April 29, 1941. W. P. MASON 2,240,309

PIEZOELECTRIC CRYSTAL APPARATUS

Filed Sept. 30, 1939 2 Sheets-Sheet 1

FIG. 1

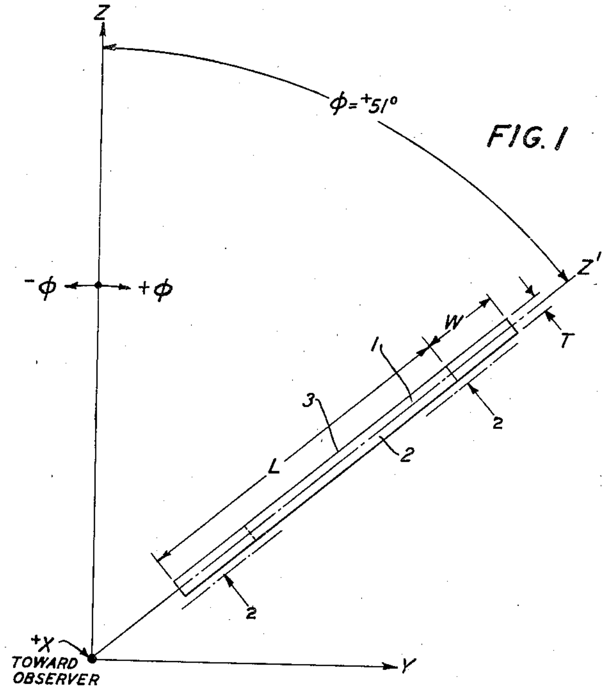

FIG. 2

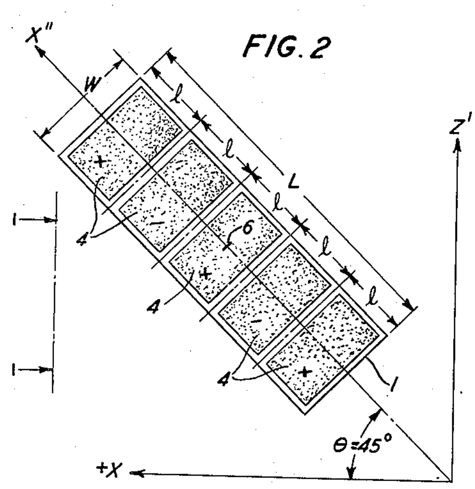

FIG. 3

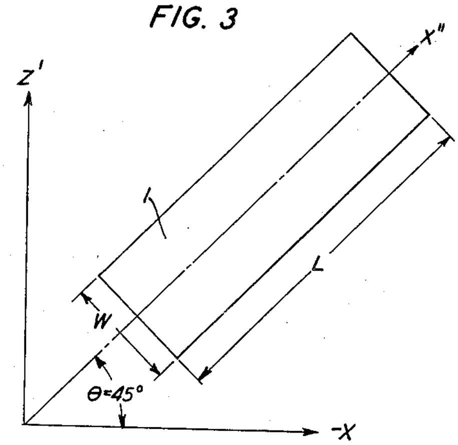

FIG. 4

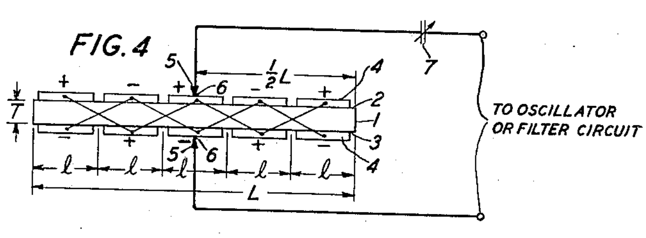

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FIG. 5

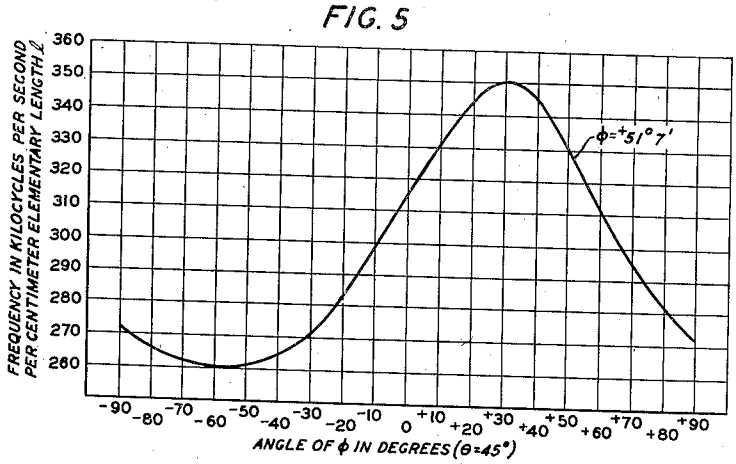


FIG. 6

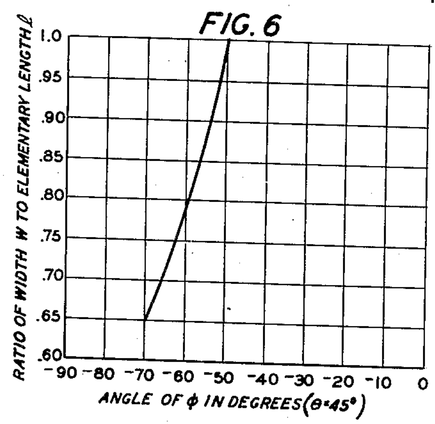


FIG. 7

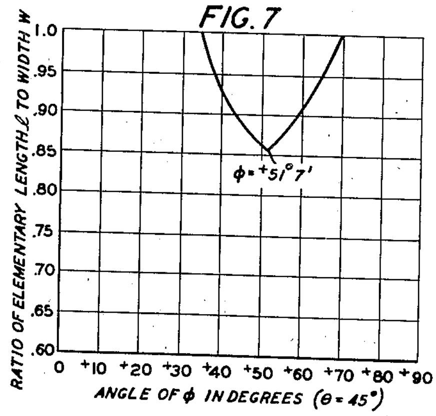


FIG. 8

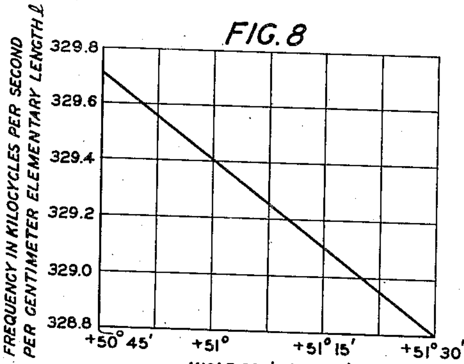
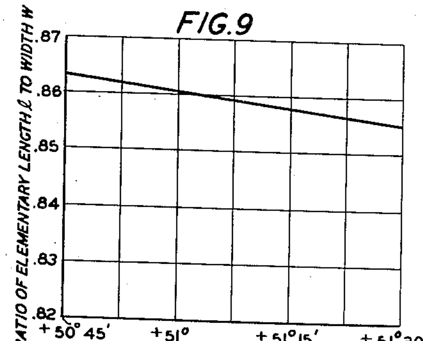


FIG. 9



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UNITED STATES PATENT OFFICE

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PIEZOELECTRIC CRYSTAL APPARATUS

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Application September 30, 1939, Serial No. 297,259

14 Claims. (Cl. 171—327)

This invention relates to piezoelectric crystal apparatus and particularly to harmonic piezoelectric quartz crystals 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. 2,204,762 granted June 18, 1940, on application Serial No. 180,921 filed December 21, 1937, fundamental mode quartz crystal elements of low or substantially zero temperature coefficient of frequency are described. In this application, harmonic mode quartz crystal elements are described which have much the same characteristics as the fundamental mode crystals referred to.

One of the objects of this invention is to obtain relatively high frequency piezoelectric crystals of low or substantially zero temperature coefficient of frequency.

Another object of this invention is to obtain relatively high frequency piezoelectric crystals of very constant vibrational frequency throughout a wide range of temperatures.

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

Another object of this invention is to adjust or reduce the temperature coefficient of frequency of piezoelectric crystals having a low temperature coefficient resonant frequency.

In single side-band short wave radio systems and in radio broadcasting and other systems, it is often desirable to obtain very constant frequency oscillators which do not vary appreciably with temperature change. For the relatively lower frequencies, this requirement is met very well by fundamental mode crystals of the type described in my patent application Serial No. 180,921 referred to, 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 longest or major axis length dimension of the crystal plate in a coupled mode of motion which consists of an harmonic longitudinal or extensional vibration along such length dimension giving the 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 edge bulge vibrations alternately bulging outwardly and inwardly the opposite elementary portions of the longest edges of the crystal plate. The orientation of the crystal plate may be any of several, the major axis or length dimension of the crystal plate being in every such case inclined either about 45 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 −50 and −70 degrees or between about +35 and +70 degrees. Such quartz crystal plates when suitably proportioned as to relative width and length dimensions produce, for the harmonic longitudinal mode resonant frequency mentioned, 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 +51 degrees with respect to the Z axis and the fundamental or elementary length of each of the elementary areas of the harmonic mode crystal plate is related to the above-mentioned width dimension in the ratio of about 0.86, the longitudinal mode harmonic resonant frequency referred to has a very constant or flat frequency characteristic throughout a wide range of temperatures, the mid-temperature of such constant frequency range being about +16° 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 same sign as that for the crystal, the result being 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 greatly enlarged views of an harmonic 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 mode operation, and a condenser connected in series circuit relation with the crystal plate;

Fig. 5 is a graph showing the calculated relation between the orientation angle and the resonant frequency of quartz crystals in accordance with this invention;

Figs. 6 and 7 are graphs showing the relation between the orientation angle and the dimensional ratio of quartz crystals in accordance with this invention, the dimensional ratios being plotted against values of φ for $\theta=45$ degrees and representing those dimensional ratios which, for the various angles represented by these curves, give zero or low temperature coefficient of frequency;

Fig. 8 is a graph showing the relation between the orientation angle, the resonant frequency and the temperature range of quartz crystals in accordance with this invention for φ angles in the region of substantially +51 degrees, the frequencies being plotted against values of φ for $\theta=45$ degrees and representing those frequencies which, for the angles represented by the curve, have zero or low temperature coefficients when the dimensional ratios are those given by the curve of Fig. 9 for the corresponding angle. The curve of Fig. 8 represents that part of the curve of Fig. 5 in the region of $\varphi=+51$ degrees but drawn to larger scale; and

Fig. 9 is a graph showing the relation between the orientation angle, the dimensional ratio and the temperature range of quartz crystals embodying this invention for φ angles in the region of substantially +51 degrees, the dimensional ratios being plotted against values of φ for $\theta=45$ degrees and representing those dimensional ratios which, for the angles represented by the curve, give zero temperature coefficient of frequency. The curve of Fig. 9 represents that part of the curve of Fig. 7 in the region of $\varphi=+51$ degrees drawn to larger scale.

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 of the piezoelectric body as illustrated in Figs. 1 and 2, the orientation angles φ and θ respectively, designate 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 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 thinnest 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 +51 degrees 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 positive (+) 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 drawing 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 major 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 major 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 major axis 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 mode along the length dimension L by means of a plurality of pairs of equal area opposite electrodes disposed adjacent the opposite major faces **2** and **3** of the crystal plate **1**. The electrodes 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 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. 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 major axis length dimension L. These harmonic mode electrode and connection platings may be such as to leave three edges of the crystal body entirely free of any plating in order to make edge grinding adjustments of the frequency and the temperature coefficient of frequency.

The harmonic mode crystal plates 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 by soldering or otherwise attaching electrically conductive spring wires, to any pair such as the middle pair of the crystal electrodes **4**, at the opposite points designated **6** in Figs. 2 and 4. Such 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 major 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 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 of 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 follow those values given for the fundamental mode crystals of the corresponding orientation described in application Serial No. 180,921 referred to, and also that the mechanical coupling between the harmonic mode longitudinal vibrations along the major axis length dimension L and the vibrations along the width dimension W of these harmonic mode crystals **1** is as strong as it is when both vibrations are fundamental mode as in the application Serial No. 180,921 referred to.

Fig. 5 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. 5 gives the approximate frequency constant corresponding thereto in terms of frequency in kilocycles per second per centimeter of the elementary length dimension 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. 5 for any value of the angle φ selected. These calculated values of resonant frequency approximate the measured values.

The curves of Figs. 6 and 7 give the orientation angles of φ and the corresponding dimensional ratios that may be used to construct quartz plates to obtain a low or substantially zero temperature coefficient of frequency. 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 major axis 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. 6 gives the dimensional ratios in terms of the width W with respect to the elementary length l for all of the corresponding negative angles of φ between about −50 and −70 degrees while the curve of Fig. 7 gives the dimensional ratios in terms of the elementary length l with respect to the width W for all of the corresponding positive angles of φ between about +35 and +70 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 these ranges as given in Figs. 6 and 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 curves of Figs. 6 and 7 are substantially given by the curve of Fig. 5 at the intercept of the particular value of φ selected. For example, when φ is substantially +51 degrees, θ being substantially 45 degrees, and the dimensional ratio of the elementary length l with respect to the width W of the quartz plate 1 is substantially 0.86 as indicated by the curves of Figs. 7 and 9, the frequency constant is about 329 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 329 or about 1645 kilocycles per second which remains substantially constant throughout a wide range of temperatures, the mid-temperature of the constant frequency temperature range being about +16° C. as shown by the curves of Figs. 8 and 9.

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. 5, 6 and 7 for any angle of φ selected between about +35 and +70 degrees or between about −50 and −70 degrees.

It will be noted that for the positive angles of φ, these harmonic type crystals of low or substantially zero temperature coefficient of frequency have a width dimension W slightly larger than the length l of the fundamental element of the crystal plate. For example, fifth harmonic mode crystal plates of a positive φ angle of +51 degrees have a total length L a little less than 5 times the width dimension W of the crystal; while for negative angles of φ, fifth harmonic mode crystals having negative φ angles between −50 and −70 degrees have an over-all length dimension L that is a little greater than 5 times the width dimension W.

The curves of Figs. 8 and 9 illustrate the corresponding values of resonant frequency, dimensional ratio and orientation angle that may be used in the φ angle region of +51 degrees to obtain harmonic 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 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 mode resonant frequency, for angles of φ in the region of substantially +51 degrees 7 minutes, the characteristic curve of the harmonic mode longitudinal resonant frequency as a function of temperature is substantially flat throughout a wide range of temperatures in the region above and below about 16° C.; while for angles of φ outside the region of +51 degrees but within the φ angle regions from about −50 to −70 degrees and +35 to +70 degrees, the characteristic curves of frequency as a function of temperature are more or less parabolic somewhere within the range of temperatures between −50° and +100° C.

When the crystal element is driven, as described in the harmonic mode longitudinal vibrations along the length dimension L by means of a number of pairs of opposite electrodes 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 width dimension W which is mechanically coupled to the harmonic longitudinal vibration along the major axis length L is a bulge vibration when the elementary face area is square or nearly so as when the dimensional ratio of L/n with respect to the width W is about 0.86. There is a strong coupling between such width vibrations and the harmonic longitudinal vibration resonant frequency. Accordingly, for an 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 harmonic longitudinal mode are given in Fig. 5 for every angle of φ and approximate the measured values. Those given in Fig. 8 are more precisely stated for angles of φ in the region of substantially +51 degrees.

The 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 +51 degrees. It will be noted that for crystals having an angle of φ of about +51 degrees, a θ angle of about 45 degrees and a dimensional ratio of about 0.86 for the elemental length l with respect to the width W, the frequency constant is about 329.4 kilocycles per second per centimeter of elemental length dimension l or 5 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 28.78 millimeters, a width W of about 6.59 millimeters and a thickness of about 1.0 millimeter will have a fifth harmonic resonant frequency of about 580,300 cycles per second.

By a slight change in the φ angle of +51 degrees and in the corresponding dimensional ratio, the mid-temperature of the constant frequency temperature range may be shifted and raised or lowered as desired. For example, as shown in Figs. 8 and 9, when the angle φ is about +51 degrees and 30 minutes, the dimensional ratio of the elementary length l with respect to the width W about 0.855, and the frequency about 328.8 kilocycles per second per centimeter of elementary length l, then the mid-temperature of the constant frequency temperature range is about +50° C.; where the angle φ is about +51 degrees 7 minutes, the dimensional ratio of the elementary length l to the width W about 0.859, and the frequency constant about 329.2, the mid-temperature of the constant frequency temperature range is about +25° C. Other values of corresponding dimensional ratio and frequency constant as a function of the angle φ and the mean temperature of the constant frequency temperature range may be similarly obtained from the curves of Figs. 8 and 9.

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 major axis length dimension L, the frequency of a slightly oversize crystal plate 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 values. 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 major axis length dimension L.

The temperature coefficient of frequency and the frequency of these crystals having a φ angle in the region of +51 degrees may be so adjusted that their temperature coefficients of frequency are less than 1 part in 10 million per degree centigrade 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 months, 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 mode crystals of low or substantially zero temperature coefficient of frequency may be used 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 changing the desired resonance frequency or the temperature coefficient of the crystal. 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 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 +51 degrees, 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 $\pm 10°$ 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 $\pm 10°$ 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 the same 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. As an example, the condenser 7 may consist of one or more "Ceramicon" series connected condensers having a suitable composite temperature coefficient of frequency and capacitance. These "Ceramicon" condensers are readily obtainable on the market with both positive and negative temperature coefficients of frequency. Using such a condenser having a temperature coefficient of −800 parts in a million per degree centigrade, for example, negative temperature coefficients of frequency up to about 2.5 parts in 10 million per degree centigrade in either fundamental mode or harmonic mode crystal plates of φ angles in the region of +51 degrees may be adjusted to very nearly zero temperature coefficient of frequency for the combined crystal and series connected condenser arrangement. Similarly, using a condenser having a temperature coefficient of +250 parts in a million per degree centigrade, for example, positive temperature coefficients of capacitance up to about +0.08 part in 10 million per degree centigrade or less in such crystal plates may be adjusted to very nearly zero over-all temperature coefficient of frequency.

The construction of such "Ceramicon" condensers of ceramic dielectric material may be roughly described as follows: These "Ceramicon" condensers use as a dielectric either titanium dioxide, which has a high negative temperature coefficient of dielectric constant and a high dielectric constant, or talc which has a positive temperature coefficient of dielectric constant and a lower dielectric constant. By mixing the relative proportions of the two materials, a condenser can be obtained which has a temperature coefficient of capacitance varying from −800 parts per million per degree centigrade to +250 parts per million per degree centigrade.

The temperature coefficient of the resonant frequency of a combination crystal 1 and a condenser 7 connected in series therewith is given by the expression:

$$T_k = T_c - \frac{C_o C_A T_{C_A}}{2(C_o + C_A)^2 r}$$

where C_0 is the static capacity of the crystal, r its ratio of capacities, C_A the temperature variable capacity, T_c the temperature coefficient of frequency of the crystal,

$$T_{C_A}$$

the temperature coefficient of the capacity C_A, and T_k the temperature coefficient of frequency of the combination crystal and capacity element.

The maximum effect on the temperature coefficient of frequency will occur when $C_o = C_A$ as may be seen from the equation. Hence with the condenser referred to having a negative temperature coefficient of frequency of −800 parts per million per degree centigrade for the value of

$$T_{C_A}$$

the maximum effect of such a series connected condenser will be to raise the combined temperature coefficient of frequency by 0.25 part per million per degree centigrade as previously stated. Similarly, for the positive coefficient condenser of +250 parts referred to, the combined temperature coefficient of frequency will be lowered by 0.0782 part as previously stated.

The measured reactance-resistance ratio Q of these "Ceramicon" condensers referred to is of the order of 900 at 100 kilocycles per second but the combined Q of the combination crystal and condenser is not greatly affected by the low value of Q for the condenser at resonant frequency. For example, where the Q of the original crystal is of the order of 100,000, the maximum effect of such a series connected condenser would be to lower it by about 7 per cent.

With a fixed value of temperature coefficient of frequency

$$T_{C_A}$$

for the condenser, the composite temperature coefficient of frequency of the series connected crystal and condenser may be varied by varying the value of capacity C_A of the condenser.

The frequency will be raised somewhat by putting the condenser 7 in series with the crystal 1. As an illustrative example, a fundamental mode GT crystal having a φ angle of substantially +51 degrees, mounted in a sealed and evacuated container, and operated in a bridge oscillator as disclosed in United States Patent No. 2,163,403, granted June 20, 1939, to L. A. Meacham, had a negative temperature coefficient of frequency of about −0.191 part per million per degree centigrade, a fundamental mode frequency of 100,003.8 cycles per second, a static capacity of 59 micro-microfarads, a ratio of capacities of 403, a resistance at resonance of 125 ohms, and a value of Q=87,100. By using a negative temperature coefficient of frequency condenser of 170 micro-microfarad capacity connected in series circuit relation with such crystal plate and sufficient inductance placed in series therewith to bring the frequency of the bridge oscillator to 100 kilocycles per second, the over-all temperature coefficient of frequency was changed to an average value of +0.0045 part per million per degree centigrade which is very close to zero, the impedance of the crystal was raised somewhat, and the frequency was raised about 30 cycles per second but the reactance-resistance ratio Q of the crystal remained nearly the same, and frequency stabilities of the order of 1 part in 10 million per degree centigrade were obtained without temperature control when this crystal-condenser combination was used in a bridge oscillator of the type disclosed in United States Patent No. 2,163,403 to L. A. Meacham.

It will be understood that the condenser 7 may consist of a plurality of condenser units. For example, a condenser of fixed capacity may be connected in series circuit relation with the crystal 1. The frequency of the crystal will always be changed the same amount by such a series connected condenser. The temperature coefficient of frequency may then be adjusted by adding the correct ratio of positive and negative temperature frequency coefficient condensers. For example, if a 200 micro-microfarad capacity is connected in series circuit relation with the crystals, then temperature coefficients of frequency of −0.175 and +0.055 therein may be adjusted to nearly zero by utilizing a series connected condenser having temperature coefficients of frequency of −800 or +250 parts per million per degree centigrade respectively. For any other temperature coefficients of frequency, the adjustment may be effected by choosing the proper ratio of negative coefficient to positive coefficient condenser. It will be understood that the 100 kilocycle per second crystal referred to may itself be adjusted about 30 cycles per second under the desired 100 kilocycle per second value and its temperature coefficient of frequency adjusted to nearly zero by the use of the series connected temperature variable condenser. By such adjustment of the frequency of the crystal itself to a proper value below the desired frequency, the series-connected inductance coil may be eliminated, and the frequency brought to its desired value by means of the condenser 7.

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 overall temperature coefficient of frequency for the combined crystal and condenser when used with a crystal which has a temperature coefficient of frequency lying between about −0.25 and +0.08 parts per million per degree centigrade, for example, 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. Such temperature coefficients of frequency ranging from about −0.25 to +0.08 part per million per degree centigrade exist in the crystals described herein when the φ angle is in the region of +51 degrees as illustrated in Figs. 8 and 9.

It will be understood that such series connected condenser apparatus is useful in reducing the temperature coefficient of frequency of the harmonic mode crystals described in this application, the fundamental mode crystals described in my application Serial No. 180,921 now U. S. Patent 2,204,762 dated June 18, 1940, or any other crystal of low or substantially zero temperature coefficient of frequency that is operated near its resonant frequency.

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 consender may consist of a thin mica sheet having conductive material such as silver or other suitable conductive 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 +51 degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the major axis 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 0.86 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 +51 degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the major axis 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 0.86 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 +51 degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the major axis 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 0.86 with respect to said width dimension, and elec-

trodes 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 +51 degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the major axis 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 0.86 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 at a resonant frequency of low temperature coefficient, and a condenser connected in series circuit relation with said electroded crystal body, said condenser having a temperature coefficient of capacitance of a value sufficient to reduce said low temperature coefficient of frequency of said 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 +51 degrees with respect to the Z axis as measured in a plane substantially perpendicular to said major faces, the major axis 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 0.86 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 major axis 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 major axis 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 +51 degrees 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 0.86.

7. A piezoelectric quartz crystal body adapted to vibrate at a harmonic frequency dependent mainly upon its major axis length dimension, the major plane of said body being substantially parallel to an X axis and inclined substantially +51 degrees 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 0.86 of said width dimension, said frequency being substantially 329 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 a harmonic frequency dependent mainly upon the major axis 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 +51 degrees with respect to the Z axis as measured in a plane perpendicular to said major faces, said major axis of said major plane 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 0.86.

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 major axis 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 within the range substantially from +50° 45′ to +51° 30′ with respect to the Z axis, said major axis 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. 9, and the frequency for each of said elementary length dimensions being given by the curve of Fig. 8 at the intercept for said angle.

10. A piezoelectric quartz crystal body, the major axis 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 major axis dimension, the major faces of said body being substantially rectangular, substantially parallel to an X axis and inclined at an angle within the range substantially from −50 to −70 and from +35 to +70 degrees with respect to the Z axis, said major axis 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. 5, 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 major axis 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 major axis length dimension arithmetically divided by

the numerical order of said harmonic, said frequency being given by the curve of Fig. 5 for the angle corresponding to the angle given by the curves of Figs. 6 and 7, said major plane being of substantially rectangular shape, disposed substantially parallel with respect to an X axis and inclined at said angle within the range substantially from —50 to —70 and from +35 to +70 degrees with respect to the Z axis, said major axis 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 curves of Figs. 6 and 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 major axis length dimension of its substantially rectangular major plane, said major plane being substantially parallel to an X axis and inclined at an angle between substantially +35 and +70 degrees with respect to the Z axis as measured in a plane perpendicular to said major plane, said major 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 with respect to the width dimension of said major plane being between substantially 0.85 and 1.0, 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 harmonic frequency dependent mainly upon the elementary lengths of the major axis length dimension of its substantially rectangular major plane, said major plane being substantially parallel to an X axis and inclined at an angle between —50 and —70 degrees with respect to the Z axis as measured in a plane perpendicular to said major plane, said major axis being inclined substantially 45 degrees with respect to said X axis, the dimensional ratio of the width dimension of said major plane with respect to each of said elementary or fundamental lengths of said major axis length dimension being between substantially 0.64 and 1.0, said angle and said dimensional ratio having such relative values as to produce a low or substantially zero temperature coefficient of frequency for said harmonic frequency.

14. A piezoelectric quartz crystal element havits major plane and major faces substantially parallel to an X axis and inclined substantially +51 degrees with respect to the Z axis, the edges of said major plane being inclined substantially 45 degrees with respect to said X axis, said crystal element having a resonant frequency of low temperature coefficient of frequency, electrodes adjacent said major faces, and means including a condenser connected in series circuit relation with said crystal element for reducing said low temperature coefficient of frequency of said crystal element.

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