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2,282,369

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Aug. 3, 1940

FIG. 1

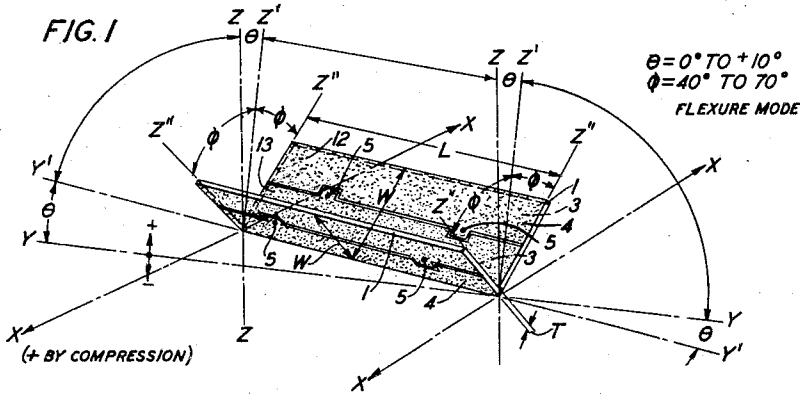


FIG. 2

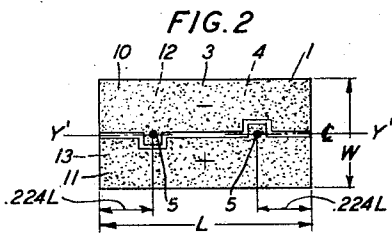


FIG. 3

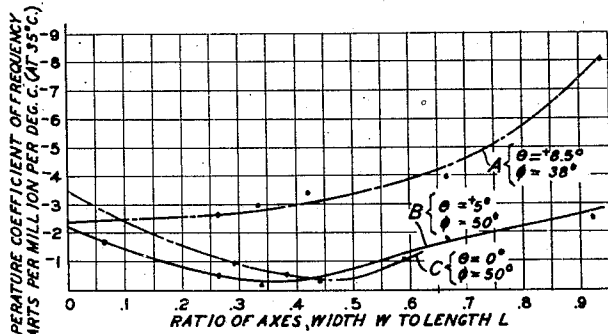
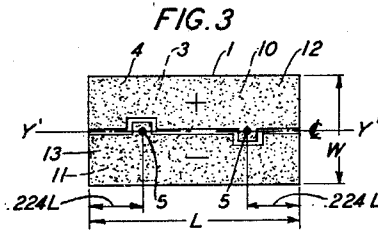


FIG. 4

FIG. 5

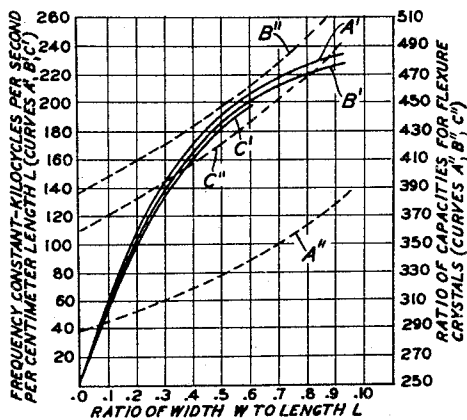
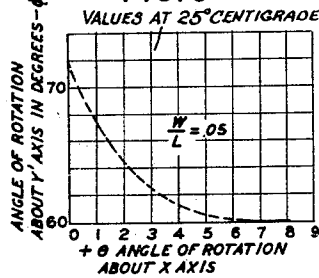


FIG. 6



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PIEZOELECTRIC CRYSTAL APPARATUS

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Application August 3, 1940, Serial No. 350,903

16 Claims. (Cl. 171—327)

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

One of the objects of this invention is to provide piezoelectric crystals having a low or substantially zero temperature coefficient of frequency.

Another object of this invention is to provide relatively low frequency piezoelectric crystals having a nearly constant vibrational frequency throughout a range of ordinary temperatures.

Another object of this invention is to provide piezoelectric crystals substantially free from interfering vibrational modes and free from any harmful or undesired frequencies near to the desired frequency.

Another object of this invention is to provide piezoelectric crystal elements of relatively small and economical sizes at relatively low frequencies.

Another object of this invention is to provide piezoelectric crystal elements having a small variation in temperature coefficient of frequency over a wide range of dimensional ratios.

In such systems as electric wave filter systems or oscillation generator systems, for example, it is often desirable to utilize flexure mode vibrating crystals which have a low or substantially zero temperature coefficient of frequency over a range of temperatures and which are so constructed that any undesired prominent secondary resonances therein may be moved or placed remotely or at convenient ratios from the desired main mode of vibration where they will cause no harm. It is also desirable that such crystal elements, when utilized at the relatively lower frequencies such as, for example, below about 50 to 100 kilocycles per second, be of relatively small and convenient size in order to avoid the expense that is usually involved in crystal elements of the relatively larger sizes.

The piezoelectric crystal elements provided in accordance with this invention may have a low temperature coefficient of frequency over a wide range of dimensional ratios, and on account of this feature, they are advantageous for use in filter systems since any undesired secondary resonance frequency therein may, by adjustment of the major surface dimensional ratio, be placed at a remote position where it will cause no harm, without disturbing the temperature coefficient of the desired resonant frequency. Also since the crystal elements provided in accordance with

this invention may have a relatively small size at low frequencies, they may be constructed economically down to 5 kilocycles per second or less, and accordingly are advantageous for use in low frequency oscillators, filters and other low frequency systems where a low frequency of low or substantially zero temperature coefficient is desired. The low frequency flexure mode crystals of this invention have not only a low temperature coefficient of frequency but also a large electromechanical coupling and are useful in such systems as low frequency filters, or oscillators such as the oscillators of frequency modulation broadcast systems or the oscillators of high frequency carrier wave systems, for example.

In accordance with this invention, relatively thin piezoelectric quartz crystal plates of suitable orientation with respect to the X, Y and Z axes of the quartz material and of suitable dimensional ratios may be subjected to a thickness direction electric field and vibrated at a resonance frequency dependent mainly upon the longest or major axis length dimension and the width dimension of the crystal plate in a mode of motion which may be called a flexural mode. The orientation angles and the dimensional ratios of the crystal plate may be any of several to produce for the first or fundamental flexural mode of motion, a low or substantially zero temperature coefficient of frequency at temperatures within a range between about 0 and +80° centigrade over a wide ratio of the width to length dimensions of its major faces, the frequency of the fundamental flexural mode vibration along the length or longest dimension of the crystal element being dependent upon such dimensional ratio and the length or longest dimension of the crystal element. In particular embodiments, the ratio of the width dimension W with respect to length dimension L of the major surfaces may range from about 0.05 to 1.0 and the orientation may be that of an X cut crystal element rotated in effect from 0 to about +10.0 degrees about its X axis thickness dimension, and then rotated from about 50 to 60 degrees about the major axis Y' or length dimension L.

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 drawing, in which like reference characters represent like or similar parts and in which:

Fig. 1 is a perspective view showing the ori-

entation, electrode arrangement, and nodal point regions of flexure mode piezoelectric quartz crystal elements in accordance with this invention;

Figs. 2 and 3 are views of the electrodes for the opposite major surfaces of the crystal element of Fig. 1, Fig. 2 being a view looking toward one of the major surfaces and Fig. 3 being a view looking in the opposite direction toward the other major surface of the electroded crystal element;

Fig. 4 is a graph illustrating the relation between the dimensional ratio and the temperature coefficient of frequency of typical crystal elements in accordance with this invention;

Fig. 5 is a graph showing the dimension-frequency characteristics and the ratio of capacities for various dimensional ratios of typical crystal elements in accordance with this invention; and

Fig. 6 is a graph showing the corresponding angles of θ and ϕ that produce zero temperature coefficient of frequency in low frequency crystals having a width about .05 times the length thereof.

This specification follows the conventional terminology as applied to crystalline quartz which employs three orthogonal or mutually perpendicular X, Y and Z axes, as shown in the drawing, to designate an electric axis, a mechanical axis and the optic axis, respectively, of piezoelectric quartz crystal material, and which employs three orthogonal axes X', Y' or Z' to designate the directions of axes of a piezoelectric body angularly oriented with respect to such X, Y and Z axes thereof. Where the orientation is obtained by double rotations of the quartz crystal element 1, one rotation being in effect substantially about the thickness dimension electric axis X, and the other about the length dimension axis Y' of the piezoelectric body 1, as illustrated in Fig. 1, the orientation angles ϕ and θ designate in degrees the effective angular position of the crystal plate 1 as measured from the axis Z' and from the mechanical axis Y, respectively. The width dimension axis Z'', shown in Fig. 1, indicates the result of a second rotation.

Quartz crystals may occur in two forms, namely, right-handed and left-handed. A right-handed quartz crystal is one in which the plane of polarization of a plane polarized light ray traveling along the optic axis Z in the crystal is rotated in a right-hand direction, or clockwise as viewed by an observer located at the light source and facing the crystal. This definition of right-handed quartz follows the convention which originated with Herschel Trans. Cam. Phil. Soc. vol. 1, page 43 (1821); Nature vol. 110, page 807 (1922); Quartz Resonators and Oscillators, P. Vigoureux, page 12 (1931). Conversely, a quartz crystal is designated as left-handed if it rotates such plane of polarization referred to in the left-handed or counter-clockwise direction, namely, in the direction opposite to that given hereinbefore for the right-handed crystal.

If a compressional stress or a squeeze be applied to the ends of an electric axis X of a quartz body 1 and not removed, a charge will be developed which is positive at the positive end (+) of the X axis and negative at the negative end (-) of such electric axis X, for either right-handed or left-handed crystals. The magnitude and sign of the charge may be measured in a known manner with a vacuum tube electrometer, for example. In specifying the orientation of a right-handed crystal, the sense of the angle θ which the new axis Z' makes with respect to the optic axis Z as the crystal plate is rotated in

effect about the X axis is deemed positive (+) when, with the compression positive end (+) of the X axis pointed toward the observer, the rotation is in a clockwise direction, as illustrated in Fig. 1. A counter-clockwise rotation of such a right-handed crystal about the X axis gives rise to a negative orientation angle θ with respect to the Y axis or the Z axis. Conversely the orientation angle of a left-handed crystal is positive when, with the compression positive end (+) of the electric axis X pointed toward the observer, the rotation is counter-clockwise, and is negative when the rotation is clockwise. The crystal material illustrated in Fig. 1 is right-handed as the term is used herein. For either right-handed or left-handed quartz, a positive (+) angle θ rotation of the Z' axis with respect to the Z axis, as illustrated in Fig. 1, is toward parallelism with the plane of a minor apex face of the natural quartz crystal, and a negative (-) θ angle rotation of the Z' axis with respect to the Z axis is toward parallelism with the plane of a major apex face of the natural quartz crystal.

Referring to the drawing, Fig. 1 is a perspective view of a thin piezoelectric quartz crystal element 1 cut from crystal quartz free from twinning, veils or other inclusions and made into a plate of substantially rectangular parallelepiped shape having a length or longest dimension L, a width dimension W which is perpendicular to the length dimension L, and a thickness or thin dimension T which is perpendicular to the other two dimensions L and W.

The final major axis length dimension L of the quartz crystal element 1 is determined by and is made of a value according to the desired resonant frequency. The width dimension W also is related to the frequency and the length dimension L in accordance with the value of the dimensional ratio selected. The thickness dimension T may be of the order of 1 millimeter or any other suitable value for example, to suit the impedance of the circuit in which the crystal element 1 may be utilized.

The length dimension L of the crystal element 1 lies along a Y' axis in the plane of a mechanical axis Y and the optic axis Z of the quartz crystal material from which the element 1 is cut and is inclined at an angle of $\pm\theta$ degrees with respect to said Y axis, the angle θ being one of the values between substantially 0 and +10 degrees.

The major surfaces 3 and 4 and the major plane of the bare quartz crystal element 1 are disposed or inclined at an angle ϕ with respect to the plane of the Y and Z axes mentioned, the angle ϕ being the angle between the width dimension W lying along the Z'' axis, and the Z' axis which lies in the plane of the Y and Z axes mentioned, the Z' axis being inclined at the angle θ with respect to the optic axis Z. The axis Z'' is accordingly the result of a double rotation of the width dimension W first about the X axis $+\theta$ degrees, and then ϕ degrees about the length dimension L or Y' axis. It will be noted that the crystal element 1 is in effect an X cut crystal rotated $+\theta$ degrees about the X axis and then rotated ϕ degrees about the Y' axis length dimension L. The crystal plate 1 is shown in Fig. 1 as being inclined at a ϕ angle on opposite sides of the Z axis. It will be understood that either of these positions for the ϕ angle may be used alternatively with any ϕ angle disclosed herein. When the angle θ is one of the angles substantially from 0 to +10 degrees and the angle ϕ is

one of the angles substantially from 50 to 60 degrees or more on either side of the YZ plane, the first or fundamental flexure mode vibrational frequency thereof has a low or substantially zero temperature coefficient.

As illustrated in Figs. 1 to 3, the flexure mode crystal element 1 has two nodal point regions 5 on each of its major surfaces 3 and 4. These are located on the center line length dimension L or Y' axis of the crystal element 1 at points spaced about 0.224 of the length dimension L from each end thereof, as shown in Figs. 1 to 3. At these nodal points, the crystal element 1 may be mounted by rigidly clamping it between two pairs of oppositely disposed clamping projections of small area which may be inserted in small indentations or depressions provided at the four nodal points 5 of the crystal element 1. Such small circular depressions cut in the major surfaces 3 and 4 of the crystal element 1 at the nodal points 5 thereof may have a depth of about 0.05 millimeter, and a diameter of about 0.4 millimeter as measured on the surfaces 3 and 4.

Suitable conductive electrodes, such as the crystal electrodes 10, 11, 12 and 13 of Figs. 1 to 3, for example, may be placed on or adjacent to or formed integral with the opposite major surfaces 3 and 4 of the crystal plate 1 in order to apply electric field excitation to the quartz plate 1 in the direction of the thickness dimension T, and by means of suitable electrode interconnections and any suitable circuit such as, for example a filter or an oscillator circuit, the quartz plate 1 may be vibrated in the desired first flexural mode of motion at a response frequency which depends mainly upon and varies inversely as the major axis length dimension L and which also depends upon the dimensional ratio of the width W with respect to the length L, the frequency being a value within a range roughly from 0 to about 240 kilocycles per second per centimeter of the length dimension L, the particular value depending upon the dimensional ratio of width W to length L as illustrated in Fig. 5.

The crystal electrodes 10 to 13 when formed integral with the major surfaces 3 and 4 of the crystal element 1 may consist of thin coatings of silver, gold, aluminum or other suitable metal or conductive material deposited upon the bare quartz by evaporation in vacuum, for example, or by other suitable process, and may wholly or partially cover the major surfaces of the crystal element 1.

The crystal electrodes 10 and 11 located on the major surface 3 of the crystal element 1 and the crystal electrodes 12 and 13 located on the opposite major surface 4 thereof may be longitudinally centrally separated or split along the center line length dimension L forming four separate electrodes 10, 11, 12 and 13 in order to operate the single crystal element 1 in the desired flexural mode of motion. Figs. 1 to 3 illustrate such separations of the crystal electrodes, the electrodes 10 to 13 being provided with small extensions or ears covering the nodal points 5 of the flexure mode crystal element 1 in order to there make individual contacts with the conductive clamping projections or the conductive supporting wires that may be disposed at such nodal points 5 in order to support and establish individual electrical connections with the electrode crystal element 1. The gap or separation between the electrode platings on each of the major surfaces 3 and 4 of the crystal element 1 may be about 0.365 millimeter, the center line of

such splits in the platings on opposite sides of the crystal plate 1 being aligned with respect to each other.

To drive the crystal element 1 in the desired flexure mode of motion, one pair of opposite electrodes such as the crystal electrodes 10 and 12 may apply an electric field in one direction through the thickness dimension T of the crystal element 1 in order to lengthen one long edge L thereof while the other pair of opposite electrodes 11 and 13 simultaneously apply an electric field in the opposite direction in order to shorten the opposite long edge L thereof, thereby bending the crystal element 1 about the nodal points 5 in the desired first flexural mode of motion. Instantaneous polarities of the electrodes 10 to 13 are illustrated in Figs. 2 and 3. Examples of crystal electrode arrangements and interconnections for operating the crystal element 1 in flexure mode vibrations are illustrated in W. A. Marrison United States Patent 1,823,329, dated September 15, 1931, Figs. 5 to 8, C. A. Bieling United States Patent 2,155,035, April 18, 1939, Fig. 7, and W. P. Mason United States Patent 2,259,317, granted October 14, 1941, on application Serial No. 344,892 filed July 11, 1940.

The crystal element 1 may be supported by any suitable means such as, for example, by clamping or otherwise supporting it at the nodal points 5 which are located as shown in Figs. 1 to 3.

When the relatively thin flexurally vibrated quartz crystal element 1 has a θ angle between about +7 and +8 degrees, the temperature coefficient of the flexure mode vibrational frequency is at its lowest value for a ϕ angle of 0 degrees, but still lower temperature coefficients for such flexure mode vibrational frequency are obtained as the ϕ angle is increased to higher or larger values, such as between 50 and 60 degrees or more.

The flexurally vibrated crystal element 1 of Fig. 1 may have a θ angle of any value between about 0 to +10 degrees and a ϕ angle of any value between about 40 and 75 degrees to obtain a low or a substantially zero temperature coefficient of frequency at any value within a wide range of dimensional ratios of the width W with respect to the length L thereof.

Fig. 4 is a graph showing some of the θ and ϕ angles of cut and the dimensional ratios of the width W with respect to the length L that may be utilized in connection with the crystal element 1 of Fig. 1 in order to obtain a low or a substantially zero temperature coefficient of frequency for the first flexure mode vibration thereof, the flexure mode frequency being a value within the range between 0 and about 240 kilocycles per second per centimeter of the length dimension L according to the dimensional ratio of the width W with respect to the length L selected as shown in Fig. 5. In Figs. 4 and 5, the particular ϕ angles illustrated are 38 and 50 degrees for θ angles of 0, +5 and +8.5 degrees and dimensional ratios within a range from about 0.05 or less to 0.95 or more. While only three illustrative examples are given in Figs. 4 and 5, it will be understood that the θ angles may range substantially from 0 to +10 degrees and the ϕ angles substantially from 40 to 75 degrees with dimensional ratios of the width W with respect to the length L ranging from 0.05 or less to 1.0.

As an illustrative example, when the θ angle is substantially +8.5 degrees and the ϕ angle is substantially 38 degrees, as illustrated by the curve A of Fig. 4, the ratio of the width dimension W

with respect to the length dimension L of the crystal element l may be any value between 0.05 and 0.6 to produce a flexure mode frequency having a temperature coefficient less than -4 parts per million per degree centigrade.

When the θ angle is substantially $+5.0$ degrees and the ϕ angle is substantially 50 degrees, as illustrated by the curve B of Fig. 4, the ratio of the width dimension W with respect to the length dimension L of the crystal element l may be any value within a range from about 0.20 to 0.56 to obtain a flexure mode frequency having a temperature coefficient less than 1 part per million per degree centigrade, and within a range of dimensional ratios larger than that last mentioned, the temperature coefficient of frequency is less than 2 parts per million per degree centigrade, as shown by the curve B of Fig. 4.

Similarly, as shown by the curve C of Fig. 4, when the θ angle is substantially 0 degrees and the ϕ angle is substantially 50 degrees, the ratio of the width dimension W with respect to the length dimension L of the crystal element l may be any value within the range from about 0.3 to 0.6 to obtain a flexure mode frequency having a temperature coefficient less than 1 part per million per degree centigrade.

In general, when the θ angle is between 0 and $+10$ degrees and the ϕ angle is between 50 and 60 degrees or more, the ratio of the width dimension W with respect to the length dimension L of the crystal element l may be one of the values within a range below 0.6 to obtain a low or substantially zero temperature coefficient of frequency.

While the curves A, B and C of Fig. 4 illustrate the temperature coefficients of frequency corresponding to particular values of ϕ angles and dimensional ratios of width W to length L , that may be used with crystal elements l having θ angles of substantially $+8.5$, $+5.0$ and 0 degrees, respectively, it will be understood that the curves corresponding to other values of ϕ angles and dimensional ratios for θ angles intermediate the values given or from 0 to about $+8.5$ degrees may also be obtained by measurements similar to those used in obtaining the values given by the curves A, B and C of Fig. 4.

It will be noted from the curves of Fig. 4 that for any θ angle between about 0 and $+8.5$ degrees, the dimensional ratio of the width W with respect to the length L may be less than about 0.6 with a wide range of suitable ϕ angles in the region of 50 degrees or more to obtain a flexural mode frequency that will have a low temperature coefficient at one or more temperatures within a range of temperatures between roughly 0 and 80° centigrade.

Fig. 5 is a graph showing the frequency characteristics and ratios of capacities of quartz crystal elements l having the θ and ϕ angles and the various values for the ratio of its width dimension W with respect to its length dimension L that are given by the curves A, B and C of Fig. 4. The curves labeled A', B' and C' of Fig. 5 correspond to the curves A, B and C, respectively of Fig. 4 and show the relation between the desired first flexural mode resonant frequency, expressed in kilocycles per second per centimeter of the length dimension L , and the ratio of the width dimension W with respect to the length dimension L . For example, when the dimensional ratio of the width W with respect to the length L is about 0.35, the flexural mode resonant frequency of a crystal element l having a length dimension

L of 1 centimeter and having θ and ϕ angles of substantially $+5.0$ and 50 degrees, respectively, is about 152 kilocycles per second as shown by the curve B' of Fig. 5. Since the frequency is inversely proportional to the length dimension L , a crystal element of the same orientation and dimensional ratio but having a length dimension L of 4 centimeters, for example, will have a flexural mode resonant frequency of one-fourth this value or about 38.0 kilocycles per second. Similarly, the frequency, the corresponding length dimension L , and the dimensional ratio of W to L may be obtained for any other size of crystal element from the curves A', B' and C' of Fig. 5.

Referring to the curves A, B and C of Fig. 4 which show examples of the relation between the temperature coefficient of the desired flexural mode resonant frequency and the ratio of the width dimension W with respect to the length dimension L , it will be noted that for all of the dimensional ratios of width W to length L between 0 and 0.8 , as shown by the curve labeled B of Fig. 4, the crystal element l having a θ angle of substantially $+5.0$ degrees and a ϕ angle of substantially 50 degrees has a low or substantially zero temperature coefficient of frequency over a wide range of ordinary temperatures above and below 30° centigrade, the maximum temperature coefficient of frequency at 35° centigrade as indicated by the curve B of Fig. 4, being about 2 parts per million per degree centigrade within the range of dimensional ratios between about 0 and 0.8 , and the lowest temperature coefficient of frequency occurring at the dimensional ratio value of about 0.34.

As an example, such a quartz crystal plate l having a $+5$ degree θ angle and a 50 degree ϕ angle, and having a thickness dimension T of 1.0 millimeter, a length dimension L of 66.5 millimeters, and a width dimension W of 4.65 millimeters thus giving a dimensional ratio of width W with respect to length L of about 0.07, has, as shown by the curve B' of Fig. 5, a first flexural mode frequency of about 35.0 kilocycles per second per centimeter of length dimension L or about 5.269 kilocycles per second for the given length dimension of 66.5 millimeters, and as shown by the curve B of Fig. 4, has a temperature coefficient of frequency at 35° centigrade of less than -2 parts per million per degree centigrade, the average temperature coefficient of frequency from 15° centigrade to 40° centigrade, which is the usual indoor temperature range, being about -1.1 parts per million per degree centigrade.

As another example, from curves the C and C' of Figs. 4 and 5, a crystal element l having a θ angle of substantially 0 degrees and a ϕ angle of substantially 50 degrees has at 35° centigrade, as indicated by the curve C of Fig. 4, a maximum temperature coefficient for its flexural mode vibrational frequency along the length dimension L of about 3 parts per million per degrees centigrade and a minimum temperature coefficient at the dimensional ratio of about 0.45.

Such flexurally vibrated crystals and especially those having orientation angles of θ between 0 and $+5$ degrees and of ϕ between 50 and 60 degrees may have a very small frequency variation throughout a wide temperature range. At the same time, they may be relatively small in size for a given frequency and can be economically made for operation below 5 kilocycles per second at the fundamental mode flexural vibration frequency which is dependent mainly on the length

dimension L lying along the Y' axis and the dimensional ratio of width W with respect to the length L of the quartz plate 1.

The curves A'', B'' and C'' of Fig. 5 give the values of the ratio of capacities for those flexural mode crystal elements, the frequency characteristics of which are given by the curves A', B' and C', respectively, of Fig. 5, and the corresponding temperature coefficients of which are given by the curves A, B and C, respectively, of Fig. 4. The ratio of capacities referred to is the ratio of the internal capacity with respect to the shunt capacity of the electroded crystal element 1 as described in a paper "Electrical wave filters employing quartz crystals as elements" published by the applicant in the Bell System Technical Journal for July 1934, pages 408 and 409.

Fig. 6 is a graph showing the corresponding angles of θ and ϕ that may be used to give a substantially zero temperature coefficient of frequency at about 25° centigrade in flexure mode low frequency quartz crystal plates or bars 1, when the dimensional ratio of the width W with respect to the length L is about .05. Such crystal bars may conveniently have a very low flexure mode frequency of the order of 4 kilocycles per second, for example, the frequency being about 25 kilocycles per second per centimeter of length dimension L as indicated by the curves A', B' and C' of Fig. 5 at a point thereon corresponding to the dimensional ratio of 0.05. For example, a quartz crystal bar 1 having a θ angle of substantially +8 degrees, a ϕ angle of substantially 60 degrees, and a dimensional ratio of width W with respect to its length L equal to substantially 0.5, will have a zero temperature coefficient flexure mode frequency of about 25 kilocycles per second per centimeter of length dimension L or about 5 kilocycles per second where the length dimension L is about 5 centimeters.

The crystal elements 1 described herein may be mounted in any suitable manner such as, for example, by rigidly clamping the electroded crystal plate 1 between one or more pairs of opposite conductive clamping projections which may contact the electroded crystal plate 1 at opposite points of very small area at the nodal points 5 only of the crystal element 1. Figs. 7 and 8 of my application Serial No. 344,892, filed July 11, 1940 (Case 63) U. S. Patent No. 2,259,317 dated October 14, 1941, illustrate a suitable holder of this type, wherein the electroded crystal element 1 is clamped at its nodal points 5 between four conductive contact clamping pins which may be composed of gold-plated brass, the clamping points thereof being individually in contact with the four electrodes 10, 11, 12 and 13 of the crystal element 1. The two clamping contact pins which are disposed on one side of the crystal element 1 may be fixed in a mounting block while the oppositely disposed clamping contact pins located on the opposite side of the crystal element 1 may be slidable in suitable brass bushings placed in openings in the mounting block, and pressed against the electroded crystal element 1 by means of separate springs which are secured to the outer surface of the mounting block. The pressure exerted by each of the springs on the movable contacts may be about 1 to 3 pounds or sufficient to hold the clamped crystal element 1 against bodily movement out of a predetermined position when placed between the two pairs of clamping points. The two pairs of clamping points are oppositely disposed with

respect to each other and axially disposed perpendicular to the major surfaces of the crystal element 1 and since they make contact only at the nodal points 5 of the crystal element 1, there is a minimum of damping of the flexural vibratory motion of the crystal element 1. The nodal points 5 of the crystal plate 1 are located as illustrated in Figs. 1 to 3. The crystal plate 1 is preferably clamped only at the nodal points 5 in order to obtain the minimum effective resistance at resonance. The crystal plate 1 may be adjusted to the desired series resonance frequency by reducing the length dimension L of the crystal plate 1. The mounted crystal plate 1 will be found to age over a period of as much as seven days after so adjusting it. During this aging period, the resonance frequency rises and the effective resistance decreases. Suitable allowance for this aging may be made so that the crystal element 1 will meet the requirements after it has become stable.

Other forms of mountings that may be utilized for clamping the crystal element 1 are illustrated in C. A. Bieling U. S. Patent 2,155,035 dated April 18, 1939, and R. A. Sykes U. S. Patent 2,124,596 dated July 26, 1938, the crystal clamping projections thereof being shaped and spaced to suit the nodal points 5 of the flexure mode crystal element 1.

Alternatively, instead of being mounted by clamping, the electroded crystal plate 1 may be mounted and electrically connected by soldering, cementing or otherwise firmly attaching four fine conductive supporting wires directly to the bare quartz or to a thickened part of the electroded crystal element 1 at its nodal points 5. The fine supporting wires referred to may be conveniently soldered to four small spots of baked silver paste or other metallic paste which has been previously applied at the nodal points 5 on the length dimension center line either directly on the bare quartz or on top of the field producing crystal electrodes 10 to 13 which may consist of pure silver applied by the known evaporation in vacuum process. Such fine supporting wires secured to the electroded crystal element 1 may extend horizontally from the vertical major surfaces of the crystal element 1 and at their opposite ends be attached by solder, for example, to four vertical conductive support rods carried by the press or other part of an evacuated glass or metal tube. The supporting wires may have one or more bends therein to resiliently absorb mechanical vibrations. Also, bumpers or stops of soft resilient material such as mica may be spaced closely adjacent the edges, ends or other parts of the electroded crystal element 1 in order to limit the bodily displacement thereof when the device is subjected to mechanical shock. In a suitable mounting of this type for the flexure mode crystal element 1, the horizontal supporting wires may be spaced along the vertical support rods at four points opposite the nodal points 5 of the electroded crystal element 1.

While the crystal element 1 is illustrated in Fig. 1 in the form of a thin rectangular plate, it will be understood that an element in the form of a tuning fork may be cut from such rectangular shaped plates 1 and utilized as low frequency fork-shaped flexure mode crystals of relatively low temperature coefficient of frequency.

Although this invention has been described and illustrated in relation to specific arrangements, it is to be understood that it is capable of application in other organizations and is therefore not

to be limited to the particular embodiments disclosed, but only by the scope of the appended claims and the state of the prior art.

What is claimed is:

1. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +10.0 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 40 to 75 degrees with respect to said plane of said Y axis and said Z axis, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95.

2. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +10.0 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 40 to 75 degrees with respect to said plane of said Y axis and said Z axis, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95, said length dimension expressed in centimeters being a value within the range from substantially 20 to 240 divided by said frequency expressed in kilocycles per second.

3. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +10.0 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 38 to 72 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95, said angles and said dimensional ratio being a set of corresponding values as given by the curves of Figs. 4, 5 and 6.

4. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +10.0 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 38 to 72 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95, said length dimension expressed in centimeters being a value within the range from substantially 20

to 240 divided by said frequency expressed in kilocycles per second, said angles and said dimensional ratio being a set of corresponding values as given by the curves of Figs. 4, 5 and 6.

5. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle from substantially 0 to +8.5 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 50 to 60 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.85.

6. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +8.5 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 50 to 60 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.85, said length dimension expressed in centimeters being one of the values between substantially 20 and 240 divided by said frequency expressed in kilocycles per second.

7. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +8.5 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 38 to 50 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.85, said angles and said dimensional ratio being a set of corresponding values as given by the curves of Fig. 4.

8. A piezoelectric quartz crystal element adapted to vibrate at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +8.5 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 60 to 72 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.05, said length dimension expressed in centimeters being substantially 25 divided by said frequency expressed in kilocycles per second, said angles being a set of corresponding values as given by the curve of Fig. 6.

9. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined substantially +8.5 degrees with respect to said Y axis, said major surfaces being inclined at an angle of substantially 60 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.05, said length dimension expressed in centimeters being substantially 25 divided by said frequency expressed in kilocycles per second.
10. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined substantially +5.0 degrees with respect to said Y axis, said major surfaces being inclined at an angle of substantially 60 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.05.
11. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and disposed substantially 0 degree with respect to said Y axis, said major surfaces being inclined at an angle of substantially 70 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.05.
12. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined substantially +5 degrees with respect to said Y axis, said major surfaces being inclined at an angle of substantially 50 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.05.
13. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined substantially +5 degrees with respect to said Y axis, said major surfaces being inclined at an angle of substantially 50 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95, said dimensional ratio and said temperature coefficient of frequency being values as given by the curve B of Fig. 4.
14. A piezoelectric quartz crystal element adapted to vibrate at a frequency of low temperature coefficient dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and disposed substantially 0 degree with respect to said Y axis, said major surfaces being inclined at an angle of substantially 50 degrees with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.05 to 0.95, said dimensional ratio and said temperature coefficient of frequency being values as given by the curve C of Fig. 4.
15. A piezoelectric quartz crystal element and means adapted to vibrate said element at a flexure mode frequency of low temperature coefficient dependent mainly upon the length and width dimensions of the major surfaces of said element, said length dimension being substantially in the plane of a Y axis and the Z axis and disposed at an angle within the range from substantially 0 to +10 degrees with respect to said Y axis, said major surfaces being inclined at an angle within the range from substantially 40 to 70 degrees with respect to said YZ plane.
16. A quartz piezoelectric crystal element of low temperature coefficient adapted to vibrate at a frequency dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined or disposed at an angle within the range from substantially 0 to +10 degrees with respect to said Y axis, and said major surfaces being inclined at an angle within the range from 40 to 70 degrees with respect to said YZ plane, two pairs of opposite electrodes formed integral with said major surfaces, and conductive means for supporting said electroded crystal element only at the nodes thereof, said nodes being along the center line length dimension at points located from the ends thereof a distance substantially 0.224 of said length dimension.

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