Crystals made clear I

Joe Carr explains how quartz crystals work, and how to get the best from them in a variety of oscillator circuits.

Radio-frequency oscillators can be built using a number of different types of frequency selective resonator. Common types include inductor-capacitor, i.e. *LC*, networks and quartz crystal resonators. The crystal resonator has, by far, the best accuracy and stability.

Piezoelectric crystals

Certain naturally-occurring and man-made materials exhibit the property of piezoelectricity: Rochelle salts, quartz and tourmaline are examples.

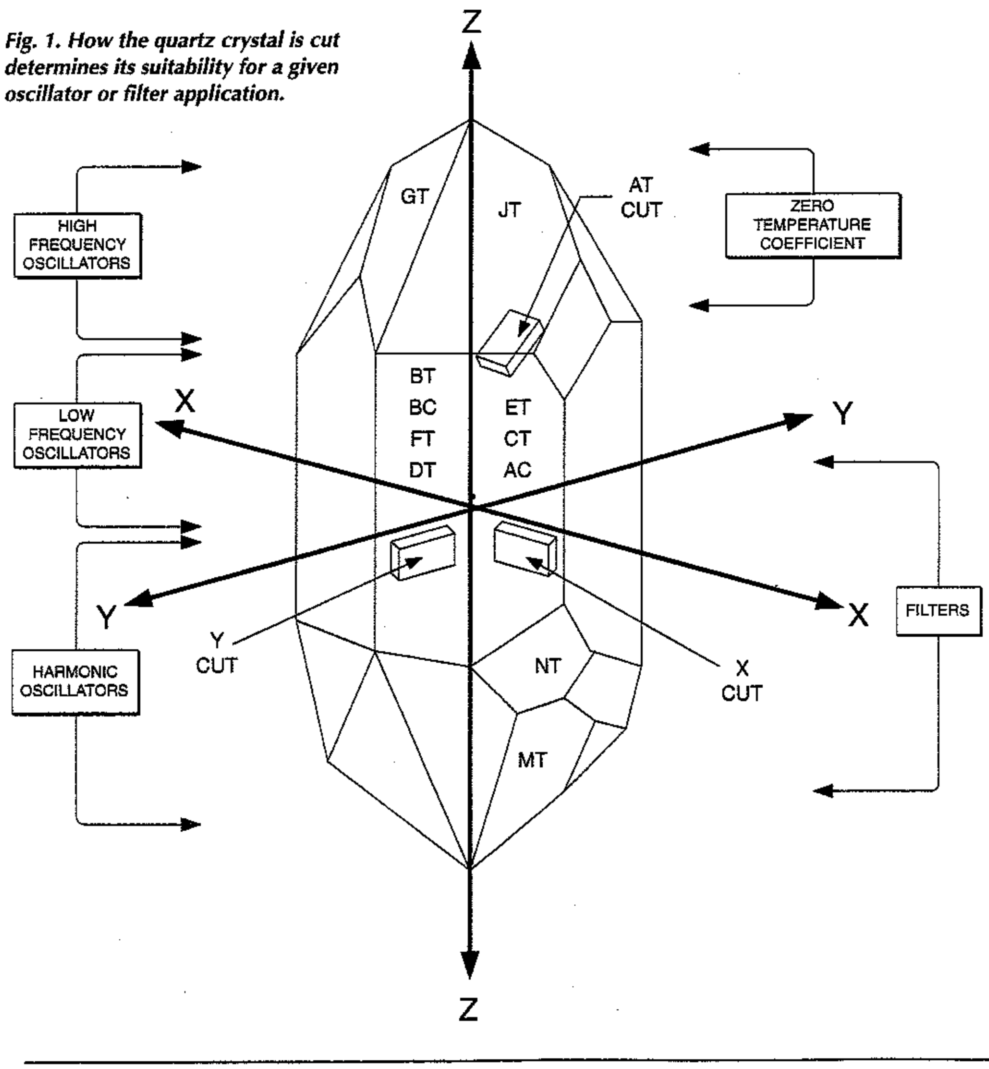
Rochelle salts crystals are not used for RF oscillators, although at one time they were used extensively for phonograph pick-up cartridges. Tourmaline crystals can be used for some RF applications, but are not often used due to high cost.

Tourmaline is considered a semiprecious stone, so tourmaline crystals are more likely to wind up as gemstones in jewelry than radio circuits. That leaves quartz as the preferred material for radio crystals.

Figure 1 shows a typical natural quartz crystal. Actual crystals rarely have all of the planes and facets shown. There are three optical axes – X, Y and Z – in the crystal used to establish the geometry and locations of various cuts.

The actual crystal segments used in RF circuits are sliced out of the main crystal. Some slices are taken along the optical axes, so are called Y-cut, X-cut and Z-cut slabs. Others are taken from various sections, and are given letter designations such as BT, BC, FT, AT and so forth.

Fig. 1. How the quartz crystal is cut determines its suitability for a given oscillator or filter application.



Piezoelectricity

All materials contain electrons and protons, but in most materials their alignment is random. This produces a net electrical potential in any one direction of zero. But

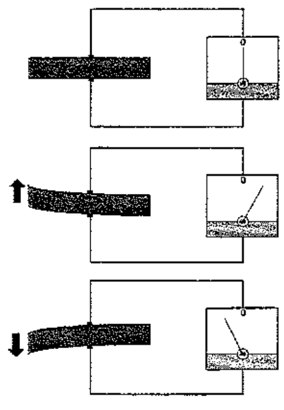


Fig. 2. Piezoelectric effect. Deflecting a quartz crystal in one direction produces a positive potential, deflecting it in the other produces a negative potential.

in crystalline materials the atoms are lined up, so can form electrical potentials. Piezoelectricity refers to the generation of electrical potentials due to mechanical deformation of the crystal.

Figure 2 shows the piezoelectric effect. A zero-center voltmeter is connected across a crystal slab. In the top circuit, the slab is at rest, so the potential across the surfaces is zero. But in the next circuit down, the crystal slab is deformed in the upward direction, and a positive potential is seen across the slab. When the crystal slab is deformed in the opposite direction, a negative voltage is noted.

If the crystal is mechanically 'pinged' once it will vibrate back and forth, producing an oscillating potential across its terminals, at its resonant frequency. Due to losses though the oscillation dies out in short order. But if the crystal is repetitively pinged, then it will generate a sustained oscillation on its resonant frequency.

It is not terribly practical though to stand there with a tiny hammer pinging the crystal all the while you want the the oscillator to run.

Fortunately though, piezoelectricity also works in the reverse mode: if an electrical potential is applied across the slab it will deform. Thus, if you amplify the output of the crystal, and then feed back some of the amplified output to electrically 're-ping' the crystal, then it will sustain oscillation on its resonant frequency.

Equivalent circuit

Figure 3a) shows the equivalent *RLC* circuit of a crystal resonator, while Fig. **3b)** shows the impedance versus frequency plot for the crystal.

There are four basic components of the equivalent circuit: series inductance, L_S, series Resistance, R_S, series capacitance, C_S, and parallel capacitance, C_P. Because there are two capacitances, there are two resonances: series and parallel. The series resonance point is where the impedance curve crosses the zero line, while parallel resonance occurs a bit higher on the curve.

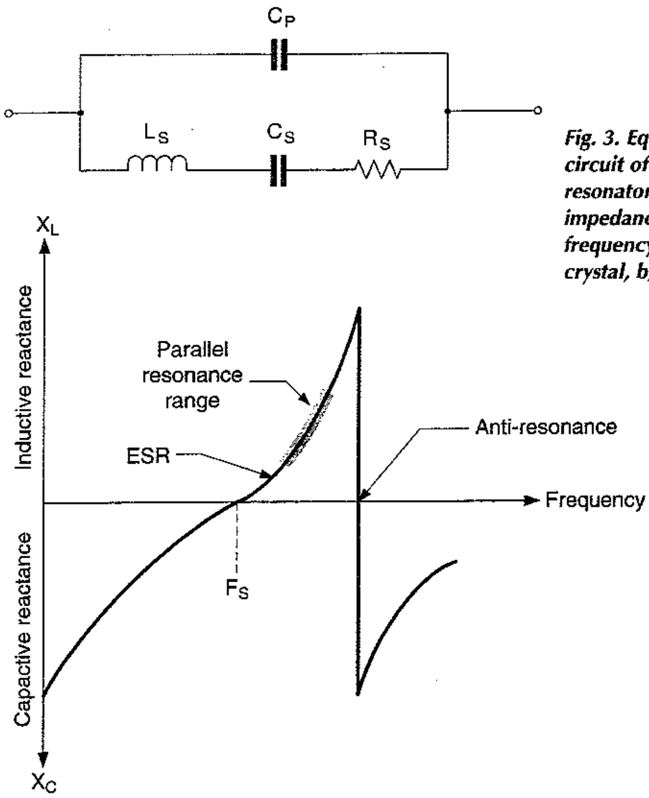


Fig. 3. Equivalent RLC circuit of a crystal resonator, a), and impedance versus frequency plot for the crystal, b).

Crystal packaging

Over the years a number of different packages have been used for crystals. Even today there are different styles. **Figure 4a)** shows a representation of the largest class of packages. It is a hermetically sealed small metal package, in various sizes. The actual quartz crystal slab is mounted on support struts inside the package, Fig. **4b)**, which are in turn mounted to either a wire header or pins.

Some crystals use pins for the electrical connections, and are typically mounted in sockets. The pin type of package can be soldered directly to a printed circuit board, but care must be taken to keep from fracturing the crystal with heat. Not all pins are easily soldered, although it can help if the pins are scraped to reveal fresh metal before soldering. Normally, however, if the crystal is soldered into the circuit a wire-lead package is used.

Some crystals may short circuit if installed on a printed circuit board with either through via holes or a ground plane on the top side of the board. In those cases, the usual practice is to insert a thin insulator between the PCB and the crystal, **Fig. 4c)**.

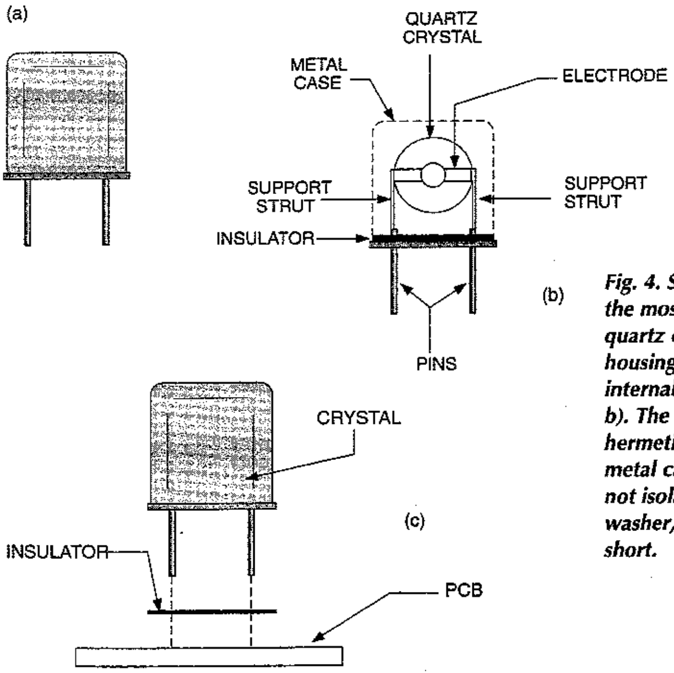


Fig. 4. Structure of the most common quartz crystal housing, a) and internal connections, b). The housing is an hermetically-sealed metal can which, if not isolated by a washer, may cause a short.

Temperature performance

There are three basic categories of crystal oscillator: room temperature crystal oscillators, or RTXOs, temperature compensated crystal oscillators, or TCXOs, and oven controlled crystal oscillators, OCXOs. Let's take a look at each of these groups.

Room-temperature crystal oscillators. The RTXO takes no special precautions about frequency drift. But with proper selection of crystal cut, and reasonable attention to construction, stability on the order of 2.5 parts per million, i.e. 2.5×10^{-6}, over the temperature range 0°C to 50°C is possible. The RTXO is only used on economy model counters used for non-critical applications.

Temperature-compensated crystal oscillators. The TCXO circuit also works over the 0°C to 50°C temperature range, but is designed for much better stability. The temperature coefficients of certain components of the TCXO are designed to counter the drift of the crystal, so the overall stability is improved to 0.5 PPM (5×10^{-7}). The cost of TCXOs has decreased markedly over the years to the point

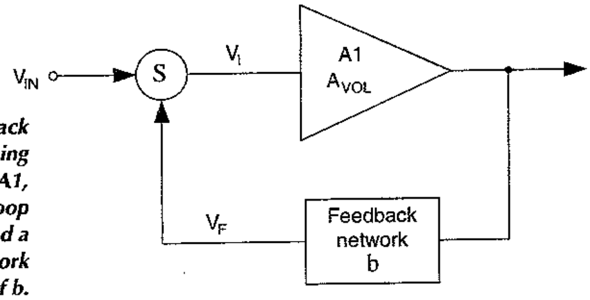


Fig. 5. Feedback oscillator comprising an amplifier, A1, with an open-loop gain of A_{vol} and a feedback network with a gain of b.

where relatively low cost upgrades to economy counters gives them a rather respectable stability specification.

Oven-controlled crystal oscillators. The best stability is achieved from the OCXO time base. These oscillators place the resonating crystal inside a heated oven that keeps its operating temperature constant, usually near 70°C or 80°C.

There are two forms of crystal oven used in OCXO designs, namely on/off and proportional control. The on/off type is similar to the simple furnace control in houses. It has a snap action that turns the oven heater on when the internal chamber temperature drops below a certain point, and off when it rises to a certain maximum point.

The proportional control type operates the heating circuit continuously, and supplies an amount of heating that is proportional to the actual temperature difference between the chamber and the set point. The on/off form of oven is capable of 0.1 ppm (10^{-7}).

Oven-controlled crystal oscillators that use a proportional control oven can reach a stability of 0.0002 ppm (2×10^{-10}) with a 20-minute warm-up and 0.0001 ppm (1.4×10^{-10}) after 24 hours.

It is common practice to design the counter to leave the OCTX turned on even when the counter is off. Some portable frequency counters, such as those used in two-way radio servicing, have a battery back-up to keep the OCXO turned on while the counter is in transit.

The variation described above is referred to as the temperature stability of the counter time base. We must also consider short-term stability and long-term stability, i.e. ageing.

Short-term stability

The short-term stability is the random frequency and phase variation due to noise that occurs in any oscillator circuit. It is sometimes also called either time domain stability or fractional frequency deviation.

In practice, the short-term stability has to be a type of RMS value averaged over one second. The short-term stability measure is given as $\sigma(\Delta f/f)(t)$. Typical values of short-term stability are given below for the different forms of clock oscillator.

RTXO	2×10^{-9}rms	0.002 ppm
TCXO	1×10^{-9}rms	0.001 ppm
OCXO, on/off	5×10^{-10}rms	0.0005 ppm
OCXO, prop.	1×10^{-11}rms	0.00001 ppm

Long-term stability

The long-term stability of the time base clock oscillator is due largely to crystal aging. The nature of the crystal, the quality of the crystal, and the plane from which the particular resonator was cut from the original quartz crystal are determining factors in defining aging. This figure is usually given in terms of frequency units per month.

RTXO	3×10^{-7}/month	0.3 ppm
TXCO	1×10^{-7}/month	0.1 ppm
OCXO, on/off	1×10^{-7}/month	0.1 ppm
OCXO, prop.	1.5×10^{-8}/month	0.015 ppm
OXCO, prop.	5×10^{-10}/day	0.0005 ppm

Feedback oscillators

A feedback oscillator, **Fig. 5**, consists of an amplifier, A1, with an open-loop gain of A_{vol} and a feedback network with a gain –or transfer function – β. It is called a 'feedback oscillator' because the output signal of the amplifier is fed back to the amplifier's own input by way of the feedback network.

Figure 5 is a block diagram model of the feedback oscillator. That it bears more than a superficial resemblance to a feedback amplifier is no coincidence. Indeed, as anyone who has misdesigned or misconstructed an amplifier knows all too well, a feedback oscillator is an amplifier in which special conditions prevail. These conditions are called Barkhausen's criteria for oscillation:

- Feedback voltage must be in-phase – at 360° – with the input voltage.
- Loop gain βA_{vol} must be unity (1).

The first of these criteria means that the total phase shift from the input of the amplifier, to the output of the amplifier, around the loop back to the input, must be 360°, i.e. 2π radians, or an integer (N) multiple of 360°, i.e. $N2\pi$ radians.

The amplifier can be any of many different devices. In some circuits it will be a common-emitter bipolar transistor, either n-p-n or p-n-p. In others it will be a junction field-effect transistor (JFET) or metal-oxide semiconductor field effect transistor (MOSFET). In older equipment it was a vacuum tube.

In modern circuits the active device will probably be either an integrated circuit operational amplifier, or some other form of linear IC amplifier.

The amplifier is most frequently an inverting type, so the output is out of phase with the input by 180°. As a result, in order to obtain the required 360° phase shift, an additional phase shift of 180° must be provided in the feedback network at the frequency of oscillation only. If the network is designed to produce this phase shift at only one frequency, then the oscillator will produce a sine wave output on that frequency.

In Fig. 5 you can see that:

$$V_i=V_{in}+V_F \quad (1)$$

So,

$$V_{in}=V_i-V_F \quad (2)$$

and also,

$$V_F=\beta V_O \quad (3)$$

$$V_O=V_iA_{VOL} \quad (4)$$

The transfer function (or gain) A_v is:

$$A_V=\frac{V_O}{V_{IN}} \quad (5)$$

Substituting equations (2) and (4) into equation (5),

$$A_V=\frac{V_iA_{vol}}{V_i-V_F} \quad (6)$$

From equation (3), $V_F=\beta V_O$, so

$$A_V=\frac{V_iA_{vol}}{V_i-\beta V_O} \quad (7)$$

But equation 4 shows that $V_o = V_i A_{vol}$, so equation (7) can be written,

$$A_V = \frac{V_i A_{vol}}{V_i - \beta V_i A_{vol}} \quad (8)$$

and, dividing both numerator and denominator by V_i,

$$A_V = \frac{A_{vol}}{1 - \beta A_{vol}} \quad (9)$$

Equation (9) serves for both feedback amplifiers and oscillators. But in the special case of an oscillator $V_{in}=0$, so $V_o \to \infty$. Implied, therefore, is that the denominator of Equation (9) must also be zero,

$$1 - \beta A_{vol} = 0$$
(10)

Therefore, for the case of the feedback oscillator,

$$\beta A_{vol} = 1$$
(11)

The term βA_{vol} is the loop gain of the amplifier and feedback network, so equation (11) meets Barkhausen's second criterion. Thus, when these conditions are met the circuit will oscillate. Hopefully, what we intended to design was an oscillator, and not an amplifier.

In a crystal oscillator, amplified noise in the circuit at start up initiates the crystal oscillation, but it is the feedback voltage that is used to continuously 're-ping' the crystal to keep it oscillating.

General types of rf oscillator circuits

There are several different configurations for RF oscillators, but the fundamental forms are Colpitts and Hartley. **Figure 6** shows the basic difference between these two oscillators. Keep in mind that these are block diagrams, not circuit diagrams, so the apparent 'short' through the coil from the output to ground is not a problem here – there is no DC.

The Colpitts oscillator is shown in Fig. **6a)**. The oscillator is tuned by the resonance between inductor L_1 and the combined capacitance of C_1 and C_2 in series. In actual oscillators there will also be a tuning capacitor in parallel with L_1, and the total capacitance used in resonance will include the tuning capacitance, plus C_1 and C_2 in series.

The characteristic that distinguishes the Colpitts oscillator is that the feedback network consists of a tapped capacitive voltage divider, C_1/C_2. Output from this voltage divider is fed back to the input of amplifier A1.

A special variation on the Colpitts theme is the Clapp oscillator. The difference is that the Colpitts uses parallel resonant tuning, while the Clapp uses series-resonant tuning. Otherwise, they are identical – both use the capacitive voltage divider. Both variations on the Colpitts theme find extensive use in RF crystal oscillator circuits.

The Hartley oscillator is shown in Fig. **6b)**. Here, the tuning is done by an LC network, as in other RF oscillators, consisting of L_1 and C_1. The Hartley oscillator is identified by the fact that tapping the tuning inductor L_1 derives the feedback voltage.

Variations on the Hartley theme use a tapped coil as part of the feedback network, but a crystal to actually set the frequency of oscillation.

Colpitts crystal oscillator circuit

Figure 7 shows a basic Colpitts oscillator circuit. The active element is an n-p-n bipolar transistor, although in circuits to be discussed later FET and IC versions will be shown.

The transistor's DC bias is derived from resistor R_1 connected between V+ and the transistor base terminal. The crystal resonator is connected from the base to ground on this common emitter circuit. This circuit is usable from about 1MHz to 18MHz or so.

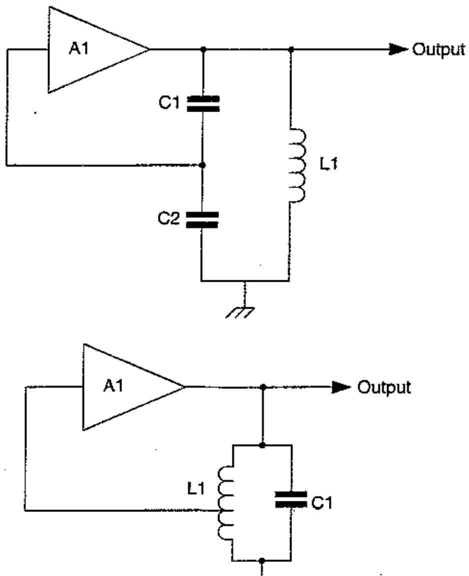


Fig. 6. In the Colpitts oscillator, L₁ and C₁,₂ combined determine resonance, a). In the Hartley oscillator, b), tuning is determined by L₁ and C₁.

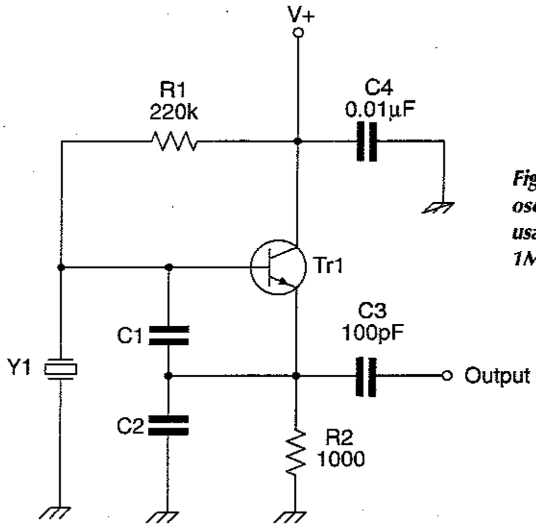


Fig. 7. Colpitts oscillator. This circuit is usable from about 1MHz to 18MHz or so.

The circuit of Fig. 7 is a Colpitts oscillator, so uses a capacitive voltage divider, C_1 and C_2, for the feedback network. When this circuit is initially turned on, current will begin to flow collector-to-emitter. When this current first flows the crystal is electrically pinged, so will begin to oscillate.

Following initial start-up, a sample of the signal at the emitter is fed to C_1/C_2, and from there to the base. Because the emitter AC signal voltage is in phase with the base signal voltage, the Barkhausen requirements are met.

Some experimentation will yield the optimum values of C_1, C_2 and R_2 to ensure proper starting and running. The general rule for R_1 is to use the lowest value that will permit sure starting when the circuit is powered up.

There seems to be two approaches to finding values for C_1 and C_2 presented in the literature, but both assume that the total capactive reactance of the two capacitors in series is 300Ω. In one scheme, the initial trial values require $C_1=C_2$, while in other recommendations $C_2=3C_1$ or $4C_1$. ■

In a second article on this topic, Joe takes a look at practical crystal oscillator circuits, including additional Colpitts variants, overtone oscillators and other forms.