

Jan. 7, 1941.

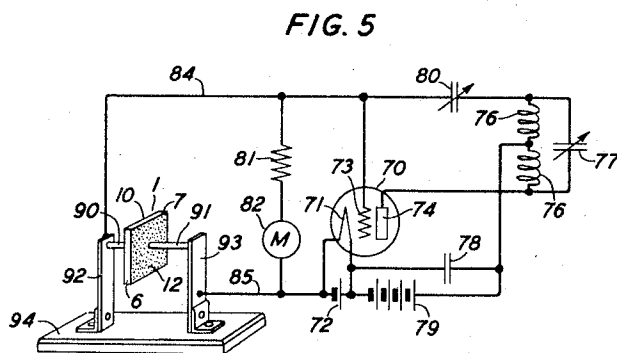
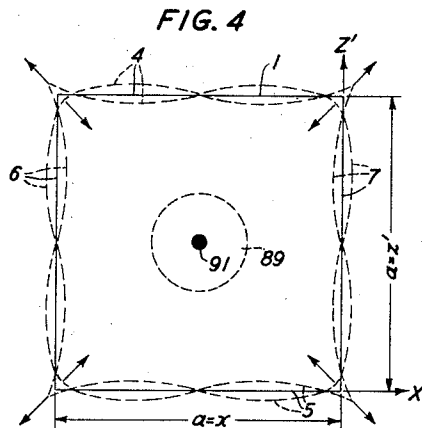
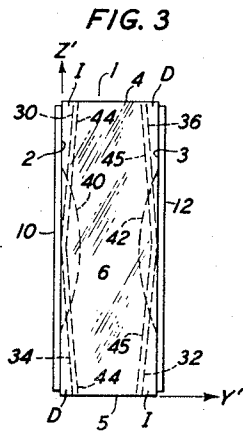
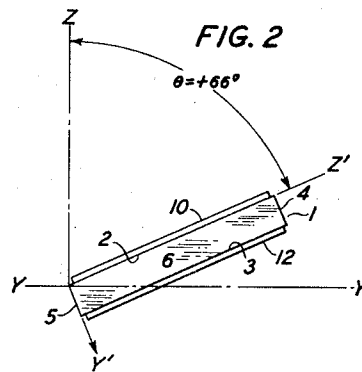
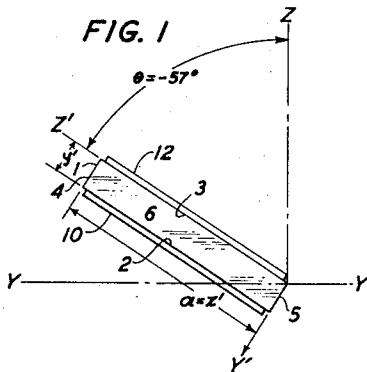
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2,227,904

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Dec. 21, 1937

2 Sheets-Sheet 1



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PIEZOELECTRIC CRYSTAL APPARATUS

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2 Sheets-Sheet 2

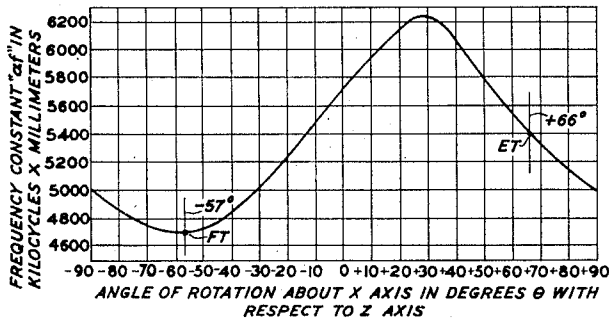


FIG. 6

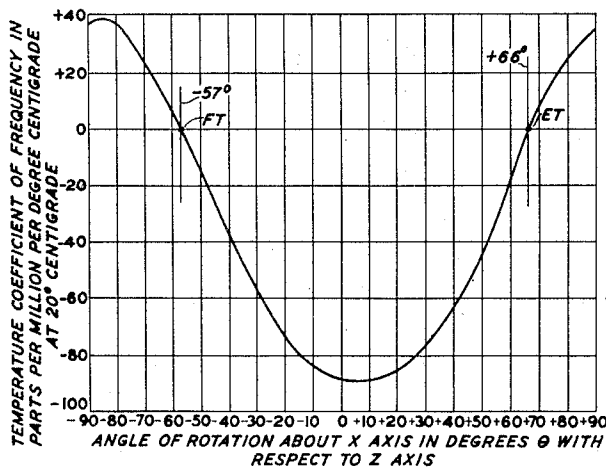


FIG. 7

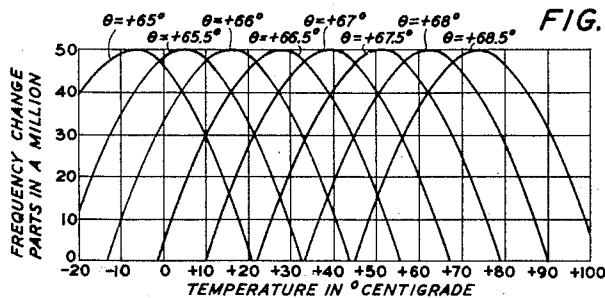


FIG. 8

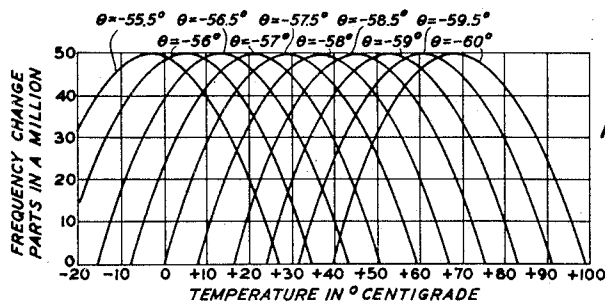


FIG. 9

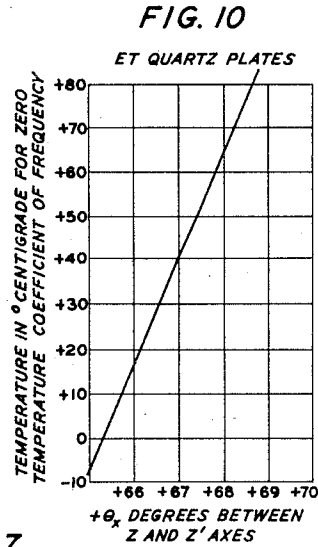


FIG. 10

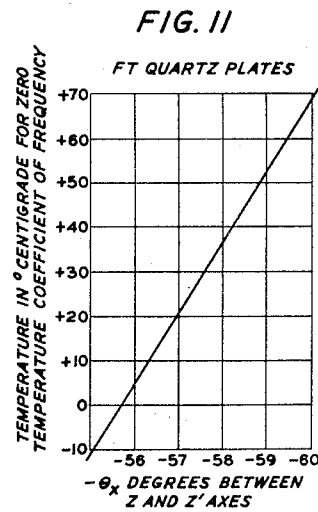


FIG. 11

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PIEZOELECTRIC CRYSTAL APPARATUS

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Application December 21, 1937, Serial No. 180,937

18 Claims. (Cl. 171—327)

This invention relates to piezoelectric apparatus and particularly to piezoelectric quartz crystal elements suitable for use as circuit elements in oscillation generator systems and in electric wave filter systems, for example.

One of the objects of this invention is to provide a piezoelectric crystal element having a substantially zero or other desired predetermined temperature coefficient of oscillation frequency, either positive or negative.

Another object of this invention is to provide a piezoelectric body adapted to vibrate in such a mode of motion as to possess a relatively large frequency constant (product of frequency and dimension) thereby allowing the body to be of a convenient shape and size and yet have a frequency of vibration in the range from about 120 to 1000 kilocycles per second, for example, and also simplifying the physical task of adjustment of the body to a precise frequency.

Another object of this invention is to provide a piezoelectric vibrator which has a relatively large nodal area by means of which the body may be supported or clamped in position by suitable contacting projections and resilient appliances, for example.

Another object of this invention is to provide a piezoelectric body having a frequency substantially independent of changes in temperature throughout a substantial range of temperatures to permit temperature regulating apparatus to be simplified or eliminated and to permit a constant vibration frequency to be maintained.

Another object of this invention is to provide adjustments in the frequency and in the temperature coefficient of frequency of a piezoelectric crystal body.

Another object of this invention is to provide a multifrequency piezoelectric body having more than one natural period of vibrations, the frequencies of said vibration being primarily dependent upon different dimensions of the body and hence being substantially separately and independently adjustable and usable.

The temperature coefficient of frequency of a piezoelectric body adapted for vibration in a particular mode of motion in accordance with one feature of this invention may be made substantially zero at a desired temperature and of a small value of about two parts per million per

degree centigrade over a wide range of temperatures within the range from -20° to $+60^{\circ}$ centigrade, by so cutting the piezoelectric body from the crystal material that the relative position of its surfaces with respect to the crystallographic axes thereof results in a compensatory relationship between the various components which together make up the temperature coefficient of the body, or, more particularly so that the resultant of the component temperature coefficients of the elastic constants thereof, of at least one dimension thereof and of the density thereof is substantially zero. In the case of quartz, this may involve a rotation or angular orientation about one or more of the orthogonal crystallographic axes thereof so that the principal or major faces of the quartz body are inclined with respect to two or more of the orthogonal crystallographic axes thereof.

In accordance with a particular embodiment of this invention, a relatively thin, substantially square, quartz crystal plate of rectangular parallelepiped form may be vibrated and piezoelectrically excited in a certain mode of motion at a relatively low frequency which is determined by the square major surface dimensions or areas thereof. Such vibration as described hereinafter may be excited by means of suitable electrodes made integral with or spaced from the major surfaces of the crystal and connected in circuit with a suitable oscillator circuit suitably tuned with respect to the vibration frequency of the crystal. To secure substantially zero temperature coefficient of frequency at about 20° centigrade for such quartz plate, the major plane and the electrode surfaces of the quartz element may be made parallel or substantially parallel to an electric or X axis and inclined substantially either -57 degrees or $+66$ degrees with respect to the optic or Z axis thereof as measured in a plane perpendicular to said X axis.

For a clearer understanding of the nature of this invention and the additional features and objects thereof, reference is made to the following description taken in connection with the accompanying drawings, in which like reference characters represent like or similar parts and in which:

Fig. 1 is an edge view of a quartz crystal plate

having an orientation angle of θ =substantially -57 degrees in accordance with this invention;

Fig. 2 is an edge view of the quartz crystal plate shown in Fig. 1 but illustrating another orientation angle where θ =substantially $+66$ degrees;

Fig. 3 is a view illustrating in enlarged scale some adjustments in the frequency and in the temperature coefficient of frequency for the crystals shown in Figs. 1 and 2;

Fig. 4 is a view illustrating in enlarged scale the square-shaped major surface of the quartz crystals of Figs. 1 and 2 vibrating in a low frequency face mode of motion in accordance with this invention;

Fig. 5 is a circuit diagram of an oscillation generator controlled by a piezoelectric element;

Figs. 6 and 7 are graphs of the frequency constant and temperature coefficient of frequency respectively of square-shaped quartz crystal plates vibrated in the face mode of vibration illustrated in Fig. 4 for different angles of rotation about an electric or X axis measured in degrees θ with respect to the Z axis;

Figs. 8 and 9 are graphs showing temperature-frequency curves of the quartz crystals of Figs. 1 and 2 for several orientation angles θ when vibrated in the mode of motion illustrated in Fig. 4; and

Figs. 10 and 11 are graphs of curves plotted from the peaks of the parabolic curves of Figs. 8 and 9, respectively, and showing the relation between the orientation angle θ and the temperature at which zero temperature coefficient of frequency is obtained.

This specification will follow the standard or conventional terminology as applied to crystal-line quartz which employs the orthogonal axes X, Y and Z to designate the electric, the mechanical and the optic axes, respectively, of piezoelectric quartz crystal material and which employs the orthogonal axes X', Y' and Z' to designate the directions of axes or surfaces of a piezoelectric body angularly oriented with respect to any or all of the X, Y and Z axes thereof. Where the orientation is obtained by rotation of the quartz element about an electric or X axis, as particularly illustrated herein, the orientation angle θ designates the effective angular position of the crystal in degrees as measured between the optic axis Z and the Z' axis in the YZ plane perpendicular to said X axis.

Quartz crystals may occur in two forms, namely, right-hand and left-hand. A quartz crystal is designated as right-hand if it rotates the plane of polarization of plane polarized light traveling along the optic or Z axis in the sense of direction of a right-hand screw or in a clockwise direction when facing in the direction of propagation of the light; and is designated as left-hand if it rotates such plane of polarization in the opposite direction to the left or in the counter-clockwise direction when facing in the direction of propagation of the light. If a compressional stress or squeeze be applied to the ends of an electric axis X of a quartz body and not removed, a charge will be developed which is positive at the positive end of the electric axis and negative at the negative end of the electric axis for either right-hand or left-hand crystals. The magnitude and sign of the charge may be measured with a vacuum tube electrometer, for example. In specifying the orientation of the right-hand crystal, the sense of the angle θ which the new axis Z' makes with the optic axis Z as the crystal plate is rotated about the electric

axis X is deemed positive when with the compression positive end of the X axis pointed toward the observer the rotation is in a clockwise direction. A counter-clockwise rotation of such a crystal about the X axis gives rise to a negative orientation angle θ . Conversely, the orientation angle of a left-hand crystal is positive when, with the compression positive end of the electric axis pointed toward the observer, the rotation is counter-clockwise and is negative when the rotation is clockwise. In one species of this invention as applied to quartz the principal or major faces of the quartz body are substantially parallel to an X or electric axis and are oriented or inclined at a positive angle of approximately $+66$ degrees with respect to the optic axis as measured in a plane perpendicular to said X axis as illustrated in Fig. 2. In another species, the major faces are inclined at an angle of approximately -57 degrees with respect to the optic axis as illustrated in Fig. 1. The crystals illustrated in Figs. 1 and 2 are right-hand quartz crystals as defined hereinbefore.

Referring to the drawings, Figs. 1 and 2 illustrate right-hand piezoelectric quartz crystal circuit elements suitable for obtaining substantially zero temperature coefficient of frequency at a relatively low frequency of vibration such as for example, within the oscillation frequency range of about 120 to 1000 kilocycles per second. The crystal elements illustrated in Figs. 1 and 2 may be produced by cutting from crystal quartz a relatively thin plate 1 of substantially rectangular parallelepiped form having its opposite major or electrode surfaces 2 and 3 substantially square in shape as shown in Fig. 4, having one pair of its opposite edge faces 4 and 5 disposed in a direction substantially parallel to an electric or X axis thereof, the X axis being perpendicular to the plane of the drawing in Figs. 1 and 2, having the other pair of its opposite edge faces 6 and 7 disposed in a direction perpendicular to said electric axis X and having its major plane and its major surfaces 2 and 3 inclined at an acute orientation angle with respect to the optic or Z axis of θ =about -57 degrees as illustrated in Fig. 1 or of θ =about $+66$ degrees as illustrated in Fig. 2, the angle θ being measured in the YZ plane which is perpendicular to said X axis. Suitable conductive electrodes 10 and 12 may be placed on or adjacent the square-shaped major faces 2 and 3 of the crystal plate 1 in any suitable manner and by means of a suitable circuit such as illustrated in Fig. 5, for example, the crystal plate 1 may be excited to vibrate in a face mode of vibration as illustrated in Fig. 4 at a response frequency as given by the curve in Fig. 6, which depends primarily upon the z' shear elastic constant s'_{55} and is determined by the large dimensions x and $z'=a$ or area of the square-shaped major surfaces 2 and 3 of the quartz crystal plate 1.

The exciting electric field may be applied to the crystal 1 in the direction of the small or thickness dimension y' of the crystal 1 by means of suitable electrodes 10 and 12 associated with the large surfaces 2 and 3 of the crystal 1 and may be utilized, to operate the crystal in a face mode of vibration in the XZ' plane thereof to cause the square crystal plate 1 to deform periodically approximately into a shape as illustrated in greatly enlarged scale in Fig. 4 and to vibrate at a frequency determined by the large dimensions, namely the x and z' dimensions of the crystal plate 1 which preferably have an equal

length a as illustrated in Fig. 4. The effects of coupling between the desired mode of vibration and undesired vibrations therein may be reduced to an ineffective value by making the thickness dimension y' sufficiently small relative to the other or large dimensions a of the crystal plate 1.

Reducing either the x or z' dimensions, which are the major surface dimensions of the crystal plate 1, increases the vibration frequency and accordingly by suitable selection of the x and z' dimensions, substantially the desired oscillation frequency for the crystal 1 may be obtained such as, for example, a frequency within the limits roughly from 120 to 1000 kilocycles per second. While either a negative or a positive angle may be utilized for such frequencies, for frequencies below 160 kilocycles, a negative angle such as, for example, $\theta = -57$ degrees as illustrated in Fig. 1, may be more advantageously utilized and for frequencies above 500 kilocycles, a positive angle such as, for example, $\theta = +66$ degrees as illustrated in Fig. 2, may be more advantageously utilized while for frequencies between 160 and 500 kilocycles, either type may be conveniently utilized.

It will be understood that the orientation angle θ of Figs. 1 and 2 may be varied slightly from the values mentioned of $\theta = +66$ degrees and $\theta = -57$ degrees to obtain the desired zero temperature coefficient of oscillation frequency best suited to the range of the temperatures to be applied thereto. For example, the orientation angle θ of Fig. 2 may be any angle substantially from $+65$ degrees to $+68$ degrees to obtain substantially zero temperature coefficient of frequency at some definite temperature within the range from about -7° centigrade to about $+63^\circ$ centigrade as shown in Fig. 8, the $+65$ degree orientation angle θ giving the zero temperature coefficient of frequency at about -7° centigrade, a $+65^\circ 30'$ orientation angle θ giving the zero temperature coefficient of frequency at about 5° centigrade, the $\theta = +66$ degree orientation angle giving the zero temperature coefficient of frequency at about 17° centigrade, and the $\theta = +66^\circ 30'$ and $+67$ degrees angle giving the zero temperature coefficient of frequency at about respectively 28° and 39° centigrade as shown in Figs. 8 and 10. Similarly, the orientation angle θ of Fig. 1 may be any angle substantially from -55 degrees to -60 degrees to obtain substantially zero temperature coefficient of frequency at a definite temperature within the range from about -10° centigrade to about $+70^\circ$ centigrade as shown in Fig. 9, the -56 degree orientation angle θ giving the zero temperature coefficient of frequency at about $+5^\circ$ centigrade, the -57 degree orientation angle θ giving the zero temperature coefficient of frequency at about $+21^\circ$ centigrade, the -58 degree orientation angle θ giving the zero temperature coefficient of frequency at about $+37^\circ$ centigrade, etc. as shown in Figs. 9 and 11. It will be understood that the values given in Figs. 8 to 11 obtain when the crystal 1 of Figs. 1 and 2 is excited in the face mode of vibration illustrated in Fig. 4 to give a frequency constant as shown in Fig. 6 and a response frequency which depends primarily upon the z'/x shear elastic constant s'_{ss} . It will be noted that, as shown in Fig. 8, the frequency changes less than 17 parts per million from the mean value over a 50° centigrade change in temperature for any of the type ET orientations θ shown therein; and, as shown in Fig. 9, the frequency changes less than 20 parts per million from the mean

value, over a 50° centigrade change in temperature for any of type FT orientations θ shown therein.

The slope of the temperature versus frequency curves of Figs. 8 and 9 gives the temperature coefficient of frequency at the temperature under consideration. Where the slope of the curves is zero or horizontal, the temperature coefficient of frequency is zero. The zero temperature coefficient of frequency occurs only at a specific temperature represented by the peak of each parabola and is controlled mainly by the orientation angle θ , but is also affected somewhat by the relative dimensions of the quartz plate 1 and the air-gap, if any, between the crystal plate 1 and its electrodes 10 and 12. In the neighborhood of the proper angle for zero temperature coefficient of frequency small changes in the orientation angle θ have the effect of moving the temperature-frequency parabola to a new position without materially affecting its form. Thus, different orientations produce zero temperature coefficient of frequency at different temperatures and families of temperature-frequency curves for varying orientations are obtained as illustrated in Figs. 8 and 9. It will be noted that frequency changes only are represented on these curves of Figs. 8 and 9 and that each successive parabola occurs at a slightly higher (or lower) frequency than its neighbor as a result of the effect of orientation on the absolute frequency. The accuracy with which these curves represent actual cases is within the errors caused by present practical limits of accuracy. More precise results may be obtained with greater accuracy in measurements of temperature, frequency and orientation angles.

The curves of Figs. 10 and 11 are based on the sets of parabolic curves of Figs. 8 and 9, respectively, and represent the loci of the peaks of the parabolas thereof. They are useful in selecting an orientation angle θ to produce zero temperature coefficient of frequency at a desired temperature and at the same time a low temperature coefficient of frequency throughout a wide range of temperatures.

The frequency-temperature curves of quartz plates oriented for low temperature coefficient of frequency are concave downward and parabolic within the temperature ranges illustrated in Figs. 8 and 9 and may be extrapolated to cover a two-hundred degree temperature range extending one hundred degrees above and below the parabolic peak.

In designing crystals to operate with zero temperature coefficient of frequency at a certain temperature, corrections may be applied according to the conditions of air-gap and the comparative crystal plate dimensions. A change in the thickness dimension y' relative to the x dimension of the crystal plate 1 affects the position of the parabola without appreciably altering its form and results in a slight shifting of the zero temperature coefficient of frequency point to a new temperature. Thus, a single orientation may be employed to produce zero temperature coefficient of frequency at a desired temperature by adjustment or proper design of the thickness y' of the plate 1, or small changes in the temperature coefficient of frequency may be made without appreciably affecting the frequency by adjusting the thickness y' of the plate 1. The effect of departure from a square plate shifts the position of each of the parabolas of Figs. 8 and 9 and lowers the temperature for zero tempera-

ture coefficient of frequency for a decrease in the ratio of the

$$\frac{x}{z'}$$

dimensions. Since reducing either dimension x or z' raises the frequency, the choice of the dimension x or z' to be ground may depend upon the direction in which it is desired to shift the position for zero temperature coefficient of frequency.

Increasing the air-gap between the crystal and an electrode disposed adjacent its major surface causes the zero temperature coefficient of frequency to occur at a lower temperature, the temperature-frequency parabola maintaining its form but moving to the left in Figs. 8 and 9 so that the peak or position of zero slope occurs at a lower temperature. By means of this effect the temperature coefficient of frequency of a crystal and its holder may be adjusted to zero at the temperature at which operation is expected without changing the orientation angle θ or the thickness dimension y' of the quartz plate.

Accordingly, it will be understood that the frequency-temperature curves of the quartz plates constructed and vibrated in accordance with this invention are in general parabolic and concave downward as illustrated in Figs. 8 and 9, that slight changes in the orientation angle θ , or relative dimensions, or air-gap cause the temperature-frequency parabolas to shift without appreciable change in form, that the temperature at which the temperature coefficient of frequency is zero may be altered by changing the orientation angle θ , or by changing the thickness y' of the plate or its electrode air-gap, or by departure from the square shape of the plate 1. While the invention has been particularly described and illustrated in connection with quartz plates 1 having square major surfaces 2 and 3, it will be understood that the mode of motion involved in Fig. 4 may be set up in quartz plates that are not square such as rectangular or circular plates. In such cases, the zero temperature coefficient of frequency may occur at a slightly different angle θ than those given in Figs. 7 to 11 for the square plates. The frequency of rectangular plates that are nearly square can be obtained on the basis of the arithmetic means of the two dimensions x and z' , using the same frequency constant "af" as for square plates as given in Fig. 6.

The mode of vibration illustrated in Fig. 4 which produces the frequency constants as given in Fig. 6 may be considered as the result of flexures in the $z'x$ plane combined with and excited by the simple $z'x$ shear. The frequency of vibration of quartz plates of square or nearly square shape as illustrated in Figs. 1 to 5 excited in the mode of vibration as illustrated in Fig. 4 by suitable electrodes and circuit connections as illustrated in Fig. 5, for example, is substantially proportional to the quartz elastic modulus

$$\frac{1}{\sqrt{s'_{55}}}$$

but is altered slightly from this proportionality by the effects of the flexures, and is given by the empirical expression:

$$f = \frac{1308 \times 10^{-5}}{a} \frac{1}{\sqrt{s'_{55} \rho}} (1 - .072 \sin 2\theta) (1 + 1.416 \times 10^{-9} \theta^4) \quad (1)$$

where

$a = x = z'$ for a square plate, or

$$a = \frac{x + z'}{2}$$

for a nearly square plate, x and z' being the edge dimensions of the crystal plate 1 in the directions of the X and Z' axes, respectively;

ρ is the density of the quartz; and s'_{55} is the $z'x$ shear elastic constant of the quartz corresponding to and a function of the orientation angle θ .

The $z'x$ shear elastic constant s'_{55} is given by the expression:

$$s'_{55} = s_{44} \cos^2 \theta + s_{66} \sin^2 \theta + 4s_{14} \sin \theta \cos \theta \quad (2)$$

where

s_{44} , s_{66} and s_{14} are known elastic constants of quartz as given, for example, by W. Voigt, page 753 of the *Lehrbuch der Kristallphysik*, or by R. B. Sosman, page 463 of *The Properties of Silica*; and

θ is the angle between the Z' axis of the crystal plate and the optic or Z axis obtained by rotation about the X or electric axis.

A plot of the frequency constant "af" in terms of the product of kilocycles per second frequency and millimeters of dimension a , against the orientation angle θ as measured experimentally when vibrating in the mode of motion illustrated in Fig. 4 is shown in Fig. 6 and is in close accord with these equations.

The temperature coefficient of frequency of the quartz plate 1 vibrating in the mode of motion illustrated in Fig. 4 is the combined result of the individual temperature coefficients of the various factors involved in the determination of the frequency, as given by Equation 1 for example, and by proper orientation of the quartz plate these individual temperature coefficients may be so balanced against one another as to produce substantially any desired temperature coefficient of frequency within the range of +30 to -90 parts in a million per degree Centigrade, as shown in Fig. 7. The primary controlling influence on the frequency, as shown by Equation 1, is the quartz elastic modulus s'_{55} of Equation 2 and hence the temperature coefficient of frequency follows the general trend of the temperature coefficient of s'_{55} which is given by the expression:

$$T s'_{55} = \frac{[s_{44} T s_{44} \cos^2 \theta + s_{66} T s_{66} \sin^2 \theta + 4s_{14} T s_{14} \sin \theta \cos \theta]}{s'_{55}} \quad (3)$$

where $T s_{44}$, $T s_{66}$, and $T s_{14}$ are the temperature coefficients of the elastic constants s_{44} , s_{66} , and s_{14} referred to in Equation 2, where s_{44} , s_{66} , and s_{14} are the elastic constants referred to in Equation 2, and where θ is the orientation angle referred to in Equation 2.

The variations in frequency and in temperature coefficient of frequency of a square quartz crystal 1 operated in the mode of vibration illustrated in Fig. 4, as the angle of rotation θ is varied, are shown in Figs. 6 and 7, respectively.

The curve in Fig. 6 which is drawn through points obtained by experimental measurement, may be calculated from the following empirical expression derived from Equation 1:

frequency constant = af =

$$\frac{80}{\sqrt{s'_{55}}} \times 10^{-5} \times (1 - .072 \sin 2\theta) \times (1 + 1.416 \times 10^{-9} \theta^4) \text{ kc.mm.} \quad (4)$$

where the units of s'_{55} are

$$\left(\frac{\text{cm}^2}{\text{dy}}\right)$$

5 and which shows the calculated relation between the frequency constant "af" and the orientation angle θ for square-shaped quartz plates operated in a mode of vibration as shown in Fig. 4 at a frequency determined by the major surface dimensions and having the major plane substantially parallel to an X or electric axis and disposed at a selected orientation angle θ with respect to the optic or Z axis by rotation about the electric or X axis of the quartz material. The
10 ordinates in Fig. 6 express the frequency constant "af" in terms of the arithmetic product of kilocycles per second into millimeters (kc. mm.) and the abscissae express the corresponding orientation angle θ in degrees of arc from -90 degrees to $+90$ degrees as measured in the YZ plane from the Z or optic axis. The position designated as ET on the curve in Fig. 6 gives the value of the frequency constant "af" as substantially 4700 for the quartz plate 1 illustrated in Fig. 1 having its
25 major plane parallel to an electric or X axis and inclined substantially $\theta = -57$ degrees with respect to the optic or Z axis of the natural quartz material from which it has been cut. The position designated as ET on the curve shown in Fig. 6 gives the value of the frequency constant "af" as substantially 5400 for the quartz plate 1 illustrated in Fig. 2 having its major plane parallel to an electric or X axis and inclined substantially $\theta = +66$ degrees with respect to the optic
30 or Z axis thereof. The values obtained by Equation 4 agree well or within about 2 per cent of the experimental results as given by the curve in Fig. 6 for all angles of θ .

The curve in Fig. 7 is based on values obtained experimentally and shows the relation between the temperature coefficient of frequency and the orientation angle θ for square-shaped quartz plates 1 excited in a $z'x$ mode of vibration as shown in Fig. 4 at a frequency determined by the major surface dimensions as illustrated in Fig. 4 and having the major plane thereof substantially parallel to an electric or X axis and disposed at any selected orientation angle θ with respect to the optic or Z axis of the quartz material. The
45 ordinates of the curve shown in Fig. 7 express the temperature coefficient of frequency of the quartz plates in parts per million per degree centigrade. The position designated as FT in Fig. 7, represents the zero temperature coefficient of frequency quartz plate 1 illustrated in Fig. 1 having its major plane substantially parallel to an electric or X axis and inclined substantially $\theta = -57$ degrees with respect to the optic or Z axis thereof. The position designated as ET in Fig. 7 represents the zero temperature coefficient of frequency quartz plate 1 illustrated in Fig. 2 having its major plane parallel to an electric or X axis and inclined substantially $\theta = +67$ degrees with respect to the optic or Z axis thereof.

As indicated by the frequency Equations 1 and 2 and the frequency-constant curve shown in Fig. 6, it will be noted that the frequency of the quartz plate is substantially proportional to

$$\frac{1}{\sqrt{s'_{55}}}$$

70 varies with the orientation angle θ , is near the minimum value at $\theta = \text{about } -57$ degrees, and is near the maximum value at $\theta = \text{about } +30$ degrees; and as indicated in Equations 3 and 4 and in Fig. 7, that the temperature coefficient of fre-

quency varies mainly with the temperature coefficient of $z'x$ shear elastic constant s'_{55} and hence with the orientation angle θ and passes through zero at substantially $\theta = -57$ degrees and $\theta = +66$ degrees, and accordingly the face mode of vibration as illustrated in Fig. 4 may be utilized at orientations of substantially -57 or $+66$ degrees to secure a low temperature coefficient of frequency over a wide range of temperatures and a zero temperature coefficient of frequency within said
10 range.

As illustrated on an exaggerated scale in Fig. 3, the temperature coefficient of frequency and also the frequency of the quartz crystal plates 1 illustrated in Figs. 1 and 2, may be adjusted to precise values by final hand grinding or by otherwise suitably reducing of the dimensions of selected parts of the selected surfaces thereof. The temperature coefficient of frequency thereof may be made either more positive or more negative at will and thus reduced to zero or other predetermined value of temperature coefficient of frequency, with only slight effect upon the frequency and the frequency may then be either raised or lowered at will with substantially no effect upon
25 the temperature coefficient of frequency thereof.

More particularly, the temperature coefficient of frequency of the crystal 1 may be substantially precisely adjusted to substantially zero or other predetermined value by selectively changing the orientation thereof as illustrated in Fig. 3. If one or both of the opposite halves of the opposite electrode faces 2 and 3 of the crystal 1 are uniformly tapered as by grinding or otherwise reducing the surfaces 2 and 3 in the regions I to
35 form new tapered plane surfaces 30 and 32, the effective orientation angle θ is slightly increased and the temperature coefficient of frequency is accordingly made or rendered slightly more positive. Similarly, if on the other hand, one or both of the opposite halves of the opposite electrode faces 2 and 3 are uniformly tapered as by grinding or otherwise reducing the surfaces 2 and 3 in the regions D to form new tapered plane surfaces 34 and 36, the effective orientation angle
45 θ is slightly decreased and the temperature coefficient of frequency is made slightly more negative. Thus, if a particular crystal 1, originally cut to give zero temperature coefficient of frequency as illustrated in Figs. 1 and 2, is found to have a small undesired negative or positive temperature coefficient of frequency, it may be selectively ground or otherwise reduced in the regions I or D, respectively, to bring the temperature coefficient of frequency to substantially
55 precisely zero or other desired predetermined value. It will be understood that the tapered regions I and D may cover substantially one-half of each electrode face 2 and 3 as illustrated by the tapered surfaces 30, 32, 34 and 36 in Fig. 3, or may cover more or less than one-half of each electrode face 2 and 3. If the whole face of each opposite surface 2 and 3 is ground flat, the resulting crystal electrode surfaces may be plane and parallel but uniformly thinner or nearer
65 together. The effective orientation angle θ and the temperature coefficient of frequency of the crystal 1 may be changed more with thick plates than with thin ones. Usually the amount of change required to adjust the temperature coefficient of frequency to a desired value is less than the maximum change that can be obtained in a particular crystal.

It will be noted that reducing the thickness of the crystal 1 by tapering the major surfaces 2 75

and 3 thereof as illustrated in Fig. 3 to selectively change the effective angle of orientation and the temperature coefficient of frequency thereof introduces only a small change in frequency since the frequency of the crystal 1 is dependent not mainly upon the thickness thereof but primarily upon the dimensions of the electrode surfaces 2 and 3 and since, as illustrated in Fig. 6, the frequency is dependent only to a relatively small extent upon small variations in the angular orientation θ . Accordingly, grinding the major surfaces 2 and 3 of the crystal 1 as illustrated in Fig. 3 for example, to correct the temperature coefficient of frequency thereof introduces only a small change in the frequency of the zero temperature coefficient of frequency crystals illustrated in Figs. 1 and 2. However, since the frequency adjustments about to be described are attended with substantially no change in the temperature coefficient of frequency of the crystal 1, these frequency adjustments are preferably carried out after completing such adjustment of the temperature coefficient of frequency.

To selectively lower the frequency of the crystal 1 illustrated in Figs. 1 and 2, the center or nodal region of the crystal plate 1 may be thinned a desired amount by grinding or otherwise reducing the central areas of the electrode surfaces 2 and 3 as illustrated on an exaggerated scale by the symmetrical spherical concavities 40 and 42 in Fig. 3. The frequency of the crystal 1 may then be raised by uniformly and symmetrically grinding the margins or outer regions of the major surfaces 2 and 3 of the plate 1 as illustrated by the surfaces 44 and 45 shown in Fig. 3. While the frequency of the crystal 1 may also be raised by grinding any or all of the four edges 4 to 7 of the plate 1, thus reducing the larger dimensions a and the area of the electrode surfaces 2 and 3, the method of lowering and raising the frequency by thinning respectively the central and outer marginal regions of the major surfaces 2 and 3 of the plate 1, changes the frequency less than does the method of edge grinding for a given fractional change in dimension. Where the plate 1 is symmetrically thinned by symmetrically grinding the central and marginal regions of the electrode surfaces 2 and 3, it will be noted that the frequency of the crystal 1 may be selectively raised or lowered to a desired value without changing the effective angular orientation of the crystal 1 and therefore without changing the temperature coefficient of frequency thereof.

It will be understood that the crystal plate 1 may be successively center face and marginally or edge ground until the desired resulting frequency is obtained in the particular circuit utilized, that the crystal 1 need not be rendered unusable by overgrinding and that the amount of crystal material removed in the final grinding of a group of crystals may be greatly reduced since the crystals may be originally cut, within manufacturing limits, to the exact size desired without rendering unusable those which are slightly undersize.

It will be noted that the mode of vibration of the crystal 1 as illustrated in Fig. 4 is such that the temperature coefficient of frequency thereof may be selectively raised or lowered by final hand grinding with only very small frequency changes therein; and also that the mode of vibration is such that the frequency thereof may be selectively raised or lowered without changing the temperature coefficient of frequency thereof.

Accordingly, not only may the temperature coefficient of frequency be selectively raised or lowered to a precise value but also the frequency may be selectively raised or lowered without affecting the temperature coefficient of frequency.

It will be noted also that this mode of vibration is such that the frequency constant has an unusually large value as shown in Fig. 6, which further facilitates the adjustment to a precise predetermined frequency by effecting smaller changes in frequency for a given amount of grinding or for the removal of a given amount of material by any method.

While the precision adjustments of the temperature coefficient of frequency and of the frequency have been described in connection with the particular crystal 1 illustrated in Figs. 1 and 2, it will be understood that they may apply also to crystals having other orientations of the angle θ as rotated about the electric or X axis and excited in the face mode of vibration as illustrated by Fig. 4 and the graph in Fig. 6 for example. It will be understood that the frequency adjustments disclosed may apply generally to any crystal the frequency of which is determined by the larger dimensions thereof and that the temperature coefficient adjustments may apply generally to crystal plates the frequency of which depends upon the angle of orientation and upon the larger dimensions of the plate.

Fig. 5 illustrates by way of example, an oscillator circuit which may be utilized for exciting in piezoelectric crystals, low frequency face vibrations as illustrated in Fig. 4. The arrows in Fig. 4 indicate, in greatly enlarged scale, the directions and nature of these vibrations. It will be understood that the broken lines in Fig. 4 representing the edges 4 to 7 in distorted position, due to vibration of the crystal, do not necessarily indicate the exact vibrational configuration of these edges but are merely illustrative of the movement of the edges 4 to 7 as indicated in greatly enlarged scale by the arrows in Fig. 4.

The oscillator circuit may include, as illustrated for example in Fig. 5, a vacuum tube 70 having a cathode filament 71 heated by a battery 72, a grid electrode 73, and a plate electrode 74. The output circuit may include a tuning coil 76 connected in parallel circuit relation with a variable condenser 77 and may be connected as illustrated with the plate electrode 74 and with the cathode 71 through a by-pass condenser 78 and a point on the coil 76. A battery 79 may supply a suitable positive voltage to the plate electrode 74. A circuit including a condenser 80 may feed back radio frequency voltage to the grid electrode 73. A grid leak resistance 81 and a milliammeter 82 may be connected between the grid electrode 73 and the cathode 71. The piezoelectric crystal, which may be the crystal 1 illustrated in Fig. 1 or Fig. 2 having electrodes 10 and 12 which may be thin aluminum or other suitable metallic platings or coatings formed integral with the opposite major surfaces thereof, may be connected by connectors 84 and 85 between the cathode 71 and the grid electrode 73 as illustrated in Fig. 5 or alternatively may be between the grid electrode 73 and the plate electrode 74 or between the cathode 71 and the plate electrode 74 for example.

The oscillator circuit may be tuned by varying the condenser 77 to adjust the resonance frequency of the circuit to a suitable value with respect to that of the quartz crystal 1 to excite therein vibrations as illustrated in Fig. 4 at fre-

quencies as given in Fig. 6. To obtain zero temperature coefficient of frequency, the orientation angle θ may be substantially -57 degrees or $+66$ degrees for the mode of motion illustrated in Fig.

4. To excite the crystal 1 in the face mode of vibration as illustrated in Fig. 4 the crystal electrodes 10 and 12 may be placed as illustrated in Figs. 1, 2, 3 and 5 to provide a component of the electric field in the thickness direction Y' as illustrated.

For the mode of vibration illustrated in Fig. 4 the crystal may be mounted, as illustrated in Fig. 5, between a pair of coaxial clamping projections 90 and 91 which may rigidly clamp the crystal 1 within the large central nodal areas 89 in the center of both major faces thereof, by means of suitable springs 92 and 93 supported on an insulating base 94. When the crystal electrodes as the electrodes 10 and 12 are disposed between the crystal 1 and the clamping projections 90 and 91, as illustrated in Fig. 5, the projections 90 and 91 and the supporting springs 92 and 93 may form part of the electrical circuit as illustrated in Fig. 5.

It will be noted that by the nature of the mode of vibration illustrated in Fig. 4, the nodal or substantially stationary portions where there is relatively little motion or strain in the vibrating quartz crystal plate 1 comprise relatively large areas 89 oppositely and symmetrically disposed about the geometrical centers of the large faces 2 and 3 of the plate 1, in contrast to the much smaller point and line nodes which occur in other modes of vibration. By means of these large nodal areas 89, the clamping members 90 and 91 for nodally clamping the crystal 1 and for establishing electrical contact with the plated electrodes 10 and 12 thereof may be of a size and form which makes contact over either a considerable portion or a very small portion of the nodal areas 89 and may be of any suitable type such as, for example, those illustrated in United States Patent No. 1,978,188, granted October 23, 1934, to D. F. Ciccolella. Where coated electrodes are used, the coating may be made thicker over a small area in the center of the major surfaces 2 and 3 and clamping applied in that thickened area.

Alternatively the crystal 1 may, if desired, be mounted in a holder in which the crystal is nowhere clamped and may be restrained from bodily movement by proximity to the electrodes 10 and 12 and by a suitable retainer surrounding the edges 4 to 7 thereof. In such a holder, the unclamped crystal may rest upon a flat or a slightly spherically convex bottom electrode which may be disposed horizontally or inclined to the horizontal direction. The convex electrode may make contact only with the bottom surface of the crystal 1 at the nodal area 89 to reduce friction. The upper surface of the crystal 1 may be separated from the flat upper electrode by a very small uniform air-gap made sufficiently small, such as, for example, .002" to prevent arcing between the electrode and the crystal. The crystal may be kept from moving or wandering about between the two electrodes by a retainer which may fit very closely to the crystal 1 on all four edges 4 to 7 and which may be fastened to the bottom electrode.

While particular arrangements have been described for mounting the crystal in clamped or in unclamped position, it will be understood that any suitable holder may be utilized for mounting the crystals and that the mode of vibration illus-

trated in Fig. 4 which produces the frequency characteristics of Fig. 6 may be excited by electrodes covering the entire major surfaces as shown in Figs. 1 to 3 and 5 or by smaller electrodes placed on the major surfaces 2 and 3 at the four corners, one or more pairs at a time, or placed on the major surfaces at the middle of the four sides, one or more pairs at a time. The distribution of charges resulting from the distortions involved in this mode of motion is such that this type of crystal may be used in two or four mesh filter circuits, each corner section of the crystal being used in one branch of the filter circuit.

It will be understood that other vibrations may be excited in the crystal 1 having frequencies, two, three, four, five and etc. times the frequency of the vibrations of Fig. 4 illustrated herein in Fig. 6 and that for each of these, a zero temperature coefficient of frequency may occur at one positive angle θ and at one negative angle θ . For example, a vibration with a frequency nearly double that of the vibration illustrated in Figs. 4 and 6 may be excited by an E_y field as shown in Figs. 1, 2 and 5 which produces a substantially zero temperature coefficient of frequency at $\theta =$ substantially $+49^\circ$.

It will be noted that the piezoelectric crystals disclosed herein may have over a wide range of temperatures a low value of temperature coefficient of frequency which at a given temperature may be adjusted substantially to zero temperature coefficient of frequency by final hand grinding, that the frequency may be adjusted either up or down by final hand grinding, that the frequency may be more precisely adjusted because the frequency constant " a_f " is unusually large, that the temperature coefficient of frequency may be made different from zero and either positive or negative to balance the temperature coefficient of the crystal holder and/or the circuit associated therewith, that the elastic coupling to other modes of vibration in the crystal is relatively very small and ineffective thereby giving substantially a single frequency response at the desired frequency, that the node of motion of the type of vibration employed in Fig. 4 is a large finite area, that these crystals may be mounted either by rigidly clamping at the center of the major faces thereof since the central area is a node of motion or by loosely supporting the crystal in unclamped position, that the frequency spectrum may be simplified, and the amount of power that can be controlled without fracture of the crystal may be increased.

In accordance with another feature of this invention the piezoelectric element may be vibrated separately in any one of several modes of motion, each of the modes having a different natural period of vibration, the frequencies of at least two of these modes depending upon a different dimension, or different groups of dimensions of the parallelepiped, and the temperature coefficient of frequency of at least one of these frequencies being substantially zero or other predetermined value. The piezoelectric quartz crystal element may be in the shape of a thin flat rectangular-parallelepiped or circular disk having its major plane or major surface containing an electric axis X and inclined at any angle θ within either of the ranges of $+30$ to $+70$ degrees or -45 to -60 degrees with respect to the optic axis as measured in a plane perpendicular to said X axis, and having its dimensions so

chosen that the plate may be operated with high efficiency in any one of several modes of motion producing as many different frequencies, the absolute values of at least two of these frequencies being amenable to separate and independent adjustment by the process of adjusting separately and independently the particular dimensions upon which depend the periodicities of vibration of the particular modes of motion employed, the frequency of at least one of these modes depending upon the thickness or smallest dimension y' of the plate 1 and that of at least one other mode depending upon one or both of the large dimensions x and z' of the plate, and the temperature coefficients of the frequencies of all the modes being simultaneously selected by the particular choice of orientation angle θ . These several modes of vibration may be piezoelectrically excited in the same manner as described hereinbefore and require no change in electrode arrangement or the direction of application of the Ey' electric field. Particular modes of vibration which may be employed in this manner in conjunction with the E and F mode described hereinbefore and illustrated in Fig. 4 are referred to herein as the A, B, C and D modes, and are those modes of vibration which occur in the AT, BT, CT and DT quartz plates respectively, as described by F. R. Lack, G. W. Willard and I. E. Fair in the Bell System Technical Journal for July 1934 and by S. C. Hight and G. W. Willard in the Proceedings of the Institute of Radio Engineers for May 1937. These A and B, C and D, and E and F modes are three different modes or manners of vibrations which may occur and may be piezoelectrically excited in rectangular parallelepiped bodies, the relative positions of the surfaces of which bear certain relationships to the direction of the crystallographic axes of the material of which the body is composed. The frequency of vibration of either the A or B modes depends upon the thickness dimension y' of the parallelepiped while the frequencies of the C or D and the E or F modes depend upon the two larger dimensions x and z' or the area determined by them.

As shown by the curves of Fig. 6 and Fig. 9, a quartz crystal 1 oriented at $\theta = -57^\circ$ as illustrated in Fig. 1 may be piezoelectrically excited in an F mode of motion as illustrated in Fig. 4 by connection of its electrodes 10 and 12 to an electrical circuit such as that shown in Fig. 5, and the temperature coefficient of frequency of such vibration will be substantially zero and the frequency of vibration in kilocycles per second will be about 4720 divided by

$$\frac{x+z'}{2}$$

in millimeters and may be selected or controlled in absolute value by proper selection or control of the large dimensions x and z' of the plate 1. With the crystal 1 so connected, it may also be made to vibrate on either the B mode (XY' shear) or the D mode (Z'X shear) by altering the circuit only, as for example by changing the inductive value of the coil 76 or the capacitive value of the condenser 77 of Fig. 5. The frequency of the B mode of motion depends upon the thickness y' of the plate 1 and hence can be selected or controlled separately and independently of the F mode of motion illustrated in Fig. 4. The temperature coefficients of the frequencies of the B and D modes of the crystal 1 oriented at the particular angle of $\theta = -57^\circ$ being

particularly discussed here for illustrative purposes, would be approximately -15 and $+10$ parts in a million per degree centigrade respectively, and the frequencies in kilocycles per second would be about 2520 divided by the y' dimension in millimeters for the B mode and 2060 divided by

$$\frac{x+z'}{2}$$

millimeters for the D mode. By proper selection of the orientation of the plate 1 relative to its natural crystalline axes, the temperature coefficient of frequency of any one of those three modes of vibration of the plate 1 may be made zero or other predetermined value. It may be desirable in some applications to select an orientation whereby several of the modes have small temperature coefficients of frequency but none of them being actually of zero temperature coefficient of frequency. As examples of plates of this type, a plate 1 as shown in Fig. 1 but oriented at an angle of $\theta = -51^\circ$ with respect to the optic axis Z may be operated in the B mode of vibration (XY' shear) at a frequency of

$$\frac{2510}{y'}$$

determined by the thickness y' of the plate 1, the temperature coefficient of the frequency being approximately -2 parts in a million per degree centigrade or it may be vibrated in the D mode (Z'X shear) at a frequency of

$$\frac{2060}{x}$$

determined by the major face dimensions x and z' , the temperature coefficient of the frequency being approximately -2 parts in a million per degree centigrade, or it may be operated in the F mode illustrated in Fig. 4 at a frequency illustrated in Fig. 6 and determined by the major face dimensions x and z' , the temperature coefficient of this frequency being approximately -17 parts in a million per degree centigrade as illustrated in Fig. 7. Another example of a quartz plate 1 of this type oriented in the direction as illustrated in Fig. 2 but at an angle of $\theta = +36^\circ$ with respect to the optic Z axis may be operated in any of the A (XY' shear), C (Z'X shear) or E (Fig. 4) modes of vibrations with temperature coefficients of frequency of respectively -6 , -6 , and -68 parts in a million per degree centigrade, and the absolute frequencies depending upon the thickness y' and being

$$\frac{1660}{y'}$$

in the case of the A mode and upon the major face dimensions x and z' in the C and E modes. It will be noted that such a quartz plate oriented at $+36^\circ 00'$ has equal temperature coefficients of frequency (-6) on two modes of vibration namely the A mode (XY' shear) and the C mode (Z'X shear) and hence a common correction factor can be applied. For most purposes, this temperature coefficient of frequency of -6 parts in a million per degree centigrade may be low enough to allow use without correction. However, these temperature coefficients of frequency (-6) may be lowered somewhat by using a dimensional ratio

$$\frac{x}{z'} = 1.3$$

It will be noted that in all of the quartz plates

disclosed herein the thickness or small dimension y' is relatively small with respect to the major face or x' or z' dimensions thereof and may be of the order of y' being less than $10X$ or $10Z'$, and that all of the modes of motion mentioned may be excited by an Ey' electric field which is a field along the Y' direction and perpendicular to the major faces of the quartz plate.

Accordingly, by means of a combination of orientation, dimensional ratios, and a selection of modes of vibration, a single quartz crystal plate may be excited by a single electrode arrangement and possess zero or other low temperature coefficient of frequency at two or more accurate separately adjustable frequencies or their harmonics depending individually upon different dimensions or combinations of dimensions, one of which may be a relatively high frequency such as 1000 kilocycles per second dependent on the y' dimension and another a relatively low frequency such as 100 kilocycles per second dependent on the x and z' dimensions, which may be equal or nearly equal in length.

Although this invention has been described and illustrated in relation to specific arrangements, it is to be understood that it is capable of application in other organizations and is therefore not to be limited to the particular embodiments disclosed, but only by the scope of the appended claims and the state of the prior art.

What is claimed is:

1. A piezoelectric quartz crystal element having opposite substantially square major surfaces, and means including electrodes operatively disposed with respect to said major surfaces for operating said crystal element in a face mode of vibration at such a selected frequency determined substantially by the dimensions of said major surfaces as to produce a substantially zero temperature coefficient of frequency, said major surfaces being disposed substantially parallel to an X axis and inclined with respect to the Z axis substantially $+66$ degrees as measured in a plane perpendicular to said X axis, the mean of said dimensions expressed in millimeters being determined by the relation

$$\frac{x+z'}{2}$$

equals substantially 5400 divided by said frequency expressed in kilocycles per second.

2. A piezoelectric quartz crystal element having opposite substantially square major surfaces, and means including electrodes operatively disposed with respect to said major surfaces for operating said crystal element in a face mode of vibration at such a selected frequency determined substantially by the dimensions of said major surfaces as to produce a substantially zero temperature coefficient of frequency, said major surfaces being disposed substantially parallel to an X axis and inclined with respect to the Z axis substantially -57 degrees as measured in a plane perpendicular to said X axis, the mean of said dimensions expressed in millimeters being determined by the relation

$$\frac{x+z'}{2}$$

equals substantially 4700 divided by said frequency expressed in kilocycles per second.

3. A piezoelectric quartz crystal element having a substantially square-shaped major plane disposed substantially parallel to an X axis and inclined with respect to the Z axis at such an

angle within the range substantially from $+65$ to $+68$ degrees measured in a plane perpendicular to said X axis as to obtain substantially a zero temperature coefficient of frequency in a face mode of vibration having a frequency constant as given substantially by the curve of Fig. 6 for said angle.

4. A piezoelectric quartz crystal element having a substantially square-shaped major plane disposed substantially parallel to an X axis and inclined with respect to the Z axis at such an angle within the range substantially from -55 degrees to -60 degrees measured in a plane perpendicular to said X axis as to obtain substantially a zero temperature coefficient of frequency in a face mode of vibration having a frequency constant as given substantially by the curve of Fig. 6 for said angle.

5. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency adapted to vibrate in a mode of vibration having a frequency constant given substantially by the curve of Fig. 6, said element having a major plane substantially parallel to an electric axis and inclined at an angle of substantially $+66$ degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis.

6. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency adapted to vibrate in a mode of vibration having a frequency constant given substantially by the curve of Fig. 6, said element having a major plane substantially parallel to an electric axis and inclined at an angle of substantially -57 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis.

7. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency having substantially the shape of a rectangular parallelepiped, having substantially square-shaped major faces and having one pair of its edge faces substantially parallel to an electric axis thereof, said major faces being inclined at an angle of substantially -57 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said element being adapted to vibrate at a frequency determined substantially by the dimensions of said major faces, the product of said frequency in kilocycles per second into the dimension in millimeters of one side of said square-shaped major face being substantially 4700.

8. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency having substantially the shape of a rectangular parallelepiped, having substantially square-shaped major faces and having one pair of its edge faces substantially parallel to an electric axis thereof, said major faces being inclined at an angle of substantially $+66$ degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said element being adapted to vibrate at a frequency determined substantially by the dimensions of said major faces, the product of said frequency in kilocycles per second into the dimension in millimeters of one side of said square-shaped major face being substantially 5400.

9. A piezoelectric quartz crystal element of substantially the shape of a rectangular parallelepiped having its smallest or thickness dimension along a Y' axis and having its two other dimensions of substantially equal length along an X

axis and a Z' axis, respectively, the orientation of said element being such that the angle between said Z' axis and the Z axis is substantially +66 degrees, said element being adapted to vibrate at a frequency determined substantially by said dimensions along said X and Z' axes, arithmetical product of said frequency in kilocycles per second into the arithmetical mean of said dimensions in millimeters along said X and Z' axes being substantially 5400.

10. A piezoelectric quartz crystal element of substantially the shape of a rectangular parallelepiped having its smallest or thickness dimension along a Y' axis and having its two other dimensions of substantially equal length along an X axis and a Z' axis, respectively, the orientation of said element being such that the angle between said Z' axis and the Z axis is substantially -57 degrees, said element being adapted to vibrate at a frequency determined substantially by said dimensions along said X and Z' axes, the arithmetical product of said frequency in kilocycles per second into the arithmetical mean of said dimensions in millimeters along said X and Z' axes being substantially 4700.

11. A piezoelectric quartz crystal element of substantially the shape of a rectangular parallelepiped having its smallest or thickness dimension along a Y' axis and having its two other dimensions of substantially equal length along an X axis and a Z' axis, respectively, the orientation of said element being such that the angle between said Z' axis and the Z axis is substantially one of the angles determined by the curves of Figs. 8, 9, 10 and 11, said element being adapted to vibrate at a frequency determined substantially by said dimensions along said X and Z' axes, the arithmetical product of said frequency in kilocycles per second into the arithmetical means of said dimensions in millimeters along said X and Z' axes being substantially that determined by the curve of Fig. 6 for said angle.

12. A piezoelectric quartz crystal element of substantially the shape of a rectangular parallelepiped having its smallest or thickness dimension along a Y' axis and having its two other dimensions of substantially equal length along an X axis and a Z' axis, respectively, the orientation of said element being such that the angle between said Z' axis and the Z axis is substantially one of the angles determined by the curve of Fig. 7 for a desired temperature coefficient of frequency given thereby, said element being adapted to vibrate at a frequency determined substantially by said dimensions along said X and Z' axes, the arithmetical product of said frequency in kilocycles per second into the arithmetical mean of said dimensions in millimeters along said X and Z' axes being substantially that determined by the curve of Fig. 6 for said angle.

13. A multifrequency piezoelectric quartz crystal element having its smallest or thickness dimension perpendicular to its major plane, said major plane being of a substantially square shape of predetermined dimensions in accordance with a desired vibration frequency dependent upon said predetermined dimensions of said major plane the arithmetical product of said frequency expressed in kilocycles per second into the dimension of one of said dimensions of said major plane expressed in millimeters being substantially 5400, said thickness dimension being a predetermined dimension in accordance with another desired separate and independent vibration frequency dependent upon said predetermined thickness di-

mension, said major plane being substantially parallel to an electric axis and inclined with respect to the optic axis at a predetermined acute angle of substantially +66 degrees as measured in a plane perpendicular to said electric axis, said angle simultaneously determining the temperature coefficients of said plurality of separate vibration frequencies, and electrodes for applying an electric field to said element in the direction of said thickness dimension for causing said element to vibrate independently at either of said separate frequencies dependent upon said different dimensions of said element.

14. A multifrequency piezoelectric quartz crystal element having its smallest or thickness dimension along a Y' axis perpendicular to its major plane, said major plane being of a substantially square shape of predetermined dimensions substantially along an X axis and a Z' axis, respectively in accordance with a desired vibration frequency dependent upon said predetermined dimensions of said major plane, the arithmetical mean of said X axis and Z' axis dimensions expressed in millimeters being substantially 4700 divided by said frequency expressed in kilocycles per second, said thickness dimension being a predetermined dimension in accordance with another desired separate and independent vibration frequency dependent upon said predetermined thickness dimension, said thickness dimension expressed in millimeters being substantially 2520 divided by said last-mentioned frequency expressed in kilocycles per second, said major plane being substantially parallel to said X or electric axis and inclined with respect to the optic axis at a predetermined acute angle of substantially -57 degrees as measured in a plane perpendicular to said electric axis, said angle simultaneously determining the temperature coefficients of said plurality of separate vibration frequencies, and electrodes for applying an electric field to said element in the direction of said thickness dimension for causing said element to vibrate independently at either of said separate frequencies dependent upon said different dimensions of said element.

15. A multifrequency piezoelectric quartz crystal element having its smallest or thickness dimension along a Y' axis perpendicular to its major plane, said major plane being of a substantially square shape of predetermined dimensions substantially along an X axis and a Z' axis, respectively in accordance with a desired vibration frequency dependent upon said predetermined dimensions of said major plane, the arithmetical mean of said X axis and Z' axis dimensions expressed in millimeters being substantially 4700 divided by said frequency expressed in kilocycles per second, said thickness dimension being a predetermined dimension in accordance with another desired separate and independent vibration frequency dependent upon said predetermined thickness dimension, said thickness dimension expressed in millimeters being substantially 2510 divided by said last-mentioned frequency expressed in kilocycles per second, said major plane being substantially parallel to said X or electric axis and inclined with respect to the optic axis at an angle of substantially -51 degrees as measured in a plane perpendicular to said electric axis, said angle simultaneously determining the temperature coefficients of said plurality of separate vibration frequencies, and means for applying an electric field to said element in the direction of said thick-

ness dimension and for causing said element to vibrate independently at either of said separate frequencies dependent upon said different dimensions of said element.

5 16. A multifrequency piezoelectric quartz crystal element having its smallest or thickness dimension along a Y' axis perpendicular to its major plane, said major plane being of a substantially square shape of predetermined dimensions substantially along an X axis and a Z' axis, respectively in accordance with a desired vibration frequency dependent upon said predetermined dimensions of said major plane said frequency expressed in kilocycles per second being substantially 6200 divided by the arithmetical mean of said X and Z' dimensions expressed in millimeters, said thickness dimension being a predetermined dimension in accordance with another desired separate and independent vibration frequency dependent upon said predetermined thickness dimension said last-mentioned frequency expressed in kilocycles per second being substantially 1660 divided by said thickness dimension Y' expressed in millimeters, said major plane being substantially parallel to said X or electric axis and inclined with respect to the optic axis at an angle of substantially +36 degrees as measured in a plane perpendicular to said electric axis, said angle simultaneously determining the temperature coefficients of said plurality of separate vibration frequencies, and means for applying an electric field to said element in the direction of said thickness dimension and for causing said element to vibrate independently at either of said separate frequencies dependent upon said different dimensions of said element.

17. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency having substantially the shape of a rectangular parallelepiped, having substantially square-shaped major faces and having one pair

of its edge faces substantially parallel to an electric axis thereof, said major faces being inclined at an angle of substantially -57 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said element being adapted to vibrate at a frequency determined substantially by the dimensions of said major faces, the product of said frequency in kilocycles per second into the dimension in millimeters of one side of said square-shaped major face being substantially 4700, electrodes adjacent said major faces, and means including projections for clamping said electroded element therebetween at regions on said opposite major faces to hold said electroded element against bodily movement out of a predetermined position between said projections.

18. A piezoelectric quartz crystal element of substantially a zero temperature coefficient of frequency having substantially the shape of a rectangular parallelepiped, having substantially square-shaped major faces and having one pair of its edge faces substantially parallel to an electric axis thereof, said major faces being inclined at an angle of substantially +66 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said element being adapted to vibrate at a frequency determined substantially by the dimensions of said major faces, the product of said frequency in kilocycles per second into the dimension in millimeters of one side of said square-shaped major face being substantially 5400, electrodes adjacent said major faces, and means including projections for clamping said electroded element therebetween at regions on said opposite major faces to hold said electroded element against bodily movement out of a predetermined position between said projections.

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