PIEZOELECTRIC CRYSTAL APPARATUS

Filed Dec. 12, 1940 2 Sheets-Sheet 1

FIG. 1

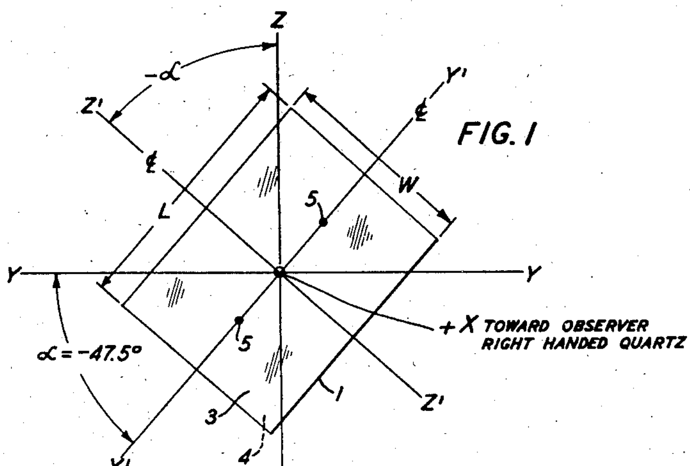


FIG. 2

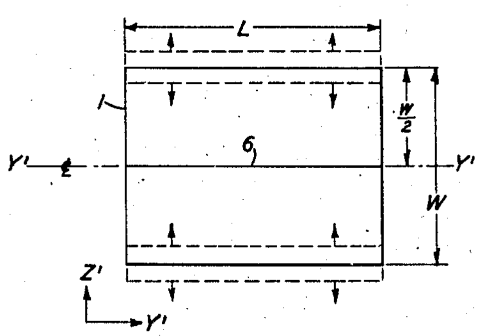


FIG. 3

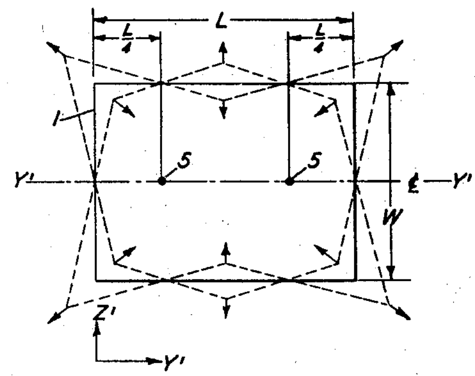


FIG. 4

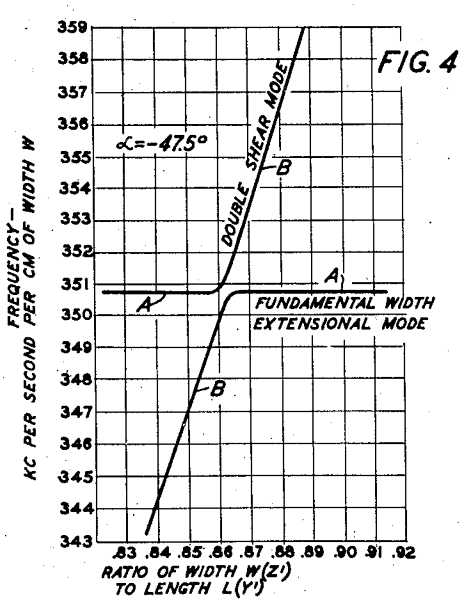


FIG. 11

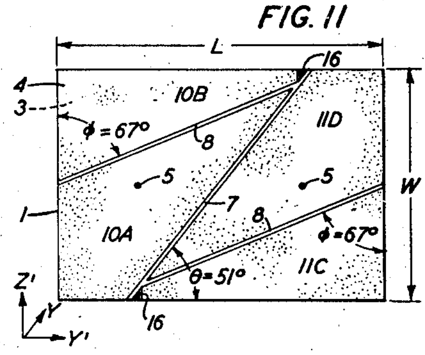
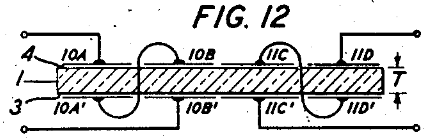


FIG. 12



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March 31, 1942. H. J. McSKIMIN ET AL 2,277,709

PIEZOELECTRIC CRYSTAL APPARATUS

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FIG. 5

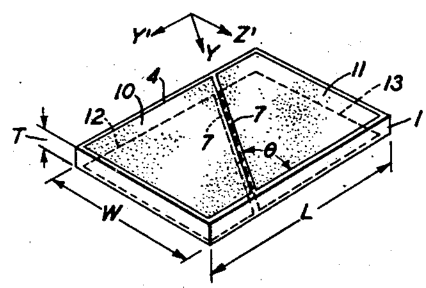


FIG. 8

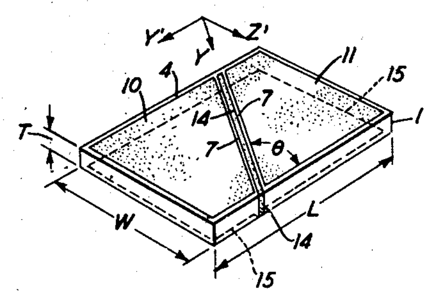


FIG. 6

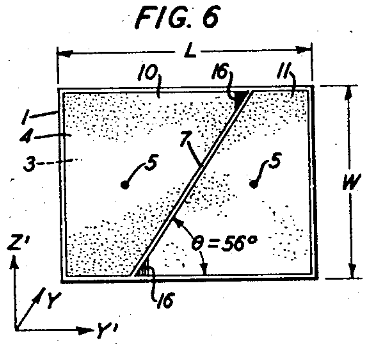


FIG. 9

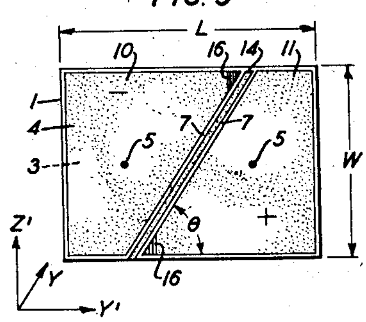


FIG. 7

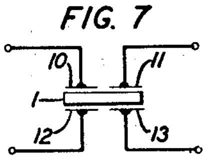
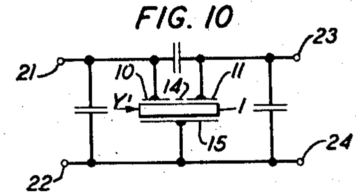


FIG. 10



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Patented Mar. 31, 1942

2,277,709

UNITED STATES PATENT OFFICE

2,277,709

PIEZOELECTRIC CRYSTAL APPARATUS

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Application December 12, 1940, Serial No. 369,694

10 Claims. (Cl. 171—327)

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

One of the objects of this invention is to provide a piezoelectric crystal element having a plurality of useful modes of motion that may be utilized simultaneously.

Another object of this invention is to provide a crystal element having a plurality of independently controlled frequencies that are substantially uncoupled and free from spurious frequencies.

Another object of this invention is to reduce the number and the cost of crystals used in electric wave filter systems and other wave transmission networks.

Piezoelectric crystal elements generally can be excited in many different modes of motion. When applied to filter systems for example, it is generally desirable to have all of the undesired or extraneous modes therein considerably higher, or lower, in frequency than the desired main mode or modes since otherwise the extraneous resonance frequencies therein may introduce undesirable frequencies or pass bands in the filter characteristic. Accordingly, it is desirable that the two or more separate desired main modes of motion of a crystal element be substantially uncoupled and independently controlled so that they may be given any desired frequency values to obtain a prescribed filter characteristic.

In accordance with this invention, a wave filter or other system may comprise as a component element thereof, a single piezoelectric crystal element adapted to vibrate simultaneously in a plurality of substantially uncoupled modes of motion in order to provide simultaneously a plurality of useful effective resonances which may be independently controlled and placed at predetermined frequencies of the same or different values for use in an electric wave filter or elsewhere.

The crystal element may be a quartz crystal plate of suitable orientation and dimensional proportions provided with a suitable electrode arrangement for simultaneously driving two desired modes of motion and controlling the relative strengths of the two resonances independently.

In a particular embodiment, the orientation of the crystal element may be that of an X-cut quartz crystal plate rotated in effect substantially —47.5 degrees about its X-axis thickness dimension, and the ratio of the width dimension of its major surfaces with respect to the length dimension thereof may be a value within the range from about 0.80 to 0.90 in order to obtain therefrom simultaneously two useful independently controlled resonant frequencies resulting from two independently controlled modes of motion one of which is referred to herein as the fundamental width dimension longitudinal mode and the other as the double shear mode in the major plane of the crystal element.

Such a crystal element when provided with suitable electrodes may be connected into a filter circuit in such a way that one of the resonances is effective in the line branch and another of the resonances is effective in the diagonal branch of the lattice portion of the equivalent network thereof, to obtain filter circuits using only a single crystal which are electrically equivalent to circuits requiring two crystals thereby reducing the number and cost of crystals therein. Such crystal elements may be utilized for example in balanced or unbalanced filter structures.

For a clearer understanding of the nature of this invention and the additional advantages, features and objects thereof reference is made to the following description taken in connection with the accompanying drawings, in which like reference characters represent like or similar parts and in which:

Fig. 1 is a major face view of a piezoelectric quartz crystal element in accordance with this invention and illustrates particularly the orientation thereof with respect to the X, Y and Z axes of the natural crystal from which it may be cut;

Figs. 2 and 3 are major face views of the crystal element of Fig. 1 illustrating in enlarged scale two types of motion which may be simultaneously utilized in crystal elements of the orientation illustrated in Fig. 1, Fig. 2 illustrating the width dimension longitudinal mode of motion and Fig. 3 illustrating the double shear mode of motion;

Fig. 4 is a graph illustrating the frequencies of the two independent modes of motion illustrated in Figs. 2 and 3 in crystal elements of the orientation illustrated in Fig. 1;

Figs. 5 to 12 are views illustrating types of electrodes and connections therewith which may be utilized with the crystal element of Fig. 1 to drive the crystal element simultaneously in the two independent modes of motion illustrated in Figs. 2 and 3 in order to obtain the resonance frequencies given by the graphs of Fig. 4;

Fig. 5 is a perspective view of the piezoelectric crystal element of Fig. 1 and associated electrodes therefor;

Fig. 6 is a major face view of the electroded crystal element of Fig. 5;

Fig. 7 is a schematic diagram illustrating an example of balanced filter connections for the crystal element of Figs. 5 and 6;

Fig. 8 is a perspective view of a piezoelectric crystal element similar to that of Fig. 5 but illustrating another form of associated electrodes therefor;

Fig. 9 is a major face view of the electroded crystal element of Fig. 8;

Fig. 10 is a schematic diagram illustrating an example of unbalanced filter connections for the electroded crystal element of Fig. 8;

Fig. 11 is a major face view of the crystal element of Fig. 1 similar to that of Fig. 6 but provided with another form of electrodes therefor; and

Fig. 12 is a schematic diagram illustrating a form of filter connections for the electroded crystal element of Fig. 11.

This specification follows the conventional terminology as applied to crystalline quartz which employs three orthogonal or mutually perpendicular X, Y and Z axes, as shown in the drawings, to designate an electric axis, a mechanical axis and the optic axis, respectively, of piezoelectric quartz crystal material, and which employs three orthogonal axes X′, Y′ and Z′ to designate the directions of axes of a piezoelectric body angularly oriented with respect to such X, Y and Z axes thereof. Where the orientation is obtained by a single rotation of the quartz crystal element 1, the rotation being in effect substantially about the thickness dimension electric X of the piezoelectric body 1, as illustrated in Fig. 1, the orientation angle α=substantially −47.5 degrees designates in degrees the effective angular position of the crystal plate 1 as measured from the optic axis Z and from the mechanical axis Y.

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 (1812); 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 α 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 α with respect to the Y axis or the Z axis. Conversely, the orientation angle of a left-handed crystal is positive when, with the compression positive end (+) of the electric axis X pointed toward the observer, the rotation is counter-clockwise, and is negative when the rotation is clockwise. The crystal material illustrated in Fig. 1 is right-handed as the term is used herein. For either right-handed or left-handed quartz, a position (+) angle α rotation of the Z′ axis with respect to the Z axis is toward parallelism with the plane of a minor apex face of the natural quartz crystal, and a negative (−) α angle rotation of the Z′ axis with respect to the Z axis as illustrated in Fig. 1 is toward parallelism with the plane of a major apex face of the natural quartz crystal.

Referring to the drawings, Fig. 1 is a major face view of a thin piezoelectric quartz crystal element 1 cut from crystal quartz free from twinning, veils or other inclusions and made into a plate of substantially rectangular parallelepiped shaped having a length or longest dimension L, a width dimension W which is perpendicular to the length dimension L, and a thickness or thin dimension T which is perpendicular to the other two dimensions L and W. In accordance with the values given by the curves of Fig. 4, the final width dimension W of the quartz crystal element 1 is determined by and may be made of a value according to the desired longitudinal mode resonant frequency. The width dimension W also may be related to the length dimension L in accordance with the value of the dimensional ratio selected to obtain the desired double shear mode resonant frequency. The thickness dimension T may be of the order of 1 millimeter or any other suitable value for example, to suit the impedance of the circuit in which the crystal element 1 may be utilized.

As shown in Fig. 1, the length dimension L of the crystal element 1 lies along a Y′ axis in the plane of a mechanical axis Y and the optic axis Z of the quartz crystal material from which the element 1 is cut and is inclined at an angle of α degrees with respect to said Y axis, the angle α being one of the values in the region of substantially minus (−) 47.5 degrees. The major surfaces 3 and 4 and the major plane of the bare quartz crystal element 1 are disposed parallel or nearly parallel with respect to the plane of the Y and Z axes, the length dimension L and the width dimension W lying along the Y′ axis and the Z′ axis, respectively, both of which lie in the plane of the Y and Z axes mentioned, the Y′ axis and the Z′ axis being inclined at the angle α with respect to the Y axis and the optic axis Z, respectively. The axis Z′ is accordingly the result of a single rotation of the width dimension W about the X axis $-\alpha$ degrees. It will be noted that the crystal element 1 is in effect an X-cut quartz crystal plate rotated $-\alpha$ degrees about the X axis.

Suitable conductive electrodes, such as the crystal electrodes of Figs. 5 to 12, for example, may be placed on or adjacent to or formed integral with the opposite major surfaces 3 and 4 of the crystal plate of Fig. 1 in order to apply electric field excitation to the quartz plate 1 in the direction of the X-axis thickness dimension T, and by means of suitable electrode inter-connections and any suitable circuit such as, for example, a filter circuit, the quartz plate 1 may be vibrated simultaneously in the desired width fundamental longitudinal mode illustrated in Fig. 2, and the double shear mode of motion illustrated in Fig. 3 at independent resonant response frequencies which depend upon different sets of dimensions involving the width dimension W and the dimensional ratio of the width W with respect to the length L, the frequencies being values within a range roughly from about 340 to 360 kilocycles per second per centimeter of the width dimension W, as illustrated by the curves of Fig. 4.

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

When the quartz crystal plate 1 has an orientation angle of $\alpha=-47.5$ degrees as illustrated in Fig. 1, the S'23 and S'34 constants thereof are both of zero value. Accordingly, when the angle α is about -47.5 degrees, the Z'z fundamental longitudinal or extensional mode along the width dimension W of the quartz plate 1 may be used simultaneously, and without coupling to, either (a) the second harmonic extensional mode along the Y' axis length dimension L involving the S'23 constant, or (b) the double shear mode in the Y'Z' plane of the crystal element 1 involving the S'34 constant.

The principal modes of interest that are particularly considered herein are the width longitudinal mode along the Z' axis, and the double shear mode in the Y'Z' plane of the crystal element 1, as illustrated in Figs. 2 and 3. More particularly, Figs. 2 and 3 are major face views of the quartz crystal element of Fig. 1 illustrating, in enlarged scale, the types of motion generated in the major plane Z'Y' of the crystal element 1 for these two modes of vibration of special interest. Fig. 2 illustrates the width longitudinal or extensional mode of motion, and Fig. 3 illustrates the double shear mode of motion. In Fig. 2, the broken lines and associated arrows indicate that the longitudinal width mode operates to alternately lengthen and shorten the width dimension W of the crystal element 1 about a nodal line 6 which extends across the center line ℄ length dimension L of the crystal element 1. Similarly, in Fig. 3, the broken lines and associated small arrows indicate that the double shear mode operates to alternately extend and shorten the opposite corners and edges of the crystal element 1 about nodes 5 located at two points on the center line length dimension L of the crystal element 1.

It will be understood that the broken lines in Figs. 2 and 3 represent, in greatly enlarged scale, the general configuration of the edges of the crystal element 1 due to the vibration of the crystal element 1 and are not intended to indicate the exact vibrational configuration of these edges but are merely illustrative representations of the types of motion involved in the width longitudinal mode and the double shear mode.

Since the nodes 5 involved in the double shear mode of motion of Fig. 3 are located on the nodal line 6 involved in the width longitudinal mode of Fig. 2, the crystal element 1 may be mounted by clamping or otherwise at any or all of the nodal points 5 without damping or interfering with the simultaneous operation of either the width mode longitudinal vibration or the double shear mode vibration. As illustrated in Figs. 1 and 3, the two nodal point regions 5 on each of the major surfaces 3 and 4 are located on the Y' axis center line length dimension L of the crystal element 1 at points spaced about 0.25 of the length dimension L from each end thereof, as shown in Fig. 3. Accordingly, at these nodal points 5, the crystal element 1 may be mounted by rigidly clamping it between two pairs of oppositely disposed clamping projections of small contact area which may be inserted in small indentations or depressions provided at the four nodal points 5 of the crystal element 1. Such small depressions cut in the major surfaces 3 and 4 of the crystal element 1 at the nodal points 5 thereof may have a depth of about 0.05 millimeter and a diameter of about 0.4 millimeter as measured on the surfaces 3 and 4.

Fig. 4 is a graph illustrating the values of the resonance frequencies associated with the width longitudinal mode and the double shear mode of Figs. 2 and 3, in a quartz crystal element 1 having an α angle of -47.5 degrees and having dimensional ratios of width W with respect to length L in the region from about 0.83 to 0.91. The fundamental of the Z' axis width W longitudinal mode frequency is represented by the two sections of the horizontal line curve A of Fig. 4 and has a frequency-dimension constant of about 351 kilocycles per second per centimeter of width dimension W independent of the dimensional ratio of the width W with respect to the length L. The other mode of interest here—the so-called double shear mode—is represented by the two sections of the oblique line curve B of Fig. 4 and has a frequency constant of from 343 to 361 kilocycles per second per centimeter of width dimension W dependent upon the value of the selected dimensional ratio of width W with respect to length L within the range from about 0.83 to 0.90. The frequencies of these two modes of motion, as shown by the curves A and B of Fig. 4, approach each other when the ratio of the Z' axis width dimension W with respect to the Y' axis length dimension L is in the region of about 0.86. In this region of special interest, the resonances of these two modes are substantially uncoupled or only very loosely coupled as is to be expected since the S'34 is equal to zero when the α angle of the quartz crystal element 1 has a value of -47.5 degrees as illustrated in Fig. 1.

Accordingly, as shown in Fig. 4, when the dimensional ratio of W/L is in the region of 0.86 the frequencies of these two independent modes of vibration are close together but sufficiently uncoupled to provide simultaneously two independent frequencies from the same crystal element 1, which may be usefully employed in a filter system for example, to give conveniently frequencies of the order of 100 to 200 kilocycles per second for example within a range of frequencies from 100 or less to 500 or more kilocycles per second.

The frequency in kilocycles per second of the longitudinal width mode vibration is given by the relation:

$$fz'_z=\frac{350.8}{W}$$

where W is the length of the width dimension W of the crystal element 1 along the Z' axis expressed in centimeters. This frequency relation is illustrated by the two sections of the horizontal line curve A of Fig. 4, and the type of motion there involved is illustrated in Fig. 2.

The frequency in kilocycles per second of the double shear mode vibration is given by the relation:

$$fy'_z=188.5k\sqrt{\left(\frac{2}{L}\right)^2+\left(\frac{1}{W}\right)^2}$$

where L and W are respectively the length dimension L and the width dimension W of the crystal plate 1 expressed in centimeters, and where k is a function of the coupling and proximity of flexure modes, and in this case has a value of approximately 0.931. This frequency relation is illustrated by the two sections of the oblique curve B of Fig. 4, and the type of motion involved therein is illustrated in Fig. 3.

The temperature coefficients of both the double shear mode frequency and the width W longitudinal mode frequency are negative, and are respectively of the order of about 23 and 49 parts per million per degree centigrade.

The principal extraneous frequencies which may occur in such crystal elements 1 are about 12 per cent away from the two desired main modes of motion described.

Figs. 5 to 12 illustrate several forms of electrode and connection arrangements which may be utilized to drive the crystal elements 1 of Fig. 1 simultaneously in the desired width longitudinal mode and the desired double shear mode illustrated in Figs. 2 and 3 respectively, in order to obtain simultaneously therefrom two independent resonance frequencies of values as given by the curves A and B of Fig. 4. As shown in Figs. 5 to 12, the desired double shear mode of motion may be driven by means of divided electrodes placed on one major surface only or on both of the major surfaces 3 and 4 of the crystal element 1, while the desired longitudinal width mode may be driven at the same time by one of the connected sets of electrode platings, with the result that the two desired resonance frequencies of the crystal element 1 may be made to appear simultaneously.

As illustrated in Figs. 5 and 6, the quartz crystal element 1 of Fig. 1 may be provided with four equal-area electrodes 10 to 13, two of the electrodes 10 and 11 being placed on one major surface 4 of the crystal element 1 with a narrow transverse split or gap or dividing line labeled 7 therebetween, and the other two electrodes 12 and 13, being oppositely disposed and placed on the opposite major surface 3 of the crystal element 1 and separated with a similar narrow and oppositely disposed split or dividing line 7 therebetween, the dividing lines 7 preferably extending generally in the direction of the Y axis of the crystal element 1, according to the value of the θ angle selected, θ being the angle between the direction of the dividing line 7 and the direction of the Y' axis length dimension L.

The gap or separation line 7 between the electrode platings on each of the major surfaces 3 and 4 of the crystal element 1 may be of the order of about 0.3 millimeter, with the center line of such splits in the platings on the opposite sides 3 and 4 of the crystal plate 1 being aligned with respect to each other.

Fig. 7 is a schematic diagram illustrating an example of balanced filter connections which may be used with the electroded crystal elements 1 of Figs. 5 and 6 in order to obtain a filter system comprising a single crystal element 1 having two independent simultaneously effective resonances which may be placed at any desired frequencies, one of which may appear in the line branch of the equivalent lattice and the other in the diagonal branch thereof.

The balanced circuit of Figs. 5 to 7 may be converted into an unbalanced filter structure by interconnecting the two electrodes 12 and 13 on one of the major surfaces 3 of the crystal element 1. In this case, the two electrodes 12 and 13 of Figs. 5 to 7 may be replaced by a single electrode 15 as shown in Fig. 8, and the electroded crystal element 1 of Figs. 8 and 9 may be connected as shown schematically in Fig. 10.

As illustrated in Figs. 8 to 10, to reduce the magnitude of the shunting capacitance appearing in the line branch of the lattice portion, a narrow grounding strip 14 of metallic plating may be placed on one major surface 4 of the crystal element 1 between the electrodes 10 and 11 and may extend around one edge of the crystal element 1 to the opposite major surface 3 thereof where it may be electrically connected to the large electrode 15, as illustrated in Figs. 8 to 10. As illustrated in Figs. 8 to 10, the ground strip 14 of metallic plating may be approximately 1 millimeter in width and may be placed between and separated from the two electrodes on the same major surface of the crystal celment 1 in order to provide shielding and to reduce stray capacities to a minimum. The strip of plating 14 may extend from one major surface continuously over and around one edge only or both edges of the crystal plate 1 to the opposite major face thereof where it may make contact with the integral electrode on that surface.

It will be noted that in order to drive the crystal element 1 in the double shear mode, one half of the crystal plate is made of opposite polarity to that of the other half, as indicated by the + and − signs in Fig. 9, and that this may be accomplished by utilizing a crystal element 1 having divided metallic coatings 10 and 11 placed on one of its major surfaces and connected in the form of a T network, for example, as illustrated in Fig. 10. Inductance coils may be added in the usual manner in series or in parallel with the network of Fig. 10 to produce broad band low or high impedance filters for example.

It will be noted that Fig. 10 is a schematic diagram illustrating an example of connections that may be utilized for connecting the electroded doubly resonant crystal element 1 of Figs. 8 and 9 in a filter system. In order that the crystal impedance may appear in both arms of the lattice structure of Fig. 10, one mode is driven when the terminals 21 and 23 are both of the same polarity, and the other mode is driven when these terminals 21 and 23 are of opposite polarity. Since both modes are substantially uncoupled or only loosely coupled mechanically, they may produce simultaneously two independent resonances of predetermined frequencies of values given in the graphs of Fig. 4.

In order to control the relative impedance levels of the two desired crystal resonances, the crystal electrodes associated with one half of the major surface or surfaces of crystal element 1 may be extended to cover a portion of the other half thereof. This may be done by adjustment of the position of the electrode dividing line angle θ with respect to the length dimension L. The angle θ may be any desired value over a wide range of angles. This adjustment does not materially affect the impedance of the longitudinal width mode resonance, but with decreasing values for the angle θ will increase the impedance level of the double shear mode resonance, without materially affecting the impedance of the width longitudinal mode resonance.

Thus, by changing the angle of inclination of the split or division line 7 between the electrodes 10 and 11 with respect to the Y' axis length dimension L of the crystal element, as illustrated by the angle θ in Figs. 5, 6, 8, 9, 11, the internal capacity associated with the double shear mode, which is nearly a maximum value when θ equals 90 degrees, may be varied and adjusted to a desired value without changing the internal capacity associated with longitudinal width mode.

Also, by scraping off or otherwise removing a small amount of the electrode coating in the regions indicated at 15 in Figs. 5 to 11, precise adjustments in the internal capacity may be made. While there is an appreciable variation of the relative capacities with the θ angle position of the dividing line 7 between the electrodes for example, for any given angle of θ between 45 and 120 degrees, the ratio of internal capacities is not influenced to any appreciable degree by a change in dimensional ratio of the width W with respect to the length L between the limits of about 0.87 and 0.89 for example which represents a useful range as indicated by the graph of Fig. 4. The dividing line 7 between the electrodes is preferably placed in the general direction toward parallelism with the Y axis of the crystal plate 1, as illustrated in Figs. 5 to 11.

Figs. 11 and 12 illustrate another form of electrode and connection arrangement which may be utilized to drive the crystal element 1 simultaneously in the two desired modes of vibration, namely the fundamental longitudinal width mode and the so-called double shear mode, the frequency-dimension constants for which are given in Fig. 4. As shown in Figs. 11 and 12, four electrodes may be provided on each of the major surfaces 3 and 4 of the crystal element 1.

Adjustments in the internal capacities of the crystal element 1 may be made by selecting a suitable thickness dimension T for the crystal element 1 as well as by changes in the areas of metallic plating on the crystal element 1. If relatively small capacities are required to suit a particular circuit, the crystal element 1 may become inconveniently or excessively thick in the thickness direction dimension T. In this event, a relatively thin crystal element 1 may still be used with its metallic platings split as illustrated in Figs. 11 and 12. In this arrangement of crystal platings, effectively one-fourth of the crystal element 1 is placed in series with another fourth, thus making one-eighth the total internal capacity appear in the lattice network. As illustrated in Figs. 11 and 12, the areas of the four platings 10A, 10B, 11C and 11D on one face of the crystal element 1 may all be made of equal area, regardless of the angle θ selected for the proper or desired ratio of internal capacities. The angle ϕ of Fig. 11 which satisfies this condition of equal-area platings 10A, 10B, 11C and 11D and also of the oppositely disposed equal-area electrodes 12A', 12B', 13C' and 13D' is given by the relation:

$$\phi=\tan^{-1}\left[\frac{(L)^2}{(W)^2}\tan\theta+\cot\theta\right]$$

where ϕ is the angle between the direction of the Z' axis width dimension W and the direction of the separation lines 8 of the electrodes 10A and 10B, 10A' and 10B', 11C and 11D, 11C' and 11D'; where θ, W and L have the significance hereinbefore described.

As an example, the quartz crystal element 1 may have length L, width W and thickness T dimensions respectively of 34.64, 31.12 and 0.75 millimeter with plating angles of $\theta=51$ degrees and $\phi=67$ degrees to obtain a frequency in cycles per second of 115,857 for the double shear mode and 112,595 for the width longitudinal mode.

Connections between the electrode platings of Fig. 11 are illustrated schematically in Fig. 12 and may be made on the crystal element 1 itself by extending the integral metallic platings over and around two edges only of the crystal element 1, thus leaving the other two edges thereof free of plating for adjustment purposes.

It will be understood that Figs. 7, 10 and 12 represent particular circuits. In these and other forms of filter circuits, the doubly resonant crystal element 1 may be utilized. If desired, mutual inductance may be used between the end coils of the crystal filter to obtain improved attenuation characteristics as described in U. S. Patent No. 2,198,684, granted April 30, 1940, to R. A. Sykes on application Serial No. 230,775, filed September 20, 1938.

The electroded doubly resonant crystal element 1 may be mounted in any suitable manner, such as by clamping it, or otherwise. Where the clamping form of mounting is used, two pairs of opposite conductive clamping projections may resiliently contact the electroded crystal element 1 at its four nodal points 5 only in order to support and to establish individual electrical connections therewith.

Alternatively, instead of being mounted by clamping the electroded crystal plate 1 may be mounted and electrically connected by soldering, cementing or otherwise firmly attaching four fine conductive supporting wires directly to a thickened part of the electrodes of the crystal element 1 at its four nodal points 5 only. The four fine supporting wires referred to may be conveniently soldered to four small spots of baked silver paste or other metallic paste, which have been previously applied at the nodal points 5 on the bare quartz underneath the field producing crystal electrodes, which may consist of pure silver applied by the known evaporation in vacuum process. Such fine supporting wires secured to the electroded crystal element 1 may extend horizontally from the vertical major surfaces of the crystal element 1 and at their other ends be attached by solder, for example, to four vertical conductive wires or rods carried by the press or other part of an evacuated or sealed glass or metal tube. The supporting wires and rods may have one or more bends therein to resiliently absorb mechanical vibrations. Also, bumpers or stops of soft resilient material such as mica may be spaced closely adjacent the edges, ends or other parts of the electroded crystal element 1 in order to limit the bodily displacement thereof when the device is subjected to mechanical shock. It will be understood that any holder which will give stability, substantial freedom from spurious frequencies and a relatively high Q or reactance resistance ratio for the crystal element 1 may be utilized for mounting the crystal element 1.

Although this invention has been described and illustrated in relation to specific arrangements, it is to be understood that it is capable of application in other organizations and is therefore not to be limited to the particular embodiments disclosed, but only by the scope of the appended claims and the state of the prior art.

What is claimed is:

1. A piezoelectric quartz crystal element having its substantially rectangular major surfaces substantially in the plane of a Y axis and the Z axis, the major axis length dimension of said major surfaces being inclined at an angle of substantially −47.5 degrees with respect to said Y axis, the dimensional ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values between substantially 0.80 and 0.93.

2. A piezoelectric quartz crystal element having its substantially rectangular major surfaces

substantially in the plane of a Y axis and the Z axis, the major axis length dimension of said major surfaces being inclined at an angle of substantially —47.5 degrees with respect to said Y axis, the dimensional ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values between substantially 0.80 and 0.93, and means including electrodes adjacent said major surfaces for operating said element simultaneously at a plurality of independent frequencies dependent upon different sets of said major face dimensions.

3. A piezoelectric quartz crystal element having its substantially rectangular major surfaces substantially in the plane of a Y axis and the Z axis, the major axis length dimension of said major surfaces being inclined at an angle of substantially —47.5 degrees with respect to said Y axis, the dimensional ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values between substantially 0.80 and 0.93, and means including electrodes adjacent said major surfaces for operating said element simultaneously at a plurality of independent frequencies dependent upon said major face dimensions, one of said frequencies being dependent upon the fundamental of the longitudinal or extensional mode vibration along said width dimension.

4. A piezoelectric quartz crystal element having its substantially rectangular major surfaces substantially in the plane of a Y axis and the Z axis, the major axis length dimension of said major surfaces being inclined at an angle of substantially —47.5 degrees with respect to said Y axis, the dimensional ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values between substantially 0.80 and 0.93, and means including electrodes adjacent said major surfaces for operating said element simultaneously at a plurality of independent frequencies dependent upon said major face dimensions, one of said frequencies being dependent upon the fundamental of the longitudinal or extensional mode vibration along said width dimension, and another of said frequencies being dependent upon the double shear mode vibration in said ZY plane.

5. A piezoelectric quartz crystal element adapted to vibrate simultaneously at a plurality of desired independent frequencies dependent mainly upon the length and width dimensions of its substantially rectangular major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined at an angle of substantially —47.5 degrees with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane, the ratio of said width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the region of substantially 0.86.

6. A piezoelectric quartz crystal element adapted to vibrate simultaneously at a plurality of desired independent frequencies dependent mainly upon the length and width dimensions of its substantially rectangular major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined at an angle of substantially —47.5 degrees with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.80 to 0.93, said width dimension expressed in centimeters being a value within the range from substantially 340 to 370 divided by one of said frequencies expressed in kilocycles per second.

7. A piezoelectric quartz crystal element adapted to vibrate simultaneously at a plurality of independent frequencies dependent mainly upon the length and width dimensions of its substantially rectangular major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined at an angle of substantially —47.5 degrees with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.80 to 0.93, said width dimension and said dimensional ratio being a set of corresponding values as determined by the curves of Fig. 4.

8. A piezoelectric quartz crystal element adapted to vibrate simultaneously at a plurality of desired frequencies dependent mainly upon the length and width dimensions of its substantially rectangular major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined at an angle of substantially —47.5 degrees with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane, the ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values within the range from substantially 0.83 to 0.90, said width dimension expressed in centimeters being a value within the range from substantially 340 to 360 divided by one of said frequencies expressed in kilocycles per second, said width dimension and said dimensional ratio being a set of values as given by the curves of Fig. 4.

9. A piezoelectric quartz crystal element and means including two pairs of opposite electrodes adapted to vibrate said element simultaneously at a plurality of desired frequencies dependent mainly upon the length and width dimensions of the major surfaces of said element, said length dimension being substantially in the plane of a Y axis and the Z axis and disposed at an angle of —47.5 degrees with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane.

10. A quartz piezoelectric crystal element adapted to vibrate simultaneously at a plurality of desired frequencies dependent mainly upon the length and width dimensions of its major surfaces, said length dimension being substantially in the plane of a Y axis and the Z axis and inclined at an angle of substantially —47.5 degrees with respect to said Y axis, and said major surfaces being substantially parallel with respect to said YZ plane, two electrodes formed integral with one of said major surfaces, said electroded crystal element having nodes, said nodes being along the center line of said length dimension at points located from the ends thereof a distance substantially 0.25 of said length dimension.

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