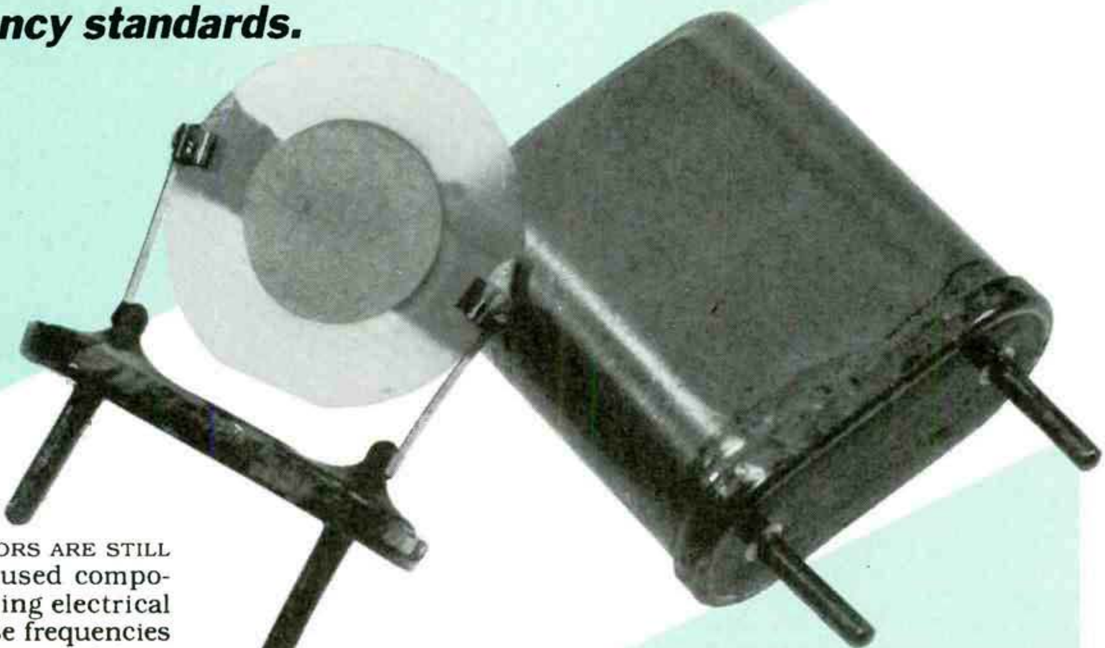
Learn the fundamentals of crystal resonators —how and why they work in oscillators and frequency standards.

DAN BECKER



CRYSTAL OSCILLATORS

CRYSTAL RESONATORS ARE STILL the most widely used components for converting electrical energy into precise frequencies for communications and timing. Among the many instruments, products, and systems that depend on crystals to produce their precise, stable frequencies are frequency counters, radio transmitters, electronic navigation systems (transmitters and receivers), TV sets, and VCR's.

This article reviews the fundamentals of crystal resonators. Because of their utility and low cost, it emphasizes those made from quartz—how and why they work. The distortion of crystal resonators by the application of an alternating voltage across its faces is explained by the piezoelectric effect. Although synthetically produced quartz is still the leading material for manufacturing piezoelectric resonators, many other natural and man-made materials exhibit similar properties.

The information presented here is an introduction to the second installment in this series addressing the design and application of crystal-controlled oscillators such as the Colpitts, Pierce, and Butler. These oscillators, originally designed as vacuum-tube oscillators, have been adapted to transistors, and they include crystal resonators.

Armed with the information we'll present on the mechanical and electrical properties of crystal resonators, you'll have a better understanding of how to purchase and use low-cost crystals in your experiments or electronic projects.

Properties of crystals

The starting point in this subject is crystallography, the study of the form, structure, properties, and classification of crystals. This specialized subject linking physics, chemistry, geology, and mechanical engineering, is usually touched on only briefly in formal electronics engineering courses. With the wealth of subject matter to cover, instructors rarely say much about crystal resonators except to note that they are readily available components and can be viewed as electrically equivalent to high-Q LCR tank circuits.

Crystallography deals with lattices, bonding, and the behavior of slices that have been cut at various angles with respect to the crystal's axes. The mechanical properties of crystal lattices permit the important piezoelectric effect. Sections of crystal blanks that have been cut and polished according to well known rules vibrate when alternating voltages are applied across their faces.

The dimensions of the crystal slice—particularly its thickness and where and how it was cut from the blank— determine its electrical and mechanical properties. Other factors are the form of the electrodes and how the crystal is supported.

A resonant crystal's behavior can be simulated as either a parallel or series tank circuit with capacitors, an inductor, and a resistor. As tank circuits, crystals have figures of merit or Q's that are orders of magnitude superior to those of discrete-component resonant circuits.

Piezoelectric effect.

To understand how and why a crystal resonates as a tank circuit, it is necessary to understand the *piezoelectric effect*. Occurring in both man-made and natural crystals, there are two reciprocal modes to this effect. The first, as shown in Fig. 1-*a*, is the generation of a voltage between the opposite faces of a piezoelectric crystal as a result of stressing the crystal along its longitudinal axis.

The stress can take the form of squeezing (compression), stretching (tension), twisting (torsion), or shearing. In fact, if the crystal is stressed periodically, the output voltage will be alternating. This effect can be seen by observing needle swing on a high-impedance voltmeter or as an alternating wave on an oscilloscope.

The second mode, shown in Fig. 1-*b*, is the mechanical deformation of the crystal caused by the application of a voltage across the opposite faces of the crystal. The degree of deformation will depend on the characteristics of the drive signal as well as those of the crystal cut. The application of an AC signal will produce periodic longitudinal, shearing or flexural motion.

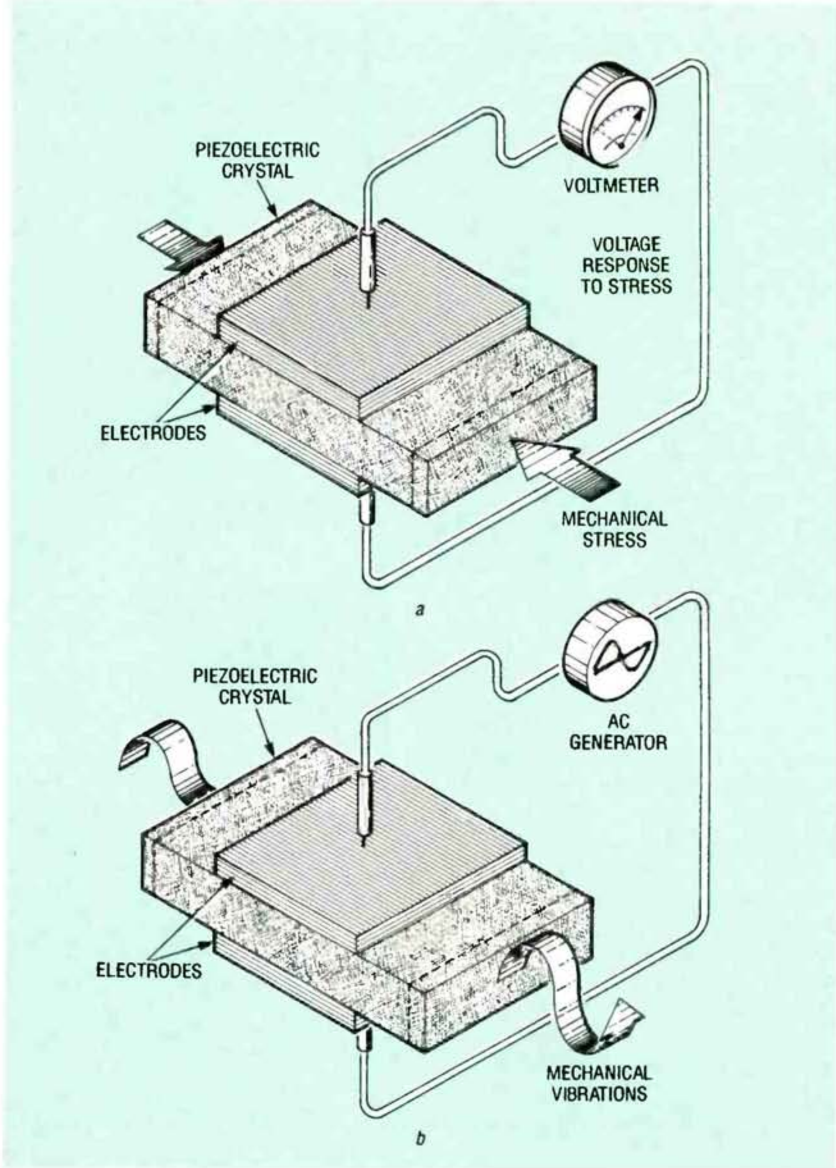


FIG. 1—THE PIEZOELECTRIC EFFECT IS RECIPROCAL. Stressing the crystal will generate a voltage which causes the meter needle to jump, a, and applying an alternating electrical signal across the electrodes will cause the crystal to be mechanically deformed, b.

In Fig. 1 the electrodes make the electrical connection to an external drive or output circuit. Here the thickness of the electrodes has been exaggerated; in practical resonators they are thin films of metal deposited on the opposing faces of the thinnest section of crystal, similar to the plates of a ceramic-disc capacitor.

The piezoelectric mode shown in Fig. 1-*a* is applied in crystal microphones, strain gauges, and receiving elements in depth sounders, for example. In those applications they are known as transducers. By contrast, the applications for the mode illustrated in Fig. 1-*b* include frequency standards for telecommunications, as frequency generators, and as time standards in watches, clocks and timebase generators. That mode is also applied in ultrasound generators and cleaning machines, and the transmitting elements of depth sounders, where they are also known as transducers. In depthsounders and ultrasonic diagnostic equipment, the transducer can function both as a transmitting and receiving element.

The piezoelectric effect is exhibited by many natural and man-made crystals; the most important natural crystals are quartz, Rochelle salt, and tourmaline. There are also many man-made piezoelectric elements such as ADP, EDT, and DKT that are used as filters and transducers. However, synthetic quartz is still the most widely used material for oscillator frequency control because of its permanence, low temperature coefficient, and high mechanical Q.

Crystal resonance

The mechanical resonant frequency of a crystal can be determined by applying an alternating voltage from a signal generator (whose range extends

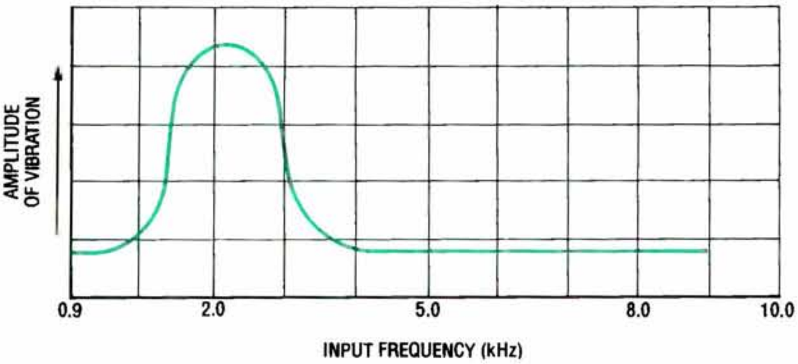


FIG. 2—A CRYSTAL'S RESONANT FREQUENCY can be determined by sweeping the input frequency until an amplitude peak representing mechanical resonance is seen on an oscilloscope.

over the likely resonance frequency) across the crystal faces. As shown graphically in Fig. 2, the applied frequency is slowly changed while observing the amplitude of the trace on an oscilloscope, the resonant frequency of a piezoelectric crystal under test can be found visually. The mechanical resonance of the crystal shown occurs at about 2.2 kHz.

The mechanical vibrations within a piezoelectric crystal slice are called *bulk acoustic waves* (BAW's). In general, the thinner (and smaller) the crystal slice, the more rapid will be the mechanical vibrations and the higher will be its resonant frequency.

Figure 3 is a perspective drawing showing various crystal cuts from a quartz blank. The orientation of the cut with respect to the blank's major crystallographic axes strongly influences its piezoelectric properties and temperature stability.

There are three principal crystal axes: X, Y, and Z (known as the *optical axis*). Figure 3 shows some of the most popular cuts and how they are oriented with respect to each other. They are designated by two letter symbols. Examples are AT, BT, CT, DT, ET, AC, GT, and JT. The angles shown relate the edges of the cuts to the blank's principal axes.

Each cut has special characteristics. The AT cut is the most popular for high-frequency and very-high frequency crystal resonators. The AT cut exhibits high frequency shear and produces a fundamental in the 800 kHz to 25 MHz range. However, it overtones (to be discussed later) permit operation up to 200 MHz. The CT and DT cuts exhibit low-frequency shear and are most useful in the 100- to 500-kHz range. The MT cut vibrates longitudinally and is useful in the 50- to 100-kHz range while the NT cut flexes and has a useful range under 50 kHz.

Practical resonators

Figure 4 is a drawing of a typical crystal resonator with its protective case or can removed. The crystal resonator is sliced, cut, and polished as a disk. It has one deposited metal electrode on each face, about 1000 angstroms thick. Electrode metal can be gold, silver, aluminum or other suitable metal. The resonator is supported on each edge at *nodal points*, places where the support will provide least damping of the vibrating crystal. Flexible support struts bonded to each side of the crystal connect the electrodes to base pins.

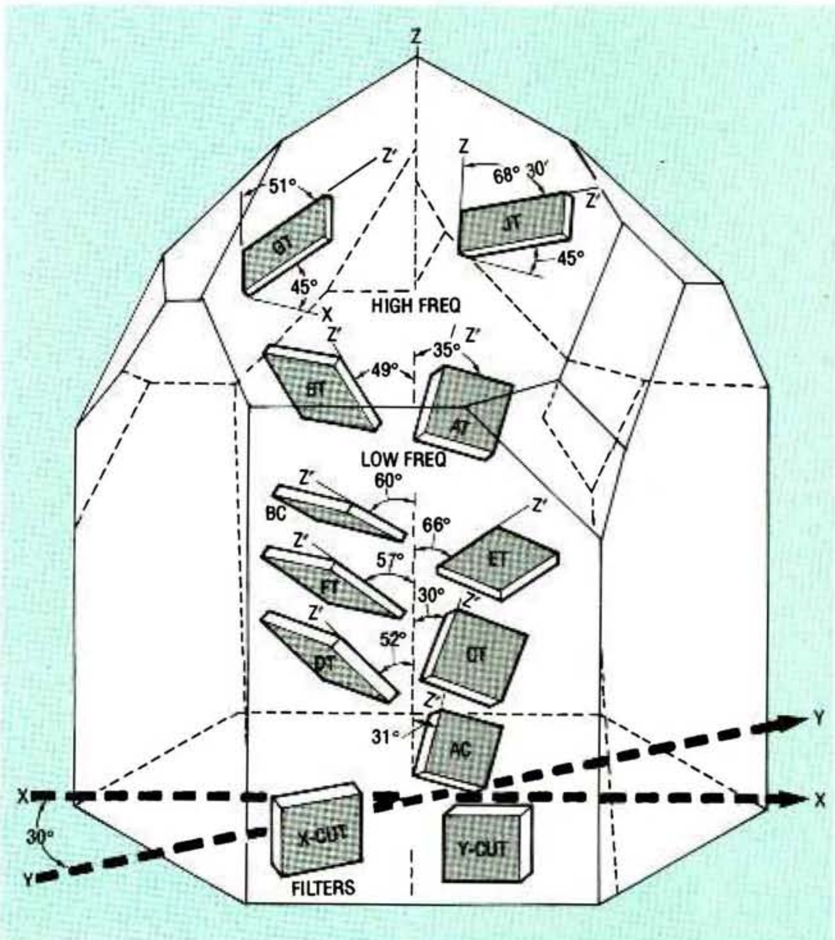


FIG. 3—CRYSTAL SLICES ARE CUT FROM A QUARTZ blank at different angles with respect to the axes to yield different mechanical and electrical characteristics.

Crystal manufacturers refer to the complete assembly of

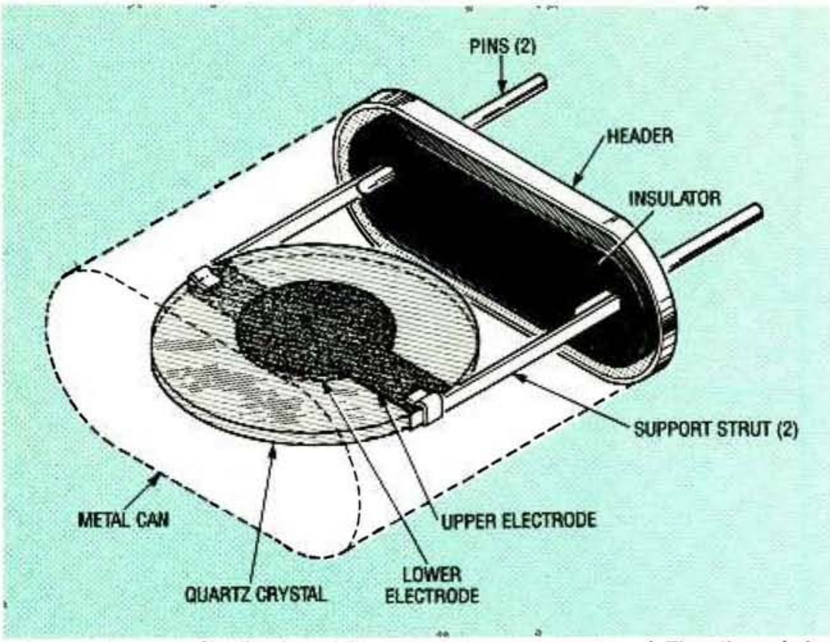


FIG. 4—A QUARTZ-CRYSTAL RESONATOR with its case removed. The silvered electrodes are on opposite sides of crystal disk and the disk is supported at its nodal points.

crystal, support, and case as a *holder*. The insulated pins in the base of the holder are for external electrical connections. The flat metal case is either soldered or welded to the base to form a hermetic seal. Sealing is typically done in a vacuum chamber which might also contain an inert gas such as nitrogen to provide additional protection for the crystal against contamination. It is essential that all moisture be removed from the case. The removal of air from the holder reduces the crystal's mechanical load and affects its resonant frequency.

Series and parallel resonance

Crystal resonators can be modeled near resonance with the equivalent circuit shown in Fig. 5. The series combination L_s, C_s, and R_s represent the electrical equivalent of the vibrational characteristics of the crystal by itself. The inductance L_s is the electrical equivalent of the crystal mass that is effective in vibration, C_s is the mechanical equivalent of the effective mechanical compliance, and R_s represents the electrical equivalent of mechanical friction.

This equivalent circuit is modified, however, when the crystal is mounted in the crystal holder. As a result, the equivalent circuit of the mounted crystal is the parallel circuit shown in Fig. 5. Capacitor C_p represents the electrostatic capacitance between the crystal electrodes and the stray capacitance associated with the holder when the crystal is not vibrating.

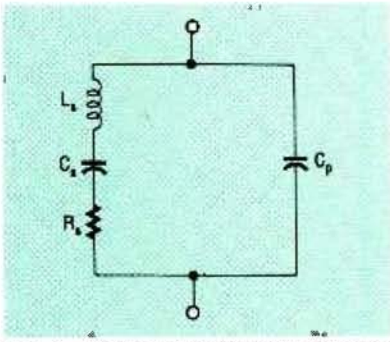


FIG. 5—IN AN EQUIVALENT CIRCUIT FOR A CRYSTAL resonator, L_s, C_s, and R_s represent the crystal, and C_p represents the capacitance of electrodes and holder.

At series resonance, the reactances of C_s and L_s cancel out, leaving resistor R_s and a small amount of capacitive reactance from static capacitor C_p. At a frequency slightly above series resonance, f_s, the reactance of C_p cancels out and the crystal looks resistive. The value of this resistance is called the *equivalent-series resistance*. Manufacturers usually specify only a maximum value of ESR because precise values are seldom needed in oscillator design. Crystals made to operate at series resonance are called *series-resonance crystals*.

A series-tuned circuit is capacitive below its series-resonant frequency f_s and inductive above it. The series-resonant frequency is given by:

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$$

At some frequency f_p, which is higher than f_s, the crystal will act as a parallel-tuned circuit because the now inductive series branch resonates with C_p. Crystal resonators made to oscillate above series resonance are called *parallel-resonance crystals* or *load-resonance* crystals. The parallel resonant frequency is:

$$f_p = \frac{1}{2\pi\sqrt{L_s C}} \quad \text{where}$$

$$C = \frac{C_s C_p}{C_s + C_p}$$

Crystal resonators intended for parallel-resonance operation include a specification called the *load capacitance*, abbreviated C_L. Typically 10 to 100 picofarads, it is called load capacitance because it is the capacitance value that the oscillator circuit presents to the crystal, that is, the crystal's load.

Load capacitance can be approximated as a 10 to 100 picofarad capacitor in series with a series-resonant circuit (the crystal). If the load capacitance is decreased, the resonant frequency of the total circuit (crystal plus load capacitor) will increase. As frequency increases, the crystal becomes more and more inductive. Most oscillator circuits call for an inductive crystal resonator. Therefore, parallel resonance crystals are very popular.

Series vs. parallel.

In an oscillator circuit a parallel-resonance crystal is usually more stable than a series-resonance crystal. The parallel-resonance crystal's change in inductive reactance per change in frequency ($\Delta X/\Delta f$) is greater above series resonance than at series resonance. This sharpens the tuning of the feedback network. Therefore, noise signals higher or lower than the resonant frequency are quickly damped out. This prevents *off-frequency oscillation*.

Figure 6 summarizes crystal resonator characteristics by plotting reactance vs. frequency. In the parallel resonance region, the magnitude of the crystal's resistance increases above its ESR value. Manufacturers usually refer to this as the crystal's maximum resistance with load capacitance or, the crystal's *load resistance*.

The frequency at which the inductive reactance abruptly changes to capacitive reactance (and resistance approaches a maximum), is called *anti-resonance*. It is not specified in data sheets for most oscillator applications.

Table 1 gives typical values for a selection of crystal resonators. The columns headed C_s, L_s, and R_s are the series values and C_p represents parallel capacitance. The C_L column is load capacitance and the R_L column is load resistance.

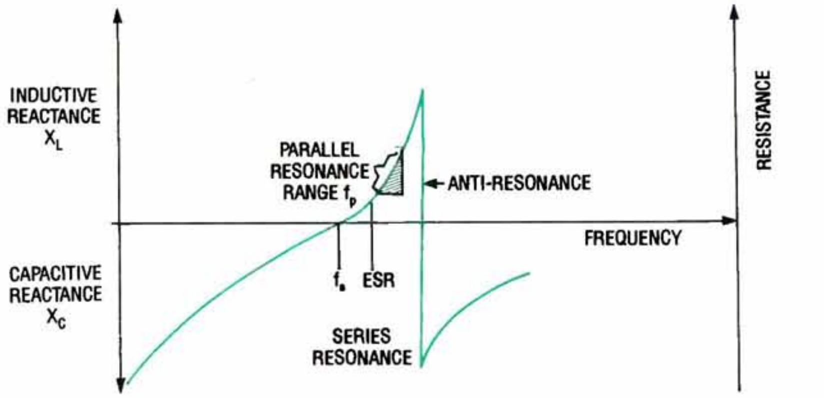


FIG. 6—CHARACTERISTICS OF CRYSTAL RESONATORS: parallel resonance, and series resonance are shown.

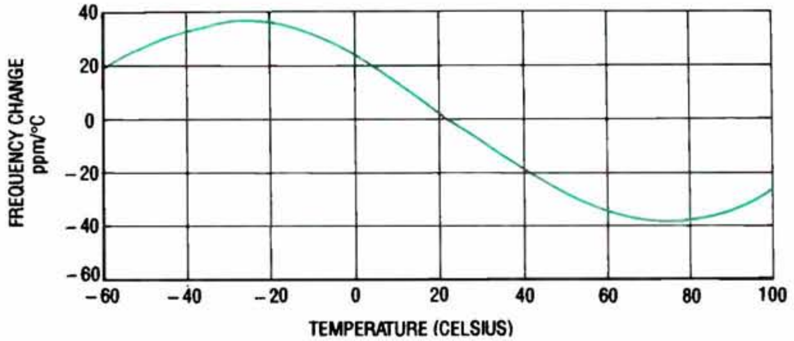


FIG. 7—Plot of frequency change with respect to temperature for a typical AT-cut crystal resonator.

that for high frequency oscillation, the quartz wafer must be very thin. This fact makes it difficult to manufacture crystal resonators with fundamental frequencies much above 30 MHz because the crystal is so thin that it is exceptionally fragile and conventional cutting and polishing could result in high production cost.

Some crystal resonator manufacturers get around this problem by using chemical etching to achieve thinner slices of quartz. This has made it possible to achieve fundamental frequencies up to about 350 MHz, but this process is more costly and it increases the cost of those resonators.

Resonant frequencies higher than 30 MHz have been obtained by making use of harmonically related vibrations that occur simultaneously with the fundamental vibration. The harmonics are odd multiples of the fundamental (3, 5, 7 and 9) and they are referred to as *overtones* because they are not true harmonics. The tradeoff is that special provisions must be made in oscillator circuits to enhance those overtone frequencies.

Manufacturers can process a crystal so that one overtone is stronger than the others. Typically, overtone crystals are available for the 3rd, 5th, 7th, or 9th mode of vibration. Thus a 30-MHz, third-overtone crystal actually has a 10-MHz fundamental, but the crystal is cut to enhance its third mode. Low-cost overtone crystals with frequencies up to 200 MHz are

TABLE 1
TYPICAL VALUES FOR A CRYSTAL EQUIVALENT CIRCUIT

CRYSTAL f(MHz)	C_S (pF)	L_S (mH)	R_S (ohms)	C_P (pF)	C_L (pF)	R_L (ohms)
0.100	0.004	633	62k	4	20	90k
1.0	0.028	905	388	7	32	575
10	0.028	9.0	16	7	32	24
20	0.028	2.2	40	7	Series Resonance	
80	0.0012	3.3	50	7	Series Resonance	

Other characteristics.

The relationship between a quartz crystal's thickness and resonant frequency is expressed as $h = 65.5/f_R$, where h is the thickness in inches, and f_R is the resonant frequency in kilohertz. This formula says available as standard commercial products. More expensive chemically-milled resonators can have overtones up to about 500 MHz.

Temperature stability

A crystal's resonant frequency changes with temperature. Crystal manufacturers express temperature-related changes in parts per million per degree Celsius (ppm/°C). Figure 7 is a plot of resonant frequency change with temperature for a typical low-cost AT-cut crystal.

When a desired operating temperature is specified, a manufacturer fabricates the crystal so that its optimum stability point (zero ppm/°C on Fig. 7) corresponds to that temperature. For low cost units, this is 25°C.

To find the maximum frequency change, locate the ppm/°C value corresponding to the given temperature. Next, multiply ppm by the nominal operating frequency (in megahertz). For example, at -20°C, a crystal can have a +38 ppm/°C rating. If its resonant frequency is specified to be 10 MHz (at 25 °C), its resonant frequency will increase by 380 Hz when its temperature drops to -20°C (38 ppm × 10 MHz).

For most practical circuits this represents a minor frequency change. However, if strict frequency control is required in any application, a crystal oven or temperature-compensated oscillator (TCXO) should be included.

Calibration tolerance.

A crystal's true frequency might not be exactly the same as the value stamped on its case. The error depends upon the crystal's calibration tolerance. Moreover, its calibration tolerance is specified at one specific temperature, usually 25°C. For example, expect a 10-MHz crystal with a ±25 ppm/°C calibration tolerance to have a resonant frequency within ± 250 Hz of 10 MHz when operating at 25°C.

Aging

Aging is a gradual change in a crystal's resonant frequency with respect to time. It is usually specified in parts per million per year (ppm/year). Typical values range from 3 to 10 ppm/year. For example, a 10-MHz crystal with an aging rate of 10 ppm/year can change by 100 hertz per year. One cause of aging is the redistribution of particles of quartz and embedded grinding compound that were not removed by careful cleaning.

These microscopic materials remain within the holder after hermetic sealing and are redistributed as a result of resonator vibration. Thus aging is directly affected by the power input or drive level.

In addition, slow leaks in the hermetic seal can allow air, moisture and contaminants into the case which will shift the resonant frequency. Stresses on the electrodes and changes in atmospheric pressure that flex the outer walls of the case can also contribute to the aging of a crystal.

Power dissipation.

As with any object that is vibrating at its resonant frequency, the vibrations can quickly build to a destructive level. To maintain temperature stability and to avoid damaging the crystal resonator, each crystal has a recommended maximum drive level. Typical maximum values range from 5 milliwatts at low frequencies to 0.1 milliwatt at high frequencies because high-frequency crystals are thinner than low frequency crystals.

Standard holders

The holders were standardized by a military specification years ago, and they are still referred to as HC numbers (for HC-XX/U) to identify resonator type and size. Crystal resonators are available from stock with resonant frequencies from about 70 kHz to 200 MHz. Specials can be ordered as custom items. We wish to acknowledge the assistance of Royden Freeland of International Crystal Mfg., Co. Oklahoma City, OK, in checking this manuscript for accuracy. **R-E**

Learn how crystal-controlled oscillators produce precise, stable output frequencies by building the circuits.

DAN BECKER

CRYSTAL OSCILLATORS

THE CRYSTAL-CONTROLLED OSCILLATOR has provided stable timing and frequency signals for years, and is now an integral part of products ranging from watches and computers to handheld transceivers and satellite receivers. First introduced in vacuum-tube form, most are now transistorized. The word *quartz* in advertising copy and specification sheets is the clue that they're inside. A time or frequency base derived from a resonating quartz crystal is the next best thing to a national time standard.

In the first installment of this two part series, resonators based on the piezoelectric effect were introduced. It was pointed out that a piezoelectric crystal produced electricity if it is subjected to physical stress and, conversely, the crystal is physically distorted if a voltage is impressed across its faces. Both properties are put to use in depthfinder transducers.

In fact, the first practical application of a piezoelectric crystal was as a transducer to generate and receive sounds underwater for the detection of submarines during World War I. Later, crystal loudspeakers, microphones, and phonograph pickups were developed. The first quartz crystal-controlled oscillator was introduced in the 1920's.

Synthetic or cultured quartz is now the dominant material of both crystal resonators and filters. The desired physical and electrical properties are obtained by cutting the quartz blank according to a set of strict rules. Packaged quartz crystal resonators are available as low-cost catalog items, and if you can't find the frequency you need, you can order a custom-made resonator.

All this is background to the subject of crystal-controlled oscillators. This article covers the fundamentals of all transistorized oscillator circuits, and includes five schematics and eight tables covering crystal-controlled oscillators complete enough for you to build your own circuits for personal instruction, experimentation or to meet a specific project requirement. All of the components are low in cost and readily available through retail stores or mail-order houses.

What is an oscillator?

An oscillator is a circuit that generates a specific frequency and maintains that frequency within limits. A transistorized inductance-capacitance (LC) oscillator depends for its operation on the resonant interchange of energy between a capacitor and inductor for its operation; a transistor amplifier supplies pulses of energy of the proper phase and magnitude to maintain oscillations.

When used in oscillator circuits, transistors become converters that change DC electrical energy from the collector power supply into AC energy in the output circuit. The amplifying characteristic of the transistor maintains the circuit oscillations.

Two conditions are necessary to sustain oscillations. First, the feedback voltage from the collector circuit must be in phase with the original excitation voltage on the base—that is, the feedback must be positive or regenerative. Second, the amount of energy fed back to the base circuits must be sufficient to compensate for the energy losses that occur in the base circuit.

It is useful to review the concept of Q before discussing oscillator operation. Q is defined as a figure of merit in a resonant system. Equal to the reactance divided by the resistance, it represents the ability of the device or network to sustain oscillations with minimum feedback. In short, the higher the Q the more efficient the resonator.

The intrinsic Q of quartz is 10 million at 1 MHz. Although the Q value for a mounted resonator crystal is reduced to levels of 20,000 to well over a million, it is still orders of magnitude better than the best LC resonator or tank circuit.

Crystal oscillator theory.

The very high Q of a crystal oscillator significantly reduces frequency drift caused by temperature and power supply voltage variations. Moreover, crystal-controlled oscillators generate less noise than conventional oscillators with LC tank circuits, so they have a purer output signal.

The simplest crystal oscillator consists of a single bipolar transistor with a simple feedback network. Figure 1-*a* shows a block diagram for a generic crystal oscillator. Here, an NPN amplifier is connected in three feedback circuits. Appropriate DC bias is assumed but not shown. Figure 1-*b* is an equivalent circuit with components L1 and C1, and C2 shown. All of the crystal oscillator circuits to be discussed here have the same basic topology, and include at least two capacitors and an inductor. The crystal can be considered to be part of the feedback circuit.

Capacitors C1 and C2 include residual transistor and junction capacitance. Capacitor C2 can be equivalent to a parallel combination of an inductor and a capacitor. This pair functions as the crystal's third overtone selector because it is capacitive only at the crystal's overtone frequency, and inductive at its fundamental. Thus, an inductor located at C2 prevents oscillation at the crystal's fundamental frequency.

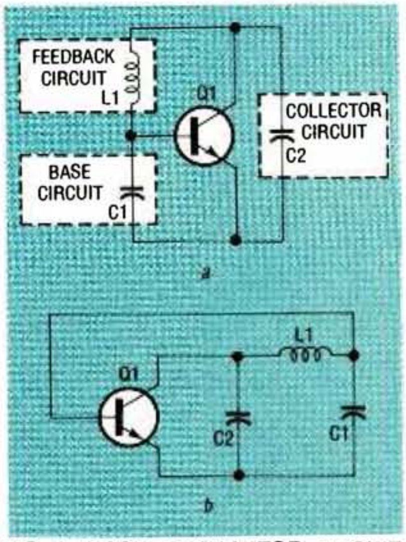


FIG. 1—BASIC OSCILLATOR CIRCUIT showing equivalent components, a and the circuit redrawn to show a feedback network, b.

In addition to amplification and feedback, an oscillator requires limiting, which occurs when an increase in the input signal no longer produces an increase in the output signal. Thus, the oscillator's output reaches a limit and stays there.

Some oscillator circuits are named for a circuit characteristic such as electron-coupled or phase-shift. However, many oscillators are named for their inventors: Among these are Butler, Colpitts, Hartley, and Miller. Five inventor-named circuit have been selected for this article; three are crystal-controlled versions of the Colpitts oscillator, one of the Pierce oscillator, and one of the Butler oscillator.

The standard Colpitts crystal-controlled oscillator has rigid load and tuning requirements, while the two semi-isolated versions are less temperamental, and are recommended as better choices for general-purpose applications. If you want very precise output frequency, the Pierce crystal oscillator is your best bet. However, if you want to experiment with oscillators, you'll find that the Butler circuit oscillates even without a crystal, you can observe the results with the crystal in or out. Table 1 compares the characteristics of each of these circuits.

Colpitts oscillators

Two versions of the Colpitts crystal-controlled oscillator are presented here: the standard and the semi-isolated. The standard circuit, shown in Fig. 2, is sensitive to variations in both crystal and load resistance. In addition, its output power is limited to less than half of the crystal's power dissipation. But, it's still a popular circuit.

Resistors R1, R2, and R3 DC bias transistor Q1. Potentiometer R2 allows up to about 1.5 milliamperes of emitter current. Capacitors C3, C4, and C6 bypass radio frequency at XTAL1's operating frequency (fundamental or overtone). Capacitor C2 functions like the feedback base circuit capacitor C1 in Fig.1. At XTAL1's operating frequency, L1 and C5 have a net capacitive reactance, and thereby form collector circuit feedback capacitor C2.

For overtone crystals, L1 and C5 act like an overtone selector, preventing oscillation at the crystal's fundamental frequency. Trimmer capacitor C1 fine tunes feedback element L1. As the value of C1 is made smaller, the oscillator's output frequency increases.

To organize a standard Colpit-

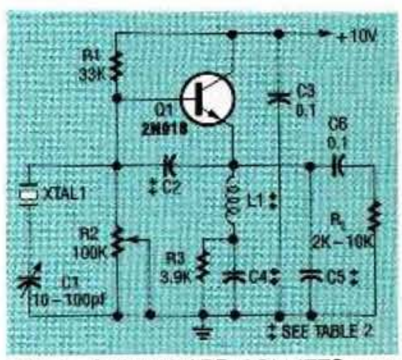


FIG. 2—A STANDARD COLPITTS crystal-controlled oscillator.

ts oscillator for your specific output frequency requirements, refer to Table 2. Note that frequencies from 1 MHz to 30 MHz are obtained with the fundamental mode, and frequencies from 35 to 60 MHz are obtained with a third-overtone crystal. The values for C2, C4, and C5 are given in picofarads, and the values for L1 are given in microhenries.

Semi-isolated Colpitts

Two versions of the semi-isolated Colpitts oscillator are described here. The first, shown in the Fig. 3 schematic, includes a fundamental-mode crystal. The second, shown in Fig. 4, is the same as that shown in Fig. 3 except that it includes overtone selector L1, C6 and radio-frequency bypass capacitor C3. Its operation requires a third-overtone crystal.

In both circuits, RF transformer T1 takes an output signal from Q1's collector current, but T1 is not part of the oscillator's feedback network. In addition, the output power is up to 100 times the crystal's power dissipation. Therefore, 15 milliwatts of output can be obtained with only microwatts of crystal dissipation! Moreover, if the output transformer is tuned to a harmonic of the oscillator's frequency, the RF load current is effectively isolated from Q1's fundamental RF current. Therefore, variations in the load or T1 do not affect oscillator tuning.

For example, if a 10-MHz crystal is used, the RF transformer can be tuned to 20 MHz, 30 MHz, 40 MHz, or higher MHz. Thus the circuit has its own built-in buffer that can drive low-impedance loads without detuning the oscillator.

However, as with the standard Colpitts circuit, the crystal is shunted by the emitter-base junction of the transistor—a low impedance. This lowers the oscillator's Q from tens of thousands to a few thousand, reducing its frequency stability. However, for most practical applications its stability is more than adequate.

Refer to the schematics shown in Figs. 3 or 4. In both circuits, resistors R1, R2, and R3 apply DC bias to transistor Q1. RF bypass capacitor C6 grounds one end of T1's primary. Capacitors C2, C5, and crystal XTAL1 form a feedback network as discussed earlier in reference to Fig. 1. Trimmer capacitor C1 serves the same function as it does in the standard Colpitts circuit. Transformer T1 and trimmer capacitor C3 (with C4) form a parallel resonant tank tuned to the desired output frequency.

If the output frequency is to be the same as the crystal's frequency, use the component values given in Table 3 or Table 5. (Tables 3 through 6 contain specifications information on winding transformer T1, which is explained under the Construction section) In this case, the oscillator, the load, and T1 are all tuned to the same frequency, and each affects the tuning of the other. (The load resistor R_L should initially be a ¼-watt resistor).

If the output frequency is to be a harmonic of the crystal's frequency, use the component values given in Table 4 or table 6. As mentioned earlier, this arrangement isolates T1 and the load, enabling the circuit to work with a wide range of load impedances.

The semi-isolated Colpitts oscillator shown in Fig. 4 requires a third-overtone crystal. Therefore, L1 and C5 appear capacitive at the third overtone, but they appear inductive at the crystal's fundamental frequency; together they form the collector circuit feedback element C2 shown in Fig. 1. Capacitor C6 bypasses DC-bias resistor R3, but it is most effective at the overtone rather than the fundamental frequency.

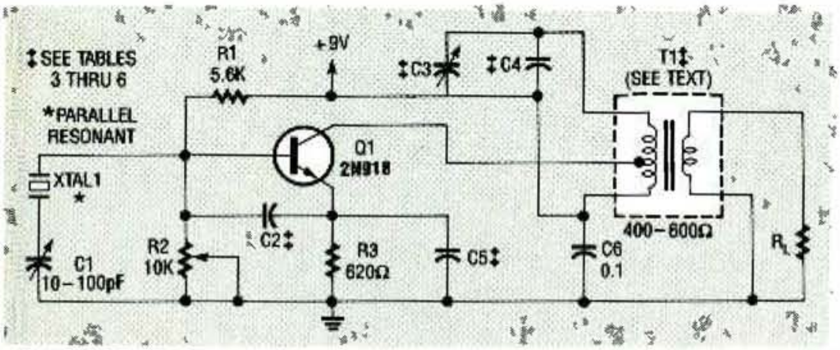


FIG. 3—A SEMI-ISOLATED COLPITTS OSCILLATOR with a fundamental-mode, parallel resonant crystal.

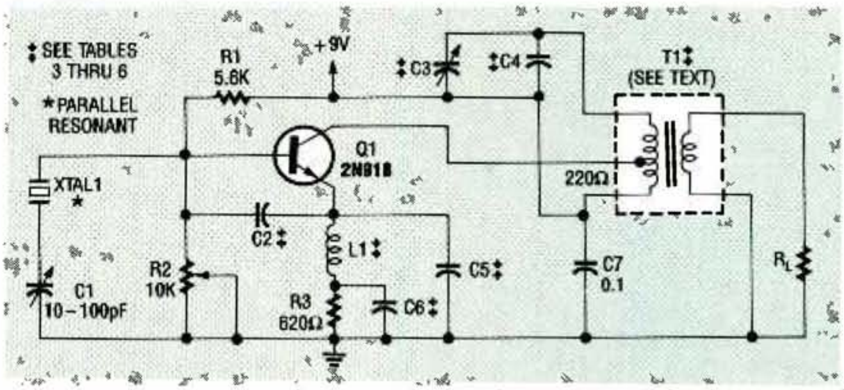


FIG. 4—A SEMI-ISOLATED COLPITTS OSCILLATOR with a parallel resonant crystal and overtone selector.

Pierce oscillator.

The best feature of the Pierce crystal oscillator, shown schematically in Fig. 5, is its very high operating Q. That very high Q is maintained because the crystal is connected between Q1's base and collector (a high impedance). This os-

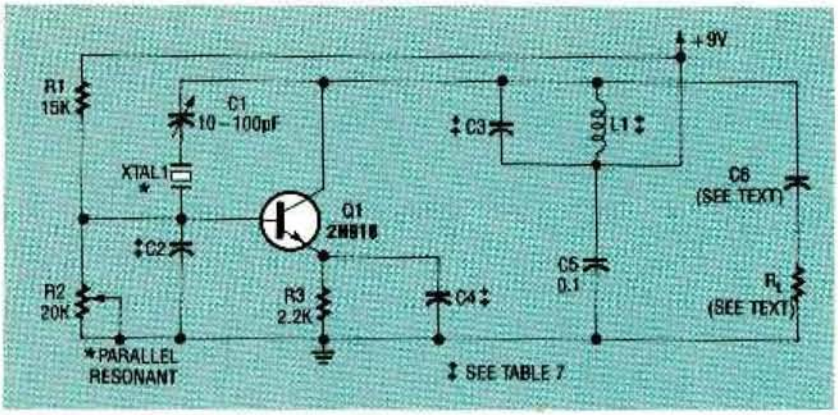


FIG. 5—A PIERCE CRYSTAL-CONTROLLED OSCILLATOR with a parallel resonant crystal.

cillator provides a very stable and accurate output frequency up to about 75 MHz. It is possible to tune this oscillator to within a few hertz of the desired frequency and expect it to remain stable there (when held at constant temperature).

If an oven-controlled crystal is used, frequency change will only be several hertz over a wide temperature range. However, the Pierce oscillator does not offer very high output power. Moreover, it requires a very high load resistance of about 3000 ohms.

Resistors R1, R2, and R3 establish the DC-emitter current. Capacitor C5 bypasses RF at all frequencies, while C4 bypasses RF current at the desired operating frequency (fundamental or, overtone only). Capacitor C2 is base circuit feedback element C1 as shown in Fig.1, and the parallel network of C3 and L1 yields a net capacitive reactance at the operating frequency and is analogous to collector circuit feedback element C2 as shown in Fig. 1. Crystal XTAL1 forms feedback inductor L1 of Fig. 1, and as with the Colpitts oscillator, trimmer capacitor C1 fine tunes the circuit's operating frequency.

The component values of the Pierce oscillator also depend on frequency and are given in Table 7. Note that a fundamental-mode crystal permits frequencies from 1 to 25 MHz, while a third-overtone crystal is required for output frequencies from 30 MHz to 75 MHz.

If a load resistance of the Pierce crystal oscillator is to be less than several thousand ohms, a 1- to 5-picofarad coupling capacitor must be used at C5 to prevent the low resistance of the load from detuning the circuit and preventing circuit oscillation.

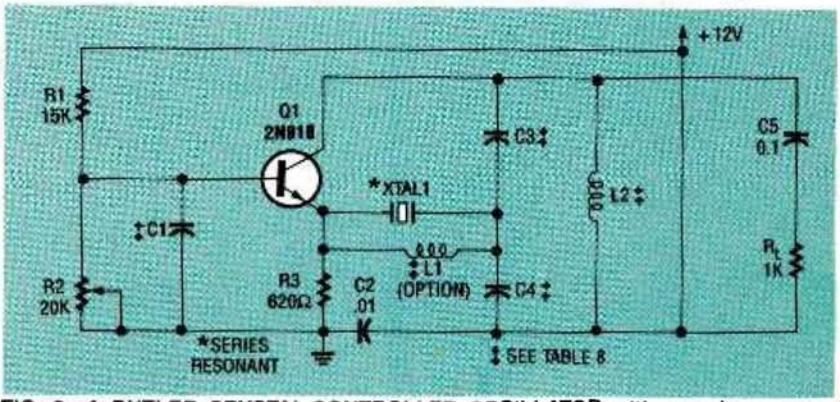


FIG. 6—A BUTLER CRYSTAL-CONTROLLED OSCILLATOR with a series-resonant crystal.

Butler oscillator

A schematic of a Butler crystal oscillator is shown in Fig. 6. The Butler oscillator demonstrates what is known as *input-resistance limiting*. Transistor Q1's DC-emitter current is directly proportional to the strength of the radio frequency input signal; in addition Q1's RF-input resistance of approximately 40 ohms is inversely proportional to the DC-emitter current. Therefore, as the RF feedback increases, Q1's DC-emitter current increases, but its RF-input resistance decreases. As Q1's RF-input resistance decreases, its RF gain also decreases, and this causes the output signal strength to reach a plateau.

The Butler oscillator's crystal circuit operates at series resonance, making it look resistive in the circuit. It is possible to substitute a 47-ohm resistor for the crystal and tune the circuit to a wide range of frequencies with variable inductor L1. But the circuit is so sensitive to variations in load resistance that a fixed resistive load must be connected to its output.

Resistors R1, R2, and R3 set the DC-emitter current. Bypass capacitors C1, C5, and C2 place transistor Q1 in a common-base configuration, couple the collector to the load, and bypass the positive supply lead, respectively. The feedback elements consist of capacitors C3 and C4, and inductor L2. The capacitors act like the base and collector elements C2, and C1 and inductor L2 act like the feedback circuit L1 in Fig.1.

Crystal XTAL1 feeds some of the RF output energy back into the emitter. Because the crystal behaves like a narrow bandpass filter, the emitter current forms clean sine waves that are low in harmonics. Inductor L1 cancels the detuning effects of the crystal's static capacitance C_p. However, if you build this circuit, get it to oscillate first without L1. Then, after it is working, install and fine tune L1 to obtain a precise output frequency.

Table 8 gives the values of the components in Fig. 6 that are shown without values. Note that a third-overtone crystal is necessary to obtain output frequencies from 20 to 55 MHz, while a fifth-overtone crystal is needed to obtain output frequencies from 60 to 100 MHz.

Selecting components

Remember that many common passive electronics components such as capacitors, resistors, and inductors that perform well at audio frequencies become inefficient and lossy in the radio frequencies. For example, the parasitic inductance of a wirewound resistor can be significant in a radio-frequency circuit. Keep this in mind when selecting oscillator components.

Power-supply regulation is important for stable oscillator operation. Low-Q oscillators that are tunable over a wide range of frequencies require very stable, low-noise supplies, but that is not a requirement for high-Q crystal- controlled oscillators because they are generally immune to voltage spikes and noise. Thus, while regulation is important, it can be obtained with low-cost integrated circuit regulators.

Even with minimal regulation, it is recommended that the power supply positive voltage lead be bypassed with a 6- to 10-microfarad tantalum capacitor and a 0.01 microfarad ceramic disc capacitor. Capacitors suitable for RF bypassing and tuning should have Q values of 100 or more, and most general purpose ceramic disc capacitors meet that requirement.

The crystal oscillators described here need only one bipolar transistor. In general, any NPN transistor with a gain-bandwidth product of at least 650 MHz is suitable. Possibilities include the 2N918 (shown in all of the circuits in this article), the MPSH-10, and the 2N2857. The 2N918 is available in plastic packages and metal cans. If you use 2N918's in metal cans, be sure to ground their cases. For frequencies below 50 MHz, a 2N3904 switching transistor will perform satisfactorily.

Inductor variety

Two basic kinds of inductors (tuning coils) are generally available: air wound, and core wound. Most are wound from number 20 to 40 AWG enamel-coated magnet wire. Inductors for RF circuits usually have both magnetic and electrostatic shielding. This is obtained by winding the coil on an iron-powder core, and then enclosing the assembly in a small metal can.

Core-wound inductors offer high Q's, good temperature stability (usually ±200 ppm/°C), and are small. Powdered-iron core materials are often mixed with other materials to make special powdered-iron alloys. Each is formulated to yield a high Q and optimum temperature stability over a specified frequency range. Oscillators or tuned circuits usually require Q's between 60 and 120. Before selecting a coil, examine the manufacturer's data to verify the coil's Q and usable frequency range.

Winding transformers

You can make your own radio-frequency transformer T1 for the semi-isolated Colpitts crystal oscillators shown in Figs. 3 and 4 from the toroidal cores and magnet wire specified in Tables 3 through 6. Under the column heading T1 (primary) these tables give the total number of primary turns, the wire gauge, and the designation for the appropriate core (e.g. T-80-2, T-50-2, T-50-10, T-50-17).

The first letter in this core code, T, stands for toroid, and the first number stands for the core outside diameter in fractions of an inch (e.g. 80 = 80/100 inch, 50 = 50/100 inch). The third number in the code designates a specific powdered-iron composition.

When winding wire on the core, first wind on approximately 12.5% of the total primary turns on the core (or three turns, whichever is larger). Then make a tap by twisting together several inches of wire to form a loop, and continue winding until all the primary turns have been wound. The loop can then be formed into a tap by cutting the loop and scraping the insulation off of the ends. This tap is then ready to be connected to Q1's collector as shown in Figs. 3 and 4 and soldered during the circuit assembly procedure.

The secondary of transformer T1 should reflect the load impedance shown on the schematics of Figs. 3 and 4 (at the primary's tap). The turns ratio between the secondary and the primary's tap should be the square root of tap resistance divided by load resistance. The secondary winding can be wouund from the same gauge wire as the primary.

For example, to reflect a tap resistance of 500 ohms, a 50-ohm load would require a primary-tap to secondary-turns ratio of 3.16:1 (the square root of 500 divided by 50). Therefore, if the primary tap consists of three turns, use a one turn secondary. After you find that the circuit oscillates with the initial transformer, you can experiment by substituting other transformers with different turns ratios.

Oscillator construction

Carefully designed printed-circuit boards are preferable to standard perforated boards as substrates for radio-frequency oscillators to minimize noise and interference. When building radio-frequency circuits, it is important that all components be inserted so they lie as close as possible to the board.

Use coaxial cable or TV twin-lead to conduct high-frequency signals for any distances over an inch. RCA-type audio connectors work well up to frequencies of 30 MHz, but BNC, F, and equivalent 50- or 75-ohm connectors should be used at the higher radio frequecies.

The Colpitts and Pierce crystal-controlled oscillator circuits discussed here include parallel-resonance crystals, but the Butler oscillator has a series-resonance crystal. In all circuits the crystal's load capacitance rating can be from 12 to 32 picofarads.

However, the higher frequencies require a smaller load capacitance so the crystal will provide enough inductive reactance to prevent oscillation above the desired frequency. Therefore, a 12- to 20-picofarad load capacitor should be used in circuits expected to operate at frequencies above 15 MHz.

After building the standard Colpitts oscillator, and before trying it for the first time, set variable capacitor C1 to its maximum capacitance value. The following start-up directions apply to all Colpitts oscillators and the Pierce oscillator, but *not* the Butler oscillator:

- Initially, couple a 4.7 K ohm resistor to the 0.1 microfarad load-coupling capacitor (C6 in Figs. 2 and 5).
- Adjust trimmer potentiometer R2 until the circuit oscillates. When the circuit is oscillating properly, a different load resistor value can be substituted. For 0.1 microfarad load-coupling capacitors, R_L must be a resistive load of 2 to 10 K ohms
- For coupling a low-impedance load, use a 1- to 47-picofarad capacitor.
- If the output frequency is to be the same as the crystal's resonant frequency, refer to the component values given in Table 3 or Table 5. In this case, the oscillator, the load, and T1 are all tuned to the same frequency, and each affects the tuning of the other. Therefore, a ¼- watt resistor should be inserted initially at R_L.

After completing the Pierce oscillator, lightly couple a radio-frequency or oscilloscope probe to Q1's collector with a 5 picofarad capacitor. Then carefully adjust trimmer potentiometer R2 until the circuit oscillates properly.

As stated earlier, a 47-ohm resistor can be substituted for the crystal in building the Butler oscillator. The circuit can be tuned to a wide range of frequencies with the variable inductor L2. Be sure to keep a fixed resistive load connected to the oscillator's output because it is sensitive to variations in load resistance.

It was also stated earlier that a second optional inductor L1 will cancel the detuning effects of the crystal resonator's parallel capacitance C_P. Complete the construction and make sure the circuit oscillates before installing L1 and fine tuning it. **R-E**

RANDOM DOTS

continued from page 23

eyes slightly. If you do that, however, the image will be inverted; whatever would appear as floating above the page would now be recessed.

Where do they come from?

Our random-dot images were created on a PC with the *Stare-EO Workshop* software from N.E. Thing Enterprises (P.O. Box 1827, Cambridge, MA 02139. 617-621-7174). The software lets you turn graphics, text, and PCX files into professional-looking random-dot images. The $40 disk for a PC-compatible computer can run on nearly any machine. All it requires is 512K of memory, and an HGA, CGA, MCGA, EGA, or VGA display. A mouse and hard disk make the program a little easier to use, but neither is required. The images you create can be printed on most graphics printers. There's also a Mac version of the software available for $35.

continued on page 90

POWER SUPPLY

continued from page 46

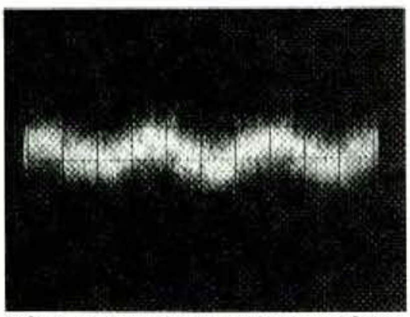


FIG. 4—THERE IS ONLY 20 MILLIVOLTS of ripple in the 250-volt DC output.

back to the voltage range and adjust the HV ADJUST knob for 250 volts. Adjust the voltmeter calibration trimmer R8 so the meter reads full scale.

Although the outputs can "float," it's best to connect one of them to the ground jack. Due to the voltage rating of typical potentiometers we do not advise floating the output more than 150 volts above ground. **R-E**

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise noted.

R1—6.8 ohms
R2—10 ohms
R3, R4—220 ohms
R5—470 ohms, 1-watt
R6—1000-ohms, potentiometer
R7—5000-ohms, potentiometer
R8—50,000-ohms, potentiometer
R9, R10—220,000 ohms, ½-watt
R11—470,000 ohms
R12—1 megohm, panel-mount potentiometer

Capacitors

C1–C4—0.01 µF, 500 volts, ceramic disk
C5—0.1 µF, ceramic disk
C6—220 µF, 25 volts, electrolytic
C7, C8—220 µF, 200 volts, electrolytic

Semiconductors

IC1—LM317T variable positive regulator
D1–D5—1N4005 diode (600V, 1A)
Q1—2SC1308 NPN high-voltage transistor, TO-3 type (Radio Shack #276-2055)
Q2—2N3904 NPN transistor

Other components

T1, T2—120/25.2 volt center-tapped 2-amp power transformer
J1—banana jack, red
J2—banana jack, black
J3—banana jack, green
F1—½-amp slow-blow fuse
S1, S2—DPDT switch, (6A, 250VAC)
M1—1 milliamp panel-mount DC meter
NE1—neon indicator lamp with built-in series resistor
NE2—neon lamp

Miscellaneous: Fuse holder, edge-mount perforated construction board and matching edge connector (optional, see text), enclosure, heatsink, TO-3 mounting hardware for Q1, standoffs, knob for R12, wire, solder, etc.