

Dec. 30, 1941.

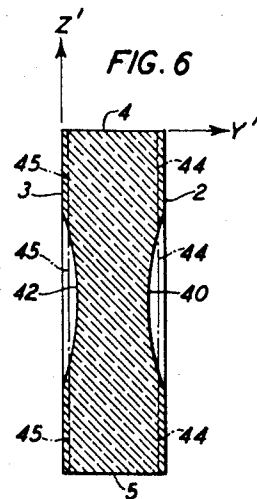
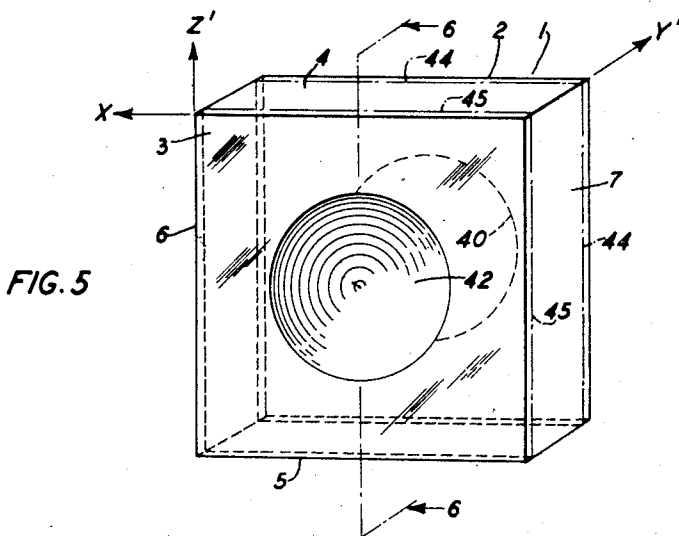
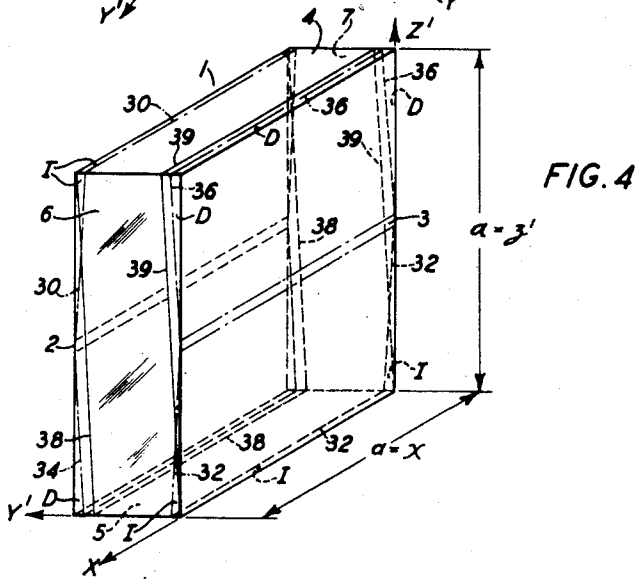
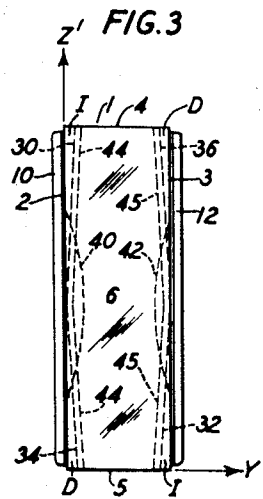
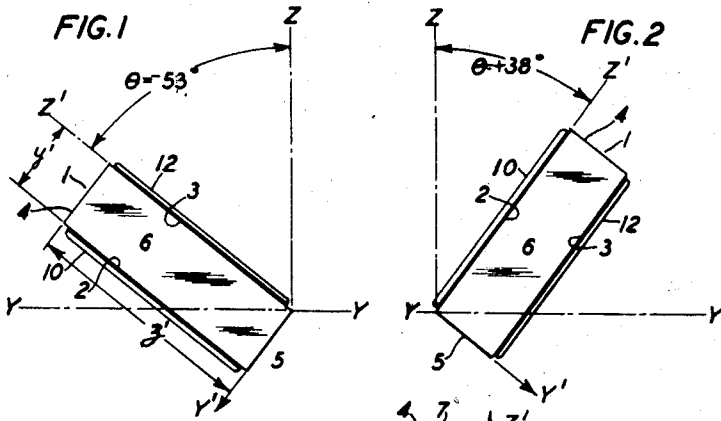
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2,268,365

PIEZOELECTRIC APPARATUS

Filed May 1, 1936

3 Sheets-Sheet 1



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PIEZOELECTRIC APPARATUS

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3 Sheets-Sheet 2

FIG. 7

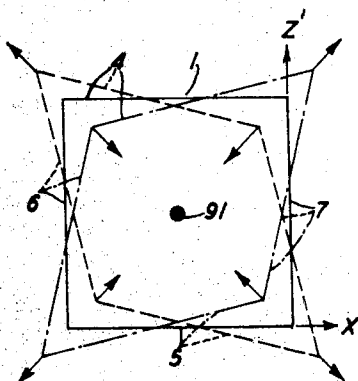


FIG. 8

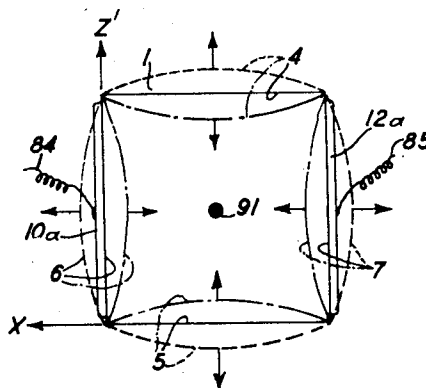


FIG. 9

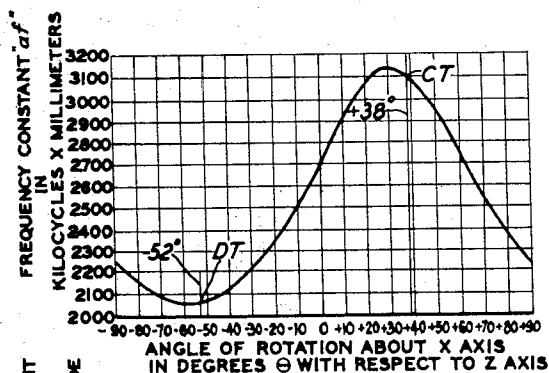


FIG. 10

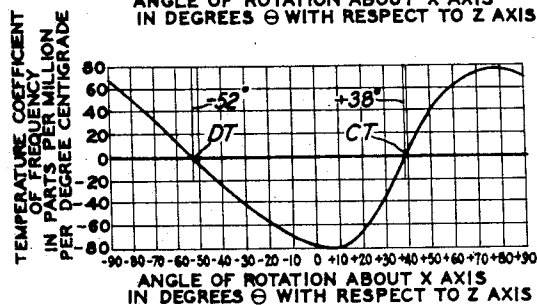
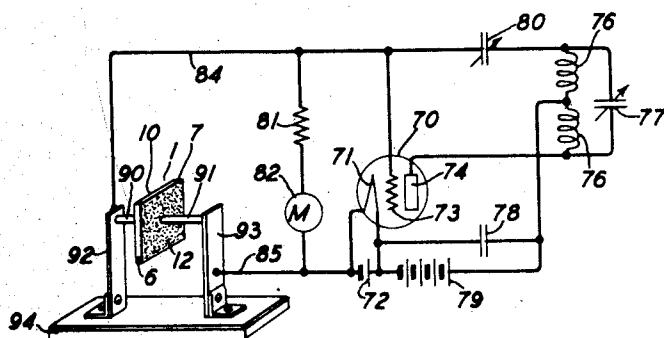


FIG. 11



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3 Sheets-Sheet 3

FIG. 12

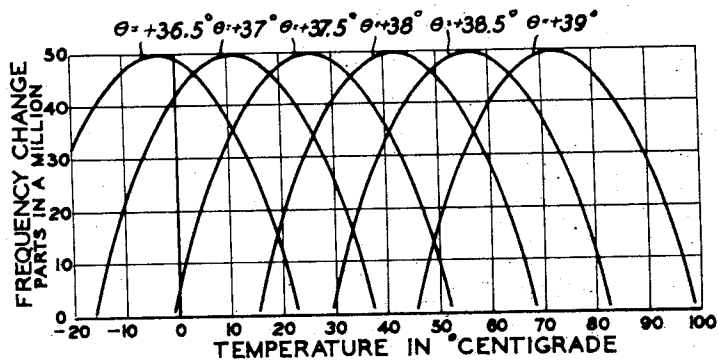
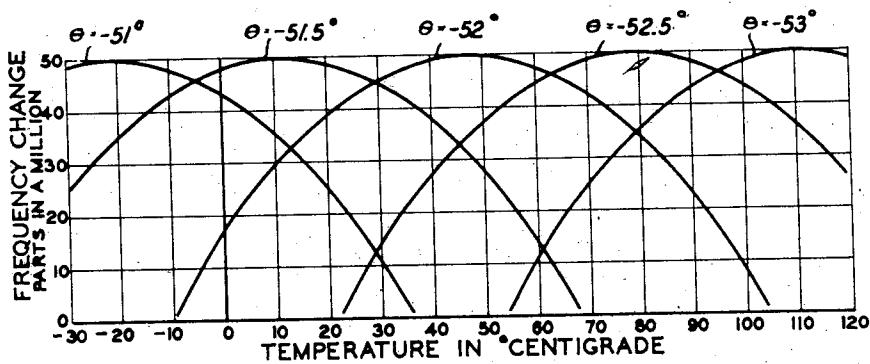


FIG. 13



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2,268,365

PIEZOELECTRIC APPARATUS

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Application May 1, 1936, Serial No. 77,325

19 Claims. (Cl. 171—327)

This invention relates to piezoelectric apparatus and particularly to piezoelectric crystals 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 produce a piezoelectric crystal element that may have substantially zero or other desired predetermined temperature coefficient of oscillation frequency either positive or negative and that may be of a convenient size and shape and yet have a relatively low-frequency vibration in the range from about 30 to 500 kilocycles per second, for example.

Another object of this invention is to produce a piezoelectric body that may have a frequency substantially independent of changes in temperature over 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 adjust to a relatively precise value the temperature coefficient of frequency of a piezoelectric crystal body with minimum effect upon the frequency thereof.

Another object of this invention is to adjust to a relatively precise value the frequency of a piezoelectric crystal body with substantially no effect upon the temperature coefficient of frequency thereof.

According to this invention, the temperature coefficient of frequency of a relatively low-frequency piezoelectric body may be made substantially zero over a wide range of temperatures as, for example, 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 so that the resultant of the component temperature coefficients of an elastic constant 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 body are inclined with respect to two or more of the orthogonal crystallographic axes thereof.

In accordance with other features of this invention, small final adjustments in the frequency and in the temperature coefficient of frequency

of piezoelectric crystals such as quartz crystal plates may be made. The possibility of making small final adjustments in the temperature coefficient of frequency is of particular importance

5 in producing crystal plates having zero or other predetermined temperature coefficient of frequency to balance the temperature coefficient of the crystal mounting or of the circuit associated therewith, for example. Where by proper final
10 hand grinding or otherwise reducing the dimensions of the crystal, the temperature coefficient of frequency thereof may be precisely adjusted in either direction, positively or negatively, so that zero or other desired temperature coefficient of frequency thereof may be selectively
15 approached from either side, the difficulties of manufacture are reduced. Moreover, it is desirable that the frequency of the crystal plate may be lowered, as well as raised, by hand grinding. This is of great advantage in making precise adjustment of the frequency to a predetermined value, for then the crystal plate is not rendered useless by slight overgrinding in raising the frequency.

25 In accordance with a particular embodiment of this invention, a relatively thin, substantially square, quartz crystal plate of rectangular parallelepiped form may be vibrated or excited in a shear mode of motion at a relatively low frequency as determined by the square major surface dimensions or areas thereof. Such vibration may be excited by means of suitable electrodes made integral with or spaced from the major surfaces of the crystal and connected in
30 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 for such quartz plate, the major or electrode surfaces thereof may be made parallel to an electric or X axis and inclined substantially either -53 degrees or $+38$ degrees with respect to the optic or Z axis thereof. To adjust the temperature coefficient of frequency of such type of quartz plates to precisely zero or other predetermined value with only a slight
35 effect upon the frequency, selected opposite halves of the opposite major surfaces thereof may be tapered slightly as by hand grinding to change the orientation angle and the temperature coefficient of frequency either positively or negatively to a desired value. To adjust the frequency of such type of quartz plates to a precise value without affecting the temperature coefficient of frequency thereof, the frequency may be lowered to a desired value by concaving as by

spherically concaving symmetrically the central portions of both major surfaces thereof, and the frequency may thereafter be raised to a desired value by uniformly reducing the thickness of the margins of both major surfaces between such central concaved portions and the edges of the crystal, or by grinding or otherwise reducing the edges of the quartz plate.

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 and other features in accordance with this invention;

Fig. 2 is a view illustrating another orientation of the crystal plate shown in Fig. 1;

Fig. 3 is a view illustrating adjustments of the crystal shown in Figs. 1 and 2;

Fig. 4 is a perspective view illustrating the adjustments in the temperature coefficient of frequency of piezoelectric crystals;

Fig. 5 is a perspective view illustrating the adjustments in the frequency of piezoelectric crystals;

Fig. 6 is a sectional view taken on the line 6—6 of Fig. 5;

Fig. 7 is a view illustrating the square-shaped quartz crystal of Figs. 1 and 2 vibrating in a low frequency shear mode of motion as rhombic distortion;

Fig. 8 is a view illustrating a crystal vibrating in edge bulge distortion;

Figs. 9 and 10 are graphs of the frequency constant and temperature coefficient of frequency respectively of square-shaped quartz crystal plates for the face shear mode of vibration illustrated in Fig. 7 for different angular orientations about an electric or X axis;

Fig. 11 is a circuit diagram of an oscillation generator controlled by a piezoelectric element; and

Figs. 12 and 13 are graphs showing temperature-frequency curves of the quartz crystals of Figs. 1 and 2 for several orientation angles θ .

This specification will follow the standard terminology as applied to quartz which employs the orthogonal axes X, Y and Z to designate the electric, the mechanical and the optic crystallographic axes, respectively, or piezoelectric 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 crystallographic axes thereof. Where the orientation is obtained by rotation 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.

Quartz crystals may occur in two forms, namely right-hand and left-hand. A 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 a right-hand direction and is designated as left-hand if it rotates the plane of polarization to the left. If a compressional stress be applied to the ends of the electric axis 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 axis for either right-

hand or left-hand crystals. The amplitude and sign of the charge may be measured with a vacuum tube electrometer. In specifying the orientation of the right-hand crystal, 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 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 gives rise to a negative orientation angle. Conversely, the orientation angle of a left-hand crystal is positive when, with the 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 faces are parallel to an X or electric axis and are oriented or inclined at a positive angle of approximately +38 degrees with respect to the optic axis as illustrated in Figs. 2 and 12. In another species the faces are inclined at an angle of approximately -53 degrees with respect to the optic axis as illustrated in Figs. 1 and 13. The crystals illustrated in this specification are right-hand quartz crystals.

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 30 to 500 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 rectangular parallelepiped form having its opposite major or electrode surfaces 2 and 3 substantially square, having one pair of its opposite edge faces 4 and 5 disposed substantially parallel to an electric or X axis thereof, the X axis being perpendicular to the plane of the drawings, in Figs. 1 and 2, having the other pair of its opposite edge faces 6 and 7 perpendicular to the electric axis X and having its major surfaces 2 and 3 inclined at an acute orientation angle with respect to the optic or Z axis of θ —about -53 degrees as illustrated in Fig. 1 or of θ —about +38 degrees as illustrated in Fig. 2. 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 as illustrated in Fig. 11, for example, the crystal plate 1 may be excited to vibrate in a face shear mode of vibration as illustrated in Fig. 7 so that the response frequency thereof depends upon the $z'x$ shear elastic constant s'_{55} thereof and is determined by the dimensions or areas of the major surfaces 2 and 3 of the crystal plate 1.

The exciting electric field may be applied to the crystal 1 in the direction of the small dimension or thickness 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 shear mode of vibration in the XZ' plane thereof to cause the square crystal plate 1 to deform periodically approximately into a rhombus as illustrated in greatly enlarged scale in Fig. 7 and to vibrate at a frequency determined by the large dimensions, namely, the x and z' dimensions of the crystal plate 1 which have an equal length a as illustrated in Fig. 4. The effects of coupling between the desired mode of vibration and unde-

sired vibrations therein may be reduced to an ineffective value by making the thickness y' small relative to the other dimensions a of the crystal plate.

Reducing either the x or z' dimensions which are the major surface dimensions of the crystal 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 30 to 500 kilocycles per second. For frequencies below 80 kilocycles, the negative angle such as, for example, $\theta = -53$ degrees as illustrated in Fig. 1, may be advantageously utilized. For frequencies above 200 kilocycles, the positive angle such as, for example, $\theta = +38$ degrees as illustrated in Fig. 2, may be advantageously utilized while for frequencies between 80 and 200 kilocycles, either type may be utilized.

It will be understood that the orientation angle θ of Figs. 1 and 2 may be varied slightly from the values mentioned of $\theta = +38$ degrees and $\theta = -53$ degrees to obtain the desired zero temperature coefficient of oscillation frequency best suited to the range of the temperature to be applied thereto. For example, the orientation angle θ of Fig. 2 may be substantially from $+37$ degrees to $+39$ degrees to obtain substantially zero temperature coefficient of frequency from about 10° centigrade to about 70° centigrade as shown in Fig. 12, the $+37$ degree orientation angle θ giving the zero temperature coefficient of frequency at about 10° centigrade, $+37^\circ 30'$ orientation angle θ giving the zero temperature coefficient at about 25° centigrade, the $\theta = +38$ degree orientation angle giving the zero temperature coefficient at about 38° centigrade, and the $\theta = +38^\circ 30'$ and $+39.0$ degree angles giving the zero temperature coefficient at about respectively 56° and 73° centigrade as shown in Fig. 12. Similarly, the orientation angle θ of Fig. 1 may be substantially from -51 degrees to -53 degrees to obtain substantially zero temperature coefficient of frequency from about -10° centigrade to about $+110^\circ$ centigrade as shown in Fig. 13, the -51 degree orientation angle θ giving the zero temperature coefficient at about -10° centigrade, the -52 degree orientation angle θ giving the zero temperature coefficient at about $+48^\circ$ centigrade, the -53 degree orientation angle θ giving the zero temperature coefficient at about $+110^\circ$ centigrade, as shown in Fig. 13. It will be understood that the values given in Figs. 12 and 13 obtain when the crystal 1 of Figs. 1 and 2 is excited in the face shear mode of vibration as illustrated in Fig. 7 so that the response frequency thereof depends upon the $z'x$ shear elastic constant s'_{55} about to be described. It will be noted that, as shown in Fig. 12, the frequency changes are less than 25 parts per million per degree centigrade from the mean value over a 50° centigrade change in temperature for any of the type CT orientations θ shown therein; whereas, as shown in Fig. 13, the frequency changes are less than 25 parts per million per degree centigrade from the mean value, over a 100° centigrade change in temperature for any of the type DT orientations θ shown therein.

The frequency of quartz crystal plates of square or nearly square shape as illustrated in Figs. 1 to 6, excited in the $z'x$ shear mode of vibration as illustrated in Fig. 7 by suitable elec-

trodes and circuit connections as illustrated in Fig. 11, for example, is given by the expression:

$$f = \frac{1.25}{2a} \frac{1}{\sqrt{s'_{55}}} \quad (1)$$

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 against the orientation angle θ calculated in accordance with these equations, is shown in Fig. 9.

The temperature coefficient of frequency of the quartz plate may be derived from the Equation 1 for the frequency and is given by the expression:

$$T_f = -\frac{T s'_{55}}{2} - \frac{T \rho}{2} - T a \quad (3)$$

where

$T \rho$ is the temperature coefficient of density,

$T a$ is the temperature coefficient of the dimension a referred to in Equation 1, and $T s'_{55}$ is the temperature coefficient of the $z'x$ shear elastic constant s'_{55} , referred to in Equation 2, and given by the expression:

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

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 such square quartz crystals operated in shear vibration in the XZ' plane, as the angle of rotation θ is varied are shown in Figs. 9 and 10 respectively.

The curve in Fig. 9 is drawn through points obtained from the following expression derived from Equation 1:

$$\text{frequency constant } af = \frac{.383}{\sqrt{s'_{55}}} \times 10^{-3} \text{ kc. mm.}$$

where the units of s_{55} are

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

and shows the calculated relation between the frequency constant af and the orientation angle

θ for square shaped quartz plates operated in a z' shear mode of vibration at a frequency determined by the major surface dimensions and having the major plane substantially parallel to or in the direction of 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 ordinates in Fig. 9 express the frequency constant af in terms of kilocycles X millimeters (kc.mm.) and the abscissae express the orientation angle θ in degrees from -90 degrees to $+90$ degrees as measured from the Z or optic axis. The position designated as DT on the curve in Fig. 9 represents the frequency constant af of the quartz plate 1 illustrated in Fig. 1 having its major plane parallel to an electric or X axis and inclined substantially -53 degrees with respect to the optic or Z axis of the natural quartz material from which it has been cut. The position designated as CT on the curve shown in Fig. 9 represents the frequency constant af of the quartz plate 1 illustrated in Fig. 2 having its major plane parallel to an electric or X axis and inclined substantially $+38$ degrees with respect to the optic or Z axis thereof. The values obtained experimentally agree well or within 2 per cent of the calculated results as shown by the curve in Fig. 9.

The curve in Fig. 10 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 excited in a z' shear mode of vibration at a frequency determined by the major surface dimensions as illustrated in Fig. 7 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 ordinates of the curve shown in Fig. 10 express the temperature coefficient of frequency of the quartz plates in parts per million per degree centigrade. The theoretical values as obtained from the Equations 3 and 4 agree well with the experimental values given in Fig. 10 and give temperature coefficients, in parts per million per degree centigrade, differing therefrom by less than 10 parts for positive angles θ and by less than 20 parts per million for negative angles θ .

The position designated as DT in Fig. 10, represents the zero temperature coefficient quartz plate 1 illustrated in Fig. 1 having its major plane substantially parallel to an electric or X axis and inclined substantially -52 or -53 degrees with respect to the optic or Z axis thereof. The position designated as CT in Fig. 10 represents the zero temperature coefficient quartz plate 1 illustrated in Fig. 2 having its major plane parallel to an electric or X axis and inclined substantially $+38$ degrees with respect to the optic or Z axis thereof.

As indicated by the frequency Equation 1 and the frequency constant curve shown in Fig. 9, it will be noted that the frequency of the quartz plate is substantially proportional to

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

varies with the orientation angle θ , is near the minimum value at θ about -52 or -53 degrees, and is near the maximum value at θ about $+38$ degrees; and as indicated in Equations 3 and 4 and in Fig. 10, that the temperature coefficient of frequency varies mainly with the tem-

perature coefficient of the z' shear elastic constant s'_{55} and hence with the orientation angle θ and passes through zero at substantially $\theta = -52$ or -53 degrees and $\theta = +38$ degrees, and accordingly the face shear mode of vibration as illustrated in Fig. 7 may be utilized at orientations of substantially -52 or $+38$ degrees to secure substantially zero temperature coefficient of frequency over wide ranges of temperature. At the two zero temperature coefficient orientations of θ about $+38$ and about -52 degrees, the change of frequency with orientation angle θ is very small as illustrated in Fig. 9.

It will be noted that these crystals illustrated in Figs. 1 and 2 are cut nearly 90 degrees different from those particularly described in copending application Serial No. 728,640 filed June 2, 1934, by F. R. Lack, G. W. Willard, and I. E. Fair, now United States Patent 2,218,200, dated October 15, 1940, that they are excited by an electric field also nearly 90 degrees different in direction from the latter, operate at a low frequency, the frequency being determined by the larger dimensions of the crystal instead of the smaller dimension, and that the s elastic constants instead of the c elastic constants are used in the equations to obtain the desired frequency of vibration.

As illustrated on an exaggerated scale in Figs. 3 to 6, the temperature coefficient of frequency and also the frequency of the low frequency shear vibration quartz crystal plate 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. The frequency may then be either raised or lowered at will with substantially no effect upon 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 Figs. 3 and 4. 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 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 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

precisely zero or other desired predetermined value.

It will be understood that the tapered regions I and D may be substantially one-half of each electrode face 2 and 3 as illustrated by the tapered surfaces 30, 32, 34 and 36 in Figs. 3 and 4, or may cover more or less than one-half of each electrode face 2 and 3. If the whole face of each opposite surface is ground flat, the resulting crystal electrode surfaces may be plane and parallel but uniformly thinner or nearer together as illustrated by the surfaces 38 and 39 in Fig. 4. The effective orientation angle θ and the temperature coefficient of frequency of the crystal I 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 I by tapering the major surfaces 2 and 3 thereof as illustrated in Figs. 3 and 4 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 I is dependent not upon the thickness thereof but primarily upon the dimensions of the electrode surfaces 2 and 3 and since as illustrated in Fig. 9 the frequency is dependent only to a small extent upon the angular orientation θ in the regions where $\theta =$ substantially $+38$ or -53 degrees. Accordingly, grinding the major surfaces 2 and 3 of the crystal I as illustrated in Figs. 3 and 4, for example, to correct the temperature coefficient of frequency thereof introduces only a small change in the frequency of the zero temperature coefficient crystal 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 I, frequency adjustments are preferably carried out after completing the adjustment of the temperature coefficient of frequency.

To selectively lower the frequency of the crystal I illustrated in Figs. 1 and 2, the center or nodal region of the crystal plate I 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 Figs. 3, 5 and 6. The frequency of the crystal I may then be raised by uniformly and symmetrically grinding the margins or outer regions of the major surfaces 2 and 3 of the plate I as illustrated by the surfaces 44 and 45 shown in Figs. 3, 5 and 6. While the frequency of the crystal I may also be raised by grinding any or all of the four edges 4 to 7 of the plate I, 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 I, changes the frequency less than does the method of edge grinding for a given fractional change in dimension. Where the plate I 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 I may be selectively raised or lowered to a desired value without

changing the effective angular orientation of the crystal I and therefore without changing the temperature coefficient of frequency thereof.

It will be understood that the crystal plate I 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 I need not be rendered unusable by over-grinding 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 orientation angle and also the mode of vibration of the crystal I are 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 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.

While the precision adjustments of the temperature coefficient of frequency and of the frequency have been described in connection with the particular crystal I illustrated in Figs. 1 and 2 it will be understood that they may apply also to crystals having other orientations rotated about the electric or X axis and excited in the shear mode of vibration as illustrated by the graph in Fig. 9 for example, and further to crystals of this general type having other modes of vibration such as for example a mode of vibration in which the opposite side edges periodically bulge outwardly and inwardly as illustrated in Fig. 8 as well as to any crystals rotated about the electric or X axis in which the low frequency Z'X shear mode is excited as illustrated in Fig. 7. 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. 11 illustrates by way of example, an oscillator circuit which may be utilized for exciting in piezoelectric crystals low frequency shear or rhombic vibrations as illustrated in Fig. 7 or edge bulge vibrations as illustrated in Fig. 8. The arrows in Figs. 7 and 8 indicate, in greatly enlarged scale, the directions and nature of these vibrations. It will be understood that the dash lines and also dash-dot lines in Figs. 7 and 8 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 Figs. 7 and 8.

The oscillator circuit may include, as illustrated for example in Fig. 11, 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 con-

nected 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 plating formed integral with the major surfaces thereof, may be connected by connectors 84 and 85 between the cathode 71 and the grid electrode 73 as illustrated in Fig. 11 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 shear vibrations as illustrated in Fig. 7 or edge bulge vibrations as illustrated in Fig. 8. Since, for the same crystal, the frequency thereof will be different for excitation in these two different modes of vibration, the circuit frequency adjustment will be made correspondingly to suit the particular mode of vibration. To obtain zero temperature coefficient of frequency, the orientation angle θ may be substantially -52 degrees or $+38$ degrees for the shear mode illustrated in Fig. 7 and $\theta = +40^\circ$ to $+47^\circ$ or about -15° for the edge bulge mode illustrated in Fig. 8.

To excite the crystal 1 in the edge bulge mode of vibration illustrated in Fig. 8, the crystal electrodes 10a and 12a may be placed on or adjacent the opposite edge faces 6 and 7 as illustrated in Fig. 8 or in any other suitable positions that provide a component of the electric field in the direction of the electric or X axis thereof.

To excite the crystal 1 in the shear mode of vibration as illustrated in Fig. 7, the crystal electrodes 10 and 12 may be placed as illustrated in Figs. 1, 2, 3, and 11 to provide a component of the electric field in the thickness direction Y' as illustrated.

For either mode of vibration illustrated in Figs. 7 and 8, the crystal may be mounted, as illustrated in Fig. 11, between a pair of coaxial projections 90 and 91 which may rigidly clamp the crystal 1 at the nodal center 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. 11, the projections 90 and 91 and the supporting springs 92 and 93 may form part of the electrical circuit as illustrated in Fig. 11.

It will be understood that the clamping members for nodally clamping the crystal 1 or for establishing electrical contact with the plated electrodes 10 and 12 thereof may be of any suitable type such as, for example, those illustrated in U. S. Patent No. 1,978,188 granted October 23, 1934, to D. F. Cicoella. Alternately the crystal 1 may, if desired, be mounted in a holder in which the crystal is nowhere clamped and in which the unclamped crystal 1 may be restrained from moving by proximity to the electrodes 10 and 12

and by a suitable retainer surrounding the edges 4 to 7 thereof. 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 contact the bottom surface of the crystal at the nodal area only to reduce friction. The upper surface of the crystal 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.

It will be noted that the piezoelectric crystals disclosed herein may have a low value of temperature coefficient of frequency which may be adjusted substantially exactly to zero temperature coefficient of frequency by final hand grinding with small effect on the frequency thereof, that the frequency may be adjusted either up or down by final hand grinding without affecting the temperature coefficient of frequency, 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 these crystals may be mounted either by rigidly clamping at the center of the major faces thereof since the center is a node of motion or by loosely supporting the crystal in unclamped position, that the temperature coefficient of frequency may be reduced practically to zero over a wide range of temperatures as from -40° C. to $+60^\circ$ C. for example, that the frequency spectrum may be simplified, and the amount of power that can be controlled without fracture of the crystal may be increased.

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 plate having opposite substantially square electrode surfaces, and means including electrodes operatively disposed with respect to said electrode surfaces for operating said crystal in a shear mode of vibration at a selected frequency determined by the dimensions of said electrode surfaces, said electrode surfaces being substantially parallel to an electric axis of said crystal and inclined substantially $+38$ degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis to obtain substantially zero temperature coefficient of frequency therefor, at least one of said electrode surfaces having a uniformly tapered marginal portion for obtaining substantially precisely said zero temperature co-

efficient of frequency, and at least one of said electrode surfaces having a central cavity for obtaining substantially precisely said selected frequency.

2. A piezoelectric quartz crystal plate having substantially square major faces and having one pair of its edge faces substantially parallel to an electric axis thereof, said major faces being substantially parallel to said electric axis and inclined at an angle of substantially +38 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, and means for exciting said plate to vibrate at a frequency determined by the dimensions of said major faces, at least one of said major faces having a central cavity of a value for obtaining a desired value for said frequency.

3. A piezoelectric quartz crystal plate having opposite substantially square electrode surfaces, and means including electrodes operatively disposed with respect to said electrode surfaces for operating said crystal in a shear mode of vibration at a selected frequency determined by the dimensions of said electrode surfaces, said electrode surfaces being substantially parallel to an electric axis of said crystal and inclined substantially -53 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis to obtain substantially zero temperature coefficient of frequency therefor, at least one of said electrode surfaces having a uniformly tapered marginal portion for obtaining substantially precisely said zero temperature coefficient of frequency, and at least one of said electrode surfaces having a central cavity for obtaining substantially precisely said selected frequency.

4. A piezoelectric quartz crystal having a substantially square-shaped major plane substantially parallel to an electric axis and inclined at an angle within the range extending substantially from -51 degrees to -53 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said major plane having such a shape with respect to the magnitude and sense of direction of said angle as to obtain substantially zero temperature coefficient of frequency when subjected to an electric field in a direction perpendicular to said major plane and vibrated in a shear mode of motion at a frequency which is determined substantially by the dimensions of said major plane.

5. A piezoelectric quartz crystal element having a substantially square-shaped major plane substantially parallel to an electric axis and inclined at an angle given by the curves of Fig. 13 said angle being an angle within the range extending substantially from -51 degrees to -53 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, said major plane having such a shape with respect to the magnitude and sense of direction of said angle as to obtain substantially zero temperature coefficient of frequency when subjected to an electric field in a direction perpendicular to said major plane and vibrated in a shear mode of motion at a frequency which is determined substantially by the dimensions of said major plane.

6. A piezoelectric quartz crystal, and means for exciting said crystal in a shear mode of motion at a frequency determined substantially by the major surface dimensions thereof, said crystal having a substantially square shaped major plane disposed substantially parallel to an

electric axis and inclined substantially at an angle within the range from -51 degrees to -53 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis to obtain substantially zero temperature coefficient of frequency.

7. A piezoelectric quartz crystal plate having substantially square major faces and having one pair of its edge faces substantially parallel to an electric axis thereof, said major faces being substantially parallel to said electric axis and inclined at an angle of substantially -53 degrees with respect to the optic axis thereof as measured in a plane perpendicular to said electric axis, and means for exciting said plate to vibrate at a frequency determined by the dimensions of said major faces.

8. A quartz piezo-electric element having its substantially square electrode faces substantially parallel to an electric (X) axis and inclined substantially 53 degrees with respect to the optic (Z) axis in the negative direction or toward parallelism with a major apex face of the mother crystal from which said element is cut, whereby said element exhibits a substantially zero temperature coefficient of frequency when vibrated at a fundamental frequency which is a function of one of its greater dimensions.

9. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 52.5° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 79.3, and the other dimension of said surfaces similarly expressed is equal to substantially 1.06 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its X-axis mode of vibration and a substantially zero temperature coefficient of frequency.

10. A piezoelectric quartz crystal element adapted to vibrate at a face mode frequency of low temperature coefficient, said element having substantially square major surfaces, said major surfaces being disposed substantially parallel to an X axis and inclined at an angle of substantially -52 degrees with respect to the Z axis as measured in a plane perpendicular to said major surfaces, each of the edge dimensions of said substantially square major surfaces expressed in millimeters being equal to substantially 2050 divided by the value of said frequency expressed in kilocycles per second.

11. A piezoelectric quartz crystal element adapted to vibrate at a desired frequency of low temperature coefficient dependent upon the dimensions of its substantially square major surfaces, one pair of the opposite edges of each of said major surfaces being substantially parallel to an X axis and the other pair of the opposite edges thereof being inclined at an angle of substantially -52 degrees with respect to the Z axis, the value of each of said edge dimensions expressed in millimeters being substantially 2050 divided by the value of said frequency expressed in kilocycles per second.

12. A piezoelectric crystal element having a selected temperature coefficient of frequency and having a selected frequency determined by the area of the opposite major surfaces thereof, at least one of said major surfaces having a tapered marginal portion for obtaining said selected temperature coefficient of frequency, and at least one of said major surfaces having a cavity for obtaining said selected frequency. 5
13. A piezoelectric crystal element having a selected temperature coefficient of frequency and having a frequency determined by the area of the opposite major surfaces thereof, at least one of the opposite halves of said opposite major surfaces being tapered for obtaining said selected temperature coefficient of frequency. 10
14. The method of adjusting the temperature coefficient of frequency of a piezoelectric crystal which includes the step of selectively tapering opposite halves of opposite major surfaces thereof. 15
15. The method of selectively changing the temperature coefficient of frequency of a piezoelectric crystal which includes the step of selectively tapering at least one of the opposite halves of opposite electrode faces thereof. 20
16. The method of selectively changing the frequency of a piezoelectric crystal without changing the temperature coefficient of frequency thereof which includes the steps of symmetrically thinning the central region thereof to lower the frequency thereof and uniformly thinning the marginal region between the central region and the edges to raise the frequency thereof. 25
17. The method of adjusting the frequency of a piezoelectric crystal which includes the steps of symmetrically spherically concaving the central part of opposite major surfaces thereof to lower the frequency and uniformly and symmetrically thinning the margins of said surfaces to raise the frequency. 30
18. The method of adjusting the temperature coefficient of frequency and the frequency of a piezoelectric crystal which includes the steps of selectively tapering at least one of the opposite halves of opposite surfaces thereof and thereafter concaving the central region of at least one of said surfaces.
19. The method of adjusting the temperature coefficient of frequency and the frequency of a piezoelectric crystal which includes the steps of selectively tapering at least one of the opposite halves of opposite surfaces thereof and thereafter concaving the central region of at least one of said surfaces, and thereafter thinning the margin of said surface between said central region and the edges of said crystal.

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