

Oct. 21, 1941.

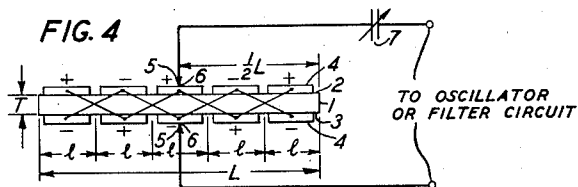
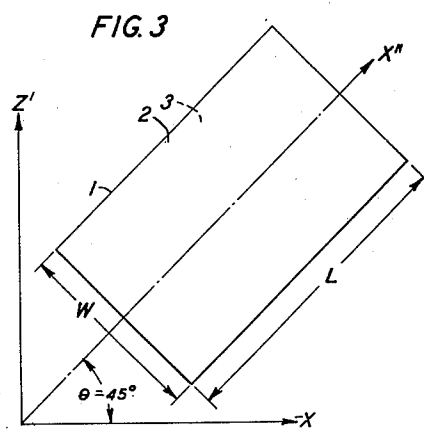
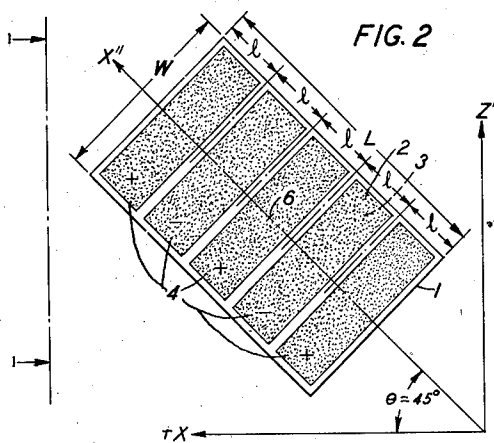
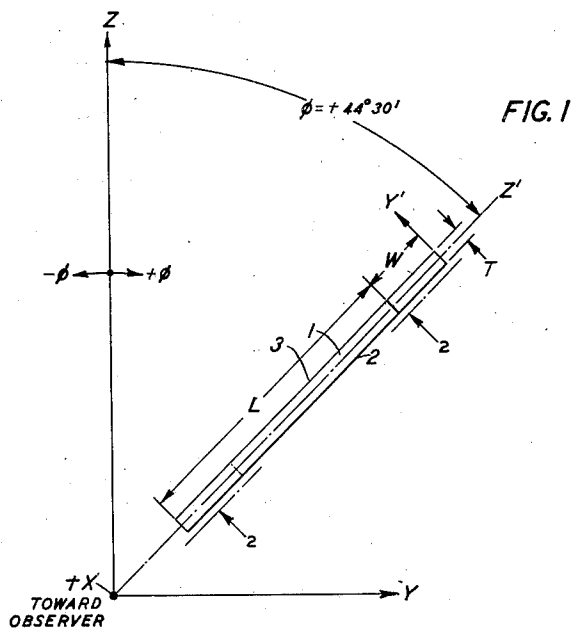
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2,259,529

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Oct. 19, 1940

2 Sheets-Sheet 1



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PIEZOELECTRIC CRYSTAL APPARATUS

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2 Sheets-Sheet 2

FIG. 5

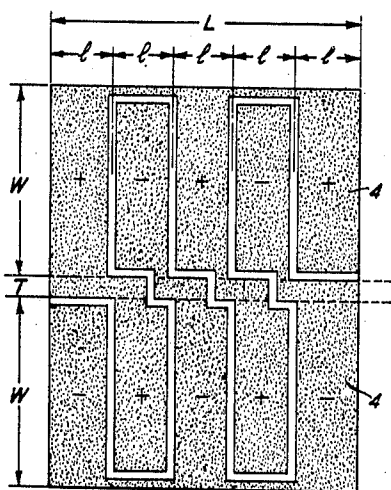


FIG. 7

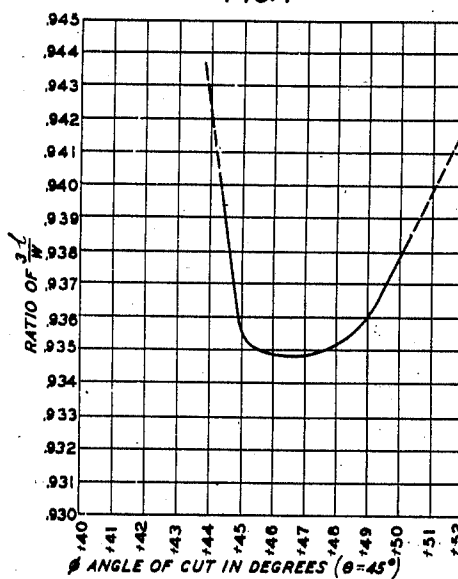
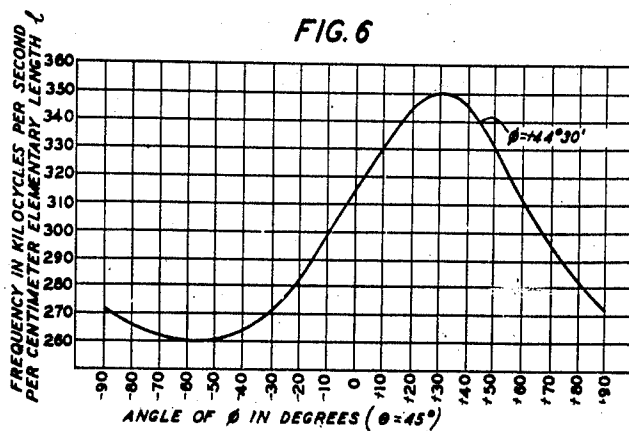


FIG. 6



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2,259,529

PIEZOELECTRIC CRYSTAL APPARATUS

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Application October 19, 1940, Serial No. 361,857

13 Claims. (Cl. 171-327)

This invention relates to piezoelectric crystal apparatus and particularly to harmonic longitudinal mode piezoelectric quartz crystal elements adapted for use as circuit elements in such systems as electric wave filter systems and radio frequency oscillation generator systems for example.

In my United States Patent No. 2,240,309, granted April 29, 1941 on application Serial No. 297,259 filed September 30, 1939, harmonic mode quartz crystal elements of low or substantially zero temperature coefficient of frequency are described. In the present application, another series of harmonic mode quartz crystal elements of low temperature coefficient of frequency are described which have much the same frequency characteristics as those of the former application but differ therefrom as to orientation, dimensional ratio, and impedance.

One of the objects of this invention is to obtain relatively high frequency piezoelectric crystal elements having a low or substantially zero temperature coefficient of frequency and a low impedance.

Another object of this invention is to obtain relatively high frequency piezoelectric crystal elements of nearly constant vibrational frequency throughout a wide range of ordinary temperatures.

Another object of this invention is to obtain high frequency piezoelectric crystal elements substantially free from interfering vibrational modes and of low temperature coefficient of frequency.

In single side-band short wave radio systems and in radio broadcasting and other systems such as wide band filter systems at high frequencies, for example, it is often desirable to obtain a constant frequency which does not vary appreciably with temperature change. For the relatively lower frequencies, this requirement is met by fundamental mode crystals of the type described in my U. S. Patent 2,204,762 dated June 18, 1940, but for the relatively higher frequencies, such fundamental mode crystals in some instances may be inconveniently small in size. It is the purpose of this invention to provide harmonic mode crystals of low or substantially zero temperature coefficient of frequency which are capable of giving very good stability for frequencies up to several megacycles per second, the harmonic mode quartz crystal elements having such related orientation, dimensional ratio and vibrational mode as to obtain the desired low or substantially zero temperature coefficient of frequency within temperature ranges that may occur in practice.

In accordance with this invention, a relatively thin piezoelectric quartz crystal plate of suitable orientation with respect to the X, Y and Z axes thereof, and of a suitable dimensional ratio corresponding to the orientation, may be subjected to a thickness direction or Y' electric field and vibrated at an odd or an even harmonic resonance frequency dependent mainly upon the length dimension of the crystal plate in a coupled mode of motion which consists of a harmonic longitudinal or extensional vibration along such length dimension giving the desired harmonic resonance frequency referred to and mechanically coupled therewith transverse vibrations along the width dimension of the substantially rectangular major plane of the crystal plate. The width or transverse vibrations referred to are in the nature of third overtone edge bulge vibrations alternately bulging outwardly and inwardly the opposite elementary portions of the edges of the crystal plate. The orientation of the crystal plate may be any of several, the length dimension of the crystal plate being in every such case inclined either about 45 degrees, or alternatively about 135 degrees, with respect to an electric axis X, and the major plane being in every case parallel or nearly parallel to such X axis and inclined with respect to the optic axis Z at any angle between about +43 and +52 degrees. Such quartz crystal plates when suitably proportioned as to relative width and length dimensions produce, for the harmonic longitudinal mode resonant frequency mentioned of any order, a low or substantially zero temperature coefficient of frequency at temperatures within a temperature range between -40 and +100° C. In a particular species where the major plane of the crystal plate is inclined about +44°30' with respect to the Z axis, and the fundamental or elementary length l of each of the elementary areas of the harmonic mode crystal plate is related to the above-mentioned width dimension W in the ratio of about

$$\frac{3l}{W} = 0.9394$$

the longitudinal mode harmonic resonant frequency referred to of any order such as the third or fifth harmonic frequency, has a very constant or flat frequency characteristic throughout a range of temperatures from about 5° to 45° C., the mid-temperature of such constant frequency range being about +25° C.

To further reduce the temperature coefficient of frequency of such crystals operating at or near

the resonant frequency and having a small temperature-frequency coefficient, a condenser of small capacity may be connected in series circuit relation with the crystal, the condenser itself having a temperature coefficient of capacitance of such magnitude and sign with respect to that for the crystal, that it will balance that of the resonant frequency of the crystal thereby reducing the over-all temperature coefficient of frequency of the combination.

For a clearer understanding of the nature of this invention and the additional 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:

Figs. 1 and 2 are enlarged views of an harmonic longitudinal mode piezoelectric quartz crystal plate embodying this invention, Fig. 1 being a projected edge view taken in the horizontal direction indicated by the arrows 1—1 of Fig. 2, and Fig. 2 being a major face view taken in the direction indicated by the arrows 2—2 of Fig. 1;

Fig. 3 is a major face view of a quartz plate similar to that of Fig. 2 but having an alternative 45-degree orientation angle with respect to the X axis;

Fig. 4 is an edge view of the crystal plate of Figs. 1 to 3 provided with electrodes and electrode connections for fifth harmonic longitudinal mode operation;

Fig. 5 is a developed view of an electrode and electrode interconnection plating arrangement that may be utilized on the crystal element of Figs. 1 to 4;

Fig. 6 is a graph showing the relation between the orientation angle and the desired longitudinal mode resonant frequency of quartz crystals in accordance with this invention;

Fig. 7 is a graph showing related values of orientation angle and dimensional ratio that may be utilized to obtain a zero temperature coefficient of frequency in quartz crystals embodying this invention, for ϕ angles in the region of substantially +44 to +52 degrees.

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, a mechanical and the optic axes, 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 double rotations of the quartz crystal element 1, one rotation being in effect substantially about an electric axis X, and the other about another axis Y' of the piezoelectric body as illustrated in Figs. 1 and 2, the orientation angles ϕ and θ respectively, designated in degrees the effective angular position of the crystal plate 1 as measured from the optic axis Z and from the orthogonal electric axis X, respectively. The length axis X'' shown in Figs. 2 and 3 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 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 Figs. 1 to 3 is right-handed as the term is used herein. For either right-handed or left-handed quartz, a 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, Figs. 1 and 2 are respectively an edge view and a major face view of a right-handed relatively thin piezoelectric quartz crystal plate 1 of substantially rectangular parallelepiped shape having an over-all length 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 length dimension L and the width dimension W. As shown in Fig. 1, the major plane and the opposite major faces 2 and 3 of the crystal plate 1 may be parallel or nearly parallel to an electric or X axis of the quartz material and inclined with respect to the optic axis Z at a ϕ angle of about +44° 30' as measured between the Z and Z' axes in a plane which is perpendicular to the X axis and to the major plane of the crystal plate 1. Small angle departures up to 5 degrees or more, for example of the major faces 2 and 3, from parallelism with respect to the X axis do not greatly alter the corresponding ϕ angle required to obtain the low or substantially zero temperature coefficient of frequency. Since the minor apex faces of the natural quartz crystal from which the quartz plate 1 is cut occur at a ϕ angle of about +38 degrees with respect to the optic axis Z, the posi-

tive (+) sense for the ϕ angle is equivalent to a rotation about the X axis from the Z axis toward parallelism with the plane of a minor apex face for either right-handed or left-handed quartz.

In Fig. 1, the X axis is perpendicular to the plane of the drawings with the compression positive end (+) of the X axis pointed towards the observer, and is also perpendicular to both the Y and Z axes. The over-all length dimension L of the crystal plate 1 lying along the axis X' as shown in Figs. 2 and 3 may be inclined at an angle θ of about 45 degrees with respect to the above-mentioned X axis in either direction as illustrated by the alternative θ angle orientations shown in Figs. 2 and 3. While the X' axis length dimension L of the crystal plate 1 of Fig. 2 is inclined at a different 45-degree θ angle with respect to the X axis than that of Fig. 3, it will be understood that either of these 45-degree positions for the angle θ may be used alternatively with any of the ϕ angles disclosed herein.

Suitable conductive electrodes such as the electrodes 4 in Figs. 2 and 4 may be placed on, adjacent or be formed integral with the opposite major faces 2 and 3 of the crystal plate 1 to apply harmonic mode electric field excitation to the quartz plate 1 in the direction of the thickness dimension T, and by means of any suitable circuit such as, for example, a filter or an oscillator circuit, the quartz plate 1 may be vibrated in the desired longitudinal mode of motion at an odd or an even harmonic vibration response frequency which depends mainly upon and varies inversely as the length dimension L and the elementary length dimension l . It will be understood that the crystal plate 1 may be operated in any desired odd or even harmonic longitudinal mode along the length dimension L by means of a plurality of pairs of equal area opposite electrodes 4 disposed adjacent the opposite major faces 2 and 3 of the crystal plate 1. The electrodes 4 may be interconnected as illustrated schematically in Fig. 4 so that all positive (+) electrodes are connected together and all negative (-) electrodes are connected together but no positive electrode is connected with a negative electrode. The number of pairs of opposite electrodes 4 to be used corresponds to the numerical order of the desired harmonic which may be any odd or even overtone of the fundamental mode. For example, to drive the crystal 1 in the fifth harmonic longitudinal mode, five pairs of equal area opposite electrodes 4 may be utilized as illustrated in Figs. 2 and 4; and similarly to drive the crystal plate 1 in third harmonic longitudinal vibrations along the length dimension L, three pairs of opposite electrodes which may partly or nearly wholly cover the equal elementary lengths l of the major faces 2 and 3 may be utilized. The odd harmonic mode is of special interest since then the crystal plate 1 may be clamped at its geometrical center 6 at the centers of the middle pair of opposite electrodes 4. Reference is made to my United States Patent No. 2,185,599 granted January 2, 1940 on application Serial No. 65,022, filed February 21, 1936 for examples of harmonic mode electrode and electrode connection arrangements that may be utilized to drive any of the crystal plates described herein in harmonic mode longitudinal vibrations along the length dimension L. As illustrated in Fig. 5, in developed form, the harmonic mode electrode and connection platings may be such as to leave three edges of the crystal body 1 entirely free of any plating in order to make edge grinding ad-

justments of the frequency and the temperature coefficient of frequency.

The harmonic mode crystal plates 1 described herein may be mounted in any suitable manner such as, for example, by clamping the electroded crystal plate 1 between a pair of opposite conductive clamping projections 5 which may contact the electroded crystal plate 1 at opposite points of very small area designated 6 in Figs. 2 and 4. As an illustrative example, an evacuated holder of the type disclosed in United States Patent No. 2,203,486, granted June 4, 1940, on application Serial No. 248,437, filed December 30, 1938 by W. L. Bond may be utilized for this purpose.

Alternatively, the electroded crystal plate 1 may be supported and electrically connected by soldering or otherwise attaching electrically conductive spring wires to one or more pairs or any pair such as the middle pair of the crystal electrodes 4, at the opposite nodal points designated 6 in Figs. 2 and 4. Such conductive wires may support and hold the electroded crystal plate 1 in spring suspension.

It will be understood that any holder which will give stability and a relatively high reactance-resistance ratio, Q, may be used to mount these harmonic mode crystals.

The desired resonant frequency of the harmonic mode crystal plate 1 is a function of the X' axis length dimension L and of the several equal elementary or fundamental lengths l , the over-all length L being equal to the n times the elementary length dimension l where n is the numerical order of the harmonic as determined by the number of pairs of opposite electrodes 4 that are applied to the major faces 2 and 3 of the crystal plate 1 of any ϕ angle. Since the invention may be adapted to any order harmonic operation, odd or even, the correlated values of frequency and dimensional ratio corresponding to the ϕ angle selected, are given hereinafter in terms of the width dimension W and the elementary length dimensions l . It will be noted that in so far as the elementary areas are concerned, the related values of the orientation, the dimensional ratio and the frequency constant of the several elementary areas of the harmonic mode crystals of this application are the same values for any order of harmonic.

Fig. 6 is a graph giving the calculated values of frequency in kilocycles per second per centimeter of elementary length dimension l of the crystal plate 1 for all angles of ϕ from -90 to $+90$ degrees, the angle θ being always equal to 45 (or 135) degrees for every angle of ϕ . For any given angle of ϕ the curve of Fig. 6 gives the approximate frequency constant corresponding thereto in terms of frequency in kilocycles per second per centimeter of the elementary length dimension l of the crystal plate 1 or n times this value where n is the numerical order of the harmonic frequency. Since the frequency of the longitudinal mode vibrations along the length l varies inversely as the particular length dimension of l involved, the value of l in centimeters corresponding to the resonant frequency in kilocycles per second may be obtained directly from the frequency constant given by the curve of Fig. 6 for any value of the angle ϕ selected. These calculated values of resonant frequency approximate the measured values.

The curve of Fig. 7 gives the orientation angles of ϕ and the corresponding dimensional ratios that may be used to construct quartz plates 1 to

obtain a low or substantially zero temperature coefficient of frequency for any order of harmonic. The dimensional ratios are therein given in terms of the width dimension W and the fundamental or elementary length dimension l of the crystal plate 1 , the elementary length dimension l of each of the elementary areas of the crystal plate being equal to L/n where L is the over-all length dimension of the crystal plate 1 and n is the numerical order of the harmonic such as the second, third, fifth, etc. harmonic. The curve of Fig. 7 gives the dimensional ratios in terms of three times the elementary length l with respect to the width W for all of the corresponding positive angles of ϕ between about $+44$ and $+53$ degrees, the angle θ in every case being about 45 degrees as illustrated in either Fig. 2 or Fig. 3. The angles of ϕ outside of the range given in Fig. 7 do not produce the substantially zero temperature coefficient of frequency.

The corresponding frequency constants for the quartz plates 1 , oriented and dimensioned in accordance with the values given by the curve of Fig. 7 are substantially given by the curve of Fig. 6 at the intercept of the particular value of ϕ selected. For example, when ϕ is substantially $+44^\circ 30'$, θ being substantially 45 degrees, and the dimensional ratio of three times the elementary length l with respect to the width W of the quartz plate 1 is substantially 0.9394 as indicated by the curve of Fig. 7, the frequency constant is about 340 kilocycles per second per centimeter of elementary length dimension l or n times this value per centimeter of over-all length dimension L where n is the numerical order of the harmonic involved such as $2, 3, 5$, etc. For example, a fifth harmonic quartz crystal plate 1 of such an orientation and dimensional ratio and of one centimeter over-all length L will have a resonant frequency of about five times 340 or about 1700 kilocycles per second which remains substantially constant throughout a range of temperatures from about 5°C. to 45°C. , the mid-temperature of the constant frequency temperature range being about $+25^\circ \text{C.}$

Other values of corresponding orientation, dimensional ratio and frequency for crystal plates 1 that give a low or substantially zero temperature coefficient of frequency may be obtained from the curves of Figs. 6 and 7 for any angle of ϕ selected between about $+44$ and $+52$ degrees.

It will be noted that for any given angle of ϕ , the dimensional ratio of the elementary area of these harmonic type crystals for the low or substantially zero temperature coefficient of frequency is independent of what harmonic is used on the length vibration, the width dimension W being slightly larger than three times the length l of the fundamental element of the crystal plate 1 . Accordingly, a third harmonic mode crystal plate of a positive ϕ angle from $+44$ to $+51$ degrees has a total length L a little less than the width dimension W of the crystal; and for the same angles of ϕ , fifth harmonic mode crystals have an over-all length dimension L that is greater than the width dimension W .

The curves of Figs. 6 and 7 illustrate the corresponding values of resonant frequency, dimensional ratio and orientation angle that may be used in the ϕ angle region of $+45$ degrees to obtain harmonic longitudinal mode quartz crystal plates 1 giving a very constant frequency characteristic above and below the mean or mid-temperature values from about 0 to 50°C. when

used in a circuit which operates the crystal plate 1 at or near its resonant frequency such as for example an oscillator circuit of the type disclosed in United States Patent No. 2,163,403, granted June 20, 1939 to L. A. Meacham and discussed in a paper published by L. A. Meacham in The Proceedings of the Institute of Radio Engineers, vol. 26, No. 10, October 1938, page 1278. When the crystal plate 1 is used in the grid-filament circuit of a non-inductively coupled Pierce oscillator circuit, the values given are nearly the same since this circuit also operates the crystal near its resonant frequency and hence produces the nearly flat or constant frequency-temperature relationship.

When used in such circuits which operate the crystal plate 1 at or very near the harmonic longitudinal mode resonant frequency, for an angle of ϕ of substantially $+44^\circ 30'$, the characteristic curve of the harmonic mode longitudinal resonant frequency as a function of temperature is substantially flat throughout a range of temperatures from about 5°C. to 45°C. in the region above and below about 25°C. ; while for an angle of ϕ of $+45$ degrees, the characteristic curve of frequency as a function of temperature is flat within the range of temperatures between 28°C. and 72°C.

When the crystal element 1 is driven in the harmonic mode longitudinal vibrations along the length dimension L by means of a number of pairs of opposite electrodes 4 corresponding in number of pairs to the order of the harmonic with suitable interconnections therebetween, the resulting vibrations consist of harmonic longitudinal or extensional vibrations set up along the length dimension L of the crystal plate 1 which tend to set up vibrations also along the width dimension W of the crystal element. The force system so set up is favorable for the so-called bulge type of vibration and hence the possibility exists that the vibration along the wide dimension W which is mechanically coupled to the harmonic longitudinal vibration along the length L is a third overtone bulge vibration when the elementary face area has the dimensional ratio of $3L/n$ with respect to the width W of about 0.935 to 0.94 as given by the curve of Fig. 7. There is a strong coupling between such width vibrations and the desired harmonic longitudinal vibration resonant frequency. Accordingly, for any angle of ϕ , the mode of vibration is described herein as a coupled mode consisting of longitudinal harmonic mode vibrations along the length dimension L coupled with edge bulge mode vibrations along the width dimension W . The frequency constants for the desired harmonic longitudinal mode are given in Fig. 6 for every angle of ϕ , and approximate the measured values.

The proper dimensional ratio of the crystal plates described, operates to produce the low or substantially zero temperature coefficient of frequency at a given temperature and the orientation angle ϕ controls the slope of the temperature-frequency characteristic, the slope being nearly horizontal and flat in the ϕ angle region of substantially $+44^\circ 30'$. It will be noted that for crystals having an angle of ϕ of about $+44^\circ 30'$ a θ angle of about 45 degrees, and a dimensional ratio as given by the curve of Fig. 7 of about 0.9394 for three times the elemental length l with respect to the width W , the frequency constant as given by the curve of Fig. 6 is about 340.4 kilocycles per second per centimeter of elementary length dimension l or five times this value for

the fifth harmonic of the longitudinal vibration along the length L . Thus a fifth harmonic crystal plate 1 having a length dimension L of 17.29 millimeters, a width W of about 11.04 millimeters and a thickness T of about 0.5 millimeter will have a fifth harmonic resonant frequency of about 984,612 cycles per second or 1702.4 kilocycles per second per centimeter of over-all length dimension L .

By a slight change in the ϕ angle of $+44^\circ 30'$ and in the corresponding dimensional ratio as given by the curve of Fig. 7, the mid-temperature of the constant frequency-temperature range may be shifted and raised or lowered as desired. For example, as shown in Figs. 6 and 7, when the angle ϕ is about $+45$ degrees, the dimensional ratio of three times the elementary length l with respect to the width W about 0.9356, and the frequency about 340 kilocycles per second per centimeter of elementary length l , then the mid-temperature of the constant frequency-temperature range from 28°C. to 72°C. is about $+50^\circ \text{C.}$

Other values of corresponding dimensional ratio and frequency constant as a function of the angle ϕ may be similarly obtained from the curves of Figs. 6 and 7. For example, a third harmonic quartz crystal plate 1 having a ϕ angle of $+49$ degrees and a ϕ angle of 45 degrees may have, as given by the curve of Fig. 7, a ratio of $3l/W$ equal to about .936 and, for example, a length dimension L of 30.7 millimeters and a width dimension W of 32.85 millimeters to obtain a zero temperature coefficient third harmonic resonance frequency of about 324,005 cycles per second, with a ratio of capacities of the order of 400, and a series inductance of about .92 henry if the thickness dimension T is .4 millimeter. As another example, a fifth harmonic quartz crystal plate 1 having a ϕ angle of about $+49$ degrees, a ϕ angle of about 45 degrees, a length dimension of 32.0 millimeters and a width dimension of 20.48 millimeters thus giving a dimension ratio of $3l/W$ equal to 0.936 may be utilized to attain a zero temperature coefficient fifth harmonic resonance frequency of about 521,000 cycles per second with a ratio of capacities of the order of 600, and an inductance of about .518 henry for a thickness dimension of .4 millimeter.

A seventh or other higher order harmonic crystal element 1 may be similarly constructed by suitably proportioning the dimensional ratios of width W , length L to obtain a zero temperature coefficient from the desired harmonic longitudinal mode frequency along the length dimension L relatively free from interfering modes of vibration.

Any undesired resonances that may be due to flexure modes may be removed by adjusting the ratio of the thickness dimension T with respect to the length dimension L without changing the desired harmonic longitudinal mode frequency or its zero temperature coefficient. Such crystal elements may be employed, for example, in a high frequency high-pass filter of sharp cut-off where any extraneous resonance will come in the attenuated band where it will do no particular harm.

The frequency and the temperature coefficient of frequency of any of these crystal plates may be adjusted to relatively precise values by edge grinding on the edges along the width W and length L of the crystal plate. Since the frequency is controlled mainly by the X'' axis length dimension L , the frequency of a slightly oversize crystal plate 1 may be increased by

grinding on either of the edges perpendicular to the length dimension L thereby reducing the length dimension L and increasing the frequency to a value a few cycles under the desired frequency. Then by grinding on either of the longest edges perpendicular to the width dimension W , the width dimension W may be uniformly reduced thereby changing the dimensional ratio of each of the elementary areas of the crystal plate 1 until the desired lowest value of the temperature coefficient of frequency is obtained. The frequency will have been raised slightly by this last step of reducing the width dimension W . If the frequency is still too low, it may be slightly raised by again reducing the length dimension L , and then the width dimension W may be again readjusted to obtain the desired lowest value of temperature coefficient of frequency. By this process of edge grinding, both the frequency and the temperature coefficient of frequency of the crystal plate 1 may be ultimately adjusted to the correct or desired value. In addition to these adjustments, the frequency if too high may be lowered slightly by slightly concaving either of the major faces 2 or 3 of the crystal plate 1 along the width dimension W midway between the ends of any of the elementary lengths l ; and the temperature coefficient of frequency may be lowered and rendered more negative by slightly concaving either of the major faces 2 or 3 centrally along the entire length dimension L .

The temperature coefficient of frequency and the frequency of these crystals having a ϕ angle in the region of $+44^\circ 30'$ may be so adjusted that their temperature coefficients of frequency are less than 1 part in 10 million per degree C. and that their frequency is within 5 parts in a million. Using such crystals in an oscillator circuit of the type described in United States Patent No. 2,163,403 granted on June 20, 1939 to L. A. Meacham, the frequency of such oscillators may be held to 1 part in a million without temperature control and to 1 part in 10 million with a rough temperature control. After the initial aging period which may be of several weeks, the long period accuracy may be of the same order of magnitude. Such oscillators are useful in single side-band radio systems, in broadcast systems, and for many other purposes.

These harmonic longitudinal mode crystals of low or substantially zero temperature coefficient of frequency may be used also in wide band filters at radio frequencies up to 2 megacycles per second or more with substantial freedom from troublesome subsidiary or extraneous resonances. Wide band quartz crystal filters have heretofore been limited to about 500 kilocycles per second due to the extra resonances existing in high frequency crystals. In carrier systems, it is often desirable to have high- and low-pass filters of very sharp selectivity for the purpose of dropping off supergroups at intermediate points and hence to have crystals which can be used in wide band filters at frequencies up to 2 megacycles per second or more and which have relatively low impedance, low temperature coefficient of frequency, and vibrate at high frequencies with the desired frequency of vibration separated as much as possible from the frequencies of other modes. Any nearby undesired resonance that is present may, if caused by a flexure mode determined by the thickness dimension T of the crystal plate 1, be removed by changing the ratio of the thickness dimension T with respect to the length dimension L , without chang-

ing the desired resonance frequency or its temperature coefficient. Otherwise, the thickness dimension T of the crystal plate 1 may ordinarily be of the order of 1 millimeter more or less for example, or of other value to suit the impedance or other requirements of the particular circuit with which it may be associated.

Either third harmonic or fifth harmonic crystals, for example, may be used to advantage in oscillators or moderately high impedance filters. Assuming a thickness dimension T of about 0.4 millimeter, the inductance in the equivalent circuit of the crystal for the third and fifth harmonic frequencies will be respectively of the order of 2.35 henries and 1.56 henries, independent of the frequencies. Such crystals may be used in oscillator systems or in filter systems up to 3 megacycles per second, for example.

In the construction of crystals such as the harmonic mode crystal plates having a ϕ angle in the region of $+44^\circ 30'$, as described hereinbefore, it is often difficult and expensive to adjust the temperature coefficient of frequency thereof closer than 1 part in 10 million per degree centigrade by mechanical adjustments alone on the crystal itself. When used in an oscillator which is not temperature controlled, such crystals may cause a change in frequency of ± 1 part in a million if the temperature changes by $\pm 10^\circ \text{C.}$, which change in frequency may be too large a variation for some purposes. By using an electrical element which varies its impedance with temperature change, the temperature coefficient of frequency of the crystal circuit may be controlled and adjusted to a value considerably less than 1 part in 10 million for $\pm 10^\circ \text{C.}$ change in temperature, and over-all variations in the frequency of an oscillator that may be associated therewith may be considerably reduced.

For this purpose, as illustrated in Fig. 4, a condenser 7 may be connected in series circuit relation with the electroded crystal plate 1 to still further reduce the temperature coefficient of the desired resonant frequency of the crystal plate 1. The condenser 7 may have a small capacitance of the order of 150 micro-microfarads more or less, for example, and of itself have a temperature coefficient of capacitance of such magnitude and sign as to balance that of the crystal plate and thereby reduce the over-all temperature coefficient of frequency of the combination crystal element and condenser to an extremely small value.

This method for compensating the temperature coefficients of frequency of crystals by the use of series-connected temperature variable condensers may be used to obtain a very nearly zero over-all temperature coefficient of frequency for the combined crystal and condenser when used with a crystal which has a very low temperature coefficient of frequency and when it is desired to keep the frequency of the system within about 1 part in 10 million per degree centigrade without the use of temperature control apparatus.

A small trimmer condenser of suitable capacity say, for example, of the order of 20 micro-microfarads more or less may be connected in parallel circuit relation with the electrode terminals 5 of the crystal element 1 to adjust the frequency thereof to the desired final value. As an illustrative example, such a condenser may consist of a thin mica sheet having conductive material such as silver or other suitable conduc-

tive material deposited in a known manner upon the opposite major surfaces thereof. The adjustment of capacitance may be made by scraping off or otherwise removing part of the silver coating until the desired values of capacitance and frequency are obtained.

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 vibratory body having its opposite substantially rectangular major faces substantially parallel to an X axis and inclined substantially $+44^\circ 30'$ with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the over-all length dimension and the width dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, said over-all length dimension being in effect divided into a plurality of equal length elementary lengths to form a plurality of elementary areas, each of said elementary lengths having a dimensional ratio of substantially 0.3131 with respect to said width dimension.
2. A piezoelectric quartz crystal vibratory body having its opposite substantially rectangular major faces substantially parallel to an X axis and inclined substantially $+44^\circ 30'$ with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the over-all length dimension and the width dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, said over-all length dimension being in effect divided into a plurality of equal length elementary lengths to form a plurality of elementary areas, each of said elementary lengths having a dimensional ratio of substantially 0.3131 with respect to said width dimension, the number of said elementary lengths being one of the integers 2 to 5.
3. A piezoelectric quartz crystal vibratory body having its opposite substantially rectangular major faces substantially parallel to an X axis and inclined substantially $+44^\circ 30'$ with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the over-all length dimension and the width dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, said over-all length dimension being in effect divided into a plurality of equal length elementary lengths to form a plurality of elementary areas, each of said elementary lengths having a dimensional ratio of substantially 0.3131 with respect to said width dimension, and electrodes adjacent each of said elementary areas of said major faces of said crystal body.
4. A piezoelectric quartz crystal vibratory body having its opposite substantially rectangular major faces substantially parallel to an X axis and inclined substantially $+44^\circ 30'$ with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the over-all length dimension and the width dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, said over-all length dimension being in effect divided into a plurality of equal length elementary lengths to form a plurality of elementary areas, each of said elementary lengths having a dimensional

ratio of substantially 0.3131 with respect to said width dimension, means including electrodes adjacent said elementary areas of said major faces for operating said crystal body in harmonic mode vibrations, and a condenser connected in series circuit relation with said electroded crystal body.

5. A piezoelectric quartz crystal vibratory body having its opposite substantially rectangular major faces substantially parallel to an X axis and inclined substantially $+44^{\circ} 30'$ degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the over-all length dimension and the width dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, said over-all length dimension being in effect divided into a plurality of equal length elementary lengths to form a plurality of elementary areas, each of said elementary lengths having a dimensional ratio of substantially 0.3131 with respect to said width dimension, and means including electrodes formed integral with said elementary areas of said major faces for operating said crystal body in a mode of motion consisting substantially of harmonic longitudinal vibrations along said length dimension mechanically coupled with transverse vibrations along said width dimension.

6. A quartz piezoelectric body of low temperature coefficient of frequency adapted to vibrate at a harmonic frequency dependent mainly upon the length dimension thereof, said body having a major plane of substantially rectangular shape, said major plane being substantially parallel to an X axis and inclined with respect to the Z axis substantially $+44^{\circ} 30'$ as measured in a plane perpendicular to said major plane, said length dimension and the width dimension of said major plane being inclined substantially 45 degrees with respect to said X axis, said length dimension arithmetically divided by the numerical order of said harmonic frequency being related to said width dimension in the ratio of substantially 0.3131.

7. A piezoelectric quartz crystal body adapted to vibrate at a harmonic frequency dependent mainly upon its length dimension, the major plane of said body being substantially parallel to an X axis and inclined substantially $+44^{\circ} 30'$ with respect to the Z axis as measured in a plane perpendicular to said major plane, said length dimension and the width dimension of said major plane being inclined substantially 45 degrees with respect to said X axis, said length dimension arithmetically divided by the numerical order of said harmonic frequency being substantially 0.3131 of said width dimension, said frequency being substantially 340 kilocycles per second per centimeter of said length dimension arithmetically multiplied by said numerical order of said harmonic frequency.

8. A piezoelectric quartz crystal plate having substantially rectangular major faces and means including a plurality of pairs of electrodes disposed adjacent said major faces for operating said crystal plate at one of its harmonic frequencies third and fifth dependent mainly upon the length dimension of said major faces, said pairs corresponding in number to the numerical order of said harmonic and being disposed along the equal elementary lengths of said major axis dimension, said major faces being substantially parallel to an X axis and inclined substantially $+44^{\circ} 30'$ with respect to the Z axis as measured in a plane perpendicular to said major faces, said

length dimension of said major faces being inclined substantially 45 degrees with respect to said X axis, the dimensional ratio of each of said elementary lengths with respect to the width dimension of said major faces being substantially 0.3131.

9. A piezoelectric quartz crystal body of low or substantially zero temperature coefficient of frequency adapted to vibrate at a harmonic frequency dependent mainly upon each of the fundamental or elementary length dimensions along the length dimension of said body multiplied by the numerical order of said harmonic frequency, the major plane of said body being substantially rectangular, disposed substantially parallel to an X axis and inclined at an angle with respect to the Z axis, said length dimension of said major plane being inclined substantially 45 degrees with respect to said X axis, said angle and the corresponding dimensional ratio of each of said elementary length dimensions with respect to the width dimension of said major plane being substantially those values given by the curve of Fig. 7, and the frequency for each of said elementary length dimensions being given by the curve of Fig. 6 at the intercept for said angle.

10. A piezoelectric quartz crystal body, the length dimension of said body being divided in effect into equal elementary lengths in accordance with the numerical order of a harmonic selected to obtain harmonic mode vibrations along said length dimension, the major faces of said body being substantially rectangular, substantially parallel to an X axis and inclined at an angle with respect to the Z axis, said length dimension being inclined substantially 45 degrees with respect to said X axis, the dimensional ratio of said elementary lengths with respect to the width dimension of said major faces of said body being a selected value, said dimensional ratio, said angle and said frequency being such related values as given by the curves of Figs. 6 and 7 as to obtain a low or substantially zero temperature coefficient of frequency for said harmonic mode vibrations.

11. A piezoelectric quartz crystal body of low temperature coefficient of frequency adapted to vibrate in a mode of motion consisting mainly of two coupled vibrations, one along the length dimension and the other along the width dimension of the major plane thereof, and at a harmonic mode frequency dependent upon the elementary length dimension equal to said length dimension arithmetically divided by the numerical order of said harmonic, said frequency being given by the curve of Fig. 6 for the angle corresponding to the angle given by the curve of Fig. 7, said major plane being of substantially rectangular shape, disposed substantially parallel with respect to an X axis and inclined at said angle with respect to the X axis, said length dimension of said major plane being inclined substantially 45 degrees with respect to said X axis, said angle and the dimensional relation between said width dimension and said elementary length dimension being substantially those values given by the curve of Fig. 7.

12. A piezoelectric quartz crystal body adapted for longitudinal vibrations along and at a harmonic frequency dependent mainly upon the elementary lengths of the length dimension of its substantially rectangular major plane, said major plane being substantially parallel to an X axis and inclined at an angle between substan-

tially +44 and +51 degrees with respect to the Z axis as measured in a plane perpendicular to said major plane, said length dimension being inclined substantially 45 degrees with respect to said X axis, the dimensional ratio of each of said elementary or fundamental lengths of said length dimension with respect to the width dimension of said major plane being between substantially 0.311 and 0.314, said angle and said dimensional ratio having such relative values as to provide a low or substantially zero temperature coefficient for said harmonic frequency.

13. A piezoelectric quartz crystal body adapted for longitudinal vibrations along and at a fifth harmonic frequency dependent mainly upon the elementary lengths of the length dimension of

its substantially rectangular major plane, said major plane being substantially parallel to an X axis and inclined at an angle between +44 and +51 degrees with respect to the Z axis as measured in a plane perpendicular to said major plane, said length dimension axis being inclined substantially 45 degrees with respect to said X axis, the dimensional ratio of each of said elementary or fundamental lengths of said major axis length dimension with respect to the width dimension being between substantially 0.311 and 0.315, said angle and said dimensional ratio having such relative values as to produce a low or substantially zero temperature coefficient of frequency for said fifth harmonic frequency.

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