

June 2, 1942.

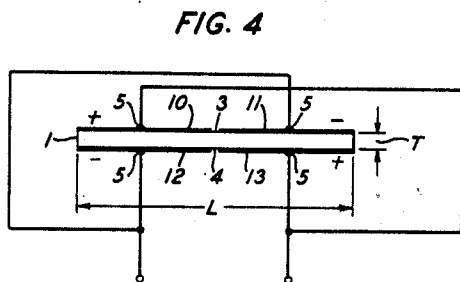
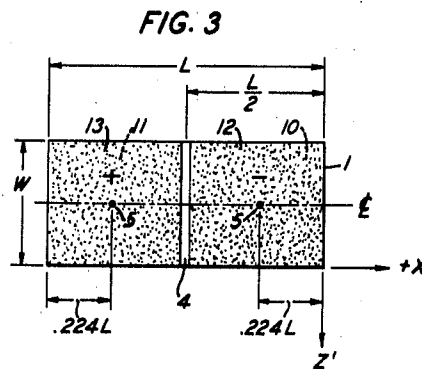
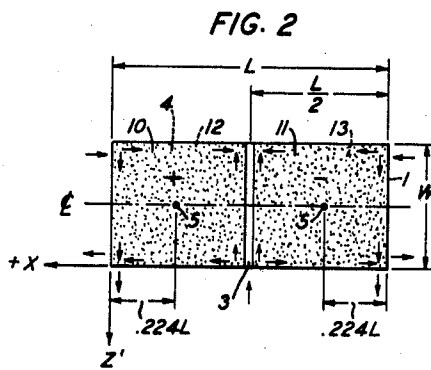
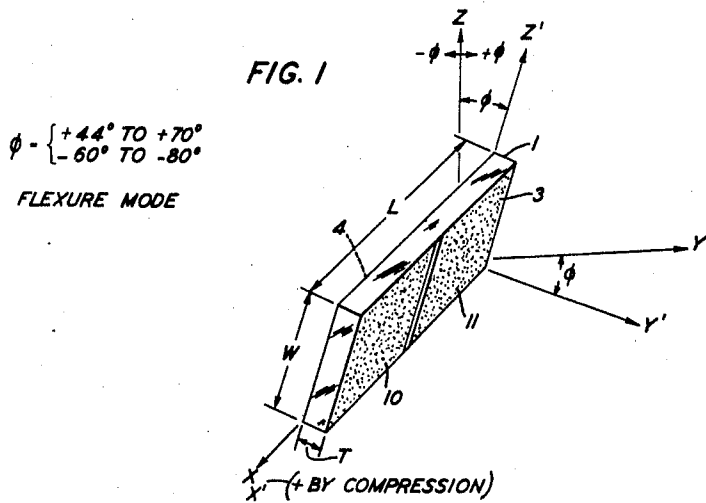
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2,284,753

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Sept. 20, 1940

2 Sheets-Sheet 1



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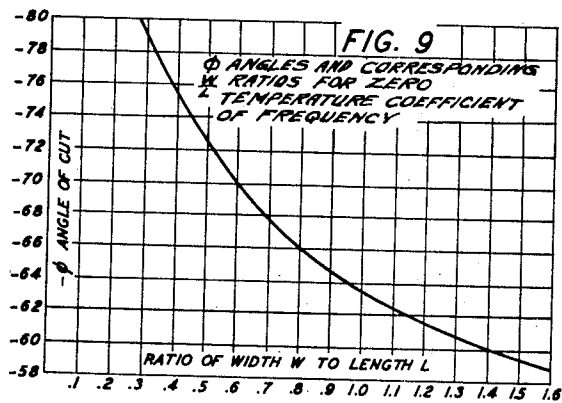
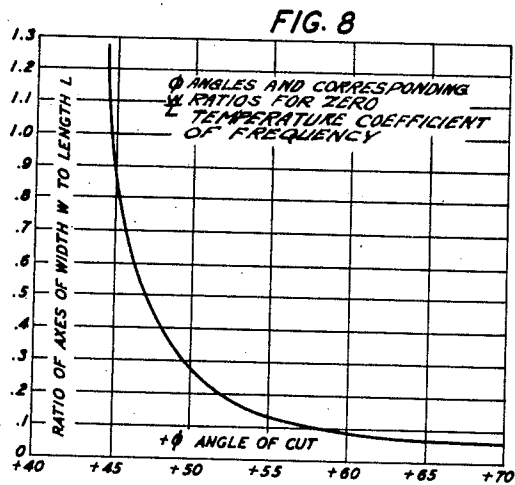
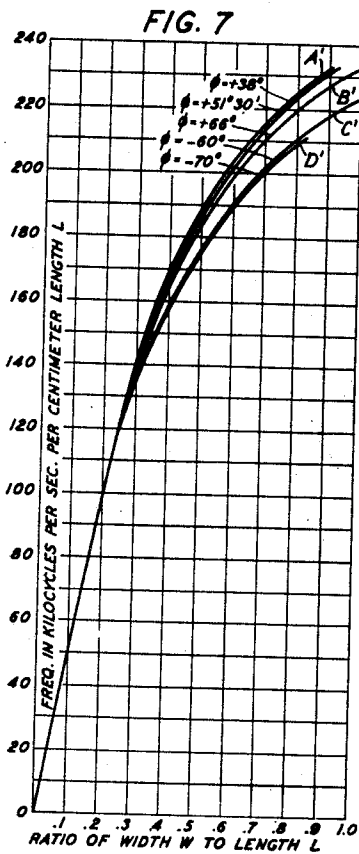
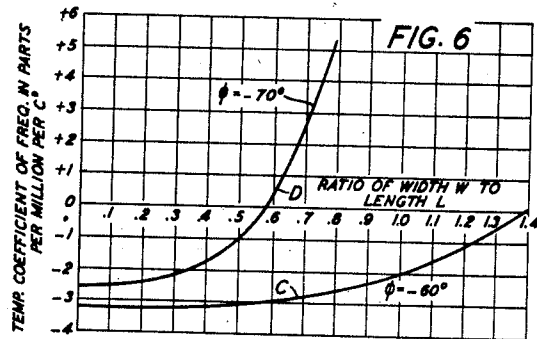
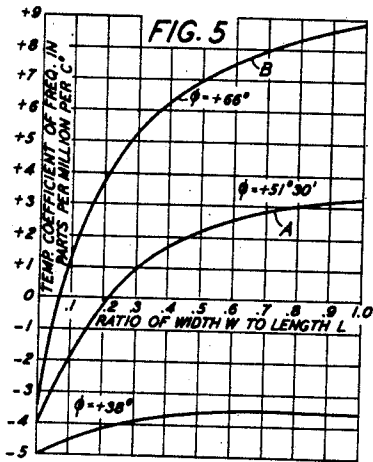
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PIEZOELECTRIC CRYSTAL APPARATUS

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2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

2,284,753

PIEZOELECTRIC CRYSTAL APPARATUS

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Application September 20, 1940, Serial No. 357,515

16 Claims. (Cl. 171—327)

This invention relates to piezoelectric crystal apparatus and particularly to flexure mode 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 crystal elements having a low or substantially zero temperature coefficient of frequency.

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

Another object of this invention is to provide piezoelectric crystal elements 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.

In such systems as electric wave filter systems or oscillation generator systems, for example, it is often desirable to utilize low frequency crystals which have a low or substantially zero temperature coefficient of frequency 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 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 within a wide range of orientation angles and corresponding dimensional ratios, and are advantageous for use in filter and other systems. 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.

In accordance with this invention, relatively thin piezoelectric quartz crystal plates of a suit-

able orientation with respect to the X, Y and Z axes of the quartz material and of a suitable dimensional ratio may be subjected to a thickness direction Y' electric field and vibrated at a resonance frequency dependent mainly upon the X 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 related values to produce for the 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 flexural mode vibration bending the length or X axis dimension of the crystal element being dependent upon such dimensional ratio, and the length dimension which may be the 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 1.6 and the orientation may be that of a Y-cut crystal element rotated in effect from +44 to +70 and from -60 to -80 degrees about its X axis length dimension L, such length dimension L being parallel or nearly parallel to said X axis.

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 showing the orientation, and electrode arrangement, 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 an edge view of the electroded crystal element of Figs. 1 to 3;

Figs. 5 and 6 are graphs illustrating the relation between the dimensional ratio and the temperature coefficient of frequency of typical flexure mode quartz crystal elements in accordance with this invention;

Fig. 7 is a graph showing the dimension-frequency characteristics for various dimensional

ratios of typical flexure mode crystal elements in accordance with this invention; and

Figs. 8 and 9 are graphs showing the corresponding orientation angles ϕ that produce a zero temperature coefficient of frequency in low frequency flexure mode crystals for various dimensional ratios of width with respect to 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 drawings, 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' and 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 a single rotation of the quartz crystal element 1, the rotation being in effect substantially about the length dimension electric axis X of the piezoelectric body 1, as illustrated in Fig. 1, the orientation angle ϕ designates in degrees the effective angular position of the crystal plate 1 as measured from the optic axis Z. The width dimension axis Z' as shown in Fig. 1, indicates the result of a single rotation about the electric axis X.

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 ϕ 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 ϕ with respect to 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 75

positive (+) angle ϕ 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 (-) ϕ 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 drawings, 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 dimension L along an electric axis X, a width dimension W which is perpendicular to the length dimension L and lies along a Z' axis, and a thickness or thin dimension T which is perpendicular to the other two dimensions L and W.

The final length dimension L along the X axis 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 for the width W with respect to the length L. 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.

As illustrated in Fig. 1, the length dimension L of the crystal element 1 is parallel or nearly parallel to the electric axis X, and the major surfaces 3 and 4 and the major plane of the bare quartz crystal element 1 are inclined at an angle ϕ with respect to the Z axis, the angle ϕ being the angle between the width dimension W lying along the Z' axis, and the optic axis Z. The axis Z' is accordingly the result of a single rotation of the width dimension W about the X axis $\pm \phi$ degrees. It will be noted that the crystal element 1 is in effect a Y-cut crystal rotated $\pm \phi$ degrees about the X axis, and that the Z' axis of the crystal plate 1 shown in Fig. 1 may be 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. When the angle ϕ is one of the angles substantially from +38 to +70 degrees and substantially from -53 to -80 degrees or more on either side of the Z axis, and the dimensional ratio of the width W with respect to the length L is of a suitable corresponding value, the flexure mode vibrational frequency thereof is of a value given by the curves of Fig. 7 and has a low or substantially zero temperature coefficient.

As illustrated in Figs. 1 to 4, 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 of the X axis length dimension L 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 4. At these nodal points 5, 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 4, 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 such as illustrated in Fig. 4, for example, and any suitable circuit such as, for example, a filter or an oscillator circuit, the quartz plate 1 may be vibrated in the desired flexural mode of motion at a response frequency which depends mainly upon and varies inversely as the 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. 7.

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, platinum 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 nearly wholly or only partially cover the major surfaces 3 and 4 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 are longitudinally centrally separated or split at the center line width dimension W 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 4 illustrate such separations in the crystal electrodes 10 to 13, the electrodes 10 to 13 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 3 and 4 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 simultaneously shorten the opposite long edge L thereof, thereby bending the length axis L of the crystal element 1 about the nodal points 5 in the desired flexural mode of motion. Instantaneous polarities of the electrodes 10 to 13 are illustrated in the direction of the width dimension W to obtain Figs. 2 to 4. Illustrative connections are shown in Fig. 4, which is an edge view of the electrode crystal element 1 of Figs. 1

to 3. As shown in Fig. 4, where the two positive electrodes 10 and 13 are connected together and the two negative electrodes 11 and 12 are connected together, the lowest impedance is obtained. The force system developed by the interconnected electrodes 10 to 13 is illustrated by the small arrows in Fig. 2. In this force system, there is one set of forces which tends to bend the length dimension L of the crystal element 1 in one direction in the major plane thereof and another set which tends to flex the length dimension L of the crystal element 1 in the opposite direction in the same major plane, but since these two sets of forces are not equal, a resultant flexure mode drive on the crystal element 1 is obtained.

The crystal element 1 may be supported by any suitable means such as, for example, by clamping or otherwise supporting it at one or all of the nodal points 5 which are located as shown in Figs. 2 to 4.

The flexurally vibrated crystal element 1 of Figs. 1 to 4 may have a ϕ angle of any positive (+) value between roughly +38 and +70 degrees and a ϕ angle of any negative (-) value between roughly -53 and -80 degrees to obtain a low or a substantially zero temperature coefficient of flexure mode frequency at some particular value within a wide range of dimensional ratios of the width W with respect to the length L thereof.

Figs. 5 and 6 are graphs showing some of the ϕ angles of cut and the corresponding 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 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. 7. In Figs. 5 and 6, the particular ϕ angles illustrated are the positive ϕ angles of +38, +51.5 and +66 degrees and the negative ϕ angles of -60 and -70 degrees, with particular dimensional ratios within a range from about 0.05 to 1.4. While only four illustrative examples of zero temperature coefficient crystals 1 are given in Figs. 5 and 6, it will be understood that the ϕ angles and the corresponding dimensional ratios for zero temperature coefficient crystals 1 may cover a wide range of values.

As an illustrative example from Fig. 5, when the ϕ angle is substantially +51.5 degrees as illustrated by the curve A of Fig. 5, the ratio of the width dimension W with respect to the length dimension L of the crystal element 1 may be any value between 0.05 or less and 1.0 or more to produce a flexure mode frequency having a temperature coefficient less than -4 parts per million per degree centigrade and may be a value of about .22 to produce a zero temperature coefficient of frequency.

When the ϕ angle is substantially +66 degrees as illustrated by the curve B of Fig. 5, the ratio of the width dimension W with respect to the length dimension L of the crystal element 1 may be any value within a range from about .04 to .1 to obtain a flexure mode frequency having a temperature coefficient less than 1 part per million per degree centigrade. Within a range of dimensional ratios larger than that last men-

tioned, the temperature coefficient of frequency is less than 2 parts per million per degree centigrade, and at a dimensional ratio of about .07, the temperature coefficient of frequency is zero as shown by the curve B of Fig. 4.

Similarly, as shown by the curve C of Fig. 6, when the ϕ angle is substantially -60 degrees, the ratio of the width dimension W with respect to the length dimension L of the crystal element I may be any value within the range from about 0 to 1.4 to obtain a flexure mode frequency having a temperature coefficient less than 4 parts per million per degree centigrade and may be about 1.4 to obtain a zero temperature coefficient of frequency.

When the ϕ angle is $+38$ degrees as illustrated in Fig. 5, the ratio of the width dimension W with respect to the length dimension L of the crystal element I may be any one of the values within a range between 0 and 1.0 or more to obtain a relatively low but not a zero temperature coefficient of frequency.

While the curves A, B and C and others of Figs. 5 and 6 illustrate particular values of ϕ angles and dimensional ratios of width W with respect to length L, that may be used with crystal elements I having the length dimension L parallel or nearly parallel to an X axis, it will be understood that the other values of ϕ angles and dimensional ratios intermediate the values given may also be obtained from the curves of Figs. 5 and 6 by interpolation.

It will be understood from the curves of Figs. 5 and 6 that for any ϕ angle within the range from about $+38$ to $+70$ and from -54 to -80 degrees, the dimensional ratio of the width W with respect to the length L may be some particular value to obtain a flexural mode frequency that will have a low or a zero temperature coefficient at a temperature within a range of temperatures between roughly 0 to 80° centigrade.

Fig. 7 is a graph showing the frequency-dimension characteristics of quartz crystal elements I having the ϕ angles and the various values for the ratio of width dimension W with respect to its length dimension L that are given by the corresponding curves of Figs. 5 and 6. For example, the curves labeled A', B' and C' of Fig. 7 correspond to the curves A, B, and C, respectively of Figs. 5 and 6 and show the relation between the desired 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 .22, the flexural mode resonant frequency of a crystal element I having a length dimension L of 1 centimeter and having a ϕ angle of substantially $+51.5$ degrees, is about 110 kilocycles per second as shown by the curve A' of Fig. 7. Since the frequency is inversely proportional to the length dimension L, a crystal element of the same orientation and same 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 110 or about 27 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 of Fig. 7.

Referring again to the curves of Figs. 5 and 6 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 the crystal element I having a ϕ angle of substantially $+38.0$ degrees has a low but not a zero temperature coefficient of frequency over a wide range of dimension ratios at ordinary temperatures above and below 30° centigrade, the maximum temperature coefficient of frequency being about 5 parts per million per degree centigrade at the dimensional ratios between about 0 and 1.0, and the lowest temperature coefficient of frequency occurring at the dimensional ratios between about .4 and 1.0.

As another example, a quartz crystal plate I having a $+66$ degree ϕ angle, and having a thickness dimension T of 1.0 millimeter for example, 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 .07, has, as shown by the curve B' of Fig. 7, 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 L of 66.5 millimeters, and as shown by the curve B of Fig. 5, has a zero temperature coefficient of frequency at 35° centigrade, the average temperature coefficient of frequency from 15° centigrade to 40° centigrade, which is the usual indoor temperature range, being about 1.0 part per million per degree centigrade.

As another example, from curves the C and C' of Figs. 6 and 7, a crystal element I having a ϕ angle of substantially -60 degrees has a maximum temperature coefficient for its flexural mode vibrational frequency of about 3 parts per million per degree centigrade, and a minimum or zero temperature coefficient of frequency at the dimensional ratio of about 1.4.

Such flexurally vibrated crystals and especially those having orientation angles of ϕ from $+44$ to $+70$ and from -60 to -80 degrees may have a very small frequency variation throughout an ordinary temperature range. At the same time, they may be relatively small in size for a given frequency and can be economically made for operation down to or below 5 kilocycles per second at the flexural mode vibration frequency which is dependent mainly on the length dimension L lying along the X axis and the dimensional ratio of width W with respect to the length L of the quartz plate I.

The values of the ratio of capacities for those flexural mode crystal elements, the frequency characteristics of which are given by the curves of Fig. 7 and the corresponding temperature coefficients of which are given by the curves of Figs. 5 and 6 range from about 1400 to 2100. Such ratio of capacities is the ratio of the internal capacity with respect to the shunt capacity of the electroded crystal element I, 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.

Figs. 8 and 9 are graphs showing the plus (+) and minus (−) angles of ϕ that may be used to give a zero temperature coefficient of frequency at about 25° centigrade in flexure mode low frequency quartz crystal plates or bars I, when the dimension ratio of the width W with respect to the length L is a value given by the curves of Figs. 8 and 9. Examples of such crystal bars having a flexure mode frequency are illustrated

in the curves of Figs. 5 to 7. For example, a quartz crystal bar 1 having a ϕ angle of substantially +66 degrees, and a dimensional ratio of width W with respect to its length L equal to substantially .07 will have a zero temperature coefficient flexure mode frequency as indicated by the curve B of Fig. 5, the curve B' of Fig. 7, and the curve of Fig. 8.

As illustrated by the curves of Figs. 8 and 9, these flexure mode crystal plates 1 may be cut at any of several definite orientation angles of ϕ and have a zero temperature coefficient of frequency at a definite dimensional ratio of axes of the width W with respect to the length L. This dimensional ratio may be varied from 0 to 1.0 or more and the corresponding angle of ϕ varied to suit, so that the frequency may be placed in the range from 15 kilocycles per second or less to 60 kilocycles per second or more, using crystals with dimensions which are easily obtainable. While such flexure mode crystal elements may be operative for any angle of ϕ the range of ϕ angles for obtaining the zero temperature coefficient of the flexure mode frequency is determined by those ϕ angles wherein the shear modulus of the crystal plate has a positive temperature coefficient. At some dimensional ratio of the width W with respect to the length L, such crystal plates will have a zero temperature coefficient of frequency when the magnitude of the ϕ angle is upwards of +38° and -54° as illustrated by the curves of Figs. 8 and 9.

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, 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. 2 to 4. If clamped, 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 only. 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 only 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 or 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 externally applied mechanical shock.

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 plate 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 parallel to an X axis, said width dimension and said major surfaces being inclined at one of the angles within the range substantially from +44 to +70 and from -60 to -80 degrees with respect to the Z axis, the ratio of said 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 0.5, said length dimension expressed in centimeters being one of the values between 20 and 190 divided by the value of said frequency expressed in kilocycles per second.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at one of the angles within the range substantially from +38 to +70 and from -54 to -80 degrees with respect to the Z axis, the ratio of said 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 1.6, said length dimension expressed in centimeters being a value within the range from substantially 20 to 250 divided by the value of 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 parallel to an X axis, said major surfaces being inclined at one of the angles within the range substantially from +44 to +70 and from -60 to -80 degrees with respect to the Z axis, the ratio of said 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 1.5, said angle and said dimensional ratio being corresponding values substantially as given by the curves of Figs. 8 and 9.

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 parallel to an X axis, said major surfaces being inclined at one of the angles within the range substantially from +44 to +70 and from -60 to -80 degrees with respect to the Z axis, the ratio of said 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 1.5, said length dimension expressed in centimeters being one of the values within the range from substantially 20 to 240 divided by said frequency expressed in kilocycles per second, said angle and said dimensional ratio being corresponding values substantially as given by the curves of Figs. 8 and 9.

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 parallel to an X axis, said width dimension and said major surfaces being inclined to an angle within the range from substantially +50 to +70 degrees with respect to the Z axis, the ratio of said 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 0.3, said length dimension expressed in centimeters being one of the values between substantially 20 and 140 divided by said frequency expressed in kilocycles per second.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle within the range from substantially +38 to +70 degrees with respect to the Z axis, the ratio of said 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 1.0, 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 parallel to an X axis, said major surfaces being inclined at an angle within the range from substantially +44 to +70 degrees with respect to the Z axis, the ratio of said 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 1.3, said angle and said dimensional ratio being corresponding values as given by the curve of Fig. 8.

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 parallel to an X axis, said major surfaces being inclined at an angle within the range from substantially -60 to -80 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.2 to 1.5, said length dimension expressed in centimeters being one of the values substantially between 100 and 250 divided by said frequency expressed in kilocycles per second, said angle and said dimensional ratio being corresponding values as given by the curve of Fig. 9.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially +38 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said length dimension thereof being one of the values substantially from 0.05 to 1.0, said length dimension expressed in centimeters being one of the values substantially from 25 to 240 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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially +51.5 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.22.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially +66 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said length dimension thereof being substantially 0.07.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially -60 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said Z axis length dimension thereof being substantially 1.4.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially -70 degrees with respect to the Z axis, the ratio of said 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 0.8, said dimensional ratio and said temperature coefficient of frequency being corresponding values as given by the curve D of Fig. 6.

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 parallel to an X axis, said width dimension and said major surfaces being inclined at an angle of substantially +51.5 degrees with respect to the Z axis, the ratio of said width dimension of said major surfaces with respect to said length di-

mension thereof being one of the values within the range from substantially 0.05 to 1.0, said dimensional ratio and said temperature coefficient of frequency being values as given by the curve A of Fig. 5.

15. A piezoelectric quartz crystal element and means including two pairs of opposite electrodes 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 parallel to an X axis, and of a greater value than said width dimension, said width dimension and said major surfaces being inclined at an angle within the range substantially from +38 to +70 and from -54 to -80 degrees with respect to the Z axis, said length dimension expressed in centimeters being one of the values between 20 and 240 divided by the value of said frequency expressed in kilocycles per second.

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 parallel to an X axis, and said major surfaces being inclined at an angle within the range from +38 to +70 and from -54 to -80 degrees with respect to the Z axis as measured in a plane perpendicular to said major surfaces, the ratio of said width dimension with respect to said length dimension being one of the values between 0.05 and 1.6, said length dimension expressed in centimeters being one of the values between 20 and 240 divided by the value of said frequency expressed in kilocycles per second, two pairs of opposite electrodes formed integral with said major surfaces, and conductive means connected with said electroded crystal element only at the nodes thereof, said nodes being along the center line of said length dimension at points located from the ends thereof a distance substantially 0.224 of said X axis length dimension.

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