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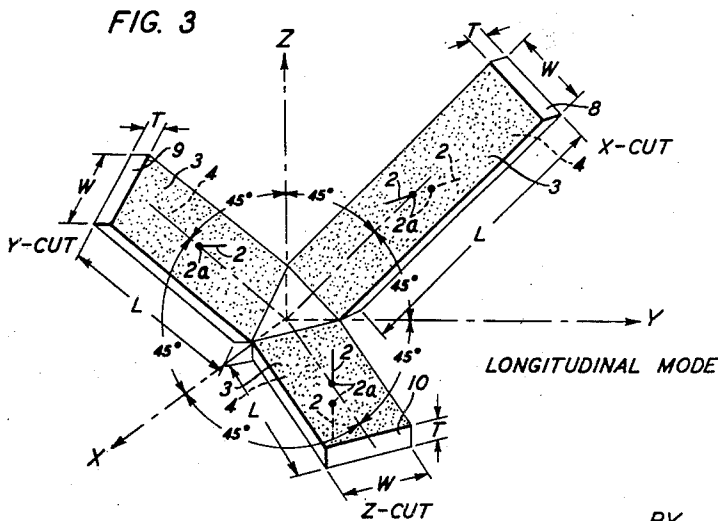
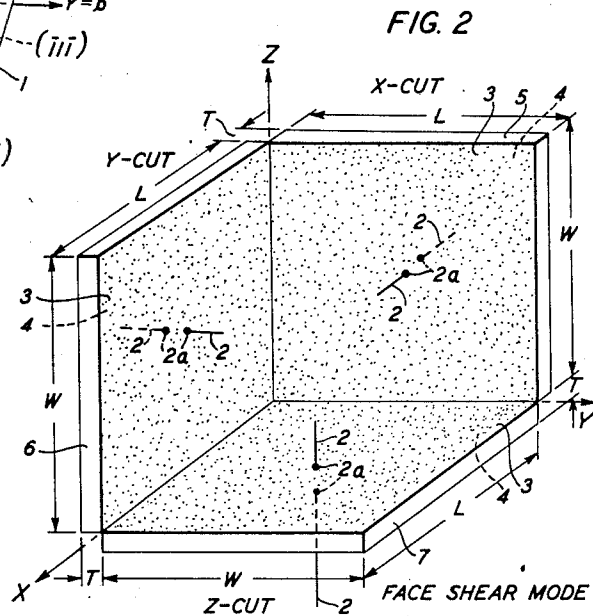
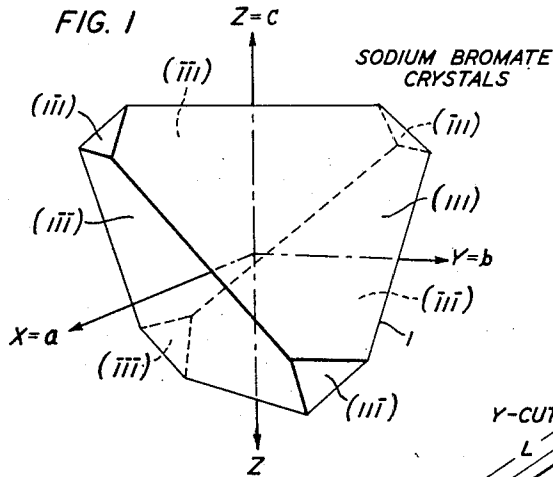
W. P. MASON

2,460,704

PIEZOELECTRIC CRYSTAL APPARATUS

Filed April 5, 1946

2 Sheets-Sheet 1



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

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W. P. MASON

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PIEZOELECTRIC CRYSTAL APPARATUS

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2 Sheets-Sheet 2

FIG. 4

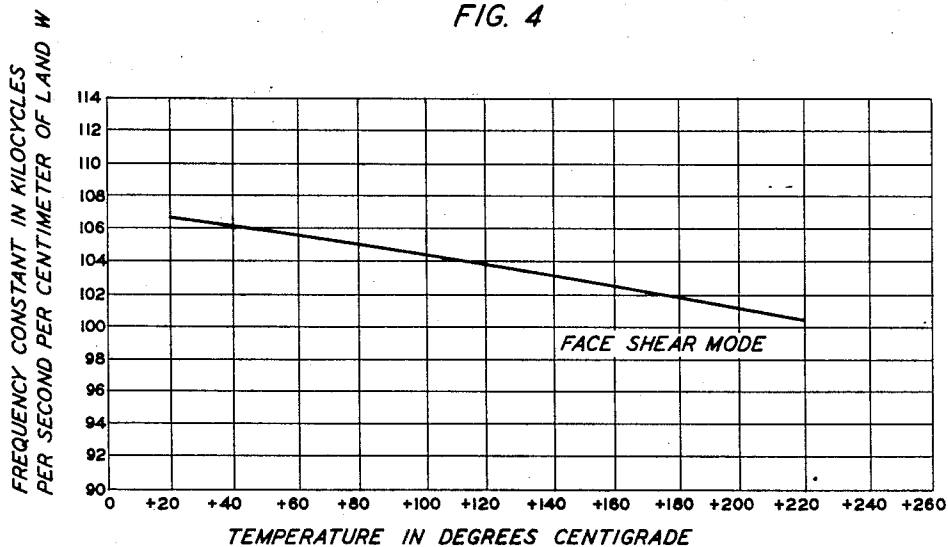
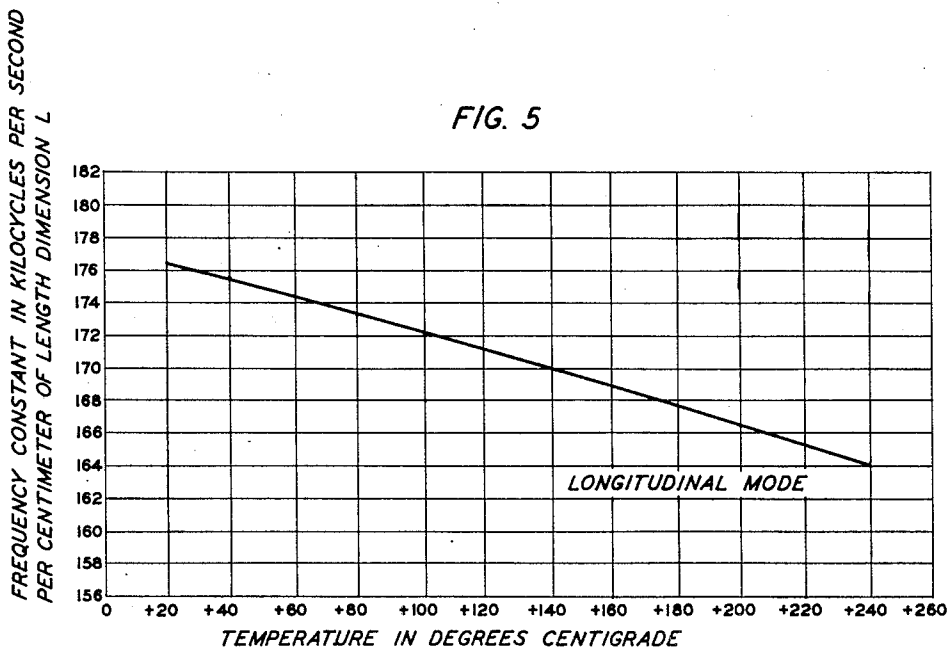


FIG. 5



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

UNITED STATES PATENT OFFICE

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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 April 5, 1946, Serial No. 659,680

13 Claims. (Cl. 171—327)

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This invention relates to piezoelectric crystal apparatus and particularly to synthetic piezoelectric crystal elements comprising sodium bromate. Such sodium bromate crystal elements may be used as circuit elements in oscillation generator systems, filter systems, temperature control systems, and in electro-mechanical systems generally.

One of the objects of this invention is to provide advantageous orientations and modes of motion in piezoelectric crystal elements cut from crystalline sodium bromate.

Another object of this invention is to take advantage of the low cost, ease of procurement and other advantages of synthetic sodium bromate crystals.

Another object of this invention is to provide sodium bromate crystal elements that may possess the maximum value of piezoelectric coupling, and the minimum coupling of the desired mode of motion with undesired modes of motion therein.

Another object of this invention is to provide synthetic piezoelectric crystal elements having a frequency which varies over a wide temperature range in a nearly linear relation with respect to the value of the ambient temperature applied thereto.

Sodium bromate (NaBrO_3) is a water soluble crystal substance which has no water of crystallization, which will stand a high temperature, and which crystallizes in the cubic tetrahedral class. As a consequence of its symmetry, there are three elastic constants, one piezoelectric constant and one dielectric constant. The dielectric and piezoelectric constants increase with increase in temperature. As the crystal approaches its melting point, the resistivity and the piezoelectric response are reduced, and the material becomes ionized.

Experimental results for the dielectric constant show that there is a component of the polarization which is practically independent of the temperature and another component which increases with temperature and becomes large as the melting point of the substance is approached. This is presumably due either to an actual orientation of the bromate dipoles as they become unfrozen at the higher temperatures, or due to an apex reversal of the position of the bromine in the molecule. Piezoelectric measurements show that the piezoelectric stress due to an applied electric field is directly proportional to the temperature variable component of the polarization and hence it is the change in orientation of the dipoles which causes the distortion of the crystal lattice and hence the piezoelectric effect.

Measurements made on sodium bromate crystal salt show that the temperature independent component of the polarization for the dielectric constant is larger than that for sodium chlorate,

indicating that the polarizability of the bromine is larger than that for chlorine. For equal temperature separations from the Curie point, which is close to the melting point, the temperature variable portion of the polarization is nearly the same size as that for sodium chlorate, indicating that the effective dipole moment is nearly the same for both sodium chlorate and sodium bromate. Piezoelectric measurements show that a given dipole polarization produces over twice as much lattice distortion and hence piezoelectric effect for sodium bromate crystals as for sodium chlorate crystals. Crystal elements comprising sodium chlorate are disclosed and claimed in my copending application Ser. No. 659,679, filed April 5, 1946.

Crystal elements of suitable orientation cut from crystalline sodium bromate 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 length and width dimensions. Also, lower frequency flexural 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.

It is useful to have available synthetic type piezoelectric crystal elements having a resonant frequency which varies in linear relation with respect to temperature. In accordance with this invention, such crystal elements may be provided, and for this purpose the cuts may be, for example, X-cut, Y-cut and Z-cut, crystal plates operating in the major face shear mode of motion and also X-cut, Y-cut and Z-cut crystal plates operating in the longitudinal mode of motion.

Such crystal elements having a resonant frequency which varies very nearly linearly with respect to temperature change may be utilized as a sensitive thermometer, thermostat or as a thermal regulator that may be continuously regulated. The crystal element may be used for holding the temperature of an enclosure very closely at one temperature, or the control temperature may be continuously varied by suitable means. The crystal elements may be taken over a very wide temperature range and have the property that the resonant frequency thereof changes quite uniformly with temperature change, and will hold their frequency quite accurately over ordinary temperature ranges. Either the face shear mode type or the longitudinal mode type

of crystal element may be utilized for such temperature control units.

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 tetrahedral crystal of sodium bromate may crystallize, and also illustrating the relation of the surfaces of the mother crystalline substance with respect to the mutually perpendicular X, Y and Z axes and the crystallographic *a*, *b* and *c*;

Fig. 2 is a perspective view illustrating 0-degree X-cut, Y-cut and Z-cut face shear mode crystal plates which may be cut from the sodium bromate mother crystal, as illustrated in Fig. 1;

Fig. 3 is a perspective view illustrating 45-degree X-cut, Y-cut and Z-cut longitudinal mode crystal plates which may be cut from the mother crystal illustrated in Fig. 1 or from the corresponding X-cut, Y-cut and Z-cut plates illustrated in Fig. 2;

Fig. 4 is a graph illustrating the relation between the frequency and the temperature for X-cut, Y-cut and Z-cut face shear mode sodium bromate crystal elements as illustrated in Fig. 2; and

Fig. 5 is a graph illustrating the relation between the frequency and the temperature, for 45-degree X-cut, 45-degree Y-cut and 45-degree Z-cut length longitudinal mode sodium bromate crystal elements, as illustrated in Fig. 3.

This specification follows the conventional terminology, as applied to piezoelectric crystal 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 corresponds to the *a* axis. The crystallographic *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 sodium bromate may crystallize. The mother crystal 1, illustrated in Fig. 1, may be grown from a saturated water solution by slowly reducing the temperature and depositing the salt on a prepared seed. The crystal 1 grows in the cubic tetrahedral form and in the case of sodium bromate crystals, the crystal habit assumes a cubic form, as illustrated in Fig. 1, the principal faces as expressed in conventional terminology being the 111 planes.

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 large mother crystal 1 of a size and shape that may be 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, Y and Z dimensions or of any size sufficient 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 sodium bromate have no water of crystallization and hence no vapor pressure, and accordingly, plates cut therefrom may be put in an evacuated container without change, and may be held in temperatures as high as 200° centigrade, or more. At a temperature considerably higher than 240° centigrade, surface decomposition and eventual melting occurs.

Tetrahedral crystals 1 comprising sodium bromate are characterized by having two interchangeable crystallographic axes *b* and *a* which are disposed at right angles with respect to each other, and a third crystallographic axis *c* which makes an angle of 90 degrees with respect to the other two crystallographic axes *b* and *a*. In dealing with the axes and the properties of such a crystal 1, it is convenient to use the mutually perpendicular system of X, Y and Z coordinance. Accordingly, as illustrated in Fig. 1, the conventional method chosen for relating the conventional right-angled X, Y and Z systems 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 axis coincide with the *b* or *a* axis, and to have the X axis coincide with the *a* or *b* crystallographic axis.

Fig. 2 is a perspective view illustrating sodium bromate X-cut, Y-cut and Z-cut crystal elements 5, 6 and 7, respectively, cut from a suitable mother crystal 1, such as that shown in Fig. 1, for example. The crystal elements 5, 6 and 7, as shown in Fig. 2, may be made into the form of plates of substantially rectangular parallelepiped shape having a length dimension L, a breadth or width dimension W, and a thickness or thin dimension T, the direction of the length, width and thickness 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 elements 5, 6 and 7. The length dimension L and the width dimension W of the crystal elements 5, 6 and 7 may be made of values to suit the desired face shear 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 elements 5, 6 and 7 may be utilized as a circuit element; and also it may be made of a suitable value to avoid nearly 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 3 and 4 may be provided adjacent the two opposite major or electrode faces of the crystal elements 5, 6 and 7 in order to apply electric field excitation thereto. The electrodes 3 and 4 when formed integral with the faces of the crystal elements 5, 6 and 7 may consist of gold, platinum, silver, aluminum or other suitable conductive material deposited upon the surfaces of the crystal elements 5, 6 and 7 by evaporation in vacuum or by other suitable

process. Accordingly, it will be understood that any of the crystal elements 5, 6 and 7 may be provided with conductive electrodes or coatings 3 and 4 on their faces of any suitable composition, shape, and arrangement, such as those known for the similar face shear mode of motion in connection with Rochelle salt or quartz crystals, for example. The crystal elements 5, 6 and 7 may be nodally mounted and electrically connected by any suitable means, such as, for example, by a pair of opposite pressure-type clamping pins, or by a pair of opposite conductive supporting spring wires 2 which may be secured and individually cemented by a spot of conductive cement 2a to the electrode coatings 3 and 4 deposited on the opposite major faces of the crystal elements 5, 6 and 7, as already known in connection with quartz, Rochelle salt and other crystals having a similar or corresponding face shear mode of motion. The support wires 2 are individually connected with the electrodes 3 and 4 which are disposed adjacent the major faces of the crystal elements 5, 6 and 7 and provide an electric field in the direction of the thickness dimension T of the crystal elements 5, 6 and 7, thereby producing a useful face shear mode of motion in the plane of the length and width dimensions L and W of the crystal elements 5, 6 and 7.

The face shear mode crystal elements 5, 6 and 7 of Fig. 2 are three differently oriented crystal elements of X-cut, Y-cut and Z-cut orientations, respectively, the frequency of which results from a face shear motion which is controlled in frequency mainly by the major face length and width dimensions L and W. As illustrated in Fig. 2, the major faces of the crystal elements 5, 6 and 7 are disposed perpendicular or nearly perpendicular with respect to one of the three mutually perpendicular X, Y and Z axes, and the opposite edges of such major faces are disposed parallel or nearly parallel with respect to two of the X, Y and Z axes, the length and width dimensions L and W accordingly being disposed at an angle of zero or nearly zero degrees with respect to two of the X, Y and Z axes. The motion in the X-cut, Y-cut and Z-cut crystal elements 5, 6 and 7 of Fig. 2 is a shear mode of motion controlled by the piezoelectric constants d_{14} , d_{25} and d_{36} , respectively, which represent conventional terminology for expressing the relation between the applied field direction and the resulting stress or type of motion. These three piezoelectric constants are of equal value in sodium bromate crystals, and consequently any of the X-cut, Y-cut and Z-cut crystal elements 5, 6 and 7 of Fig. 2 may be piezoelectrically driven with equal strength and equal characteristics.

As illustrated in Fig. 2, the X-cut crystal element 5 may have square or rectangular-shaped major faces which are disposed perpendicular or nearly perpendicular with respect to the X axis and which have edges disposed parallel or nearly parallel to the Y and Z axes in order to obtain the desired face shear mode of motion therein free from coupling to longitudinal modes of motion. Similarly, the Y-cut crystal element 6 of Fig. 2 may have its square or rectangular major faces disposed perpendicular or nearly perpendicular to the Y axis and its opposite edges parallel or nearly parallel to the X or Z axes. Similarly, the Z-cut crystal element 7 of Fig. 2 may have its square or rectangular major faces disposed perpendicular to the Z axis and its edges parallel or nearly parallel to the X and Y axes.

In all three of the crystal elements 5, 6 and 7 of Fig. 2 where the peripheral edges are disposed at a substantially zero angle with respect to two of the three mutually perpendicular X, Y and Z axes, the face shear motion is substantially free from coupling to longitudinal modes therein and has a resonant frequency which is very nearly linear with respect to temperature.

While the face shear mode crystal elements 5, 6 and 7 of Fig. 2 are shown as having substantially square-shaped major faces, they may be cut in elongated rectangular form with small or selected dimensional ratios of width W to length L or of length L to width W, and also they may be adapted to vibrate either simultaneously or independently in the first and second shear face modes of motion controlled by the width W and length L dimensions of the crystal element by means as disclosed, for example, in my United States Patent 2,309,467 dated January 26, 1943.

The frequency constants for the first or fundamental face shear mode of motion of the sodium bromate X-cut, Y-cut and Z-cut crystal elements 5, 6 and 7 of Fig. 2 is of the order of 107 kilocycles per second per centimeter of the length or width dimension L or W at a temperature of about 25° centigrade, and varies uniformly and very nearly linearly with temperature change, as illustrated by the curve in Fig. 4.

Fig. 4 is a graph illustrating an example of the variation in the resonant frequency constant with varying temperatures from about +20° to +220° centigrade, in fundamental face shear mode crystal elements 5, 6 and 7 of the X-cut, Y-cut and Z-cut orientations, as illustrated in Fig. 2. As shown by the curve in Fig. 4, the frequency constant for the fundamental face shear mode of motion in any of the X-cut, Y-cut and Z-cut crystal elements 5, 6 and 7 of Fig. 2 has a value at about 20° centigrade of about 107 kilocycles per second per centimeter of the length or width dimensions L and W, and as the temperature is increased, the value of the frequency constant decreases uniformly and very nearly linearly with respect to temperature change, giving a decrease in frequency constant of about 6 kilocycles per second over the temperature range from about +20° to +220° centigrade, as shown by the curve in Fig. 4. As an illustrative example taken from the curve of Fig. 4, an X-cut, a Y-cut or a Z-cut crystal element 5, 6 or 7 of Fig. 2 having a width dimension W of 1 centimeter and a length dimension L of 1 centimeter will have a frequency for its fundamental face shear mode of motion of about 106.6 kilocycles per second at about +25° centigrade and of about 101.5 kilocycles per second at +220° centigrade, and intermediate values between +20° and +220° centigrade, as given by the curve of Fig. 4. Similar crystal elements 5, 6 and 7 of other dimensions will have a corresponding frequency which varies inversely as the values of the width and length dimensions W and L which may be of equal or nearly equal values.

Fig. 3 is a perspective view illustrating three differently oriented face-longitudinal mode crystal elements 8, 9 and 10 which may be cut by any suitable methods from a mother crystal 1, as illustrated in Fig. 1, and which may be made into elongated crystal plates of substantially rectangular parallelepiped shape having a relatively large length dimension L, a smaller width dimension W, and a thickness or relatively thin dimension T which extends between the two opposite major faces of the crystal plates 8, 9 and 10. By proper dimensioning of the thickness dimension

T relative to the larger width and length dimensions W and L, spurious resonances may be placed in a location that is relatively remote from the desired main face mode of motion which, in the case of the crystal plates 8, 9 and 10 of Fig. 3, is a longitudinal mode of motion.

Suitable conductive electrodes, such as the crystal electrodes 3 and 4, may be placed adjacent and formed integral with the opposite major faces of the crystal plates 8, 9 and 10 in order to apply electric field excitation thereto in the direction of the thickness dimension T thereof. The crystal electrodes 3 and 4 may partially or wholly cover the opposite major faces of the crystal plates 8, 9 and 10, and when formed integral with such faces may consist of gold, platinum, silver, aluminum or other suitable conductive material deposited by evaporation in vacuum, spraying, painting, or by other suitable process.

The 45-degree X-cut, the 45-degree Y-cut and the 45-degree Z-cut crystal elements 8, 9 and 10, respectively, of Fig. 3 may be cut from the crystal plates 5, 6 and 7, respectively, of Fig. 2 or they may be cut separately from the mother crystal 1 of Fig. 1. The 45-degree X-cut crystal element 8, as illustrated in Fig. 3, has its opposite major faces disposed perpendicular or nearly perpendicular to the X axis and has its length and width dimensions L and W inclined at an angle of 45 or nearly 45 degrees with respect to the Y and Z axes. Similarly, the 45-degree Y-cut crystal element 9 and the 45-degree Z-cut crystal element 10, as illustrated in Fig. 3, have their major faces disposed perpendicular or nearly perpendicular to the Y and Z axes, respectively, and have the lengthwise dimension L thereof inclined at an angle of 45 degrees or nearly 45 degrees with respect to the other two of the three mutually perpendicular X, Y and Z axes, as shown in Fig. 3. The dimensional ratio of the width dimension W with respect to the length dimension L of the crystal elements 8, 9 and 10 may be of any suitable value, such as below 0.7 or around 0.5 or less, for example. A feature of interest is that at the bisecting angle of 45 degrees, the crystal elements 8, 9 and 10, illustrated in Fig. 3, have for the longitudinal mode of motion, the maximum value for the piezoelectric constants d_{11} , d_{21} and d_{31} , the maximum value of longitudinal motion, the minimum or zero value of coupling with the face shear mode of motion therein, and a uniform and very nearly linear variation in the longitudinal mode frequency with temperature change, as illustrated in Fig. 5.

While the 45-degree angle, as illustrated in Fig. 3, is of special interest, it will be understood that the longitudinal mode crystal elements 8, 9 and 10 may be rotated in effect about their thickness dimension T to a position at either side of and other than at the 45-degree bisecting angular position that is particularly illustrated in Fig. 3. And while the longitudinal mode of motion along the length dimension L is of special interest, it will be understood that the crystal elements 8, 9 and 10 of Fig. 3 may be operated in the longitudinal mode of motion along the width dimension W by the same electrodes 3 and 4; or they may be operated simultaneously in the length L and width W longitudinal modes of motion by electrode means, as disclosed in United States Patent 2,292,885 to W. P. Mason dated August 11, 1942; or they may be operated alone or simultaneously in the length L longitudinal mode of motion and in the width W flexural mode of motion by means

as disclosed in United States Patent 2,292,886 to W. P. Mason dated August 11, 1942.

The dimensional ratio of the width dimension W with respect to the length dimension L of the crystal elements 8, 9 and 10 may be made of any suitable value in the region less than 0.7, for example, and as particularly described herein is about 0.5 more or less for longitudinal length L mode crystal elements. 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 therein at a frequency which is remote from the fundamental longitudinal mode of motion along the length dimension L.

When the crystal elements 8, 9 and 10 are 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 and is about midway between the opposite small ends thereof; and the crystal element 8, 9 or 10 may be there nodally mounted and electrically connected by suitable means, such as by one or more pairs of coaxial spring wires 2 which may be securely cemented by a spot of conductive cement 2a to the metallic coatings 3 and 4 in the nodal region 2a of the crystal elements 8, 9 and 10.

While the crystal elements 8, 9 and 10 are particularly described herein as being operated in the fundamental longitudinal mode of motion along the length dimension L, it will be understood that they may be operated in any even or odd order harmonic thereof by means of a plurality of pairs of opposite interconnected electrodes spaced along the length dimension L thereof in a manner known in connection with longitudinal mode quartz crystal elements.

The cuts of special interest shown in Fig. 3 are the 45-degree X-cut, the 45-degree Y-cut and the 45-degree Z-cut crystal elements 8, 9 and 10, respectively, as illustrated in Fig. 3, which are adapted to vibrate in the longitudinal mode of motion along the lengthwise dimension L of the major faces thereof. These three cuts have similar characteristics and they are the orientations which give not only the maximum value of piezoelectric coupling for the lengthwise longitudinal mode of motion but also a substantially zero value of mechanical coupling of that lengthwise longitudinal mode of motion to the face shear mode of motion therein, and moreover, for all three of these cuts the frequency of that lengthwise longitudinal mode of motion varies in very nearly linear relation with respect to the temperature change over a wide range, a feature which is of interest in connection with temperature control uses. It will be noted that the 45-degree X-cut, the 45-degree Y-cut and the 45-degree Z-cut crystal elements 8, 9 and 10, respectively, have similar characteristics, and that their frequency constant expressed in kilocycles per second per centimeter of the length dimension L in a temperature range from about +20° centigrade to +240° centigrade are roughly from 176.5 to 164, according to the value of the temperature.

As an illustrative example for sodium bromate crystal elements 8, 9 and 10 having a length dimension L large relative to the width dimension W and a thickness dimension T of about 1 millimeter, the frequency constant expressed in kilocycles per second per centimeter of the length dimension L is about 176 at +30° centigrade, about 175 at +50° centigrade, about 174 at +70°

centigrade and decreases uniformly to about 164 at +240° centigrade, as given in the curve of Fig. 5.

Fig. 5 is a graph illustrating an example of the variation in the resonant frequency constant with varying temperatures from about +20° to +240° centigrade, in longitudinal mode elongated crystal elements 8, 9 and 10 of the 45-degree X-cut, 45-degree Y-cut and 45-degree Z-cut orientations which are particularly illustrated in Fig. 3. As shown by the curve in Fig. 5, the frequency constant for the fundamental longitudinal length mode of motion in any of the elongated crystal elements 8, 9 and 10 of Fig. 3 has at a temperature of about 25° centigrade a value of about 176 kilocycles per second per centimeter of the length dimension L, and as the temperature is increased the value of the frequency constant decreases uniformly and very nearly linearly with respect to temperature change, giving a decrease in frequency constant of about 10 kilocycles per second over the temperature range from about +25° to +240° centigrade, as shown by the curve in Fig. 5. The frequency of the longitudinal mode of motion along the length dimension varies inversely as the value of the temperature, and also inversely as the value of the length dimension L.

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 a piezoelectric sodium bromate crystal plate having its substantially rectangular-shaped major faces disposed substantially perpendicular to one of the three mutually perpendicular X, Y and Z axes, the opposite edges of said major faces being disposed at one of the angles of substantially 0 and 45 degrees with respect to one of the other two of said three mutually perpendicular X, Y and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal plate in a face mode of motion at a frequency which varies in substantially linear relation with respect to the value of ambient temperature applied thereto.

2. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially rectangular major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the X axis, and the edges of said major faces being disposed substantially parallel to the Y and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

3. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially square major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the X axis, and the edges of said major faces being disposed substantially parallel

to the Y and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

4. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially rectangular major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the Y axis, and the edges of said major faces being disposed substantially parallel to the X and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

5. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially square major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the Y axis, and the edges of said major faces being disposed substantially parallel to the X and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

6. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially rectangular major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the Z axis, and the edges of said major faces being disposed substantially parallel to the Y and X axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

7. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially square major faces at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature thereof, said major faces being disposed substantially perpendicular to the Z axis, and the edges of said major faces being disposed substantially parallel to the Y and X axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said face shear mode of motion at said frequency in accordance with said temperature value.

8. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for vibration in the face shear mode of motion along its substantially rectangular major faces, said major faces being disposed substantially perpendicular with respect to one of the three mutually perpendicular X, Y and Z axes, the length and width dimensions of said major faces being disposed substantially parallel with respect to one of the other two of said three mutually perpen-

dicular X, Y and Z axes, said length and width dimensions having values corresponding to the value of the frequency for said face shear mode of motion, said length and width dimensions expressed in centimeters being one of the values substantially from 107 to 100 divided by said 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 at said frequency, said frequency being a value which varies substantially linearly in accordance with the value of the ambient temperature applied to said crystal element and said frequency corresponding to a value substantially as given by the curve in Fig. 4 at a point thereon corresponding to the value of said temperature.

9. Piezoelectric crystal apparatus comprising an elongated sodium bromate crystal element adapted for vibration in the longitudinal mode of motion along the lengthwise dimension of its substantially rectangular major faces, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said lengthwise mode of motion at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature of said crystal element, said major faces being disposed substantially perpendicular to the X axis, and said lengthwise dimension being inclined at an angle of substantially 45 degrees with respect to the Y and Z axes.

10. Piezoelectric crystal apparatus comprising an elongated sodium bromate crystal element adapted for vibration in the longitudinal mode of motion along the lengthwise dimension of its substantially rectangular major faces, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said lengthwise mode of motion at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature of said crystal element, said major faces being disposed substantially perpendicular to the Y axis, and said lengthwise dimension being inclined at an angle of substantially 45 degrees with respect to the X and Z axes.

11. Piezoelectric crystal apparatus comprising an elongated sodium bromate crystal element adapted for vibration in the longitudinal mode of motion along the lengthwise dimension of its substantially rectangular major faces, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in said lengthwise mode of motion at a frequency which varies uniformly and substantially linearly over a substantial temperature range in accordance with the value of the temperature of said crystal element, said major faces being disposed substantially perpendicular to the Z axis, and said lengthwise dimension being inclined at an angle of substantially 45 degrees with respect to the Y and X axes.

12. Piezoelectric crystal apparatus comprising a sodium bromate crystal element adapted for longitudinal motion along the length dimension of its substantially rectangular major faces, said major faces being disposed substantially perpendicular with respect to one of the three mutually

perpendicular X, Y and Z axes, said length dimension being disposed at an angle of substantially 45 degrees with respect to the other two of said three mutually perpendicular X, Y and Z axes, the width dimension of said major faces being substantially less than said length dimension thereof, said length dimension having a value corresponding to the value of the frequency for said longitudinal mode of motion, said length dimension expressed in centimeters being one of the values substantially from 177 to 164 divided by said 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 at said frequency, said frequency being a value which varies substantially linearly in accordance with the value of the ambient temperature applied to said crystal element and said frequency corresponding to a value substantially as given by the curve in Fig. 5 at a point thereon corresponding to the value of said temperature.

13. Piezoelectric crystal apparatus comprising a piezoelectric sodium bromate crystal element having substantially rectangular-shaped major faces, said major faces being disposed substantially perpendicular to one of the three mutually perpendicular X, Y and Z axes, the lengthwise dimension and longest edges of said major faces being inclined at an orientation angle of substantially 45 degrees with respect to the other two of said three mutually perpendicular X, Y and Z axes, and means comprising electrodes disposed adjacent said major faces for operating said crystal element in a longitudinal mode of motion at a frequency dependent upon said lengthwise dimension and having a value which varies substantially linearly with respect to the value of the temperature of said crystal element, said orientation angle being a value corresponding to the maximum value of piezoelectric coupling for said longitudinal mode of motion, and corresponding to a substantially zero value for the coupling of said longitudinal mode of motion to the face shear mode of motion along said major faces of said crystal element, the ratio of the width dimension and shortest edges of said major faces with respect to said lengthwise dimension and longest edges thereof being a value less than 0.7, said lengthwise dimension expressed in centimeters being substantially one of the values from 177 to 164 divided by said frequency expressed in kilocycles per second.

WARREN P. MASON.

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