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The Institution of Post Office Electrical Engineers.

Piezo-Electric Quartz and its use in Telecommunications

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A Paper read before the London Centre of the Institution on 7th October, 1946, and at other Centres during the Session.

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CONTENTS.

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1. Introduction.

The authors have felt some concern in the past over the fact that while the quartz crystal has been essential to many of the major advances in telecommunications during the past 15 years, most of the terms and conceptions employed in piezo-electric work are not, in general, part of the vocabulary of communication engineers. This position, while understandable in view of the specialized nature of the quartz vibrator, does restrict familiarity with what should now be commonplace in the communication field and the opportunity afforded by this paper has been taken to discuss the subject in such a way as will, it is hoped, answer some of the many questions which are asked initially by almost all who come into contact with piezo-electric applications. As far as is practicable, the complex detail which has perhaps hitherto shrouded the subject is avoided. It should, however, be mentioned that the paper was originally prepared around a dozen or so fundamental demonstrations, designed to bring out the specific points involved. The absence of these in a published paper covering both a wide field and unfamiliar concepts is unfortunate, but it is hoped that the paper will nevertheless serve its designed purpose. Information on the geometry of the quartz crystal and on the nomenclature of the various types of quartz vibrator is given in the two Appendices, and for those interested in a more comprehensive study of the subject a bibliography is included. Following a brief description of the piezo-electric phenomenon, the quartz vibrator is considered, its application to the solution of frequency stabilization and selection problems is outlined, applications are discussed, representative performance figures are given and finally, possible future developments are outlined.

It should be stressed that the scope of the paper is wide and, in consequence, it is possible only to discuss many of the aspects in very general terms.

2. Piezo-Electricity.

The word " piezo-electricity " is from the Greek and the first part is from a root meaning " to press ". Since pressure involves stress, the whole word may be translated as the production of electric charges by stress. The converse phenomenon of converting electrical stress into mechanical strain is also comprehended in the term.

A number of materials possess the piezo-electric property and, however diverse their other properties, they are crystalline, *i.e.*, there is an ordered repetition of groups of atoms through the materials. All crystalline substances fall into one or other of 32 classes based on certain elementary configurations of atoms, and, of these classes, 20 possess the possibility of the piezo-electric property. However, the majority of naturally occurring crystals fall into the non piezo-electric group and only some 10% are possibly piezo-electric. Crystals for piezo-electric work must be large enough to handle in manufacture and to give the range of dimensions required. They must also possess a homogeneous crystal structure and be sensibly free from mechanical flaws. With the exception of quartz and tourmaline, natural piezo-electric crystals are usually very small and comparatively rare. Tourmaline in the form required for the cutting of piezo-electric crystals is generally small and has a tendency to mechanical imperfection so that usable material is rare. This leaves quartz outstanding as a mineral which can be obtained from nature in sufficient size and quantity and of good enough quality for piezo-electric purposes. Artificially grown crystals of other substances have been used for some purposes but broadly speaking they do not compete with quartz for frequency stabilization on the score of chemical and physical instability and high temperature coefficients of physical properties. It is more than possible however, that, in the future, artificially grown crystals other than quartz will find a large scale application for frequency-selection applications, *i.e.*, electric-wave filters, for which physical stability is not of such primary importance.

The external form of the natural quartz crystal, SiO_2, is illustrated by Fig. **1**, and its geometry is discussed in Appendix I. Although quartz is found in most countries, very little is suited for the piezo-electric application, and the chief source of good material is Brazil. The crystal is mined near the surface, and the average weight of selected material is some 300 to 3,000 grams.

The property of liberating electric charges when a piezo-electric crystal is stressed is due to electrical asymmetry within the atomic groups of which the crystal is built. An explanation of the effect due to Kelvin(1)* is based upon a symbolic arrangement of the constituent Si and O atoms. The atomic arrangement in a plane section of quartz containing the directions of maximum piezo-electric effect, is as shown in Fig. **2**(a), the directions of maximum effect being marked X. One of the atomic groups may be isolated as in Fig. **2**(b), and, in the unstressed condition, the resultants of the positive and negative charges associated respectively with the silicon and oxygen atoms are coincident and the material is electrically neutral. If the group undergoes a tensile stress, Fig. **2**(c), the atoms are displaced, the resultant of the three positive charges moves away from the centre in the opposite direction to that of the negative charges, and an electric moment is produced. The effect is reversible on the application of a compressional stress. A less familiar type of stress, a shear stress, produces deformation of such a type as to set-up an electric moment in a direction at right angles to that produced by direct stress.

To illustrate the effect in a practical form a neon lamp may be connected to the metallized surfaces of a piece of piezo-electric crystal such as Rochelle Salt

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* Numerical references are to the Bibliography at the end of the paper.

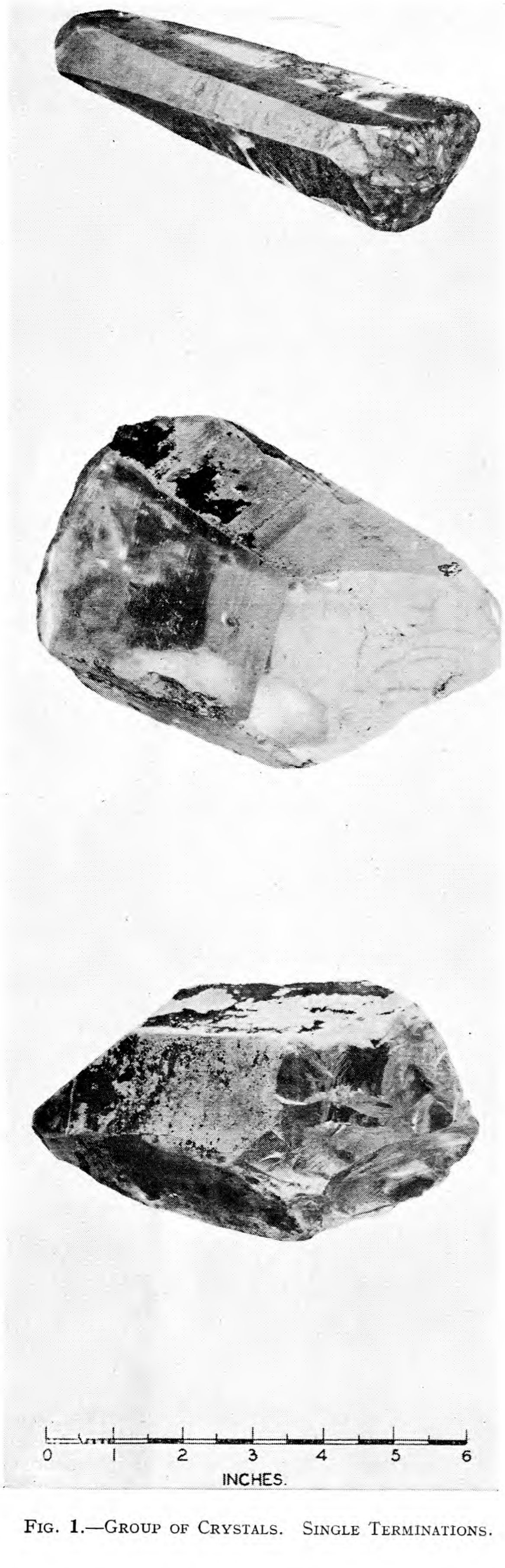
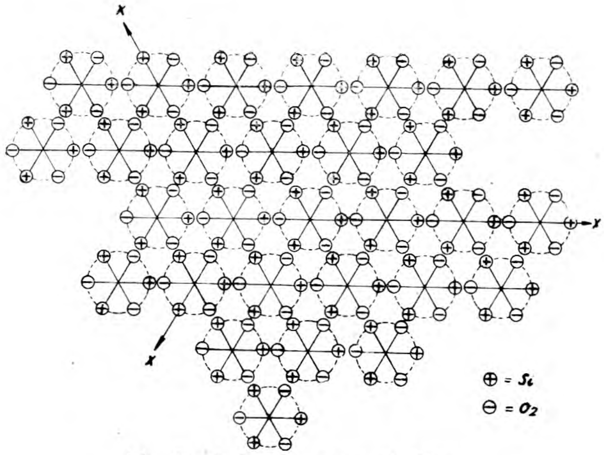
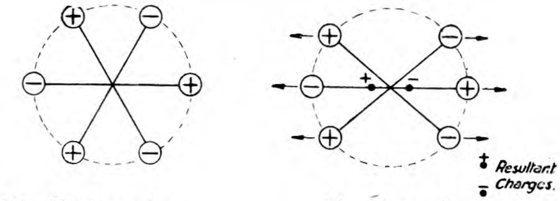


FIG. 1.—GROUP OF CRYSTALS. SINGLE TERMINATIONS.



(*a*) *Symbolic Grouping of Atoms.*



(*b*) *Unstressed Condition.*

(*c*) *Stressed Condition.*

FIG. 2.—REPRESENTATION OF PIEZO-ELECTRIC EFFECT IN QUARTZ (AFTER KELVIN).

and, when the crystal is stressed by a hammer blow, the voltage liberated is sufficient to flash the neon lamp. Another method of displaying the effect is to use a piezo-electric pressure tester consisting of a metal table to carry the material and an insulated hinged metal arm which may be brought into pressure contact with the crystal. If the voltage appearing across the crystal is applied to the grid of a direct-current amplifier, the meter in its anode circuit will deflect according to the polarity of the applied grid voltage. On releasing the pressure, the meter will deflect in the opposite direction in accordance with the laws governing the phenomenon.

3. The Quartz-controlled Oscillator.

3.1 *Application of the Piezo-electric effect to the production of sustained vibrations.*

So far it has been shown that, due to the direct piezo-electric effect, mechanical stresses produce electric charges in piezo-electric material. It can also be shown that the effect is reversible, the application of an electric field producing mechanical strain. This is known as the converse piezo-electric effect and may be demonstrated by means of a composite bar of two pieces of piezo-electric material so arranged that the application of an electric field causes one part to contract while the other expands, the bar being fixed at one end. When a voltage is applied across the coated electrodes bending is produced and this results in a rotation of the pointer attached to the top edge of the bar. The amount and sense of the rotation is governed by the magnitude and polarity of the applied voltage.

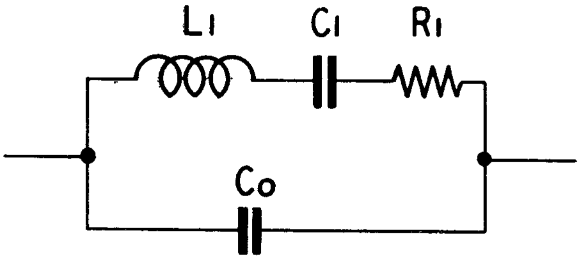
Now all elastic materials can be made to vibrate, and, furthermore, the vibration will depend upon the dimensions, elasticity, mass and damping of the vibrator. A tuning fork is a common example of such a vibrator. If then a piezo-electric element is placed in an alternating electric field, it will, by virtue of the converse effect, be forced into mechanical vibration at the frequency of the applied field. Adjustment of this frequency to coincidence with the natural vibration frequency of the element causes a large increase in the amplitude of vibration due to the fact that the movement of the element is in phase with the driving force. If a suitable piece of piezo-electric material be set in vibration by an impulsive force it will continue to vibrate, in the absence of further interference, at its own natural frequency, but with gradually diminishing amplitude. During these periodic movements the displacements will give rise to electric charges on the crystal surfaces of sign and magnitude proportional to the movement of the element. Suppose now that the element, provided with the metal electrodes necessary for the application of the electric force, is connected between the grid and cathode of a thermionic valve. The alternating potential produced by the vibration will be amplified and will produce larger voltage variations of the same frequency in the anode circuit. If these are fed back to the element to reinforce the original variations of potential they will also reinforce the vibration, which will continue so long as the circuit is connected. One method of feeding back the anode potential variations is through a small anode-grid capacitor, although in most cases a sufficient feed-back path exists in the form of inter-electrode capacitance. Other circuit connections may be used but there must be a feedback path via the piezo-electric element between an amplifier input and its output, and the voltage variations fed back must be appropriately phased with regard to the original vibration. The basic quartz-crystal oscillator circuits are discussed in section 3.4.

3.2 *Frequency Stability.*

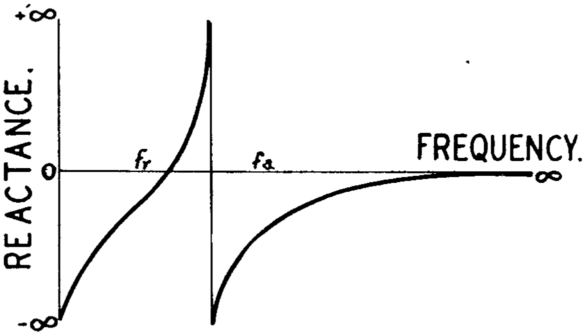
In any type of quartz-controlled oscillator, the frequency of oscillation is determined primarily by the natural vibration period of the selected quartz vibrator, the effects of circuit and supply changes on frequency stability being small. Quartz is an extremely stable substance, the frictional losses in vibration are small and special types of quartz vibrator possess sensibly zero frequency-temperature coefficients of vibration. In consequence of these factors, frequency stabilities are achievable with quartz control, of an order which cannot be approached with valve oscillators employing coil and condenser elements. Using the same argument, it is apparent that the performance realisable with other piezo-electric substances which are not so chemically and physically stable as quartz, cannot hope to give the long period frequency stability associated with the quartz-controlled oscillator. The three contributing factors to frequency stability are worthy of more detailed analysis.

The extreme physical stability of quartz crystal is reflected in the small secular frequency change of quartz-stabilized oscillators which can be reduced to not more than one or two parts in a million over periods of years, always providing that the measurements are made at the same temperature.

In examining the frictional loss it is desirable to consider the vibration in terms of electrical equivalence and the circuit elements of Fig. 3(a) may be used as a representation of a quartz element vibrating at mechanical resonance. The inductance L_1, capacitance C_1 and resistance R_1 have equivalence to the mass, stiffness and damping factor of the vibrator and, since quartz is a dielectric, C_0 is the electrical capacitance of the quartz element. In comparison with ordinary electrical tuned circuits the $\omega L/R$ or Q value is extremely high. For example, a typical quartz element of 100 kc/s natural frequency may have values, $L_1=23{\cdot}3$ henries, $C_1=0{\cdot}11\mu\mu F$, $C_0=22\mu\mu F$ and $R=50$ ohms, giving a Q value of 293,000. Similar values in purely electrical circuits would be impossible, the average Q value of such circuits being some 100 to 500 depending on frequency. The relation between reactance and frequency of a quartz element, Fig. 3(b), shows that there are two points of natural resonance, f_r, the series resonance, and f_a, the parallel resonance.



(*a*) *Equivalent Circuit of Resonator.*



(*b*) *Reactance-Frequency Characteristic of Resonator.*

Fig. 3.—Equivalent Circuit and Reactance Characteristic of Resonator.

The equivalence of the network to the piezo-electric vibrator at resonance is complete in all respects. The addition of external capacitance across the crystal has the effect of lowering the frequency of parallel resonance f_a and the insertion of capacitance in the lead to the crystal has the effect of raising the series resonant frequency f_r. There is, of course, no way in which the values of L_1 or C_1 can be independently modified by adding electrical elements. It is quite possible to excite a quartz element into vibration by means of metal electrodes which do not need to be in contact with the quartz surface since the air space merely represents a series capacitance in the equivalent circuit. This method was in fact standard for millions of thickness-shear mode crystals produced during the war and is still one of the most suitable means of mounting this type of vibrator in the frequency range 1,000 kc/s to 4,000 kc/s.

The complete equivalence of the electrical network makes it possible to adjust the frequency of a crystal-controlled oscillator by adding variable reactance to the crystal element. The reactor used is almost invariably a capacitor, for reasons of stability, range of adjustment and low loss, and a range of variation of 50×10^{-6} is easily obtainable over the whole of the available frequency range. As a converse effect any circuit reactances which may be connected to the crystal element must be highly stable in order to avoid unwanted frequency changes.

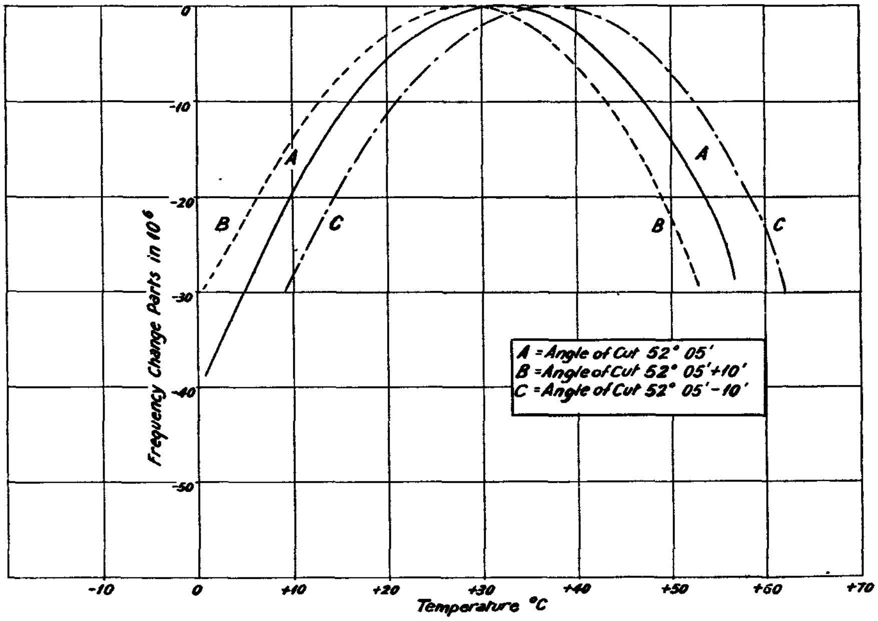


FIG. 4.—FREQUENCY-TEMPERATURE CHARACTERISTIC OF QUARTZ VIBRATOR, 500 KC/S CT—CUT.

Turning to the third factor contributing to frequency stability, the low frequency-temperature coefficient (f.t.c.) of vibration, it is now possible with one type of vibrator to achieve a f.t.c. of some 6 parts in 10^8 or better per 1°C change over the range 0 to 100°C. This type of vibrator is particularly suitable for operation over the range 100 to 150 kc/s, but with the aid of other types of cut, crystals in the range 4 to 20,000 kc/s are now practicable which have approximately parabolic frequency-temperature relations and thus give zero f.t.c. at the temperature corresponding to the peak of the parabola. The position of this peak in terms of temperature may be varied over wide limits by careful adjustment of the direction of crystal cut and by adjustment of the dimensional ratios. Fig. **4** shows typical frequency-temperature relations for three 500 kc/s crystal units of the face-shear mode type. A frequency variation of only -29×10^{-6} for a temperature range of ± 25°C about the 32°C mid point is obtainable. Other types of vibrator will have slightly different overall variations but not in general more than double those shown.

3.3. *Frequency Range.*

Quartz controlled oscillators are available in the range 4 to 20,000 kc/s and this range can of course be extended upwards and downwards by frequency multiplication and division. The frequency of any vibrator is a function of one or more of the linear dimensions and, since this relationship is usually one of inverse proportion, it is obvious that to cover the quoted frequency range with one mode of vibration would involve both impracticably large and small crystal elements. Fortunately, several modes of vibration are possible, and, by utilising only four, the whole frequency range can be covered without creating undue manufacturing difficulties in respect of practical size. Appendix II gives details of types of vibration, crystal cuts in relation to the geometric axes of the natural crystal, frequency-temperature characteristics and respective frequency ranges. The types of vibration are illustrated by Fig. **5** which shows the deformation associated with the four modes mentioned.

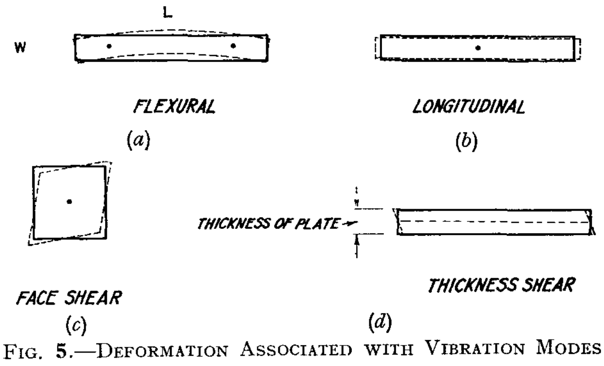


FIG. 5.—DEFORMATION ASSOCIATED WITH VIBRATION MODES.

The points marked on the elements (a), (b), (c) and (d) represent regions of minimum, or zero motion, and are thus nodal points or lines. Restraint on these regions has least effect upon the motion of the element and this fact is made use of in practical mounting systems.

The flexure mode is the only one of these four modes which cannot be directly excited by means of a simple electrode system. In order to obtain the bending moment required, it is necessary to divide the electrode on each side of the element along its centre line and suitably to interconnect pairs of electrodes. If then the polarity of the voltage applied to the top electrodes causes expansion of the element along its length the opposite polarity applied to the lower electrodes causes length contraction and the element as a whole will bend. Reversal of the polarity reverses the direction of bending so that an alternating voltage will drive the element in a flexural mode.

3.4. *Drive Circuits.*

The circuits of quartz controlled oscillators fall into two main divisions according to whether the crystal vibrator is operated at high or low impedance in terms of the characteristic of Fig. **3**(b).

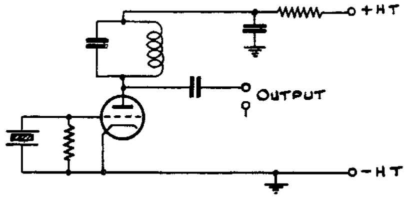
One of the simplest high-impedance circuits is that of Fig. **6**(a), and is suitable for operation up to at least 20,000 kc/s. Analysis of this circuit shows that in order to obtain the correct phase relationships for the maintenance of oscillations the reactance of the anode circuit must be inductive and that the crystal reactance must also be inductive. The latter requirement can be met only in the frequency range between f_r and f_a, and, since the capacitance of the wiring and valve is added across the crystal, variation of this stray capacitance will have some effect on the oscillation frequency. The amplitude of the crystal vibration builds up to a value determined by the saturation of the grid volts-anode current characteristic of the valve and changes in supply voltage will thus effect the amplitude of vibration. Although as already stated the oscillation frequency is determined primarily by the quartz vibrator, the possible causes of frequency variation with this circuit may be divided between the following :—

(*a*) Frequency change of crystal vibration with temperature variation.
(*b*) Variations of drive circuit components and valve changes.
(*c*) Variation of supply voltages.
(*d*) Secular frequency aging of crystal.

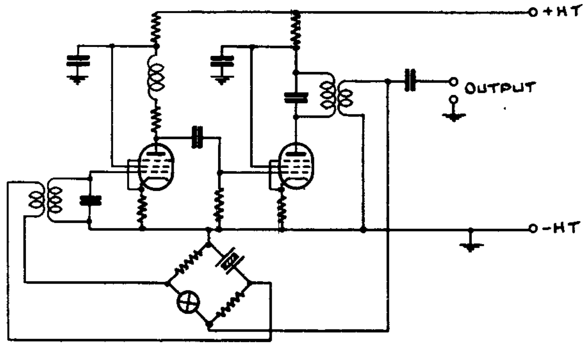
(Instability due to the effects of changes of atmospheric pressure on the frequency of the mounted crystal need not be considered since it is the present technique to mount crystals in rigid glass envelopes —usually in vacuo.)

Considering points (*a*) to (*c*), (*a*) can be calculated with good accuracy or measured during production, (*b*) necessitates good components and valves whose inter-electrode capacitances are low enough for differences between valves not to contribute more than a few parts in a million frequency change — a value of some $\pm 4\times10^{-6}$ between valves is practicable. The factor (*c*) operates partly by changing the vibration amplitude of the crystal and partly by affecting phase relationships in the drive circuit and by good design may be reduced to within 1×10^{-7} per 1% change of supply voltage. The secular frequency aging (*d*) of the crystal is not at present exactly forecastable and varies with crystal type and mounting but is unlikely to exceed about $+10\times10^{-6}$ over a period of years.

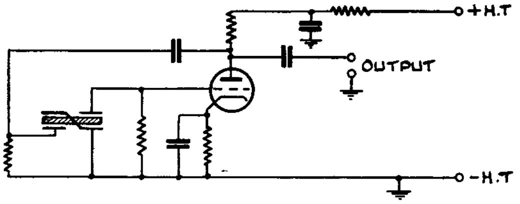
The second main type of drive, the low-impedance drive, is one in which the crystal vibrates sensibly at the frequency f_r and one form is illustrated by Fig. **6**(b), which is most suited for operation in the range 50 to 500 kc/s. The crystal is connected in a bridge network and the circuit is known as a bridge-stabilized crystal oscillator. The bridge is formed of a mounted crystal, a metal filament lamp and two fixed resistors, and is connected to the input and output of a maintaining amplifier. At series resonance, the crystal impedance is resistive and can be brought to a value of less than 100 ohms by careful design of the mounting system and care in obtaining the best finish on the crystal element itself. The bridge is balanced at the series resonance and oscillation is maintained when the amplifier gain exceeds the bridge attenuation. The lamp, whose resistance varies with current, serves to stabilize the amplitude of the crystal vibration, so that the system does not operate at the saturation point as with the high-impedance oscillator. In a typical circuit, the power dissipated in the crystal is



(a) High-Impedance Type.



(b) Low-Impedance Type.



(c) Type for Flexural Energization.

Fig. 6.—Crystal Controlled Oscillator Circuits.

less than 1mW and a 10% supply voltage change causes a frequency change of less than 3×10^{-10}, while valve changes produce a frequency variation of less than 2×10^{-8}. Thus the effects of two of the factors causing appreciable frequency variation in the high-impedance drive, namely, variation of drive circuit components and valves, and of supply voltages are reduced considerably, and the two remaining factors are :—

(*a*) Frequency change of crystal vibration with temperature variations.
(*b*) Secular frequency aging of crystal.

The effects of temperature variation can be reduced by temperature control and information on this subject has been published(2). Briefly, the practice is to employ bimetallic type thermostats for a control of ±1°C and bridge-type thermostats where closer control is necessary. These latter are capable of controlling to within 0·01°C and are used almost invariably where high precision is necessary. With both types, for use in this country, a control temperature of +50°C is generally employed.

Among the contributory causes of secular frequency aging is undoubtedly the volume-to-surface ratio of the quartz vibrator, since this determines to a large extent the proportional effect on the frequency of surface damping, of changes in the electrode system and of deterioration of the quartz surface due to processing damage. A large volume-surface ratio is desirable and this implies large linear dimensions, *i.e.*, low frequencies. When the frequency may be arbitrarily chosen, as with frequency standards, there are many advantages in choosing 100 kc/s as the crystal frequency, since, from this frequency, by multiplication and division, a train of standard frequencies in decade relation can be simply obtained and used for frequency measurement.

During recent years some attention has been given to crystal controlled oscillators operating at frequencies below 50 kc/s. Suitable crystals are those operating in a flexural vibration mode, which can be made in practicable sizes in the frequency range 4 to 75 kc/s. The divided electrode system required for operating flexural mode vibrators lends itself to using the vibrator as a four-terminal network which gives automatically the correct phase relations for maintaining oscillations when connected as shown in Fig. **6**(C).

The actual choice of a drive circuit for a specific application depends primarily on the frequency stability required, the frequency of operation, ambient temperature variations and supply voltage changes. The possible combinations of these conditions render it impossible to lay down hard and fast rules for the use of a particular drive circuit. The effects of secular frequency aging and of production frequency tolerances may be compensated by adjustment of a small trimmer capacitance in series or in parallel with the mounted crystal according to the type of circuit. It is usual to employ a form of the relatively simple high-impedance circuit, with or without thermostatic control of the crystal, for all applications calling for a stability up to about 1×10^{-6}. This stability can readily be realized with the majority of the quoted types of crystal. For higher stability, a low-impedance drive is used almost invariably together with a high-grade thermostat, and, since at present the most stable performance is obtained with crystals in the range 50 to 150 kc/s, it is usual to employ a crystal in this range and to obtain the desired frequency by frequency multiplication or division. The crystals commonly employed are the GT-cut plate and the +5° X-cut bar.

4. Electric Wave Filters employing Quartz Elements.

So far the application of the quartz vibrator to frequency stabilization has been considered, *i.e.*, the vibrator is associated with a valve system to maintain continuous oscillation, the energy being obtained from the electrical system and the oscillation frequency being determined primarily by the crystal constants. There is a second application, in which the quartz vibrator is excited by an electrical system and the vibrator does not affect the frequency of the applied oscillation. The quartz vibrator in the latter use is known as a quartz-resonator and in the former as a quartz-oscillator. The terms are perhaps a little ambiguous since a quartz element may be used either as an oscillator or resonator, but they do serve to divide the specific applications. It is apparent from the previous discussion that the equivalent circuit of a resonator is identical to that of an oscillator crystal, and for similar reasons the quartz vibrator can with advantage be used to replace some L-C circuits in certain classes of electric-wave filters. In fact the quartz resonator is just as important to frequency selection as is the quartz oscillator to frequency stabilization. The great advantage of quartz filters over networks of electrical elements lies in the high equivalent L-C ratio of the resonant circuits, their low loss (*i.e.*, high Q) and the stable frequency-impedance characteristic which can be obtained with ordinary mass produced crystals. Q values of at least 10,000 for a simple type of mounting in air and some 100,000 in vacuum can be achieved as compared with values of 300 to 500 for a very good coil-condenser network at similar frequencies. It is thus possible to produce filters, using quartz vibrators, that have exceedingly sharp cut-off regions and very high attenuation outside the pass band. The crystal element is designed in terms of an equivalent reactive electrical network which is then translated into the dimensions and angular orientation required for the equivalent quartz element. The design principles employed are similar to those for the filter employing purely electrical elements, although the art is somewhat specialized at present and perhaps more complex. There are however, severe limitations imposed on filter design when using only quartz vibrators. In the first place, the ratio f_a/f_r which determines the filter bandwidth is fixed for given angular orientations and dimensional ratios, and in quartz can never be greater than 1·004, which value occurs with X-cut resonators. It is, however, possible to design quartz band-pass filters whose pass-band width is greater or less than the 0·4% given by the f_a/f_r ratio by arranging for the pass-band ranges due to several resonators to run contiguously, but the practical limit for a single band-pass filter is still below 10%. In addition to band-pass and band-stop filters, high and low-pass filters are also practicable. A second limitation in quartz filter design lies in the practical impossibility of obtaining crystals which represent extreme values of the equivalent electrical elements. Thus the equivalent inductance of a quartz vibrator is proportional to the thickness, and, since thickness is limited by mechanical fragility and difficulties in production, the equivalent inductance attainable is also limited. Similar considerations apply to the other parameters. Finally, the presence of secondary resonances in any type of quartz vibrator may restrict the filter performance. The resonances represent additional regions of low and high attenuation characteristics which may be very undesirable, although within limits it is possible to control the positions of the secondary resonance.

The theoretical design of filters employing quartz vibrators has been covered adequately elsewhere(3)(4), and it is proposed merely to outline the types of resonator used and the practical frequency band at present available from filters so equipped.

Although any of the discussed modes of vibration may be used for resonators, bearing in mind the restrictions due to practicable size and secondary resonances, the main type of resonator which has been employed by the Department is the X-cut bar, and the characteristics of this type have been carefully determined. The frequency range of such elements operating in fundamental modes is for practical reasons limited to some 50 to 600 kc/s, but, with overtone energization, it is now possible to extend the range up to 900 kc/s.

In most applications the frequency-temperature coefficients of the quartz resonators are so small, comparatively, that temperature control is unnecessary. However, in one or two special cases when high stability with temperature is essential, simple thermostat control of the complete filter is provided.

On the question of the life of filters employing quartz resonators the original channel filters provided in 1937 for the London-Birmingham coaxial cable equipment are in continuous use and it is understood that they have not given any trouble since installation.

5. Preparation and mounting of Quartz Crystals.

Each type of vibrator discussed can be cut from the natural crystal in such a way that the finished element possesses an approximately parabolic frequency-temperature characteristic. In order to meet repetitive demands to close frequency tolerances the angles at which the quartz elements are cut with respect to the geometric axes of the natural crystal must be maintained within close limits; as close as ±10 minutes of arc of those angles which govern the frequency-temperature characteristic. Even when such tolerances are met, the resulting variation in the required position of the zero f.t.c. point may be some ±5°C. Details of production methods, including the technique of setting up the natural crystal for cutting, have been published(5), although these did not include the most recent technique whereby X-rays diffracted from the atom centres of the repetition planes of the crystal structure are used to determine the position of the cut planes with respect to fundamental directions in the natural crystal(6). Apart from this technique, the production methods up to the final surface treatment have not changed significantly. At the final stage it is now standard practice to etch the crystal surface by means of fluoride solutions so as to stabilize them by removing loose particles of quartz and grinding abrasive, in fact to take the surface down to the underlying undamaged crystal lattice. To achieve this it is essential that the grinding stages are so graded from coarse to fine that no deep scratches are left on the surfaces; ideally each successive grinding stage should remove all traces of its predecessor. Finally, with the exception of very specialized crystal units for frequency standard applications, the majority of the crystal types are now mounted, in Post Office practice, by utilizing wires soldered to metal spots fired to the quartz surfaces at the points of minimum movement, or nodal points. The electrodes, by means of which the alternating electric field is applied to the element, take the form of metal surfaces, obtained by evaporation or cathode-sputtering of suitable metals, gold and silver being the most common, directly on the crystals' major surfaces. The crystal support wires are then soldered to the nickel wires of a mica cage assembly, Fig. **7**, and final frequency adjustment is carried out either by light edge grinding of the quartz element or by adjusting the loading due to the electrode metals by plating on or off in an electrolytic bath. The adjusted crystal, wired to its cage assembly, is then enclosed in a standard type all-glass assembly. The glass envelope mounting technique is now being used for all quartz resonators employed in filters.

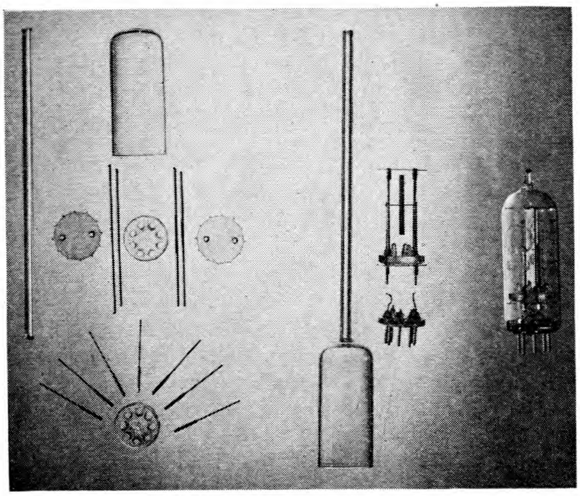
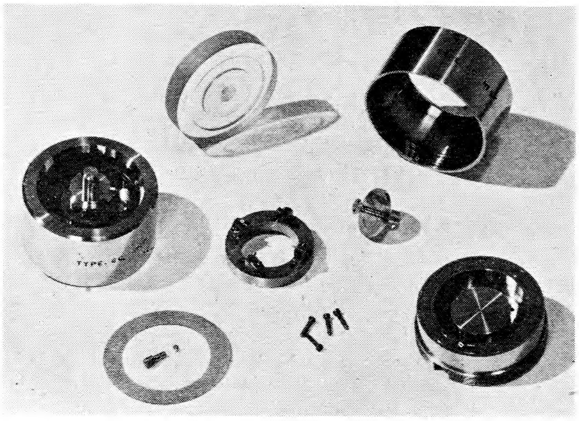
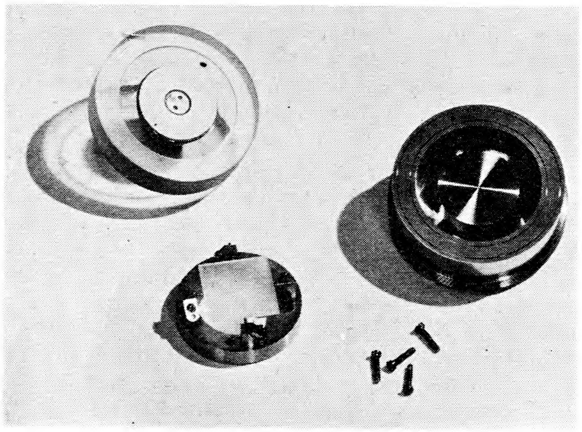


FIG. 7.—COMPONENT PARTS AND FINISHED CRYSTAL UNIT ON B7G BASE.

The technique of wire mounting has not been fully worked out for thickness-shear mode plates operating in the range 1,000 to 4,000 kc/s for which an older type of mounting is employed. In this mounting the crystal is clamped between two steel electrodes and the assembly is mounted in a two-pin bakelite case. With thickness-shear type plates for the range 400 to 1,000 kc/s it is possible, because of their rather large thickness, to employ a form of nodal clamping as shown in Fig. **8**.



Holder Components.



Mounted Crystal and Electrodes.

FIG. 8.—CRYSTAL HOLDER TYPE 6C.

It will be understood that any arbitrarily cut element of quartz will have natural frequencies corresponding to all its possible modes of vibration and to mechanical overtones of these modes. It is one of the objects of production to minimise the effects of all but the wanted modes of vibration by such means as choice of suitable dimensional ratios, variation of angle of cut and methods of mounting. The thickness-shear mode elements are particularly prone to trouble from interfering modes and it is partly due to this fact that wire-mounted elements of economic size have not so far been produced in the frequency range 1,000 to 4,000 kc/s.

The operation of crystal elements on overtone modes is now receiving much attention, and such overtone energization can readily be demonstrated with a bar-type element mounted in a glass envelope containing an atmosphere of neon gas and driven from a variable frequency oscillator. If an X-cut narrow bar, of fundamental frequency 100 kc/s, is used, then, as the driving frequency reaches coincidence with 100 kc/s, the electric stress at the node becomes a maximum and a glow discharge occurs along the nodal line. When the driving frequency is raised to that of the third overtone of the bar, two more nodal lines appear, similarly, the fifth overtone shows a total of five nodal lines. The even overtones do not appear because the method of suspension and driving damps motion at those frequencies.

6. Applications of Quartz Crystals.

As already indicated the application of quartz by the communication engineer can be considered under the two main headings of frequency stabilization and frequency selection. In the former, the quartz vibrator is employed to control the frequency of an oscillator, whereas, in the latter, the vibrator is associated with circuit elements to form an electric-wave filter for the selection or rejection of a particular band of frequencies.

Representative examples of frequency stabilization systems used by the Post Office are the primary standard of frequency, the quartz clock, the control of radio transmitters operating in the frequency range 16 to 200,000 kc/s, the master oscillators for the coaxial cable system, the 1kc/s synchronizing signal for the 12-channel system and many similar applications. Crystals have also been produced for the common-frequency operation of broadcast transmitters, the system used by the British Broadcasting Corporation during the war years.

Perhaps the best examples of the frequency selection application are the channel filters incorporated in the frequency translating equipment of the coaxial cable system, the 12-channel system and the multi-channel V.H.F. radio links employed in the trunk network. Other examples are the filters used in single-sideband operation of radio circuits, in the intermediate-frequency stage of radio receivers, and in resonance type frequency meters.

It is proposed to outline some of these representative applications and to indicate the performances realized.

6.1. *Frequency Stabilization.*

Perhaps the most spectacular application of the quartz vibrator is in the quartz clock (which is very similar to a primary standard of frequency). The subject has been described(7), but, in view of its importance (the whole edifice of frequency standardization is built on this foundation) a brief reference will be made to the performance now achieved. In its simplest form a quartz clock of Post Office design comprises a 100 kc/s crystal controlled oscillator and associated frequency dividers giving a final frequency one hundred thousandth of the oscillator frequency, *i.e.*, 1 c/s. The most precise forms of drive circuit, of temperature control and of quartz vibrator are used and the installation is necessarily very elaborate. To facilitate intercomparison it is usual to set up a minimum of three such oscillators. The Astronomer Royal is now using 18 of these oscillators which constitute the Observatory Quartz Clock. The groups of oscillators comprising the Post Office Primary Standard of Frequency are in effect quartz clocks, and the performance of one group of three oscillators is shown by Fig. **10**(a). It will be noted that the maximum frequency drift in one year was some 4×10^{-7}. It is of interest to note that the Astronomer Royal has stated that the period of the earth's rotation—our fundamental standard of time—increased during September, 1945, by some 3 milliseconds per day, *i.e.*, changed by about 3×10^{-8}, and that it has been possible to determine this change relatively quickly after it occurred with the aid of the quartz clock. In view of the possible important applications of a smaller if less accurate quartz clock, a first attempt has been made in this direction and a complete mains driven model has been produced of dimensions 12″ × 9″ × 14″. Although the performance, by virtue of its compression, is inferior to that of the much larger quartz clocks in use, it is still a very accurate timepiece, and with further development can undoubtedly be made much smaller and still be capable of keeping time to within 1 second under occupied room conditions.

Perhaps the next most important application is in the frequency control of radio transmitters. The permissible divergence of radio transmitters from their allocated frequencies is of course the subject of international agreement, and the frequency stability now demanded in many of the frequency bands can be achieved only with quartz crystal control.

The telegraph transmitter, GBR, 16 kc/s, at Rugby, is rated at some 350 kilowatts aerial power, at a frequency of 16 kc/s derived through a frequency divider chain from a 96 kc/s crystal controlled oscillator. A low-impedance circuit is employed together with precise temperature control. The crystal is +5° X-cut bar, and the long term performance is illustrated by Fig. **9**(a), which shows the results for the working and reserve drives. It is of interest to note that for experimental reasons crystal No. 2 was not finally etched in production and has a much greater aging rate than crystal No. 1 which was so treated.

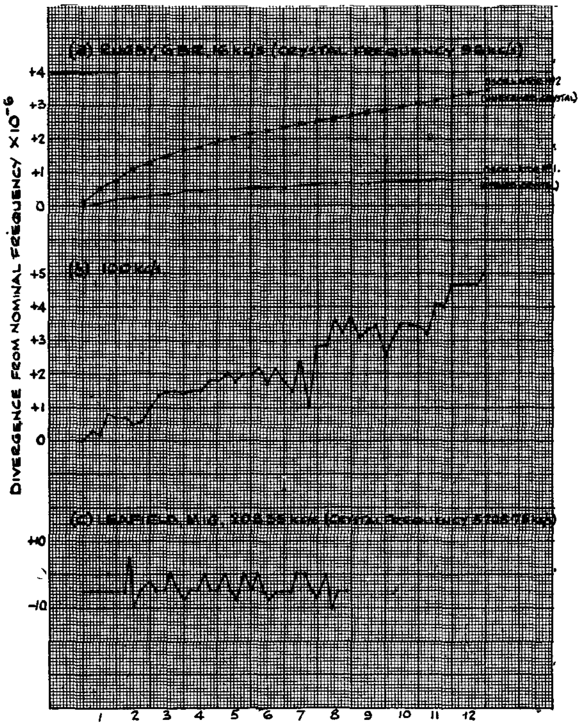


FIG. 9.—PERFORMANCE OF CRYSTAL CONTROLLED DRIVES FOR RADIO TRANSMITTERS.

In the crystal control of high-power transmitters for telegraphy and telephony operating in the range 3,000 to 25,000 kc/s it is usual to employ a crystal of frequency not greater than some 5,500 kc/s and to achieve the final frequency and power output with the aid of frequency multiplier stages (usually doublers or triplers) and amplifiers. To take an example, the Leafield telegraph transmitter, MIG, operates on an assigned frequency of 20,835 kc/s, the R.F. power fed to the aerial transmission line being some 15 kW. The drive circuit operates at one quarter of the carrier frequency, 5,208·75 kc/s, and provides a signal of about 1 watt to the first of the subsequent doubler and amplifier stages. A high-impedance oscillator, fitted with a temperature-controlled thickness-shear mode crystal, is used and the voltage supplies are stabilized. The long period performance is shown in Fig. **9**(c), and it will be seen that the mean frequency was within 5×10^{-6} of the nominal value, the variations about the mean being less than 10×10^{-6}.

The common frequency operation of broadcast transmitters during the war years is well known, but it may not be appreciated that the crystals provided for the British Broadcasting Corporation for the frequency control of their medium frequency transmitters, many of which employed common frequency working, were produced in the Post Office Radio Laboratories. The performance of these crystals mounted in holders to Fig. **8**, in drives designed by the Corporation was such as to meet a daily stability requirement of 1×10^{-7}.

The performance of a 100 kc/s bar-type crystal, wire suspended in vacuo, in a high-impedance drive circuit, non-temperature controlled, and subject to temperature variations of ±6°C and mains variations of ±6%, is shown in Fig. **9**(b). In view of the very simple circuit the performance achieved over one year is very satisfactory. The upward frequency drift due to secular aging was some 5×10^{-6}, the week-to-week stability was about $\pm 1 \times 10^{-6}$ and the minute-to-minute performance was within $\pm 2 \times 10^{-7}$.

An example with which many are familiar is the master oscillator for the coaxial system. The carrier series required at each terminal for the translation of the audio speech signals to radio frequency are generated normally from a crystal controlled oscillator installed at Faraday Building. A high-impedance type drive is used, the AT-cut crystal (400 kc/s) mounted in a holder of the type shown in Fig. **8**, is temperature controlled to ±1·0°C and the supply voltages are stabilized. The performance during 1945, Fig. **10**(b), shows that the nominal frequency was maintained within $1{\cdot}5 \times 10^{-6}$. It should be stressed that the oscillator design is over 10 years old and that newer designs, based on 100 kc/s crystals, low-impedance drives and precise temperature control are capable of a much better performance as is exemplified by the results, Fig. **10**(c), obtained on equipments recently installed at the London North East, Sheldon and Stockport repeater stations. The excellent performance achieved clearly demonstrates that " free-oscillator " operation of a coaxial system is within the bounds of possibility.

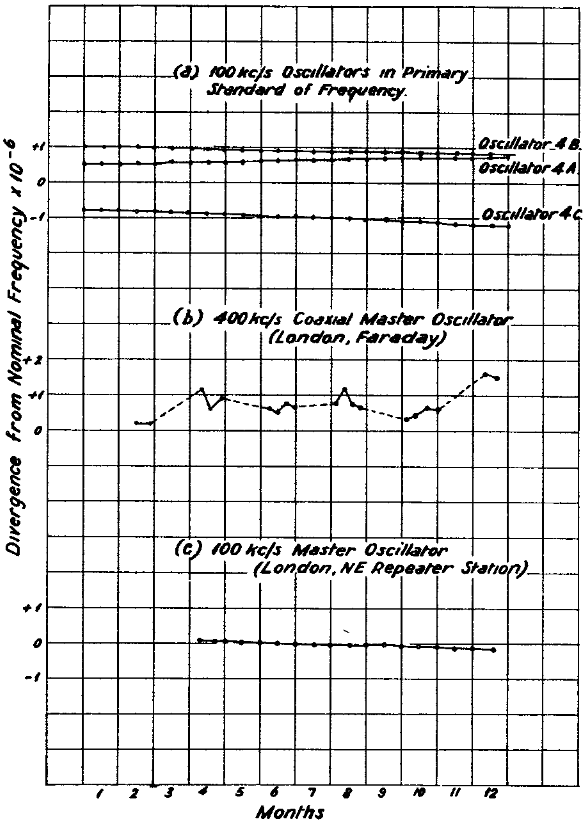


FIG. **10**.—PERFORMANCE OF CRYSTAL CONTROLLED OSCILLATORS.

The performance of all the high-grade oscillators in Post Office equipment which have been referred to are measured regularly at Dollis Hill, and the quoted performance figures have been so determined. The usual technique employed is one in which a nominal 1 kc/s signal, derived on site from the divider chain associated with the oscillator, is transmitted to Dollis Hill by land line. Here a high order harmonic of the incoming signal is generated and compared directly with an appropriate signal derived from the Primary Frequency Standard. Many Regional Officers may not have fully appreciated in the past the reason for, and the importance of this scheduled test programme. The authors would stress that the number of these high-grade oscillators in service is not large and any practical performance data which can be obtained is of great value to future developments.

6.2. *Frequency Selection.*

The circuits and performances of two types of filter incorporating quartz vibrators as used on the coaxial system for the selection of the channel carriers and in the first modulation stage and the final demodulation stage are shown in Figs. **11** and **12**. The two

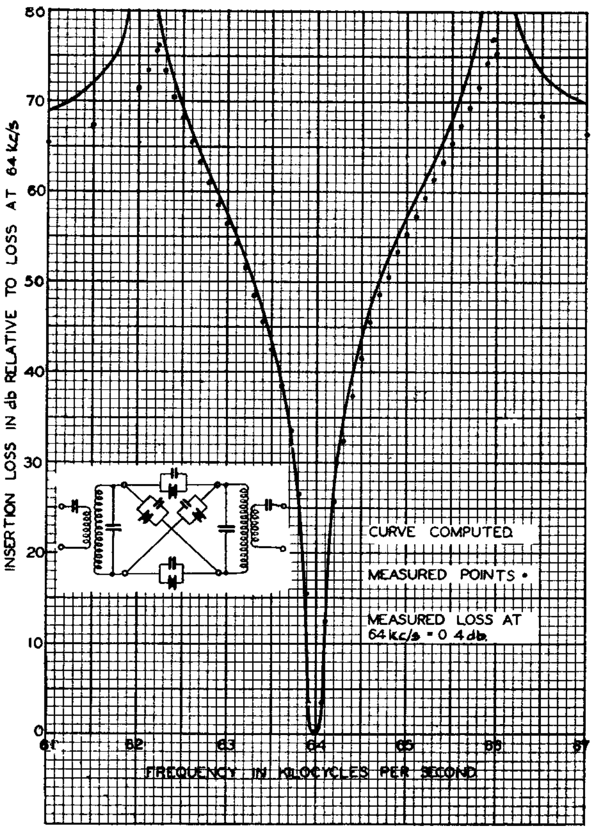


FIG. **11**.—FILTER W4/268. INSERTION LOSS CHARACTERISTIC.

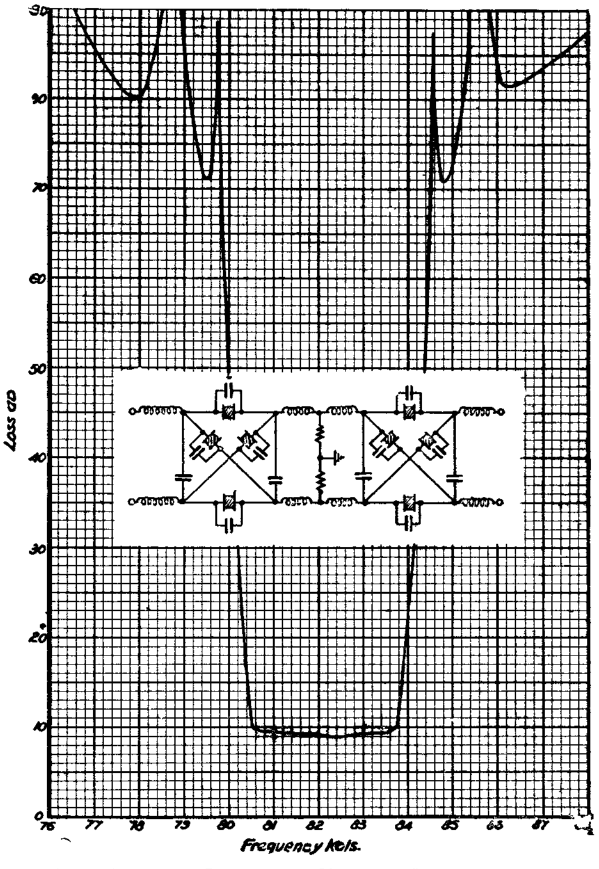


FIG. **12**.—CHANNEL EQUIPMENT NO. 8. CHARACTERISTICS OF A TYPICAL PARALLELED CHANNEL FILTER.

characteristics clearly demonstrate the performances now being achieved with quartz filters.

Another application, to frequency selection in the intermediate frequency amplifier (465 kc/s) of a radio receiver, is illustrated by Fig. **13**.

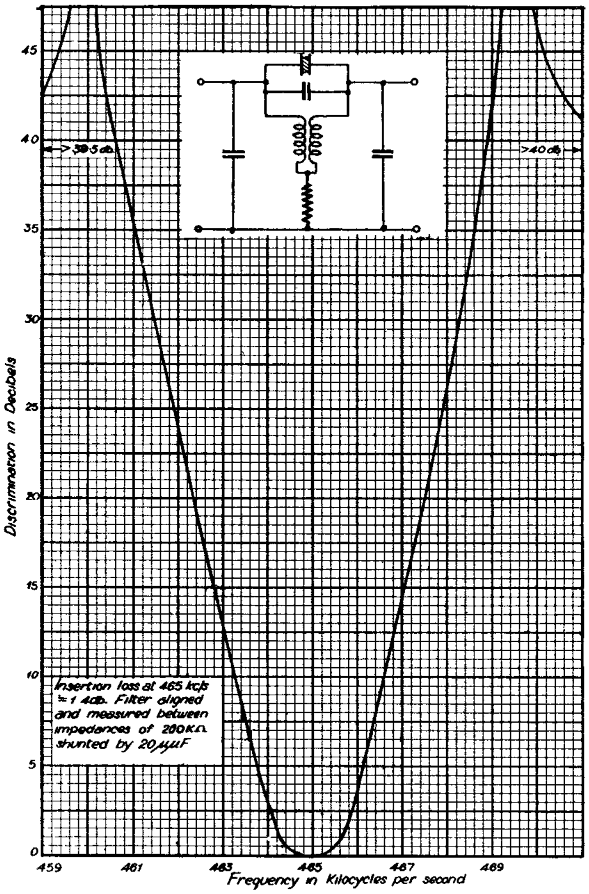


FIG. **13**.—FILTER W4/506A. DISCRIMINATION CHARACTERISTIC.

Quartz vibrators are used in many forms of resonance frequency meter, and perhaps the simplest type is the glow resonator. The resonator is set up at the radio transmitter, a coil of wire terminating on the element leads provides the necessary pick-up, and the frequency of the transmitter is adjusted to synchronism with the resonator using the glow discharge brightness as an indicator. The frequency of the transmitter can in this way be adjusted to within $\pm 10 \times 10^{6}$ of the series resonance of the quartz element.

7. Future Developments.

The techniques both of the production and of the application of quartz crystals by communication engineers are relatively young and many advances can be foreseen during the next 10 years.

On the material side there is active concern with the problem of artificially produced crystals which may displace natural quartz for some applications. Advances have already been made towards the use of piezo-electric non-quartz elements in electric-wave filters. Such artificially produced materials have not so far been of a type which equals the high physical and chemical stability of quartz. For this reason it is likely that their uses may for some time be restricted to wave filter applications in which lower stabilities can be tolerated.

In crystal production, progress is being made in production techniques and in the development of crystal types of reasonable dimensions which will extend the present frequency limits of the quartz vibrator. Much remains to be done in determining the exact cause and cure of the secular aging and frequency drift of quartz vibrators. In this connection much has been accomplished in recent years, and it may be that during the next year or two the low order drift on quartz clocks will be much further reduced to the gratification of the astronomer.

Parallel work on crystal-controlled oscillator circuit design will be towards simplification and a reduction of the effects of circuit variables on frequency stability.

Filter technique will aim at widening the frequency range in which effective electric-wave filters employing piezo-electric elements can be employed, and it is probable that in the fairly near future the band will be widened to cover 4 to 2,000 kc/s.

ACKNOWLEDGEMENTS.

It should be made clear that the art has, over many years, received impetus from workers in many lands, and, in particular, during the period 1939 to the present, there has been very close liaison in the technique of crystal production between this country and the United States of America, between all interested Government establishments in this country and between these establishments and those commercial undertakings which were charged with the huge quartz crystal demand necessary for war. All this liaison has been to the advantage of the art and has been a significant contributory factor to the great forward strides which have been taken.

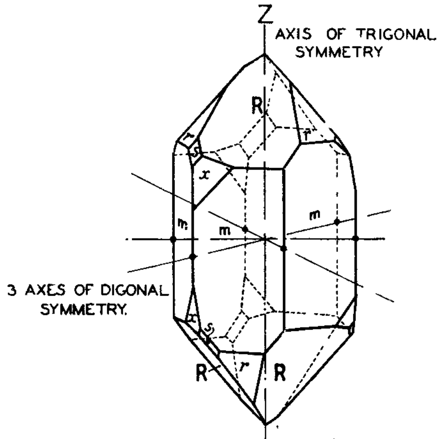
Much of the detailed work described in the paper has been carried out by three groups, Crystal, Frequency Standard and Filter groups, in the Radio Branch Laboratories over a comparatively long period, and to all members of these groups and to others who have contributed directly or indirectly the authors express their grateful thanks.

APPENDIX I.

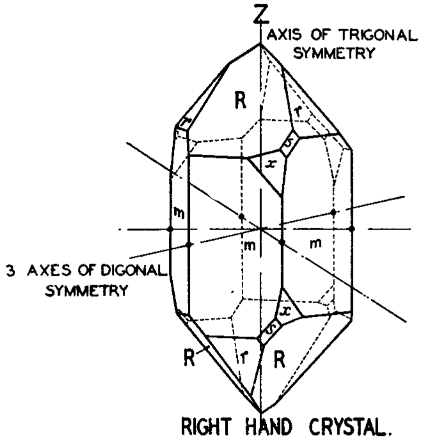
Geometry of Quartz.

Crystalline Form.

Quartz, SiO_2, is one of the commonest crystalline substances known to the crystallographer. The crystal form is a hexagonal prism terminated at each end by apparent hexagonal pyramids and is clearly illustrated by Fig. 14. Close examination will show, however, that the development and characteristic features of three alternate pyramid faces are similar and that they differ from those of the remaining three faces which in themselves are similar; in general the 'R' faces are bright and the 'r' faces dull, due to the mechanics of growth; also the opposite faces of the two terminations belong to the two different types. In fact, the crystal does not possess hexagonal symmetry, as the apparent hexagonal pyramid terminations really comprise a pair of complementary rhombohedra. These are referred to as the direct and indirect rhombohedra, the corresponding pyramid faces being the ' R ' and ' r ' faces respectively. The prism faces are known as the ' m ' faces and here again the two sets of three alternate ' m ' faces frequently differ in development and characteristics. In addition to the six ' m ' six ' R ' and six ' r ' faces, a crystal sometimes possesses small facets, ' s ' and ' x,' which appear on alternate prism edges in a homogeneous crystal. These facets occur in a fixed relation to the ' R ' faces and consequently are to be found on opposite prism edges at the two ends of the crystal.



LEFT HAND CRYSTAL



RIGHT HAND CRYSTAL.

FIG. 14.—QUARTZ CRYSTAL. CLINOGRAPHIC VIEWS OF DOUBLY TERMINATED L.H. & R.H. CRYSTALS.

It is apparent therefore that the symmetry about the axis joining the vertices of the pyramids is not hexagonal but trigonal, *i.e.*, it is necessary to rotate the crystal 120° and not 60° about this axis before the pattern is repeated. The only other axes of symmetry are three axes of digonal symmetry which, in the crystal of regular hexagonal cross section, join the middle points of opposite prism edges. These are known as the 'X' axes. The trigonal axis is also known as the principal or optic axis, so called because of the property possessed by quartz of rotating the plane of polarization of plane polarized light traversing the crystal parallel to this axis. The name of Z-axis has been given to this axis by workers concerned with the piezo-electric application.

Since the crystal possesses neither plane nor centre of symmetry it belongs to the enantiomorphous class, *i.e.*, it crystallises in two forms, one of which is the mirror image of the other. The two types are called right hand, R.H., and left hand, L.H., crystals respectively. In this connection it should be mentioned that the molecular structure is of helical form. The axis of the helix is parallel to the ' Z ' axis and the ' hand ' of the spiral is opposite for the two varieties. The presence of the s and x facets on a crystal provides a ready means of determining its hand. Thus, in a R.H. crystal, the x facet is below the right corner of an R face, and in a L.H. specimen, is below the left corner of an R face. In the R.H. crystal m x s r is in the form of a R.H. screw and in the L.H. crystal is in the form of a L.H. screw. The s face may also be covered with striae which are parallel to the sR edge.

It is probable that the conditions obtaining during the initial crystal growth determine the variety, and experience indicates that the two varieties are more or less equally distributed in nature. Very few crystals possess the double pyramidal termination, the average specimen exhibits one pyramidal termination and one rough end where it has grown from, or has been broken from, the rock. A quartz crystal is usually of irregular form, in so much as the prism is not a regular hexagon and also as the cross section perpendicular to the Z axis varies considerably in area throughout the prism length, the m faces being stepped. In addition, the areas of the R and r faces differ appreciably and the s and x facets are generally not developed. It must be remembered, however, that despite the irregular form of the average crystal the quartz crystal possesses its own set of interfacial angles, which are constant for all specimens at any given temperature. Thus the included angle between adjacent m faces is 120° and the angles of inclination of the R and r faces to the Z plane (the plane perpendicular to the Z axis) are both 51°47'.

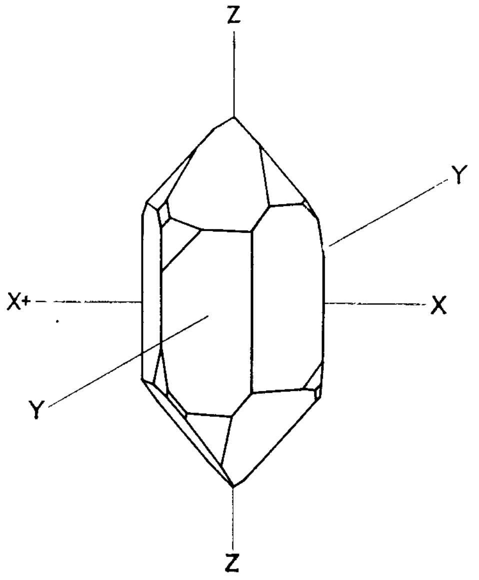
Twinning.

Lack of homogeneity of the molecular structure of a crystal is referred to as " twinning." The quartz crystal is subject to two twinning forms, electrical twinning in which one part of a crystal has suffered a 180° rotation about the Z axis with reference to the remainder, and optical twinning in which part of a crystal comprises the structure associated with the L.H. variety and the remainder that associated with the R.H. variety, both parts being on a common Z axis.

The presence of extensive twinning in a crystal normally precludes its use for piezo-electric applications, although of course the untwinned portions are serviceable. Almost all crystals are twinned to some extent by one or both varieties or even by a combination of the two. Although classical examples of twinned crystals are obtained in which the twinning is readily detected from the external crystal form, these are the exception rather than the rule and generally the presence and extent of twinning is not obvious unless recourse is made to internal examination rendered possible when the crystal is cut.

Crystal Axes.

In consequence of the piezo-electric effect along the digonal axes (X axes) these axes are called the 'electric' axes. There is a third system of axes, the Y axes, of which there are three mutually at right angles to both the X and Z axes, Fig. **15**. To summarise there are three systems of axes, the Z, X and Y axes, of which there are one, three and three respectively. The three sets of X and Y axes occur due to the trigonal symmetry of the crystal about the Z axis. The Z axis is parallel to the prism axis and the X and Y axes are perpendicular to the Z axis and respectively parallel to and perpendicular to the prism sides. It must be remembered that the X, Y and Z axes respectively refer to directions and not to unique axes. The plates and slices cut from the natural crystal by cutting planes perpendicular to the X, Y or Z axis are termed X, Y or Z-cut plates respectively.



+ Indicates Sign of Charge for Compression along X for L.H. Crystal.

FIG. **15**.—ONE SET OF X, Y & Z AXES IN QUARTZ.

APPENDIX II.

Types of Quartz Vibrator.

General.

Any arbitrarily cut element of quartz will, in general, possess natural frequencies corresponding to all the modes of vibration which are possible as a result of the relations between its elastic and piezo-electric properties. With a simple electrode system any such element will thus have resonant frequencies corresponding to longitudinal, face-shear and thickness-shear modes of vibration and to mechanical overtones of such modes. In addition, since there is a motional resemblance between even order face-shear mode overtones and odd order flexural mode fundamental and overtone modes and vice-versa, flexural mode vibrations will also be present.

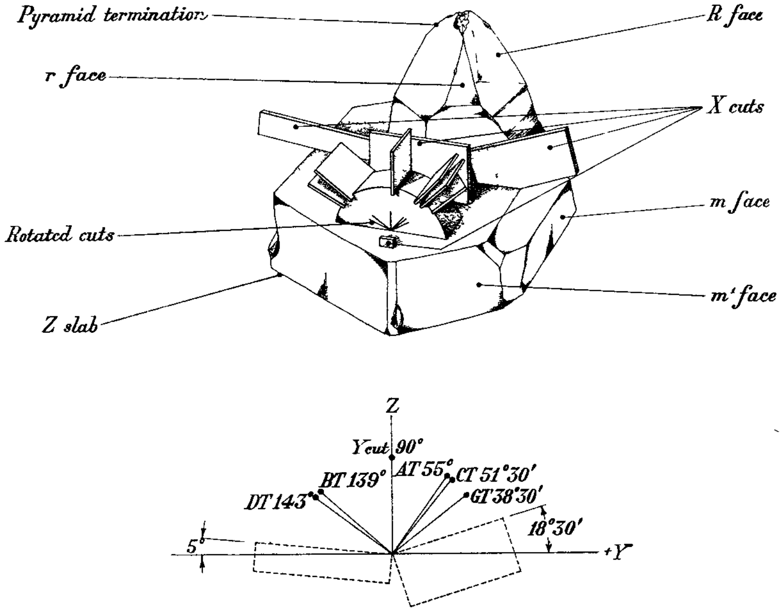
This circumstance means, in effect, that any arbitrarily cut quartz element possesses a resonance spectrum which exhibits peaks at frequent intervals of frequency between the lowest fundamental flexural frequency (determined by its elastic constants, density and dimensions) and the highest thickness-shear or longitudinal thickness vibration overtone frequency which is measurable.

The temperature coefficients of the physical constants which determine the resonant frequencies of any of these modes are, in general, different, with the result that the resonant frequency spectrum varies in respect of the frequency separation between adjacent resonance peaks according to the measurement temperature. Thus, an unwanted resonance may, with change of temperature, move through the resonant frequency range of the wanted resonance, and, in so doing, considerably modify the reactance characteristic corresponding to the required mode of oscillation. Much development has therefore been devoted to prescribing particular ways of cutting quartz elements from the natural crystal which will minimise interference from unwanted modes of vibration and at the same time produce a small variation of the frequency of the desired vibration mode with respect to temperature.

The table details the quartz cuts which possess these desired characteristics and gives also the practicable frequency range which can be covered with each cut, the mode of vibration, and the major dimensions of the crystal elements. The frequency ranges quoted for the various cuts represent, in general, limits to practicable handling size or to the size of raw material required. It will be noted that there is a frequency overlap between ranges, the choice of cut in the overlap region being determined by other desirable characteristics such as temperature performance. The GT-cut requires considerable production effort and is for this reason somewhat restricted in use.

The frequency-temperature characteristic of the cuts tabulated is, unless otherwise stated, approximately parabolic and there is thus one temperature at which the frequency-temperature characteristic (f.t.c.) is zero. The temperature of zero f.t.c. may be varied within quite wide limits by varying the controlling angle of cut and/or by varying the dimensional ratios.

The relation of the quoted types of vibrators to the geometric axes of the natural crystal are illustrated by Fig. **16**.



Angles measured in anti-clockwise sense.

FIG. **16**.—DIAGRAM SHOWING VARIOUS TYPES OF CRYSTAL CUT.

TABLE.

Properties of prescribed quartz crystal cuts.

Common name of cut	Type of vibration	Practical Frequency Range. kc/s	Major dimensions m.m. Length × Width	Remarks
NT	Flexural	4 to 75	75 × 4·5 24 × 12	Frequency is a function of width/(length^2). Dimensions quoted are realisable.
X-cut or X-cut +5° bars	Longitudinal	60 to 200	41 × a* 13·25xa*	The +5° bar has a higher zero f.t.c. range than the X-cut bar.
DT CT	Face shear	80 to 400	25·6 × 25·6 7·70 × 7·70	The CT is larger than the DT for a given frequency.
FT ET	Face shear overtone	200 to 800	23·5 × 23·5 6·70 × 6·70	The ET is larger than the FT for a given frequency.
AT BT	Thickness shear	500 to 20,000	25 × 25 (3·3 mm thick) 10 × 10 (0·128 mm thick)	The BT is larger than the AT for a given frequency. The frequency-temperature characteristic is not truly parabolic.
GT	Longitudinal (resolved shear)	90 to 200	36·5 × 31·1 16.45 × 14·05	Frequency-temperature characteristic approximately straight over wide temperature range with average slope of 6 × 10^{-8}/1C°.

**Note* : The ' a ' dimension varies according to desired temperature range, the length to width ratio is of the order of 5 to 1.

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