

Nov. 23, 1948.

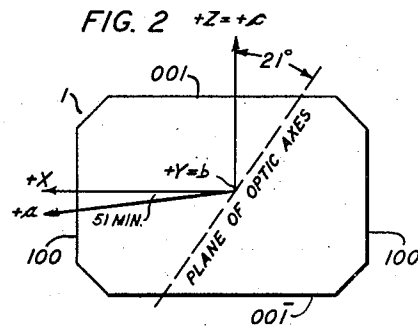
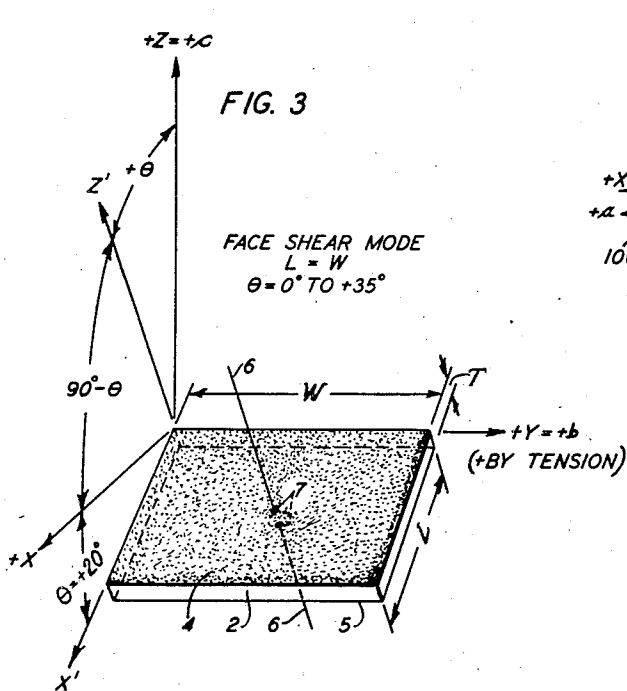
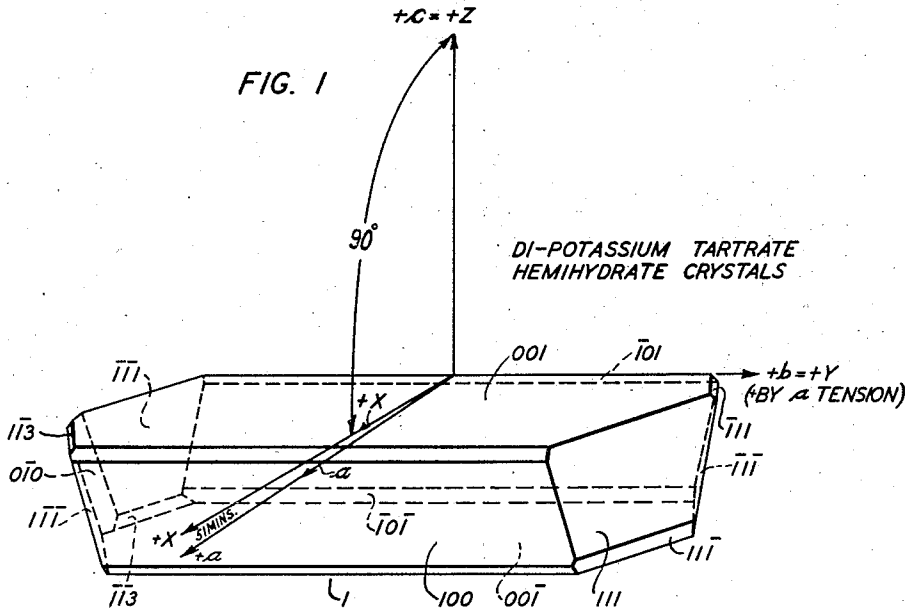
W. P. MASON

2,454,328

PIEZOELECTRIC CRYSTAL APPARATUS

Filed March 28, 1946

2 Sheets-Sheet 1



INVENTOR
W. P. MASON
BY
W. J. O'Neill
ATTORNEY

Nov. 23, 1948.

W. P. MASON

2,454,328

PIEZOELECTRIC CRYSTAL APPARATUS

Filed March 28, 1946

2 Sheets-Sheet 2

FIG. 4

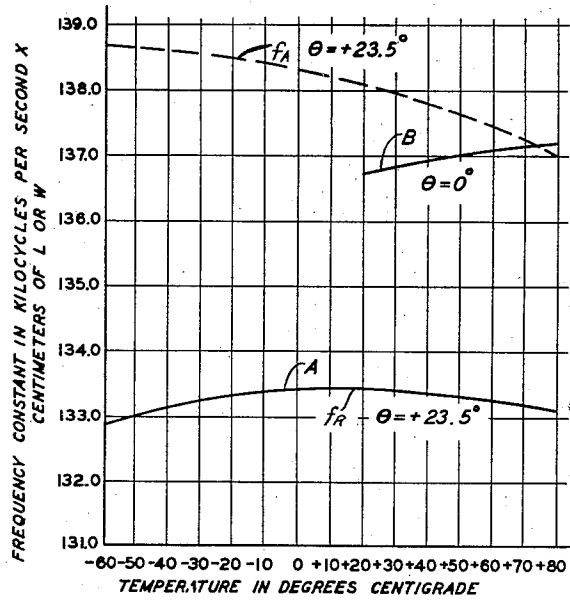


FIG. 5

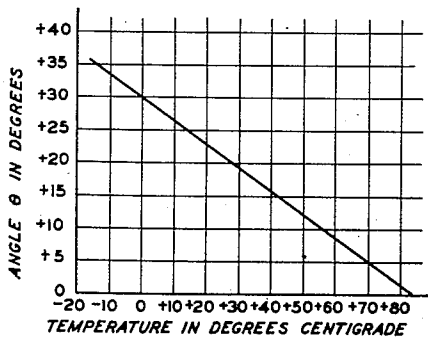
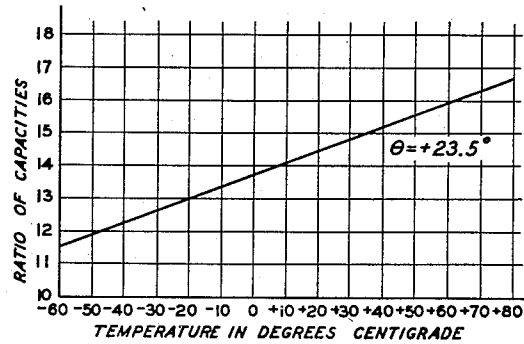


FIG. 6



INVENTOR
W. P. MASON
BY *w. j. o'neill*
ATTORNEY

UNITED STATES PATENT OFFICE

2,454,328

PIEZOELECTRIC CRYSTAL APPARATUS

Warren P. Mason, West Orange, N. J., assignor
to Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application March 28, 1946, Serial No. 657,885

17 Claims. (Cl. 171—327)

1

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 orientations for face shear 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 face shear mode 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 belongs 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 or zero temperature coefficient of frequency, and fairly high Q or low dielectric loss and mechanical dissipation.

In general, 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 dimension. Also, low frequency flexural

2

modes of motion of either the width bending flexure type or the thickness bending 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 already known in connection with other crystalline substances such as quartz, Rochelle salt and ammonium dihydrogen phosphate crystals. Longitudinal mode dipotassium tartrate crystal elements are disclosed and claimed in my copending applications Serial No. 646,639, filed February 9, 1946, and Serial No. 659,468, filed April 4, 1946, which is now Patent Number 2,440,694.

It is useful to have a synthetic type of face shear mode piezoelectric crystal element having a low or zero temperature coefficient of frequency, and having a low 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 face shear modes of motion. Such crystal elements cut from di-potassium tartrate hemihydrate may have a zero temperature coefficient of frequency, and also advantageous elastic properties whereby 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 square or nearly square major faces disposed perpendicular or nearly perpendicular to the Z or c axis and operating in the face shear mode of motion along the width and length dimensions thereof, the length dimension being inclined at an angle θ which may be an angle from 0 to 25 degrees or more with respect to the X-axis, or an angle from 15 to 25 degrees where a zero temperature coefficient of frequency is desired at ordinary room temperatures. Where the angle θ is an angle between 0 and 25 degrees or more, the piezoelectric coupling is of high value at all such θ angles. The temperature at which the zero temperature coefficient of frequency occurs for the face shear mode of motion varies according to the value of the angle of θ selected, and is at a temperature of about +84° centigrade for a θ angle of about zero degrees, at about 0° centigrade for a θ angle of about 30 degrees, and at values between 0° and +84° centigrade for values of θ angles between 0 and 30 degrees. The coupling of the face shear mode of motion to other modes of motion therein is small, and at

the θ angle in the region of about 20 degrees the zero temperature coefficient of frequency occurs at ordinary room temperature.

Accordingly, in the case of crystalline di-potassium tartrate hemihydrate there are among other useful cuts, special cuts each of which have a zero temperature coefficient of frequency and a 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 oscillator or electric wave filter, or as a frequency modulator for an oscillation generator.

The synthetic tartrate crystal elements provided in accordance with this invention have high electromechanical coupling of the order of 20 to 25 per cent, have high reactance-resistance ratios Q at resonance, and have 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 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 very high. 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 low frequencies. 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 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 another view illustrating the rectangular X , Y and Z and 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;

Fig. 3 is a perspective view illustrating face shear mode Z -cut type di-potassium tartrate

hemihydrate crystal elements rotated in effect about the Y or b axis to any position corresponding to angles of θ in the region of 20 degrees or about 15 to 25 degrees, or more broadly angles of θ from 0 to 30 degrees or more with respect to the $+X$ axis;

Fig. 4 is a graph illustrating the resonant and anti-resonant frequency characteristics of a $\theta=23\frac{1}{2}$ degrees Z -cut type face-shear-mode di-potassium tartrate hemihydrate crystal element, as a function of temperature;

Fig. 5 is a graph illustrating the relation between the zero temperature coefficient temperature of face-shear-mode rotated Z -cut type di-potassium tartrate hemihydrate crystal elements and angles of θ in the region from about 0 to 35 degrees; and

Fig. 6 is a graph illustrating the ratio of capacities of a $\theta=23\frac{1}{2}$ degree rotated Z -cut face-shear-mode di-potassium tartrate hemihydrate crystal element 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 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 crystalline di-potassium tartrate hemihydrate, is a small angle of about 51 minutes. The crystallographic a , b and c axes represent conventional terminology as used by crystallographers.

Referring to the drawing, Fig. 1 is a perspective view illustrating 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 are as shown in Fig. 1.

The mother crystal 1 , as illustrated in Fig. 1, may be grown from any suitable 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 by 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 crystallo-

graphic axis, the Y or b axis being an axis of binary symmetry. here are four dielectric constants, eight piezoelectric constants and thirteen elastic constants involved in such crystalline material.

Di-potassium tartrate hemihydrate crystals 1 have one-half molecule of water of crystallization, as compared to four 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 about 80° centigrade, there appears to be no observable dehydration of the crystalline di-potassium tartrate hemihydrate; but at 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 do not appreciably affect the crystal 1 since the stable relative humidity at 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 the presence of such cleavage planes may make the crystals 1 somewhat more difficult to cut and process, nevertheless satisfactory processing may be done by using suitable means such as a sanding belt cooled by oil or by a solution of water and ethylene glycol, for example.

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 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 optic axes of the crystal 1 may be located. A monoclinic crystal 1 is an optically biaxial crystal and for 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 X, Y and Z axes as 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 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 a plate of substantially rectangular parallelepiped shape having length dimension L, a breadth or width dimension W which may be equal or nearly equal to the length dimension L, 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 measured between the opposite parallel major or electrode faces of the crystal element 2. The length dimension L and the width dimension W of the crystal element 2 may be made of values to suit the desired 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 larger length and width dimensions L and W, may be placed in a location that is relatively remote from the desired face shear mode of motion controlled by the length and width dimensions L and W.

Suitable conductive electrodes 4 and 5 may be provided adjacent the two opposite major or electrode faces of the crystal element 2 in order to apply electric field excitation thereto. The electrodes 4 and 5 when formed integral with the 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 in divided or non-divided form as already known for other face mode type crystal elements. 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 Rochelle salt or quartz crystals for example, and that they may be nodally mounted and electrically connected by any suitable means, such as

for example, by a pair of coaxial pressure type clamping pins or by a pair of opposite conductive supporting spring wires 6 having a flat-headed end 7 cemented by conductive cement or glued to the respective metallic coatings 4 and 5 deposited on the opposite surfaces of the crystal elements 2 at suitable points thereon as already known in connection with quartz, Rochelle salt and other crystal elements having similar or corresponding face shear modes of motion.

As illustrated in Fig. 3, the crystal element 2 has its substantially square major faces disposed parallel or nearly parallel to the Y or b axis, and has its length dimension L along the X' axis which is inclined at an angle θ with respect to the +X axis where θ may be an angle in the region of 20 degrees or about from 15 to 25 degrees for ordinary room temperature ranges, or more broadly from 0 to 30 degrees or more. The angle θ is the angle of the normal Z' measured from the +Z axis in the direction of the +X axis. At the angle of θ —about 20 degrees with respect to the +X axis as particularly illustrated in Fig. 3, the crystal element 2 has good piezoelectric coupling, and also has a zero temperature coefficient of frequency at about +29° centigrade for its face shear mode of motion which is controlled by the length and width dimensions L and W, and at θ angles in that region the mechanical coupling of that face shear mode of motion to other modes of motion therein is not large. At angles of θ above and below about 20 degrees, the piezoelectric coupling is of effective values, the mechanical coupling of the face shear mode of motion to other modes of motion therein is small, and the position of the temperature at which the zero temperature coefficient of frequency occurs for the face shear mode of motion is raised or lowered from about +29° centigrade according to the angle of θ selected, as indicated in Fig. 5.

It will be noted that the natural top and bottom surfaces 001 and $\bar{0}\bar{0}\bar{1}$ respectively of the mother crystal 1 of Fig. 1 extend in the plane of the a and b axes which 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 be measured from the natural a and b axes surface of the mother crystal 1, in which case they will not be quite the same as when measured from X and Y axes by the angle of about 51 minutes. The properties of the crystal element 2 do not vary much with such a small change in the orientation angle.

As particularly illustrated in Fig. 3, the 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 +20 degrees with respect to the +X and +a axes. The other, or width dimension W of the major faces of the crystal element 2 is perpendicular to the length dimension L thereof and lies along or nearly along the b and Y axes. The thickness dimension T extends along or nearly along the Z' 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 plate normal Z' or thickness dimension T of the crystal element 2, thereby producing a useful face shear mode of motion controlled mainly by the length dimension L and the width dimension W 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 +29° 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 of 1.0 for example and as particularly described herein is about 1.0, or square, for face shear mode crystal elements 2. The values of dimensional ratios of the width W with respect to the length L, as of the order of 1.0 more or less, have the effect of spacing spurious mode of motion at a frequency remote from the fundamental face shear mode of motion.

When the crystal element 2 is operated in the fundamental face shear mode of motion controlled mainly by the length and width dimensions L and W thereof, the nodal region 7 occurs at the center of the crystal element 2 about midway between the opposite sides and diagonal corners thereof, and the crystal element 2 may be there nodally mounted and electrically connected in that nodal region 7 by any suitable means such as by a pair of coaxial wires 6 cemented to the crystal element 2 or to metallic coatings 4 and 5 in the nodal region 7 of the crystal element 2. Accordingly, it will be understood that the face shear mode crystal element 2 has a nodal point 7 which is at the center 7 and may be there mounted by one or more pairs of wires 6 cemented to the integral coatings 4 and 5 at or near the centers 7 of the major faces of the crystal element 2. Whether divided or non-divided type electrode coatings 4 and 5 are utilized, the supporting wires 6 may comprise a single pair or a plurality of pairs of opposite wires 6 disposed near the center 7 of the crystal element 2 in the manner as heretofore used in mounting a quartz CT cut face shear mode crystal element. Accordingly, the crystal element 2 may be conveniently used with non-divided or divided coatings 4 and 5 in unbalanced or balanced filters, or in filters generally.

While the crystal element 2 is particularly described herein as being operated in the fundamental face shear mode of motion dependent upon its equal or nearly equal length and width dimensions L and W, it will be understood that it may be operated in overtone face shear modes thereof.

Fig. 3 is a view which may be taken to illustrate rotated Z-cut di-potassium tartrate hemihydrate crystal elements 2 where the X' axis or length dimension L thereof is disposed at an angle θ in the region from 0 to 30 or more degrees and in particular cases is inclined at an angle θ about from +15 to +25 degrees with respect to the +X axis.

The θ —+20 degrees rotated Z-cut crystal element 2 of Fig. 3 with its length dimension L disposed at an θ angle of substantially +20 degrees from the +X axis gives a resonant frequency which has a zero temperature coefficient at about +30° centigrade, instead of at about 84° centigrade as in the case of a θ —0 degree Z-cut crystal element of Fig. 3. Accordingly, the θ —+20-degree rotated Z-cut crystal element of Fig. 3 may be preferred for use where the ambient temperature is in the region of +30° centigrade. The crystal element 2 of Fig. 3 has the width dimension W of its major faces disposed parallel or nearly parallel to the Y or b axis; and its other or length dimension L may be inclined at any θ angle such as an angle of about θ —+20 degrees with respect to the +X or +a axis, as illustrated in Fig. 3.

The thickness dimension T extends along the Z' 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 face shear mode of motion, the frequency of which is dependent upon the length and width dimensions L and W of the crystal element 2, with a high electromechanical coupling and a low temperature coefficient of frequency over an ordinary room temperature range in the region above and below about $+30^\circ$ centigrade.

As an example of the frequency spectrum of a $\theta=+20$ -degree rotated Z -cut di-potassium tartrate hemihydrate crystal element 2 of Fig. 3, for a dimensional ratio of the width W with respect to the length L of about 1.0, the main mode of motion, which is the fundamental face shear mode of vibration dependent upon the length and width dimensions L and W , has a frequency constant which varies from about 130 to 140 kilocycles per second per centimeter of the length or width dimension L or W , depending upon the temperature range selected. Thus, as an example, a $\theta=+20$ -degree rotated Z -cut square-faced crystal element 2 having a length dimension L of one centimeter and a dimensional ratio of width W to length L of about 1.0 will have a frequency of about 133 kilocycles per second for its fundamental face shear mode of motion. A similar crystal element but having equal length and width dimensions L and W of another value will have a corresponding frequency which varies inversely as the value of the equal length and width dimensions L and W thereof.

As another illustrative example, the frequency spectrum data of a square-shaped $\theta=+22\frac{1}{2}$ -degree rotated Z -cut face shear mode crystal element 2 having a length dimension L of about 16.2 millimeters, a width dimension W of about 16.2 millimeters, thus giving substantially square shaped major faces, and a thickness dimension T of about 1.0 millimeter is given in the following table:

Resonance	f_R	f_A	Resistance at Resonance	C_0 =Static Capacity	Ratio of Capacities
1 (main)-----	82,270	84,960	Ohms 130	$\mu\mu\text{f.}$ 18.4	15.8
2-----	163,775	163,813	-----	-----	2,220
3-----	163,975	163,995	-----	-----	4,080
4 (secondary)---	190,200	192,090	200	18.4	50.5

As shown by the foregoing table, the nearest resonance is spaced away at least twice as high in frequency as the main face shear mode of motion resonance 1, and the next prominent resonance is about 2.3 times as high as that fundamental mode frequency. The reactance-resistance ratio Q for the main face shear resonance may be made as high as 100,000 for a crystal element 2 suitably mounted in an evacuated holder. The ratio of capacities for the main resonance is around 15.8 and may vary about 10 per cent over an ordinary room temperature range; but a variation in impedance of this order of magnitude is not objectionable, since the main face shear resonance frequency is substantially constant over such a temperature range.

Fig. 4 is a graph illustrating by curves f_R and f_A an example of the small variation in the resonant and anti-resonant frequency constants with varying temperatures from -60 to $+80^\circ$ centigrade, in a $\theta=+23\frac{1}{2}$ -degree rotated Z -cut di-

potassium tartrate hemihydrate crystal element 2 of Fig. 3, the crystal element 2 having a length dimension L about equal to its width dimension W , the width W to length L dimensional ratio thus being about 1.0, and having a thickness dimension T of the order of 1.0 millimeter. As illustrated in Fig. 4, the variation in the anti-resonant 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. 4, the fundamental face shear mode resonant frequency f_R has a zero temperature coefficient at about $+20^\circ$ 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 Z -cut rotated type di-potassium tartrate hemihydrate crystals over a temperature range from -80° to $+100^\circ$ centigrade is of the order of 6.0 expressed in c. g. s. units.

As shown in Fig. 4 illustrating an example of the frequency characteristics of a $\theta=+23\frac{1}{2}$ -degree rotated Z -cut di-potassium tartrate hemihydrate crystal element 2 of Fig. 3 for a dimensional ratio of the width W with respect to the length L equal to about 1.0, the main mode of motion, which is the fundamental face shear mode of vibration controlled mainly by the length and width dimensions L and W is represented by the curve labeled A in Fig. 4, and has a resonant frequency constant f_R which varies from about 133 to 133.5 kilocycles per second per centimeter of the length or width dimension L or W over a temperature range from -50° to $+80^\circ$ centigrade. Thus, as an illustrative example, a $\theta=23\frac{1}{2}$ -degree Z -cut rotated crystal element 2 having length and width dimensions L and W of one centimeter each, thus giving a dimensional ratio of width W to length L of about 1.0, will have a frequency of about 133.4 kilocycles per second at $+20^\circ$ centigrade for its fundamental face shear mode of motion. It will be understood that the frequency varies inversely as the value of length and width dimensions L and W in a face shear mode crystal element.

Fig. 4 also illustrates, by curve B , an example of the small variation in the resonant frequency constant over a range in temperature from $+20^\circ$ to $+80^\circ$ centigrade, provided by a $\theta=0$ -degree rotated Z -cut di-potassium tartrate crystal element 2 of Fig. 3, the crystal element 2 having a length dimension L equal about to the width dimension W , the width W to length L dimensional ratio thus being about 1.0 and having a thickness dimension T of the order of about 1.0 millimeter. The variation in the resonant frequency is given by the curve labeled B in Fig. 4, the curve B showing that the resonant frequency has a zero temperature coefficient at about $+84^\circ$ centigrade and over the range from $+20^\circ$ to $+60^\circ$ centigrade, the total variation in frequency is small. Accordingly, as illustrated by the curve B in Fig. 4, a square-shaped Z -cut crystal element 2 which has an angle $\theta=$ zero or nearly zero degrees and which has its length L and width W dimensions of equal or nearly equal values and disposed along or nearly along the X and Y axes, has a face shear mode frequency that increases with increase of temperature, the frequency reaching a maximum value at about $+84^\circ$ centigrade. This temperature may be found to be a rather high temperature for the

equilibrium point when the crystal element 2 is to be used at ordinary room temperatures in the region of $+20$ to $+30$ degrees, for example. By rotating in effect the normal Z' and major faces of the crystal element 2 around or nearly around the Y axis to a position where the θ angle is a value greater than 0 degree, the equilibrium point for the mean temperature may be lowered and for use at ordinary room temperatures, the angle θ may conveniently be an angle between about 15 and 25 degrees, the angle θ being selected according to the ambient temperature in which the crystal element 2 is to be used. For example, the resonant frequency of a square-shaped crystal element 2 having its normal Z' rotated $\theta =$ about $+23\frac{1}{2}$ degrees about the Y axis, has a mean equilibrium temperature which comes at about $+20^\circ$ centigrade as shown by the curve A in Fig. 4 and also by the curve in Fig. 5.

Fig. 5 is a graph showing a plot of the θ angle of rotation of the X' axis length dimension L measured from the $+X$ axis and of the normal Z' measured from the $+Z$ axis in the direction of the $+X$ axis, against the temperature for the zero temperature coefficient of frequency, for rotated Z-cut face shear mode di-potassium tartrate hemihydrate crystal elements 2 of Fig. 3, when rotated in effect about the Y or b axis, the dimensional ratio of the width W with respect to the length L being about 1.0 in all cases. As shown by the curve in Fig. 5, the $\theta = +20$ -degree rotated Z-cut crystal element 2 of Fig. 3 has its zero temperature-frequency coefficient at a temperature of about $+30^\circ$ centigrade, and at the θ angle of $+23\frac{1}{2}$ degrees, the crystal element 2 of Fig. 3 has its zero temperature-frequency coefficient at a temperature of about $+20^\circ$ centigrade. Similarly, when $\theta = +22\frac{1}{2}$ degrees giving a $22\frac{1}{2}$ -degree rotated Z-cut crystal element 2, the temperature for the zero temperature-frequency coefficient is at about $+23^\circ$ centigrade. Similarly, for other angles of θ between 0 and $+35$ degrees, the temperature for the zero temperature-frequency coefficient in rotated Z-cut di-potassium tartrate crystal elements 2 may be obtained from the curve of Fig. 5. When the ambient temperature is between $+15^\circ$ and $+40^\circ$ centigrade, the corresponding angle θ may conveniently be a selected value between 15 and 25 degrees, as shown by the curve in Fig. 5.

Fig. 6 is a graph illustrating the approximate value of the ratio of capacities of a $\theta = +23\frac{1}{2}$ -degree rotated Z-cut face shear mode di-potassium tartrate hemihydrate crystal element 2 of Fig. 3, as a function of temperature over a range from -60° to $+80^\circ$ centigrade. At ordinary room temperatures from $+20^\circ$ to $+30^\circ$ centigrade, the ratio of capacities is in the region between 14 and 15 , as shown by the curve in Fig. 6. The term ratio of capacities, as used in this specification, has its usual significance.

It will be noted that among the useful cuts illustrated in Figs. 3 to 6 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 temperature ranges to be useful for example in 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. A rotated Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having a major plane section disposed substantially parallel to the Y axis and inclined at one of the angles substantially from $+15$ to $+25$ degrees with respect to the $+X$ axis.

2. A rotated Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having one pair of opposite edges of its substantially rectangular major plane section disposed substantially parallel to the Y axis, the other pair of opposite edges of said major plane section being inclined at one of the angles substantially from $+15$ to $+25$ degrees with respect to the $+X$ axis.

3. A rotated Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having its substantially square major faces disposed substantially parallel to the Y axis and inclined at one of the angles in the range of angles substantially from $+15$ to $+25$ degrees with respect to the $+X$ axis.

4. A rotated Z-cut type di-potassium tartrate hemihydrate crystal element of low temperature coefficient of frequency having substantially square major faces, said major faces having one pair of opposite edges disposed substantially parallel to the Y axis, and said major faces having another pair of opposite edges inclined at one of the angles in the range of angles substantially from $+15$ to $+25$ degrees with respect to the $+X$ axis.

5. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially square major faces, one set of edges of said major faces being disposed substantially parallel to the Y axis and another set of edges of said major faces being disposed at one of the angles from substantially 0 to $+35$ degrees with respect to $+X$ axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face shear mode of motion at a frequency dependent upon the dimensions of said major faces of said crystal element, said frequency having a substantially zero temperature coefficient at a temperature substantially as given by the curve in Fig. 5 at a point thereon corresponding to the value of said one of said angles.

6. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially square major faces, one set of edges of said major faces being disposed substantially parallel to the Y axis, and another set of edges of said major faces being inclined at one of the angles from substantially $+15$ to $+25$ degrees with respect to the $+X$ axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face shear mode of motion at a frequency dependent upon the dimensions of said major faces of said crystal element.

7. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, one set of edges of said major faces being disposed substantially parallel to the Y axis, and another set of edges of said major faces being inclined at one of the angles from substantially

+15 to +25 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face mode of motion along said major faces of said crystal element.

8. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having major faces, said major faces being disposed substantially parallel to the Y axis, said major faces being inclined at one of the angles from substantially +15 to +25 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face shear mode of motion along said major faces of said crystal element.

9. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element, the major faces of said crystal element being substantially parallel to the Y axis, said major faces being inclined at an angle of substantially +20 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face shear mode of motion along said major faces.

10. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially square major faces, one set of edges of said major faces of said crystal element being substantially parallel to the Y axis and another set of edges of said major faces being inclined at an angle of substantially +20 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face shear mode of motion along said major faces.

11. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having substantially rectangular major faces, one set of edges of said major faces being disposed substantially parallel to the Y axis, and another set of edges of said major faces being disposed at one of the angles from substantially +5 to +35 degrees with respect to the +X axis, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a face mode of motion along said major faces of said crystal element at a frequency having a substantially zero temperature coefficient within the range of temperatures between -20° and +80° centigrade.

12. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element adapted for face shear motion at a frequency in accordance with the mutually perpendicular length and width dimensions of its substantially rectangular major faces, said width dimension of said major faces being substantially parallel to the Y axis of the three mutually perpendicular X, Y and Z axes thereof, and said length dimension being inclined at an angle of substantially +20 degrees with respect to said +X axis, the ratio of said width dimension of

said major faces with respect to said length dimension thereof being a value of substantially 1.0, said length and width dimensions being a value corresponding to the frequency for said face shear mode of motion, said length dimension and said width dimension expressed in centimeters being one of the values substantially from 133 to 140 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 face shear mode of motion.

13. Piezoelectric crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element adapted for face shear motion at a frequency in accordance with the mutually perpendicular length and width dimensions of its substantially rectangular major faces, said width dimension of said major faces being substantially parallel to the Y axis of the three mutually perpendicular X, Y and Z axes thereof, and said length dimension being inclined at one of the angles from substantially +15 to +25 degrees with respect to said +X axis, the ratio of said width dimension of said major faces with respect to said length dimension thereof being a value of substantially 1.0, said length and width dimensions being a value corresponding to the frequency for said face shear mode of motion, said length dimension and said width dimension expressed in centimeters being one of the values substantially from 133 to 140 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 face shear mode of motion.

14. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having mutually perpendicular width and length dimensions for its major faces, one of said dimensions of said major faces being substantially parallel to the Y axis, and the other of said dimensions being inclined at an angle of substantially +20 degrees with respect to the +X axis, said dimensions being substantially equal.

15. Crystal apparatus comprising a di-potassium tartrate hemihydrate crystal element having mutually perpendicular width and length dimensions for its major faces, said width dimension of said major faces being substantially parallel to the Y axis, and said length dimension being inclined at one of the angles from substantially +15 to +25 degrees with respect to the +X axis, said width dimension being substantially equal to said length dimension.

WARREN P. MASON.

REFERENCES CITED

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

UNITED STATES PATENTS

Number	Name	Date
2,309,467	Mason	Jan. 26, 1943