crystal $f \, \alpha \, \frac{1}{t}$.

So to have very high frequencies, thickness of the crystal must be very small which makes the crystal mechanically weak and may get damaged under vibrations. Practical crystal oscillators are used up to $300\,kHz$

Series and Parallel Resonance

- Series resonance occurs when the reactances of the series $R \quad L \quad C$ leg are equal, i.e. $X_C = X_L$ hence $f_s = \frac{1}{2\pi\sqrt{LC}}$
- Parallel resonance (or antiresonance condition) occurs when the reactances of the series resonant leg equals the reactance of the mounting capacitance C_M . Under parallel resonance $C_{eq} = \frac{C_M C}{C_M + C}$ Hence $f_p = \frac{1}{2\pi\sqrt{LC_{eq}}}$





Crystal impedance Vs Frequency Reactance Vs Frequency

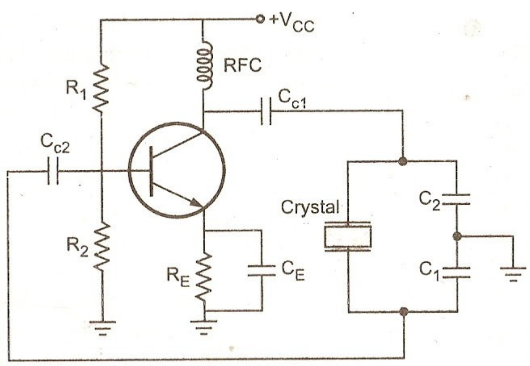
Factors affecting frequency stability of the crystal are:

- Temperature stability (change in frequency per degree change in temperature). When greater stability is required a crystal is kept in an oven (constant temperature box)
- Aging of the crystal material – long term stability. (Aging rate $= 2 \times 10^{-8}$ per year - negligible)
- Frequency drift with time – short term stability ¿ 0.0001% per day.

4. Analysis of Pierce Crystal Oscillator

Pierce Crystal Oscillator is a modification of Colpitt's Oscillator circuit whereby a crystal has replaced the inductor in the tank circuit.

Note: A crystal behaves as an inductor for frequencies slightly higher than the series resonance frequency



Functions of amplifier stage components

$R_1 \, and \, R_2$ - biasing resistance;

RFC (Radio frequency choke)- isolation between a.c. and d.c..

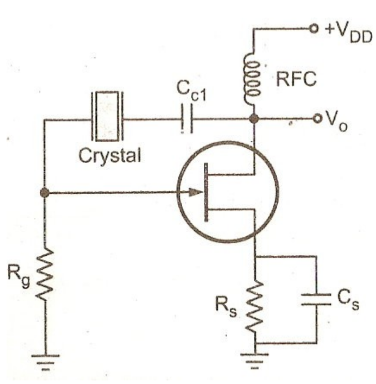
R_E -emitter circuit biasing resistor;

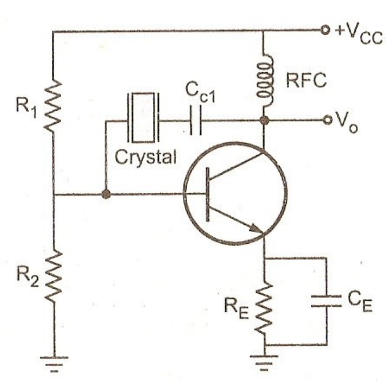
C_E -emitter bypass capacitor;

$C_1 \, and \, C_2$ -coupling capacitor

The resulting circuit frequency is set by the series resonating frequency of the crystal. Change in supply voltage, temperature and transistor parameters have no effect on the circuit operating condition hence good frequency stability is achieved.

Oscillator circuits can be modified by using the internal capacitance of transistor used instead of C_1 and C_2





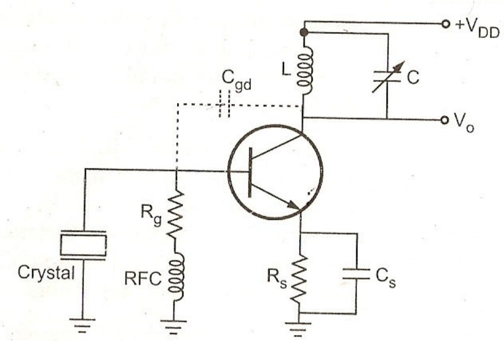
Pierce Crystal Oscillator using FET Pierce Crystal Oscillator using transistor

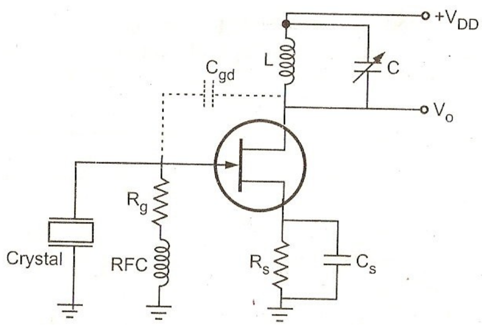
5. Analysis of Miller Crystal Oscillator

Mille Crystal Oscillator is a modification of Hartley Oscillator circuit whereby one of the inductors in the tank circuit has been replaced by a crystal. A crystal behaves as an inductor for frequencies slightly higher than the series resonance frequency.

The tuned circuit of L and C is off-tuned to behave as an inductor L_1 . The crystal behaves as another inductance L_2 between base and ground. The internal capacitance of the transistor acts as a capacitor to fulfill the elements of the tank circuit. The crystal decides the operating frequency of the oscillator .

Transistorized Miller Crystal Oscillator FET Miller Crystal Oscillator





Example

A crystal has $L=2\,H;\ C=0.01\,pF;\ and\ R=2\ k\Omega$. Its mounting capacitance is $2\ pF$. Calculate its (i) Series resonating frequency, (ii) Parallel resonating frequency

Solution

(i) $$f_s=\frac{1}{2\pi\sqrt{LC}}=\frac{1}{2\pi\sqrt{2\times0.01\times10^{-12}}}=1.125\,MHz$$

(ii) $$f_p=\frac{1}{2\pi\sqrt{LC_{eq}}}=\left|C_{eq}=\frac{(2\times0.01)\times10^{-12}}{(2+0.01)\times10^{-12}}=9.95\times10^{-15}\right|=\frac{1}{2\pi\sqrt{2\times9.95\times10^{-15}}}=1.128\,MHz$$