

Feb. 1, 1949.

W. P. MASON

2,460,520

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Feb. 9, 1946

2 Sheets-Sheet 1

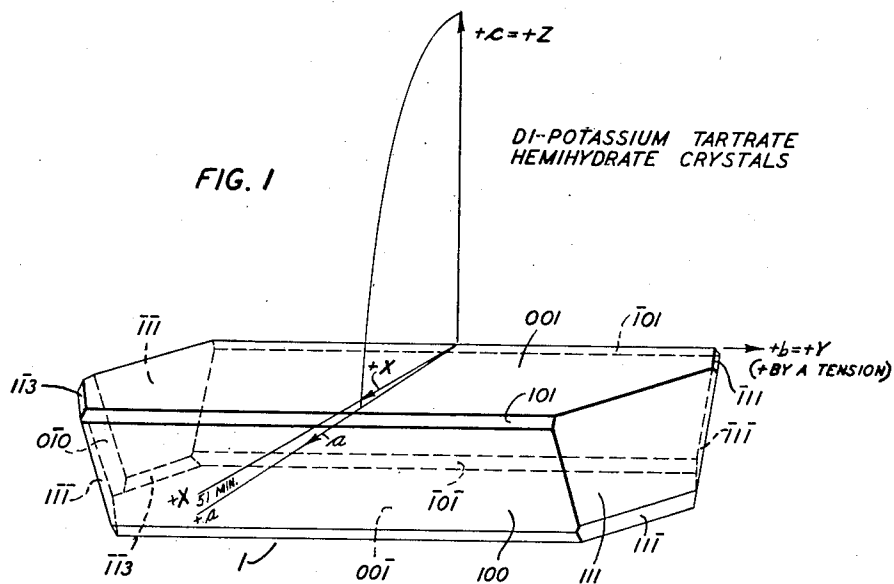


FIG. 2

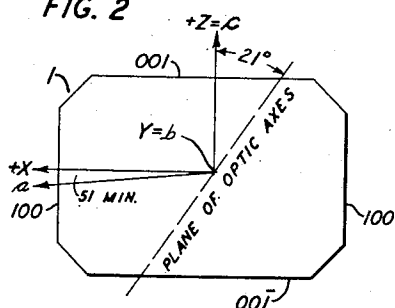


FIG. 3

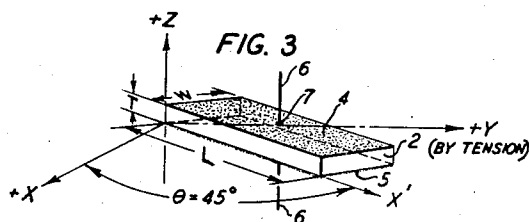


FIG. 4

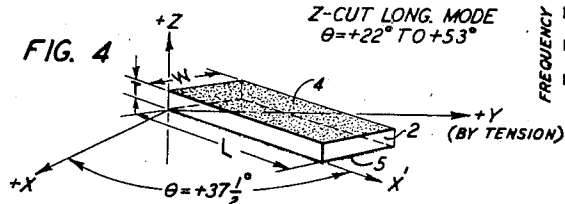
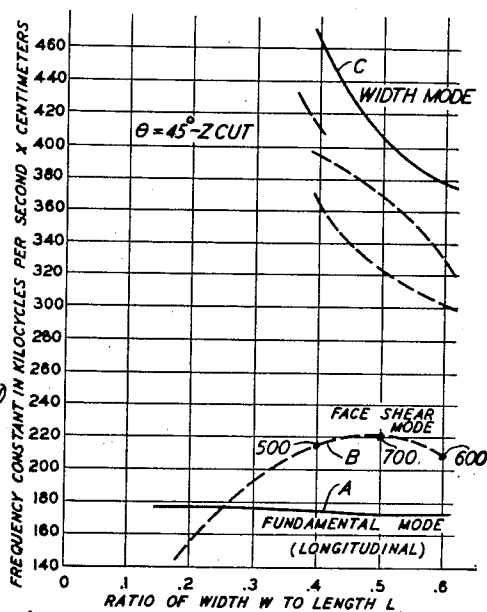


FIG. 5



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2 Sheets-Sheet 2

FIG. 6

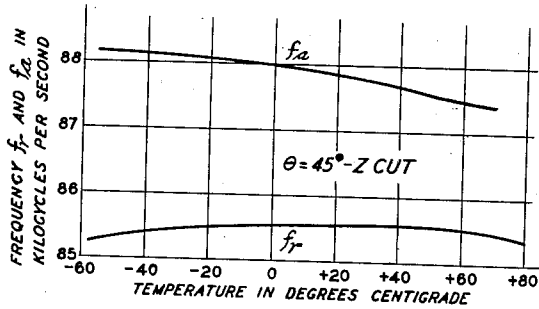


FIG. 7

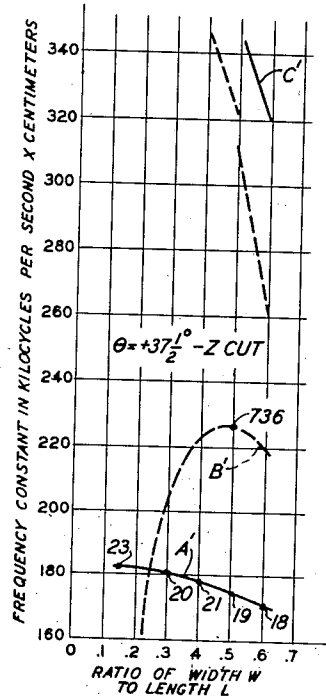


FIG. 8

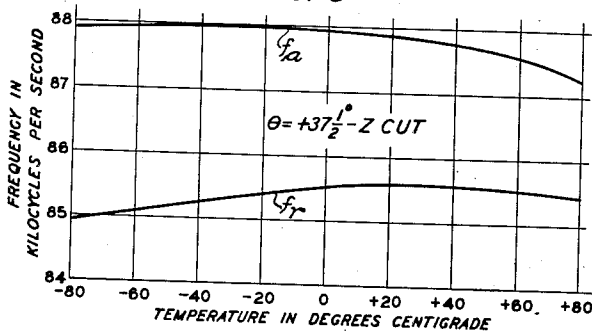


FIG. 10

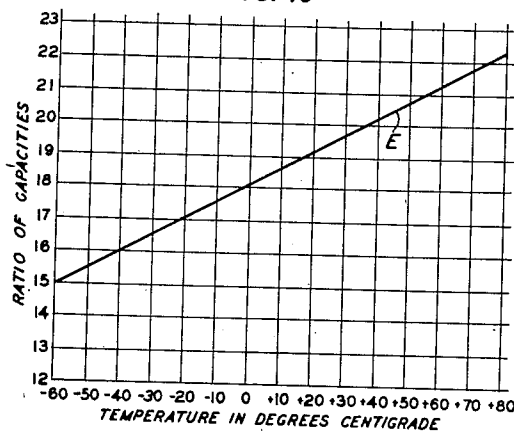
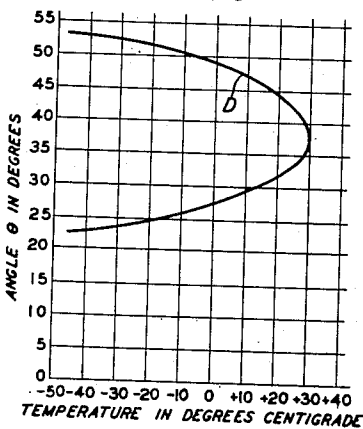


FIG. 9



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2,460,520

PIEZOELECTRIC CRYSTAL APPARATUS

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Application February 9, 1946, Serial No. 646,639

20 Claims. (Cl. 171-327)

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This invention relates to crystal apparatus and particularly to piezoelectric crystal elements comprising di-potassium tartrate hemihydrate ($K_2C_4H_4O_6 \cdot \frac{1}{2}(H_2O)$). Such crystal elements may be used as frequency controlling circuit elements in electric wave filter systems, oscillation generator systems and amplifier systems. Also, they may be utilized as modulators, or as harmonic producers, or as electromechanical transducers in sonic or supersonic projectors, microphones, pick-up devices and detectors.

One of the objects of this invention is to provide advantageous and useful orientations and modes of motion in crystal elements made from synthetic crystalline di-potassium tartrate hemihydrate.

Another object of this invention is to provide synthetic or artificial crystal elements having a low or substantially zero temperature coefficient of frequency.

Other objects of this invention are to provide crystal elements comprising di-potassium tartrate hemihydrate that may possess useful characteristics, such as effective piezoelectric constants, minimum coupling of the desired mode of motion to undesired modes of motion therein, and low or zero temperature coefficients of frequency.

A particular object of this invention is to provide di-potassium tartrate hemihydrate crystal elements having a zero temperature coefficient of frequency at ordinary room temperatures.

Di-potassium tartrate hemihydrate is a salt of dextrotartaric acid having a molecule which lacks symmetry elements. In its crystalline form, it lacks a center of symmetry and belong to a crystal class which is piezoelectric and which in this instance is the monoclinic sphenoidal crystal class. By virtue of its chemical structure, di-potassium tartrate hemihydrate will form ionic and hydrogen-bonded crystals offering high piezoelectric constants. In addition the crystalline material affords certain cuts with low temperature coefficient of frequency and with low coupling to other modes of motion therein and a fairly high Q or low dielectric loss and mechanical dissipation.

Crystal elements of suitable orientation cut from crystalline di-potassium tartrate hemihydrate may be excited in different modes of motion such as the longitudinal length or the longitudinal width modes of motion, or the face shear mode of motion controlled mainly by the major face dimensions, or the thickness shear mode of motion controlled mainly by the thickness dimen-

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sion. Also, low frequency flexural modes of motion of either the width bending flexure type or the thickness bending duplex flexure type may be obtained. These various modes of motion are similar in the general form of their motion to those of similar or corresponding names that are known in connection with other crystalline substances such as quartz, Rochelle salt and ammonium dihydrogen phosphate crystals.

It is useful to have a synthetic type of piezoelectric crystal element having a low or zero temperature coefficient of frequency, and having a low or zero coupling to other modes of motion therein. In accordance with this invention, such synthetic type crystal cuts may be provided in the form of tartrate crystals and the tartrate crystals may be suitable cuts taken from crystalline di-potassium tartrate hemihydrate adapted to operate in their major face modes of motion. Crystal elements cut from di-potassium tartrate hemihydrate may have a low or zero temperature coefficient of frequency, and also may possess advantageous elastic properties whereby the longitudinal mode of motion therein may be substantially free from coupling or interference with the face shear mode of motion therein, or the face shear mode of motion may be free from coupling with other modes of motion therein.

In accordance with this invention, the crystal elements cut from crystalline di-potassium tartrate hemihydrate may be Z-cut type crystal elements having their major faces perpendicular or nearly perpendicular to the Z or c axis and operating in the longitudinal mode of motion along the longest or length dimension thereof, the length dimension being inclined at an angle θ of about 22 to 53 degrees with respect to the X axis, or about from 30 to 45 degrees where the zero temperature coefficient of frequency is desired at ordinary room temperatures. Where the angle θ is an angle between about 22 and 53 degrees, the piezoelectric coupling is of high value at all such θ angles and has its maximum value at the θ angle of about 45 degrees. The temperature at which the zero temperature coefficient of frequency occurs for the longitudinal length mode of motion varies according to the value of the angle of θ selected, and is at about $+16\frac{1}{2}^\circ$ centigrade for a θ angle of about 45 degrees, at about $+30^\circ$ centigrade for a θ angle of about $37\frac{1}{2}$ degrees, and at values between $+16\frac{1}{2}^\circ$ and $+30^\circ$ centigrade for values of θ angles between 45 and $37\frac{1}{2}$ degrees. The coupling of the longitudinal length mode of motion to the face shear mode of motion is small, and at the particular θ angle of

about $52\frac{1}{2}$ degrees is zero, as particularly disclosed and claimed in my copending application for Piezoelectric crystal apparatus Serial No. 659,468, filed April 4, 1946 now Patent Number 2,440,694.

Accordingly, in the case of di-potassium tartrate hemihydrate crystals there are among other useful cuts, special cuts each of which have a zero temperature coefficient of frequency and a relatively high electromechanical coupling of the order of 20 to 25 per cent, and each of which may be advantageously used for example as a circuit element in an electric wave filter, or as a frequency modulator for an oscillation generator. It will be noted that the synthetic tartrate crystal elements provided in accordance with this invention have high electromechanical coupling of the order of 20 to 25 per cent, high reactance-resistance ratios Q at resonance, and a small change in frequency over a wide temperature range. These advantageous properties together with the low cost and freedom from supply troubles indicate that these crystal elements may be used in place of quartz as circuit elements in crystal filters and oscillators. Moreover, since the high electromechanical coupling existing in these crystals allows the circuit frequency to be varied in much larger amounts by a reactance tube, than can be done for the frequency of quartz, such tartrate crystal cuts may be advantageously used for frequency modulating an oscillation generator.

The tartrate crystal elements provided in accordance with this invention may be especially useful in filter systems for example. For use in channel filters for example, the electromechanical coupling in these crystal elements is so high that regular channel widths of about 3600 cycles per second for example may be obtained without the use of auxiliary coils for frequencies as low as 60 to 100 kilocycles per second for example. Accordingly, such a crystal channel filter may be produced more cheaply and put into a smaller space than one which is used with bulky and expensive coils and condensers. When such crystal filters are to be paralleled, a terminating network comprising coils and condensers may be used therewith in order to obtain no paralleling loss; or terminating resistances may be used therewith and the paralleling loss made up for by an added stage of amplification. The tartrate crystal elements in accordance with this invention have a low ratio of capacities and accordingly may be used in wide band filters such as for example in program filters where the tartrate type crystal element may be used to control the loss peaks located at some distance from the pass band, while using quartz crystals for the sharpest peaks nearest the pass band. The tartrate crystal elements in accordance with this invention have high coupling and accordingly may be used to extend the range of crystal filters to lower frequencies than have been obtained in the past. For example, voice channels down to about 12 kilocycles per second or less may be obtained using a flexure mode type tartrate crystal element, the flexure modes being obtained by methods presently used in connection with quartz crystal elements. The tartrate crystal elements in accordance with this invention may also be used for control of frequency modulated oscillators. On account of the large electromechanical coupling, the frequency variation and shift may be made of large value and may be controlled

by an applied direct current voltage or by a suitable reactance tube for example.

For a clearer understanding of the nature of this invention and the additional advantages, 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 a perspective view illustrating the form and growth habit in which a monoclinic crystal of di-potassium tartrate hemihydrate may be crystallized, and also illustrating the relation of the surfaces of the mother crystal with respect to the mutually perpendicular X, Y and Z axes, and the crystallographic a , b and c axes;

Fig. 2 is an edge view of Fig. 1 illustrating the rectangular X, Y and Z and the crystallographic a , b and c systems of axes for monoclinic crystals, and also illustrating the plane of the optic axes of di-potassium tartrate hemihydrate crystals;

Figs. 3 and 4 are perspective views illustrating longitudinal-mode Z-cut type di-potassium tartrate hemihydrate crystal elements rotated in effect about the Z or c axis to a position corresponding to angles of θ —about 45 and $37\frac{1}{2}$ degrees, respectively; or more broadly θ angles from 22 to 53 degrees with respect to the X-axis;

Figs. 5 and 6 are graphs illustrating the characteristics of a 45 degree Z-cut type di-potassium tartrate hemihydrate crystal element;

Figs. 7 and 8 are graphs illustrating the characteristics of a $37\frac{1}{2}$ degree Z-cut type di-potassium tartrate hemihydrate crystal element;

Fig. 9 is a graph illustrating the characteristics of longitudinal-mode Z-cut type di-potassium tartrate hemihydrate crystal elements having angles of θ from about 22 to 53 degrees;

Fig. 10 is a graph illustrating the ratio of capacities of di-potassium tartrate hemihydrate crystal elements as a function of temperature.

This specification follows the conventional terminology, as applied to piezoelectric crystalline substances, which employs a system of three mutually perpendicular X, Y and Z axes used as reference axes for defining the angular orientation of a crystal element. As used in this specification and as shown in the drawing, the Z axis corresponds to the c axis, the Y axis corresponds to the b axis, and the X axis is inclined at an angle with respect to the a axis which, in the case of di-potassium tartrate hemihydrate, is a small angle of about 51 minutes as illustrated in Figs. 1 and 2. The a , b and c axes represent conventional terminology as used by crystallographers.

Referring to the drawing, Fig. 1 illustrates the general form and growth habit in which di-potassium tartrate hemihydrate may crystallize, the natural faces of the di-potassium tartrate hemihydrate crystal 1 being designated in Fig. 1 in terms of conventional terminology as used by crystallographers. For example, the top surface of the crystal body 1 is designated as a 001 plane, and the bottom surface thereof as a $00\bar{1}$ plane, and other surfaces and facets thereof are as shown in Fig. 1.

The mother crystal 1 , as illustrated in Fig. 1, may be grown from any suitable saturated nutrient solution by any suitable crystallizer apparatus or method, the nutrient solution used for growing the crystal 1 being prepared from any suitable chemical substances and the crystal 1 being grown from such nutrient solution in any

suitable manner to obtain a mother crystal 1 of a size and shape that is suitable for cutting therefrom piezoelectric crystal elements in accordance with this invention. The mother crystal 1 from which the crystal elements are to be cut is relatively easy to grow in shapes and sizes that are suitable for cutting useful crystal plates or elements therefrom. Such mother crystals 1 may be conveniently grown to sizes around 2 inches or more for the X and Y dimensions or of any sufficient size to suit the desired size for the piezoelectric circuit elements that are to be cut therefrom. It will be understood that the mother crystal 1 may be grown to size by any suitable crystallizer apparatus such as for example by a rocking tank type crystallizer or a reciprocating rotary gyrator type crystallizer.

Crystals 1 comprising di-potassium tartrate hemihydrate ($K_2C_4H_4O_6 \cdot \frac{1}{2}(H_2O)$) form in the monoclinic sphenoidal class of crystals which has as its element of symmetry the Y or b crystallographic axis, the Y or b axis being an axis of binary symmetry. There are four dielectric constants, eight piezoelectric constants and 13 elastic constants involved in such crystalline material. As indicated by the chemical formula, di-potassium tartrate hemihydrate crystals 1 have $\frac{1}{2}$ molecule of water of crystallization, as compared to 4 for Rochelle salt crystals. As a result, the water of crystallization is much more tightly bound for crystals of di-potassium tartrate hemihydrate than for those of Rochelle salt. When held at a temperature of about 80° centigrade, there appears to be no observable dehydration of the crystalline di-potassium tartrate hemihydrate; but at some higher temperature of about 150° centigrade the vapor pressure of the crystal reaches atmospheric pressure and will cause bubbling that may be observed in an oil bath. If the di-potassium tartrate hemihydrate crystal is placed in a sealed container that is evacuated or filled with dry air, it will give off enough moisture to establish its equilibrium vapor pressure, which may be around 10 per cent relative humidity, and it will be stable from then on. Sudden changes of temperature will not appreciably affect the crystal 1 since the stable relative humidity at ordinary room temperature is so low.

Di-potassium tartrate hemihydrate crystals 1 have three cleavage planes which lie along the three planes determined by the three crystallographic axes a, b and c. While such cleavage planes may make the crystals 1 somewhat more difficult to cut and process, nevertheless satisfactory processing may be done by using any suitable means such as a sanding belt cooled by oil or by a solution of water and ethylene glycol, for example.

As illustrated in Fig. 1, monoclinic crystals 1 comprising di-potassium tartrate hemihydrate are characterized by having two crystallographic axes "b" and "c," which are disposed at right angles with respect to each other, and a third crystallographic axis "a" which makes an angle different than 90 degrees from the other two crystallographic axes b and c. The c axis lies along the longest direction of the unit cell of the crystalline material. The b axis is an axis of two-fold or binary symmetry. In dealing with the axes and the properties of such a monoclinic crystal 1, it is convenient and simpler to use a right-angled or mutually perpendicular system of X, Y and Z coordinates. Accordingly, as illustrated in Fig. 1

the method chosen for relating the conventional right-angled X, Y and Z system of axes to the a, b and c system of crystallographic axes of the crystallographer, is to make the Z axis coincide with the c axis and the Y axis coincide with the b axis, and to have the X axis lie in the plane of the a and c crystallographic axes at an angle with respect to the a axis, the X-axis angle being about 51 minutes above the a axis for crystalline di-potassium tartrate hemihydrate, as shown in Fig. 1. The X, Y and Z axes form a mutually perpendicular system of axes, the b or Y axis being a polar axis which is positive (+) by a tension at one of its ends, as shown in Fig. 1. In order to specify which end of the Y axis is the positive end, the plane of the two optic axes of the crystal 1 may be located. A monoclinic crystal 1 is an optically biaxial crystal and for crystalline di-potassium tartrate hemihydrate the plane that contains these optic axes is found to be parallel to the b or Y crystallographic axis and inclined at an angle of about 21 degrees with respect to the Z-axis, as illustrated in Fig. 2.

Fig. 2 is a diagram illustrating the plane of the optic axes for crystals 1 comprising di-potassium tartrate hemihydrate. As shown in Fig. 2, the plane of the optic axes of a di-potassium tartrate hemihydrate crystal 1 is parallel to the Y or b axis, which in Fig. 2 is perpendicular to the surface of the drawing; and is inclined in a clockwise direction at an angle of about 21 degrees from the +c or +Z crystallographic axis. Since the +X axis lies at a counter-clockwise angle of 90 degrees from the +c or +Z axis, and the +b = +Y axis makes a right angle system of coordinates with the X and Z axes, the system illustrated in Fig. 2 determines the positive (+) directions of all three of the X, Y and Z axes. Hence the positive directions of all three X, Y and Z axes may be specified with reference to the plane of the optic axes of the crystal 1. A similar optical method of procedure may be used for orienting and specifying the direction of the three mutually perpendicular X, Y and Z axes of other types of monoclinic crystals. Oriented crystal cuts are usually specified in practice by known X-ray orientation procedures.

Fig. 3 is a perspective view illustrating a Z-cut crystal element 2 comprising di-potassium tartrate hemihydrate that has been cut from a suitable mother crystal 1 as shown in Fig. 1. The crystal element 2 as shown in Fig. 3 may be made into the form of an elongated plate of substantially rectangular parallelepiped shape having a longest or length dimension L, a breadth or width dimension W, and a thickness or thin dimension T, the directions of the dimensions L, W and T being mutually perpendicular, and the thin or thickness dimension T being along the Z axis and measured between the opposite parallel major or electrode faces of the crystal element 2. The length dimension L, and also the width dimension W of the crystal element 2, may be made of values to suit the desired length-mode frequency thereof. The thickness or thin dimension T may be made of a value to suit the impedance of the system in which the crystal element 2 may be utilized as a circuit element; and also it may be made of a suitable value to avoid nearby spurious modes of motion which, by proper dimensioning of the thickness dimension T relative to the length and width dimensions L and W, may be placed in a location that is relatively remote from the de-

sired longitudinal mode of motion along the length dimension L.

Suitable conductive electrodes 4 and 5 may be provided adjacent the two opposite major or electrodes faces of the crystal element 2 in order to apply electric field excitation thereto. The electrodes 4 and 5 when formed integral with the major faces of the crystal element 2 may consist of gold, platinum, silver, aluminum or other suitable conductive material deposited upon the surface of the crystal element 2 by evaporation in vacuum or by other suitable process. The electrodes 4 and 5 may be electrodes wholly or partially covering the major faces of the crystal element 2, and may be provided in divided or non-divided form as already known. Accordingly, it will be understood that the crystal elements 2 disclosed in this specification may be provided with conductive electrodes or coatings 4 and 5 on their faces of any suitable composition, shape, and arrangement, such as those already known in connection with ammonium dihydrogen phosphate, Rochelle salt or quartz crystals for example; and that they may be mounted and electrically connected by any suitable means, such as for example, by pressure type clamping pins or by conductive coaxial supporting spring wires 6 cemented by conductive cement 7 or glued to the metallic coatings 4 and 5 deposited on the crystal element 2, as already known in connection with quartz, Rochelle salt and other crystals having similar or corresponding modes of motion.

As illustrated in Fig. 3, the crystal element 2 has its major faces disposed perpendicular or nearly perpendicular to the Z or c axis and has its longest or length dimension L inclined at an angle θ with respect to the +X axis, where θ may be an angle of about 45 degrees or more broadly from 22 to 53 degrees with respect to the +X or +a axes, the X axis in the case of di-potassium tartrate hemihydrate being disposed very near to the a axis. At the angle of θ = about 45 degrees with respect to the +X axis as particularly illustrated in Fig. 3, the crystal element 2 has its maximum piezoelectric coupling, and also has a zero temperature coefficient at about $+16\frac{1}{2}^{\circ}$ centigrade for its longitudinal mode of motion along the length dimension L, and at that θ angle the mechanical coupling of that longitudinal mode of motion to the face shear mode of motion therein is not large. At angles of θ above and below about 45 degrees, the piezoelectric coupling is of somewhat reduced but still effective values, the mechanical coupling of the longitudinal length L mode of motion to the face shear and other modes of motion therein is small, and the position of the temperature at which the zero temperature coefficient of frequency occurs for the longitudinal length L mode of motion is raised or lowered from about $+16\frac{1}{2}^{\circ}$ centigrade, according to the angle of θ selected, as indicated in Fig. 9.

It will be noted that the natural top and bottom surfaces 001 and 00 $\bar{1}$ of the mother crystal 1 of Fig. 1 extend in the plane of the a and b axes which plane consequently has a normal which makes an angle of about 51 minutes from the Z or c axis, as illustrated in Figs. 1 and 2. For practical purposes and ease in processing, the major faces of the crystal element 2 may follow the natural plane surface of the a and b axes of the mother crystal 1, in which case they will not be quite perpendicular to the Z and c axes, by the angle of about 51 minutes. The properties of the crystal element 1 do not vary much with

such a small change in the orientation angle. Accordingly, the crystal element 2 of Fig. 3 may have its major faces nearly perpendicular to the Z axis and in the plane formed by the crystallographic axes a and b.

As particularly illustrated in Fig. 3, the length or longest dimension L of the major faces of the crystal element 2 lies substantially in the plane of the X and Y axes and is inclined at an angle of about 45 degrees with respect to the X and Y axes. The width dimension W of the major faces of the crystal element 2 being perpendicular to the length dimension L thereof will also make an angle of about 45 degrees with respect to the X and Y axes. The thickness dimension T extends along or nearly along the Z or c axis. The electrodes 4 and 5 disposed adjacent the major faces of the crystal element 2 provide an electric field in the direction of the thickness dimension T of the crystal element 2 thereby producing a useful longitudinal mode of motion along the length dimension L of the crystal element 2 with high electromechanical coupling and a low temperature coefficient of frequency over a temperature range in the region above and below about $+16\frac{1}{2}^{\circ}$ centigrade.

The dimensional ratio of the width dimension W with respect to the length dimension L of the crystal element 2 may be made of any suitable value in the region less than 0.7 for example and as particularly described herein may be about 0.5 for longitudinal length mode crystal elements 2. The smaller values of dimensional ratios of the width W with respect to the length L, as of the order of 0.5 more or less, have the effect of spacing the width W mode of motion at a frequency which it remote from the fundamental longitudinal mode of motion along the length dimension L.

When the crystal element 2 is operated in the fundamental longitudinal mode of motion along the length dimension L thereof, the nodal line occurs at the center of and transverse to the length dimension L of the crystal element 2 about midway between the opposite small ends thereof and the crystal element 2 may be there mounted and electrically connected by any suitable means such as by wires 6 cemented by a spot 7 of conductive cement to the metallic coatings 4 and 5 in the nodal region of the crystal element 2.

While the crystal element 2 is particularly described herein as being operated in the fundamental longitudinal mode of motion along its length dimension L, it will be understood that it may be operated in any even or odd order harmonic thereof in a known manner by means of a plurality of pairs of opposite interconnected electrodes spaced along the length L thereof. Also, if desired, the crystal element 2 may be operated simultaneously in the longitudinal length L and width W modes of motion by arrangements as disclosed for example in W. P. Mason Patent No. 2,292,885 dated August 11, 1942; or simultaneously in the longitudinal length L mode of motion and the width W flexure mode of motion by arrangements as disclosed for example in W. P. Mason Patent No. 2,292,886 dated August 11, 1942.

Fig. 4 is a perspective view illustrating a $37\frac{1}{2}^{\circ}$ -degree Z-cut di-potassium tartrate hemihydrate crystal element 2 which has been cut from a mother crystal 1 such as that illustrated in Fig. 1. The orientation of the $37\frac{1}{2}^{\circ}$ -degree Z-cut crystal element 2 illustrated in Fig. 4 is similar to that of the 45-degree Z-cut crystal element 2

illustrated in Fig. 3, except for the position of the longest or length dimension L thereof, which in the case of the $37\frac{1}{2}$ -degree Z-cut crystal element 2 of Fig. 4 is inclined at an angle θ of about $37\frac{1}{2}$ degrees with respect to the $+X$ axis, instead of $\theta=45$ degrees, as in the case of the 45-degree Z-cut crystal element of Fig. 3.

The $37\frac{1}{2}$ -degree Z-cut crystal element 2 of Fig. 4 with its length dimension L disposed at substantially $37\frac{1}{2}$ degrees from the $+X$ axis gives a longitudinal length mode resonant frequency which has a zero temperature coefficient at about $+30^\circ$ centigrade, instead of at about $+16\frac{1}{2}^\circ$ centigrade as in the case of the $\theta=45$ -degree Z-cut crystal element of Fig. 3. Accordingly, the $37\frac{1}{2}$ -degree Z-cut crystal element of Fig. 4 may be preferred for use where the ambient temperature is in the region of $+30^\circ$ centigrade. The crystal element 2 of Fig. 4, like the crystal element of Fig. 3, has its major faces disposed perpendicular or nearly perpendicular to the Z or c axis; but its length or longest dimension L is inclined at an angle of θ —about $37\frac{1}{2}$ degrees with respect to the $+X$ or $+a$ axis, as illustrated in Fig. 4. The thickness dimension T extends along or nearly along the Z or c axis. The electrodes 4 and 5 disposed adjacent the major faces of the crystal element 2 provide an electric field in the general direction of the thickness dimension T of the crystal element 2, thereby producing a useful longitudinal mode of motion along the length dimension L of the crystal element 2 with a high electro-mechanical coupling and a low temperature coefficient of frequency over an ordinary room temperature range in the region above and below $+30^\circ$ centigrade.

Fig. 5 is a graph illustrating an example of the frequency spectrum of 45-degree Z-cut dipotassium tartrate hemihydrate crystal elements 2 of Fig. 3 having various dimensional ratios of the width W with respect to the length L within the range between about 0.15 and 0.65. As shown in Fig. 5, the main mode of motion, which is the fundamental longitudinal mode of vibration along the length dimension L , is represented by the curve labeled A in Fig. 5, and has a frequency constant which varies from about 177 to 169 kilocycles per second per centimeter of the length dimension L , depending upon the dimensional ratio of width W to length L selected. Thus, as an example, a 45-degree Z-cut crystal element 2 having a length dimension L of one centimeter and a dimensional ratio of width W to length L of about 0.5 will have a frequency of about 172 kilocycles per second for its fundamental longitudinal mode of motion along the length dimension L . A similar 45-degree Z-cut crystal element, but having a length dimension L of another value, will have a corresponding frequency which varies inversely as the value of its length dimension L .

The curve B in Fig. 5 represents a nearby face shear mode of motion which has a slight coupling to the length longitudinal mode of motion represented by the curve A. At a dimensional ratio of width W to length L of around 0.5 for example, the main length longitudinal mode of motion represented by the curve A has a ratio of capacities around 19.5 to 20, while the face shear mode of motion represented by the curve B has a ratio of capacities of around 500 to 700, as indicated by the numerals alongside the curve B in Fig. 5. Hence, the effect of the secondary face shear mode of motion represented by the curve B on the main length longitudinal mode of motion repre-

sented by the curve A, is comparatively negligible.

The higher frequency modes of motion shown by the upper set of curves in Fig. 5 are related to the width longitudinal mode of motion, the main fundamental longitudinal mode of motion along the width dimension W being represented by the curve C in Fig. 5. All of these higher frequency resonances which are related to the width mode of motion represented by the curve C, are, for a 45-degree Z-cut crystal element 2 having a width dimension W equal to about one-half of its length dimension L , disposed above twice as high in frequency as the frequency of the main longitudinal mode of motion represented by the curve A, and do not produce any troublesome interference therewith.

Fig. 6 is a graph illustrating an example of the small variation in the resonant and antiresonant frequencies f_r and f_a with varying temperatures from -60 to $+80^\circ$ centigrade, in a 45-degree Z-cut dipotassium tartrate hemihydrate crystal element 2 of Fig. 3, the crystal element 2 having a length dimension L of about 20.14 millimeters, a width dimension W of about 10.175 millimeters, the width W to length L ratio thus being about 0.5, and having a thickness dimension T of about 0.88 millimeter. As illustrated in Fig. 6, the variation in the antiresonant frequency is given by the curve labeled f_a , and the variation in the resonant frequency is given by the curve labeled f_r . As shown by the curve f_r in Fig. 6, the resonant frequency f_r has a zero temperature coefficient at about $+16\frac{1}{2}^\circ$ centigrade, and from about 0° to $+40^\circ$ centigrade the total variation in frequency is of the order of about 0.029 per cent, which is a sufficiently low temperature coefficient of frequency to be suitable for use in electric wave crystal filters and in other crystal systems.

The longitudinally clamped dielectric constant of all Z-cut type dipotassium tartrate hemihydrate crystals 2 over a temperature range from -80 to $+100^\circ$ centigrade is of the order of 6.0 expressed in centimeter-gram-seconds units.

Fig. 7 is a graph illustrating an example of the frequency spectrum of $37\frac{1}{2}$ -degree Z-cut dipotassium tartrate hemihydrate crystal elements 2 of Fig. 4, for various dimensional ratios of the width W with respect to the length L within the dimensional range about from 0.15 to 0.65. As shown in Fig. 7, the main mode of motion, which is the fundamental longitudinal or extensional mode of vibration along the length dimension L , is represented by the curve labeled A' in Fig. 7, and has a frequency constant which varies from about 182 to 170 kilocycles per second per centimeter of the length dimension L , depending upon the selected dimensional ratio of the width W with respect to the length L . Thus, as an illustrative example, a $37\frac{1}{2}$ -degree Z-cut crystal element 2 having a length dimension L of one centimeter and a dimensional ratio of width W to length L of about 0.5 will have a frequency of about 174 kilocycles per second for its fundamental longitudinal mode of motion along the length dimension L . It will be understood that the frequency varies inversely as the length dimension L in a length longitudinal mode crystal element.

The curve B' in Fig. 7 represents a face shear mode of motion which has a slight coupling to the main length longitudinal mode of motion represented by the curve A' in Fig. 7. At the dimensional ratio of width W to length L around 0.5 for example, the main length longitudinal mode of motion represented by the curve A' has a ratio

of capacities around 19.0 as indicated by the figure "19.0" placed alongside the curve A', while the face shear mode of motion represented by the curve B' has a ratio of capacities of about 736 as indicated by the figure "736" placed alongside the curve B' in Fig. 7. Hence the effect of the face shear mode of motion represented by the curve B' on the main longitudinal length L mode of motion represented by the curve A' is comparatively negligible.

The higher frequency modes of motion shown by the upper set of three curves in Fig. 7 are related to the width longitudinal mode of motion, the main fundamental longitudinal mode of motion along the width dimension W of the 37½-degree Z-cut crystal element 2 being represented by the curve C' in Fig. 7. All three of these higher frequency resonances related to the curve C' are, for a 37½-degree Z-cut crystal element having a width dimension W equal to about one-half of its length dimension L, disposed about twice as high in frequency as the frequency of the main longitudinal length mode of motion represented by the curve A', and do not produce any troublesome interference therewith. The numbers appearing adjacent the curves A' and B' in Fig. 7 indicate the approximate values of the ratio of capacity at regions on the curves A' and B' adjacent the numbers.

Fig. 8 is a graph illustrating an example of the small variation in the resonant and antiresonant frequencies, with change in temperature from -80 to +80° centigrade, for a 37½-degree Z-cut di-potassium tartrate crystal element 2 of Fig. 4, the crystal element having a length dimension L of about 20.36 millimeters, a width dimension W of about 10.14 millimeters, the width W to length L dimensional ratio thus being about 0.5, and having a thickness dimension T of about 0.9 millimeter. The variation in the anti-resonant frequency is given by the curve labeled f_a in Fig. 8, and the variation in the resonant frequency is given by the curve labeled f_r . As shown in Fig. 8 by the curve f_r , the resonant frequency has a zero temperature coefficient at about +30° centigrade and over the range from 0 to +60° centigrade the total variation in frequency is small, the frequency remaining constant to about 50 cycles per second out of 100 kilocycles per second.

Fig. 9 is a graph showing a plot of the θ angle of rotation of the length dimension L measured from the X-axis against the temperature for the zero temperature coefficient of frequency, for Z-cut longitudinal length mode di-potassium tartrate hemihydrate crystal elements 2 of Figs. 3 or 4, when rotated in effect about the Z axis, the dimensional ratio of width W to length L being about 0.5 in all cases. As shown by the curve D in Fig. 9, the $\theta=45$ -degree Z-cut crystal element 2 of Fig. 3 has its zero temperature-frequency coefficient at a temperature of about +16½° centigrade, and the $\theta=37½$ -degree Z-cut crystal element 2 of Fig. 4 has its zero temperature-frequency coefficient at a temperature of about +30° centigrade. Similarly, when $\theta=22½$ degrees giving a 22½-degree Z-cut crystal element, the temperature for the zero temperature-frequency coefficient is at about -45° centigrade. Similarly, for other angles of θ between 22½ and 55 degrees, the temperature for the zero temperature-frequency coefficient in Z-cut di-potassium tartrate crystal elements may be obtained from the curve D of Fig. 9. When the ambient temperature is between +15° and +30° centigrade, the corresponding angle θ may conveniently

be a value between about 30 and 46 degrees, as shown by the curve D in Fig. 9.

Fig. 10 is a graph illustrating the approximate value of the ratio of capacities of the $\theta=45$ and 37½-degree Z-cut length longitudinal mode di-potassium tartrate hemihydrate crystal elements 2 of Figs. 3 and 4, as a function of temperature over a range from -60 to +80° centigrade. At ordinary room temperatures from +20 to +30° centigrade, the ratio of capacities is in the region between 19 and 20 as shown by the curve E in Fig. 10. The term ratio of capacities, as used in this specification, has its usual significance.

It will be noted that among the several cuts illustrated in Figs. 3, 4 and 9 are orientations for which the temperature-frequency coefficient may be zero at a specified temperature T_0 , the frequency variation being sufficiently small over ordinary room temperature range to be useful for example, in wideband filter systems. The low temperature coefficient of frequency together with the high electromechanical coupling, the high Q, the ease of procurement and the low cost of production are advantages of interest for use as circuit elements in electrical systems generally.

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.

What is claimed is:

1. Piezoelectric crystal apparatus comprising means including a di-potassium tartrate crystal body for producing a substantially zero temperature coefficient of vibrational frequency within a temperature range substantially from 0° to +40° centigrade, said frequency being determined by a major face dimension axis of said crystal body, said dimension axis being made of a dimensional value corresponding to the value of said frequency, the angular orientation of said crystal body with respect to the mutually perpendicular X, Y and Z axes thereof being a value corresponding to and related to the value of said substantially zero temperature coefficient of frequency, and electric field-producing means for operating said crystal body at said substantially zero temperature coefficient of frequency.

2. Piezoelectric crystal apparatus comprising means including a di-potassium tartrate crystal body for producing a substantially zero temperature coefficient of vibrational frequency within a temperature range substantially from 0° to +40° centigrade, said frequency being determined by a major face dimension axis of said crystal body, said dimension axis being made of a dimensional value corresponding to the value of said frequency, the angular orientation of said crystal body with respect to the mutually perpendicular X, Y and Z axes thereof being a value corresponding to and related to the value of said substantially zero temperature coefficient of frequency, and electric field-producing means for operating said crystal body at said substantially zero temperature coefficient of frequency, said major face of said crystal body being disposed substantially parallel to said Y axis of said X, Y and Z axes.

3. Piezoelectric crystal apparatus comprising means including a di-potassium tartrate crystal body for producing a substantially zero temperature coefficient of vibrational frequency within a temperature range substantially from 0° to

+40° centigrade, said frequency being determined by a major face dimension axis of said crystal body, said dimension axis being made of a dimensional value corresponding to the value of said frequency, the angular orientation of said crystal body with respect to the mutually perpendicular X, Y and Z axes thereof being a value corresponding to and related to the value of said substantially zero temperature coefficient of frequency, and electric field-producing means for operating said crystal body at said substantially zero temperature coefficient of frequency, said major face of said crystal body being disposed substantially parallel to one of said X, Y and Z axes, said one axis being said Y axis, and said major face dimension axis being inclined at one of the angles between 10 and 60 degrees with respect to another of said X, Y and Z axes.

4. A Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having its major faces disposed substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at one of the angles substantially from +30 to +46 degrees with respect to the +X axis.

5. A Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having its substantially rectangular major faces disposed substantially perpendicular to the Z axis, the lengthwise axis dimension and longest edges of said major faces being inclined at one of the angles substantially from +37 to +46 degrees with respect to the +X axis.

6. A Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having its substantially rectangular major faces disposed substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at an angle of substantially +37½ degrees with respect to the +X axis.

7. A Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having its substantially rectangular major faces disposed substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at an angle of substantially 45 degrees with respect to the X axis.

8. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having mutually perpendicular width and length axis dimensions for its major faces, said major faces being substantially perpendicular to the Z axis, and said length axis dimension being inclined at an angle of substantially 45 degrees with respect to the X axis, said width axis dimension being substantially less than said length axis dimension.

9. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having mutually perpendicular width and length axis dimensions for its major faces, said major faces being substantially perpendicular to the Z axis, and said length axis dimension being inclined at an angle of substantially +37½ degrees with respect to the +X axis, said width axis dimension being substantially less than said length axis dimension.

10. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal ele-

ment having major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at one of the angles from substantially +22 to +53 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, the temperature coefficient of frequency of said crystal element being substantially zero at a temperature substantially as given by the curve in Fig. 9 at a point thereon corresponding to the value of said one of said angles.

11. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension and longest edges of said major faces being inclined at one of the angles from substantially +22 to +53 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, the ratio of the width axis dimension of said major faces with respect to said lengthwise axis dimension thereof being one of the values less than 0.7, the temperature coefficient of frequency of said crystal element being substantially zero at a temperature substantially as given by the curve in Fig. 9 at a point thereon corresponding to the value of said one of said angles.

12. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at one of angles from substantially +30 to +46 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the range substantially from +15° to +30° centigrade.

13. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension and longest edges of said major faces being inclined at one of the angles from substantially +30 to +46 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, the ratio of the width axis dimension of said major faces with respect to said lengthwise axis dimension thereof being one of the values less than 0.7, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the range substantially from +15° to +30° centigrade.

14. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise

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axis dimension and longest edges of said major faces being inclined at one of the angles from substantially +37 to +46 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the range substantially from +15° to +30° centigrade.

15. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension and longest edges of said major faces being inclined at one of the angles from substantially +37 to +46 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, the ratio of the width axis dimension of said major faces with respect to one of the values less than 0.7, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the range substantially from +15° to +30° centigrade.

16. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, said major faces being disposed substantially perpendicular to the Z axis, the lengthwise axis dimension and longest edges of said major faces being inclined at one of the angles from substantially +37 to +46 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension of said crystal element, the ratio of the width axis dimension of said major faces with respect to said lengthwise axis dimension thereof being substantially 0.5, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the range substantially from +15° to +30° centigrade.

17. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element, the major faces of said crystal element being substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at an angle of substantially 45 degrees with respect to the X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the region of substantially +16° centigrade.

18. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element, the major faces of said crystal element being substantially perpendicular to the Z axis, the lengthwise axis dimension of said major faces being inclined at an angle of substantially +37½ de-

grees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion along said lengthwise dimension.

19. Piezoelectric crystal apparatus comprising a 45 degree Z-cut di-potassium tartrate hemihydrate crystal element adapted for longitudinal motion along the length axis dimension of its substantially rectangular major faces, said major faces being substantially perpendicular to the Z axis of the three mutually perpendicular X, Y and Z axes thereof, and said length axis dimension being inclined at an angle of substantially 45 degrees with respect to said X axis, the ratio of the width axis dimension of said major faces with respect to said length axis dimension being a value not greater than substantially 0.6, said length axis dimension being a value corresponding to the frequency for said longitudinal mode of motion, said length axis dimension expressed in centimeters being one of the values substantially from 177 to 169 divided by the value of said frequency expressed in kilocycles per second, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said longitudinal mode of motion, said crystal element having a substantially zero temperature coefficient of frequency at a temperature in the region of substantially +16° centigrade.

20. Piezoelectric crystal apparatus comprising a +37½ degree Z-cut di-potassium tartrate hemihydrate crystal element adapted for longitudinal motion along the length axis dimension of its substantially rectangular major faces, said major faces being substantially perpendicular to the Z axis of the three mutually perpendicular X, Y and Z axes thereof, and said length axis dimension being inclined at an angle of substantially +37½ degrees with respect to said +X axis, the ratio of the width axis dimension of said major faces with respect to said length axis dimension being a value not greater than substantially 0.6, said length axis dimension being a value corresponding to the frequency for said longitudinal mode of motion, said length axis dimension expressed in centimeters being one of the values substantially from 182 to 169 divided by the value of said frequency expressed in kilocycles per second, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said longitudinal mode of motion.

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REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,292,885	Mason	Aug. 11, 1942
2,292,886	Mason	Aug. 11, 1942
2,440,695	Mason	May 4, 1948

OTHER REFERENCES

Piezoelectricity, by W. C. Cady; first edition, 1946, McGraw-Hill Book Company, Inc., N. Y.