The Lenkurt Demodulator

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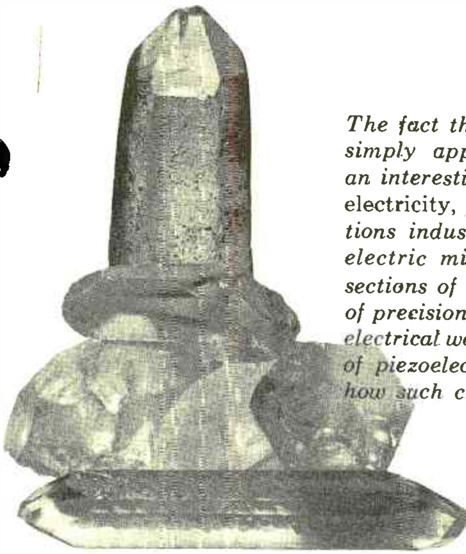
The Properties and Uses of

PIEZOELECTRIC QUARTZ CRYSTALS



The fact that electrical charges can be developed by simply applying pressure to a mineral is indeed an interesting phenomenon. This effect, called piezoelectricity, *plays an essential role in the communications industry. Probably the most important piezoelectric mineral is quartz. Properly shaped, thin sections of quartz are used to stabilize the frequency of precision oscillators and to produce highly selective electrical wave filters. This article discusses the theory of piezoelectricity, the properties of quartz crystals, how such crystals are made, and some of their uses.*

The demand for precise frequency control and frequency discrimination is inherent in the field of carrier and radio communications. Accordingly, a great deal of effort has been spent in developing highly stable oscillators and extremely selective electrical wave filters.

In the early days of radio broadcasting, transmitters contained a plate-modulated oscillator whose frequency tended to vary slightly during each modulation cycle. This instability in the transmitter frequency would, at times, produce a rather unintelligible signal in the home receivers. Many radio listeners objected to such a condition, and their complaints led to the use of piezoelectric quartz crystals to control the frequency of these oscillators. These crystals, because of their highly sensitive frequency characteristics, provided a remarkable improvement in the stability of broadcast signals.

The advancement of military radio communications greatly increased the demand for crystal-controlled oscillators. The armed services required that their radio receivers be almost instantly adjustable to several frequencies, thus permitting immediate communications between battle groups. This vital requirement led to the use of crystal-controlled local oscillators in radio receivers.

Piezoelectric crystals are also used to construct excellent electrical wave filters. Such filters are used in high-frequency transmission systems to separate the simultaneous messages that may be transmitted over a single wire, cable, or radio circuit. In addition, these crystals are used as transducers to convert mechanical or sound energy into electrical energy in such things as microphones, phonographs, and in sound and vibration detection systems.

Piezoelectricity was first observed in 1880 when Pierre and Jacques Curie put a weight on a quartz crystal and detected a proportional electric charge on its surface. A year later the converse effect was demonstrated — that is when a voltage is applied to a crystal, a displacement occurs which is proportional to the voltage. Reversing the polarity of the voltage reverses the direction of displacement. The term piezoelectricity is derived from the Greek word *piezein* meaning *to press*. Hence, a piezoelectric crystal is one capable of producing electricity when subjected to pressure.

Crystal Structure

Since all solid matter consists of electrical particles, the piezoelectric phenomenon was not unexpected. In electrically *uncharged* crystals, the positive and negative charges are balanced, and no piezoelectric properties are observed. It is necessary, then, to *unbalance* these charges in order to produce piezoelectricity. Only crystals possessing certain types of atomic symmetry can become electrically unbalanced.

Crystals form when a gas or liquid solidifies into a definite atomic pattern, called a lattice. This atomic lattice may be symmetrical with respect to a point, a line, a plane, or any combination of these. Crystal lattices that are symmetrical with respect to a point cannot be electrically unbalanced. The atomic lattices of these crystals are said to have a *center of symmetry*. To better understand the nature of crystal symmetry it is helpful to consider the crystal classification system.

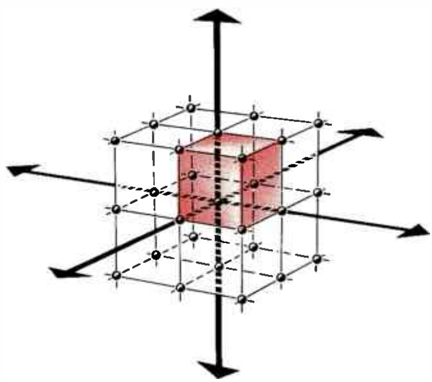


Figure 1. Atomic lattice of simple cubic crystal, showing unit cell (shaded) and the crystallographic axes.

Crystals are divided into seven crystal *systems* and 32 crystal *classes*. The lattice of each crystal is composed of a series of discrete three-dimensional atomic patterns, each forming a six-sided prism called a *unit cell*. The unit cells (Figure 1) can be considered as the *building blocks* which form the crystal. The edges of the unit cells are parallel to a set of imaginary reference lines that intersect at the ideal center of the crystal. These reference lines are called the crystallographic axes and, in piezoelectric crystals, are commonly identified as X, Y, and Z. The seven crystal systems are determined by the directions of these axes, with respect to each other, and by the length of the unit cell measured along each axis.

The symmetry exhibited by the surface of a crystal is merely an expression of the *arrangement* of the atoms within each unit cell. A total of 32 such arrangements is possible within the seven crystal systems. The 32 arrangements, or types of symmetry, constitute the 32 crystal classes. Only 20 of the 32 crystal classes exhibit piezoelectric properties.

Theory of Piezoelectricity

As previously stated, a crystal possessing a center of symmetry cannot be piezoelectric. When this type of crystal is subjected to pressure the same displacement of positive and negative charges occurs in any direction. Hence, there is no separation of the centers of opposite charges relative to each other. A distribution of charges having a center of symmetry is shown in Figure 2.

An example of the distribution of charges for a crystal *without* a center of symmetry is shown in Figure 3A. Note that the lines connecting like charges form an equilateral triangle and that the geometric centers of the two triangles coincide. As long as the centers coincide the charges remain neutral. If, however, a so-called longitudinal stress is applied to this crystal in the direction of the Y axis, a displacement of the charges occurs as shown in Figure 3B. In this example, the center of each set of like charges has shifted in opposite directions along the X axis, thus creating a dipole.

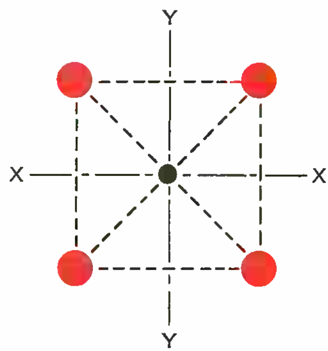


Figure 2. A molecular structure that has no charge separation when deformed. A crystal with this type of molecular symmetry has no piezoelectric property.

If the stress is applied in the direction of the X axis, as shown in figure 3C, the charge separation still occurs along the X axis, but is of opposite polarity. For this reason the X axis is called the *electrical* axis and the Y axis is called the *mechanical* axis. (These names are slightly misleading because under certain types of stress a displacement of charge centers will occur along the Y axis.) Perpendicular to these two axes is the Z axis. Because of the optical techniques used to locate this axis in a raw crystal, it is called the optical axis.

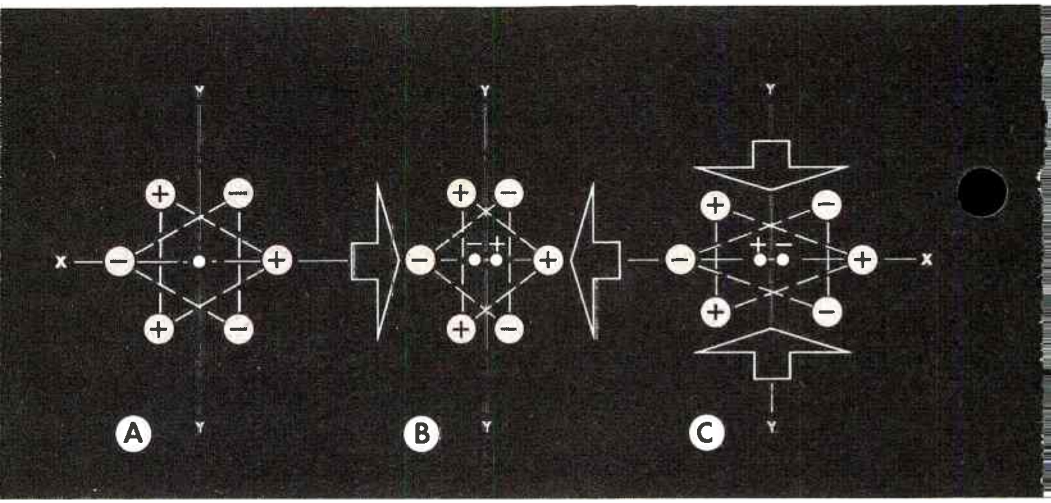


Figure 3. A model of one molecule of a quartz crystal showing the distribution of charges. When a longitudinal force is applied a charge separation occurs along the X axis. The charge appears along the Y axis if the crystal is subjected to a shearing force.

No piezoelectric effect is associated with the optical axis.

Quartz Crystals

The most commonly used piezoelectric crystal is quartz. Quartz is silicon dioxide (SiO_2) and crystallizes in the trigonal trapezohedral *class* of the trigonal *system*. This system includes all crystals which can be referred to 4 axes as shown in Figure 4. The 3 lateral axes are always equal and intersect each other at 60° angles. The fourth vertical axis may be shorter or longer than the lateral axes. A drawing of an ideal quartz crystal is shown in Figure 5. In nature, crystals of such perfect symmetry are seldom found and usually only the top formations and parts of the prism faces are visible. The different faces associated with quartz crystals are customarily designated by the lower-case letters m, r, s, x, and z.

In its original form, a raw quartz crystal is not usable in an electronic circuit. The quartz crystals found in communications equipment have been formed into various sizes and shapes, called plates, to give them particular piezoelectric properties. By slicing a raw quartz crystal at various angles with respect to its axes it is possible to obtain a variety of plates with different frequency and temperature characteristics. Certain plates have become standard and are classified into two groups; the X-Group and the Y-Group. The thickness dimension of X-Group plates is parallel to the X axis of the raw crystal from which it was cut. In Y-Group plates the thickness dimension is parallel to the Y axis. These standard plates are identified by symbols such as AT, BT, CT, or 5°X. Figure 6 shows the orientations of several commonly used plates. Listed in the accompanying table are the principal quartz plates of the two groups including the frequency ranges in which they are ordinarily used.

X-Group

Name	*Frequency Range (kilocycles)*
X	*40 to 20,000*
5°X	*0.9 to 500*
−18°X	*60 to 350*
MT	*50 to 100*
NT	*4 to 50*
V	*60 to 20,00*

Y-Group

Name	*Frequency Range (kilocycles)*
Y	*1000 to 20,000*
AT	*500 to 100,000*
BT	*1000 to 75,000*
CT	*300 to 1100*
DT	*60 to 500*
ET	*600 to 1800*
FT	*150 to 1500*
GT	*100 to 550*

The resonant frequency of a quartz crystal is determined generally by the size of the plate combined with the *mode* in which is is vibrated. Resonant frequencies achieved in standard quartz plates range from about 400 cycles per second to about 125 megacycles. The lower frequency limit is set by the dimensions of the largest usable plates obtainable from the raw crystal. The upper frequency limit of a quartz plate is reached when its size becomes so small that it is difficult to handle and is apt to shatter when put into use.

The three basic *modes of vibration* associated with quartz crystals are the flexure mode, the extensional (or longitudinal) mode, and the shear mode. Flexure motion is a bending or bowing motion, while extensional motion consists of a displacement along the length of a plate and away from the center. The more complicated shear motion involves sliding two parallel planes of a quartz plate in opposite directions with both planes remaining parallel. Each type of vibration can occur in a fundamental mode or in an overtone (harmonic) mode. The fundamental vibration of each mode is illustrated in Figure 7. The practical frequency ranges achieved in vibrating quartz plates in the three modes, including overtones, are:

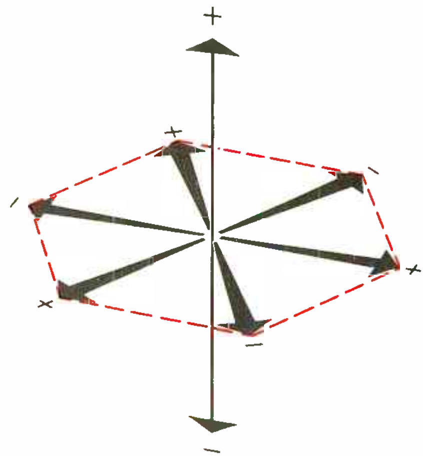


Figure 4. Crystallographic axes of the trigonal crystal system.

Flexure Mode	*0.4 to 100 kc*
Extensional Mode	*40 to 15,000 kc*
Shear Mode	*100 to 125,000 kc*

The excellent electromechanical coupling of quartz plates makes it possible to use them in electronic circuits. In addition, quartz plates exhibit an extremely high *quality factor,* or Q, which makes them highly stable and efficient. In general, the Q of a circuit can be stated as the ratio of reactance to resistance. At the resonant frequency of a circuit, the capacitive and inductive reactances are equal and opposite and therefore neutralize each other. This leaves only the resistance of the circuit to oppose the flow of current. When this resistance is high, the Q will be low, and more power must be supplied to sustain oscillation. This added power contributes to instability and drift. Thus, the higher the Q, the more stable the oscillations and the less the resistive losses.

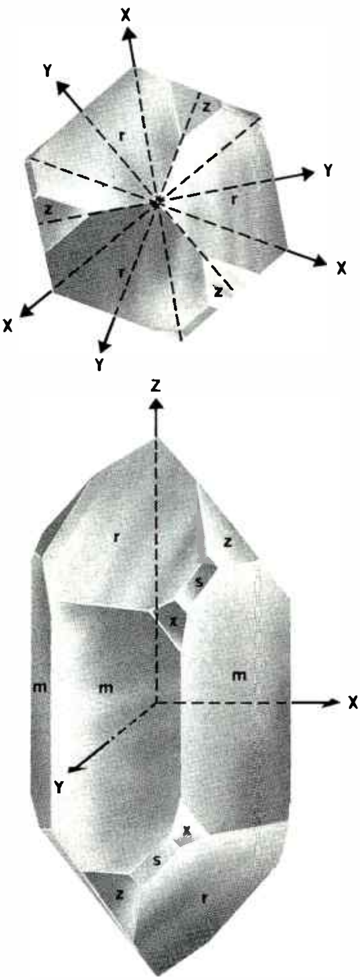


Figure 5. Ideal quartz crystal, showing the directions of the crystallographic axes. The faces of the crystal are identified by the lower-case letters.

Most of the losses in electrical resonant circuits are caused by the high resistance of coils. As a result, the Q of these circuits is comparatively low, ranging from about 10 to 400. The losses of a crystal are in its internal dissipation, mechanical mounting, and the damping of its motion by the surrounding air. The sum of these losses is very small when compared to an electrical circuit. Because of this, the Q of a crystal is comparatively high and may range from *ten thousand* to over *one million.*

Crystals possess two resonant frequencies; a series-resonant frequency and a parallel-resonant (or anti-resonant) frequency. The series-resonant frequency is determined by the distributed inductance, L_1, and the distributed capacitance. C_1, as shown in Figure 8A. The parallel-resonant frequency is determined by these same factors plus the parallel capacitance, C_0. Figure 8B shows the impedance versus frequency characteristic of a typical quartz plate. Note that the impedance of a crystal is lowest at its series-resonant frequency and highest at its parallel-resonant frequency.

Either the series-resonant or the parallel-resonant characteristics of a crystal may be used in an oscillator circuit. The mode of operation is determined primarily by the impedance of the circuit in which the crystal is connected. Figure 9 shows two transistor oscillator circuits, each employing a quartz crystal plate to control its frequency. The first circuit (Figure 9A) employs a crystal in the series-resonant mode. In this circuit the feedback loop from collector to base is established through transformer T1 and crystal Y1, which causes the circuit to oscillate at the series-resonant frequency of the crystal. Because of the high Q of the crystal the oscillator frequencies will be extremely stable over a long period of time.

The common-base Pierce oscillator, shown in figure 9B, employs a crystal in the parallel-resonant mode. Feedback is established from collector to emitter through capacitor C1. The frequency of this oscillator is controlled by crystal Y1 and the parallel capacitances of C1 and C2. The crystal operates just below its parallel-resonant frequency providing an inductance that resonates with the capacitances of C1 and C2. Hence, this circuit oscillates at a frequency

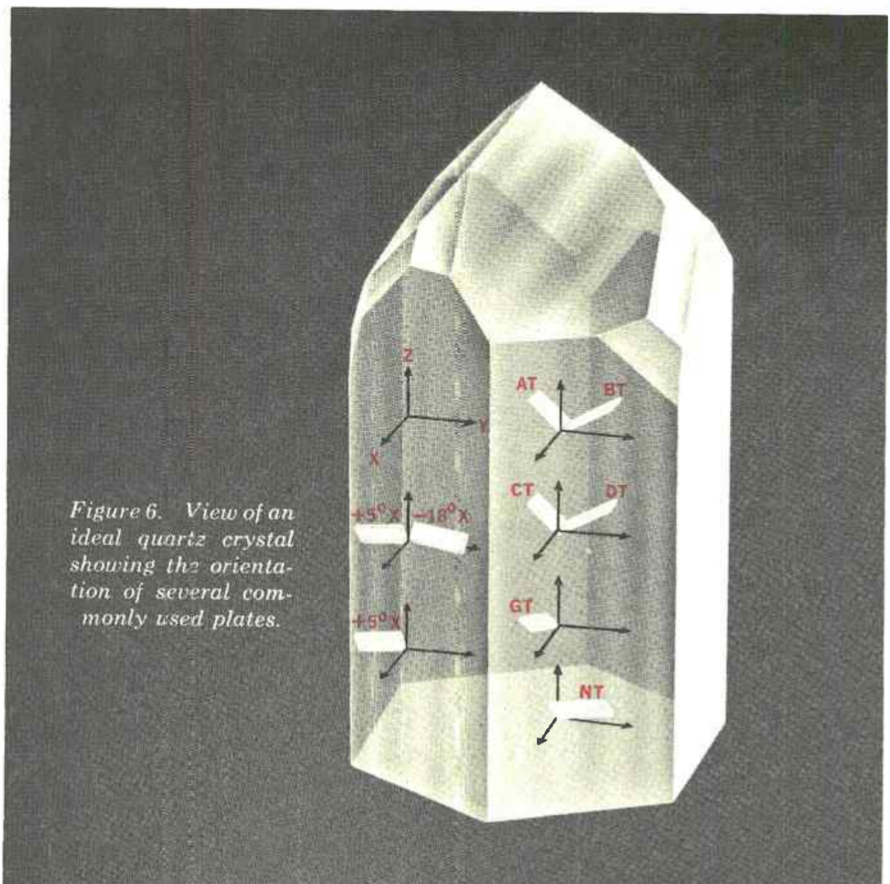
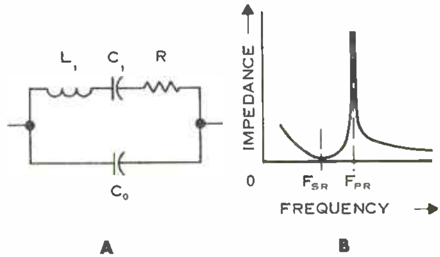


Figure 6. View of an ideal quartz crystal showing the orientation of several commonly used plates.

slightly below the crystal's parallel-resonant frequency.

Under certain conditions it may be desirable to adjust the resonant frequency of a crystal-controlled oscillator. Slight adjustments can be made by adding a variable capacitor or inductor in series with the crystal in the series-resonant mode and in parallel with the crystal in the parallel-resonant mode. The amount of adjustment can only be very small, but it does provide a means of offsetting frequency drift.

Because of their extremely high Q and stability, quartz crystals are also



$L_1 = 135$ h

$C_1 = 0.024$ pf

$R = 7500\ \Omega$

$C_0 = 3.5$ pf

$f \cong 90$ KC

$Q = \frac{2\pi f L_1}{R} \cong 10{,}000$

Figure 8. (A) The equivalent circuit and typical values for a 90-kc quartz crystal. (B) The impedance-frequency characteristic of a quartz crystal.

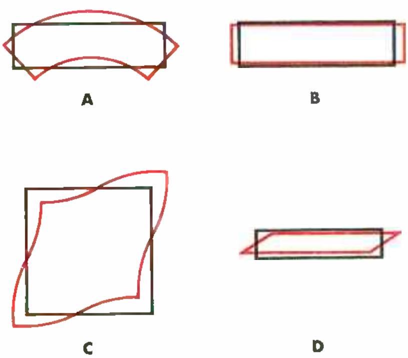


Figure 7. Fundamental vibrational modes associated with quartz crystal plates. (A) Flexure, (B) extensional (or longitudinal), (C) face shear, and (D) thickness shear.

used to produce very selective filters. Crystal filters are widely used in narrow-band applications, such as intercepting the pilot frequency in a carrier system, or separating the sidebands in a single-sideband radio system. Excellent wider band filters have been constructed using crystals with inductors and capacitors, usually in lattice-type networks. Such networks exhibit superior frequency cut-off characteristics and, therefore, are used advantageously as carrier channel filters to multiplex voice frequency signals. The sharp cut-off feature permits closer spacing of carrier channels, thereby providing more channels within a given frequency range.

Manufacturing a Quartz Crystal

There are two types of raw quartz crystals, natural and cultured. Natural quartz occurs in veins and geodes (stones) and is mined primarily in Brazil. Cultured (or synthetic) quartz is grown in a process that is analogous to growing the familiar cultured pearls. Cultured quartz crystals are usually better formed than natural quartz, resulting in a higher yield of quality plates per crystal.

Making a quartz crystal unit begins by carefully inspecting the natural or cultured crystal for imperfections and then by locating its optical (Z) axis. A

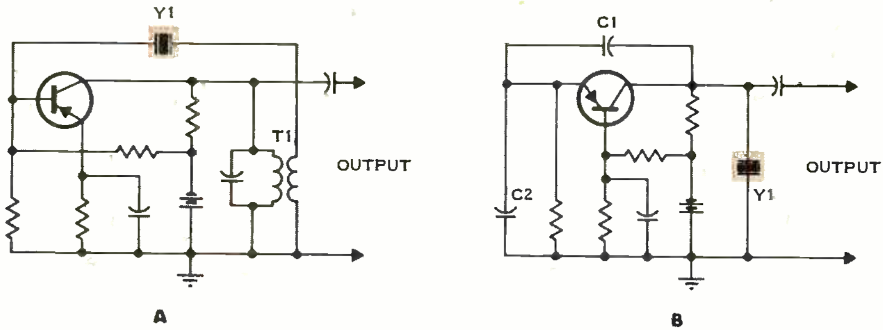


Figure 9. (A) Transistor oscillator employing a crystal in the series-resonant mode. (B) Transistor oscillator employing a crystal in the parallel-resonant mode.

face is ground on the raw crystal parallel to the optical axis. Next, the electrical (X) axis is located by an X-ray process. The mechanical (Y) axis is then known to be perpendicular to the X and Z axes.

After locating the axes, the raw crystal is sawed into sections and then into thin wafers along the Z axis so that the length of the plate is parallel to either the X or Y axis. Each wafer is then diced into small sections called *blanks*. These blanks are ground to the desired dimensions using a precision grinding process, known as lapping, and then inspected, cleaned, and etched in chemical solutions. After cleaning and etching, a spot of silver is applied to two opposite sides of each blank where the wire leads are to be attached. These same sides are then gold plated to form the electrodes required to electrically connect the crystal to the leads. Next, the leads are soldered to the silver spots. The crystal can now be frequency calibrated and placed into a holder — usually a vacuum-sealed glass tube or a hermetically-sealed metal can. After the crystal is mounted in its holder, a final frequency check is made. The crystal unit is then allowed to *age* for a short period of time, after which it is ready for use in an electronic circuit.

Aging

It is impossible to construct a crystal unit that is completely free of imperfections. Consequently, the resonant frequency of a crystal may vary slightly over a period of time. The degree to which the frequency varies depends primarily on the *quality* achieved in the manufacturing process. Poorly constructed crystals *age* faster than those made to more exacting standards. Many factors contribute to aging, including such things as leakage through the container, corrosion of the electrodes, material fatigue, frictional wear, presence of foreign matter, various thermal effects, and surface erosion of the crystal.

If, however, a crystal is very carefully

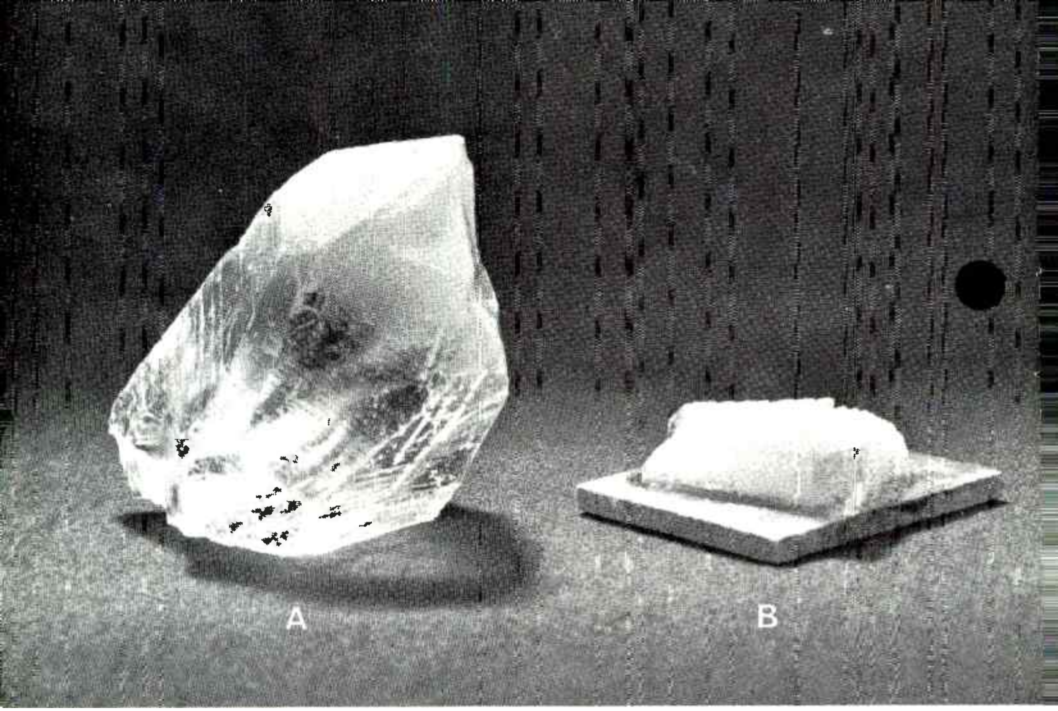


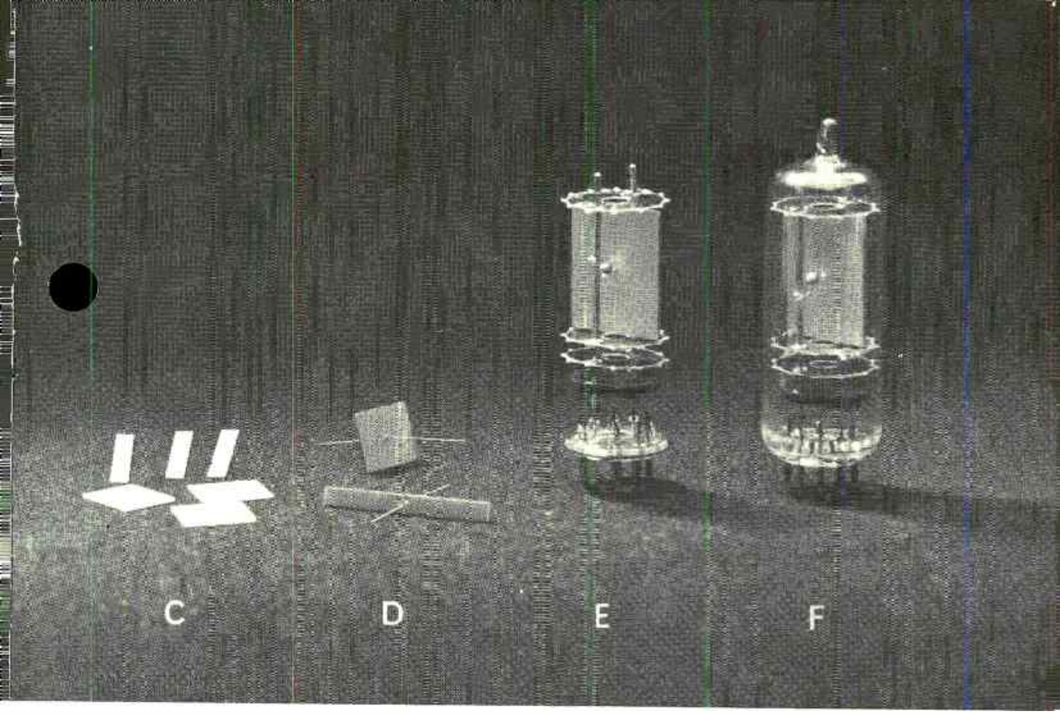
Figure 10. The various stages in the manufacture of a crystal plate installed in a vacuum-sealed glass tube. (A) Raw quartz, (B) section sliced into blanks, (C) blanks ground to the desired dimensions, (D) blanks gold-plated with leads attached, (E) crystal plate mounted in holder, and (F) finished quartz crystal unit.

constructed it will last a long time before deteriorating. To produce a high-quality crystal unit, particular care is required in the finishing processes of lapping, cleaning, and mounting. For these reasons, a few electronic equipment manufacturers, such as Lenkurt, develop and build their own crystal units to ensure that the crystals used in their equipment are of the highest standards.

Conclusion

Quartz crystals enjoy a very useful position in the communications industry and, from all observations, their usefulness will continue for some time. In the past, several possible substitutes for quartz crystals were developed, but none were too successful. Prominent among these were ammonium dehydrogen phosphate (ADP), ethylene diamine tartrate (EDT), and dipotassium tartrate (DKT). These so-called synthetic crystals were developed because of a shortage of the large size raw quartz crystals required for making filter crystal plates. When the process of growing cultured quartz crystals developed, these substitutes were no longer needed.

In recent times, a disc-shaped ceramic device with piezoelectric properties has been designed and used in filter circuits.



One advantage of the ceramic disc is its characteristic bandwidth, which is about 10 times larger than the bandwidth of quartz crystals. However, its Q is limited to below 2000 and its frequency stability to about 0.1 percent variation (as opposed to about 0.01 percent for quartz crystals). It is doubtful, therefore, that these devices will compete seriously with quartz crystals in filter applications, except in certain special cases.

Quartz crystals possess a fundamental quality which has not been practical to achieve in electrical resonant circuits. Consequently, they have become an integral part of communications equipment and have played an essential role in advancing the development of transmission systems.

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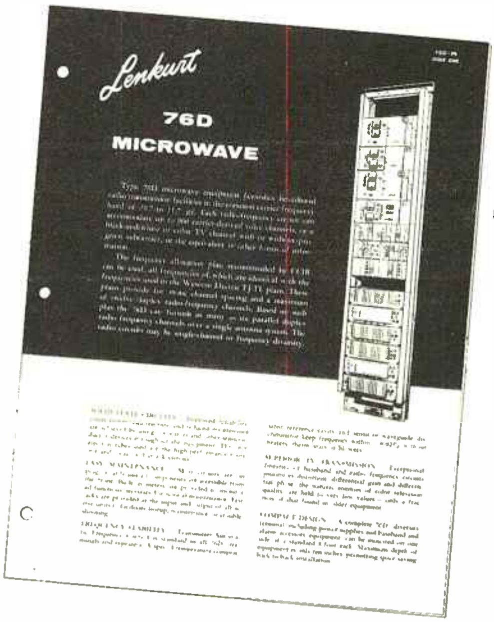

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