

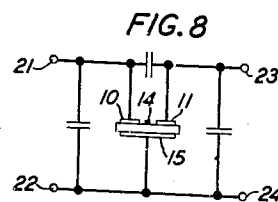
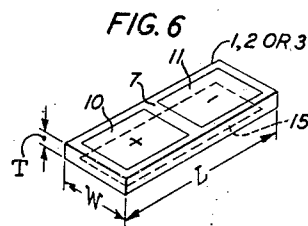
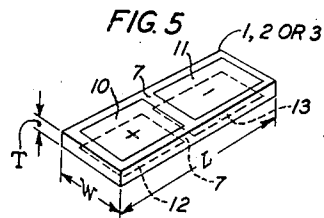
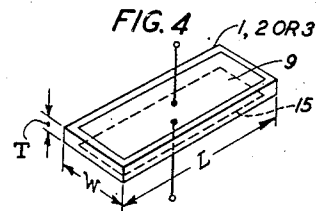
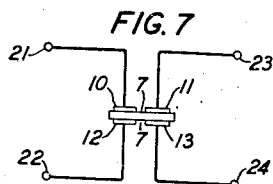
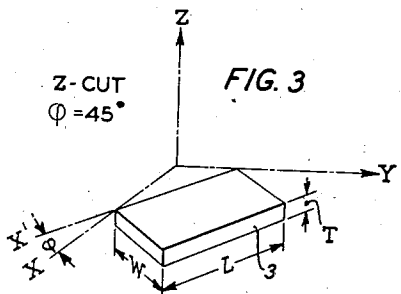
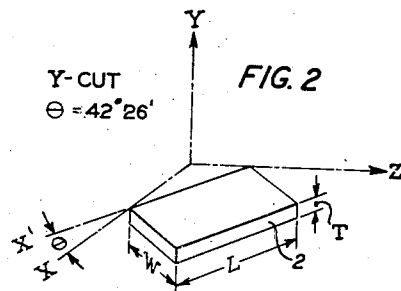
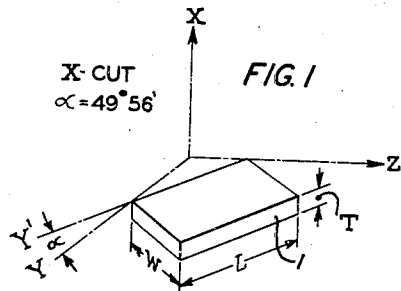
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2,292,885

ROCHELLE SALT PIEZOELECTRIC CRYSTAL APPARATUS

Filed May 9, 1941



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ROCHELLE SALT PIEZOELECTRIC CRYSTAL
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20 Claims. (Cl. 171-327)

This invention relates to piezoelectric crystal apparatus and particularly to piezoelectric Rochelle salt or sodium potassium tartrate crystal elements suitable for use as circuit elements in electric wave filter systems and oscillator systems, for example.

One of the objects of this invention is to provide a Rochelle salt type piezoelectric crystal element having one or more useful low frequency modes of motion that may be utilized either alone or simultaneously, without interference or coupling with other modes of motion therein.

Another object of this invention is to provide a Rochelle salt crystal element having a plurality of simultaneously useful and independently controlled frequencies that may be substantially uncoupled with each other and free from spurious or undesired frequencies.

Another object of this invention is to provide Rochelle salt crystal elements of such an orientation that the longitudinal length and width modes of motion thereof may be uncoupled to the face shear mode of motion thereof.

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, and to take advantage of the high piezoelectric activity and low cost of Rochelle salt.

Rochelle salt piezoelectric crystal elements generally may be excited in many different modes of motion such as, for example, extensional or longitudinal modes, flexural modes, and shear modes of motion. When crystal elements are to be applied to filter systems, for example, it is generally desirable to have all of the undesired or extraneous modes of motion therein uncoupled with and considerably higher, or lower, in frequency than the desired main mode or modes of motion of the crystal element since otherwise the extraneous resonance frequencies therein may introduce undesirable frequencies or pass bands in the filter characteristic. Accordingly, it is often desirable in filter systems and elsewhere that the desired main mode or modes of motion of a crystal element be substantially uncoupled to other modes of motion and independently controlled in order that such mode or modes of motion may be given any desired frequency values to obtain prescribed frequency characteristics.

In accordance with this invention, wave filters and other systems may comprise as a component element thereof, a single piezoelectric crystal element of Rochelle salt which may be adapt-

ed to vibrate simultaneously in a plurality of substantially uncoupled modes of motion in order to provide either separately or 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 Rochelle salt crystal plate of suitable orientation with respect to the X, Y and Z axes thereof, and of suitable dimensional proportions, and provided with a suitable electrode arrangement and connections for separately driving either, or simultaneously driving both, of two uncoupled modes of motion therein and independently controlling the relative strengths of such resonances.

In particular embodiments, the orientation of the crystal element may be that of an X-cut or a Y-cut or a Z-cut Rochelle salt crystal plate rotated in effect about its X-axis or Y-axis or Z-axis thickness dimension respectively. The width dimension of its major surfaces and the length dimension thereof may be of selected values in order to obtain therefrom, separately or simultaneously, either or both of two useful independently controlled resonant frequencies resulting from two independently controlled face modes of motion, one particular set of which is described herein as the fundamental width axis dimension longitudinal or extensional mode and the other as the second harmonic length axis longitudinal or extensional mode. Both the length and width longitudinal modes of motion referred to are in the major plane of the crystal element, and due to the crystal orientation selected may have no mechanical coupling with each other or with the face shear mode vibration.

Such Rochelle salt crystal elements when provided with suitable electrodes may be connected into a filter circuit in such a way that one of the resonances of each crystal element 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, in order to obtain filter circuits using a single crystal which are electrically equivalent to circuits requiring two crystals, thereby reducing the number and cost of crystals therein. Such Rochelle salt crystal elements may be utilized, for example, in either balanced or unbalanced filter structures such as those disclosed, for example, in W. P. Mason U. S. Patent 2,271,870, granted February 3, 1942, on my application Serial No. 303,757, filed November 10,

1939 (Case 58), and in the H. J. McSkimin and R. A. Sykes U. S. Patent 2,277,709, granted March 31, 1942, on application Serial No. 369,694, filed December 12, 1940 (Case 1-3).

By using two of such doubly resonant Rochelle salt crystal elements with or without temperature control, filter systems may be inexpensively constructed of frequencies as low as 16 kilocycles per second. With the relatively lower values of frequency, there is less absolute shift in the pass band due to temperature change and therefore temperature control often is not needed at the lower values of frequency and electric wave filters may be made using Rochelle salt crystal elements as the vibrating elements thereof, with characteristics nearly as good as those obtained when using quartz crystal elements. However, due to the relatively high temperature frequency coefficient of Rochelle salt, it is often desirable to have temperature control to about 1° or 2° C. to hold the pass bands to their required frequency. By the use of both wet and dry Rochelle salt material placed in the enclosing container, the Rochelle salt vibratory crystal may be preserved indefinitely, or for a long period of time without change in the characteristics thereof.

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

Figs. 1, 2 and 3 are respectively perspective views of X-cut, Y-cut and Z-cut type piezoelectric Rochelle salt type crystal elements in accordance with this invention, and illustrate particularly the orientation thereof with respect to the X, Y and Z axes of the Rochelle salt crystal material from which the crystal elements may be cut;

Figs. 4 to 8 are views illustrating types of electrodes and connections therewith which may be utilized with any of the Rochelle salt crystal elements of Fig. 1, 2 or 3 to drive the crystal element separately in either or simultaneously in both of two independently controlled longitudinal modes of motion, fundamental or harmonic, in order to obtain the desired resonance frequency or frequencies.

Fig. 4 is a perspective view of an electrode arrangement that may be used to drive the piezoelectric crystal element of Fig. 1, 2 or 3 in the fundamental longitudinal mode of motion along either the length or width dimension thereof;

Figs. 5 and 6 are perspective views of electrode arrangements that may be used to drive the crystal element of Fig. 1, 2 or 3 in the second harmonic longitudinal length mode of motion and the fundamental longitudinal width mode of motion, separately or simultaneously;

Fig. 7 is a schematic diagram illustrating an example of balanced filter connections that may be used in connection with the crystal electrodes of Fig. 5; and

Fig. 8 is a schematic diagram illustrating an example of unbalanced filter connections that may be used in connection with the electrodes of the crystal element of Fig. 6.

This specification follows the conventional terminology as applied to crystalline Rochelle salt, which employs three orthogonal or mutually perpendicular *a*, *b* and *c* axes or X, Y and Z axes, respectively, as shown in the drawing, to designate an electric axis, a mechanical axis and an

optic axis, respectively, of piezoelectric Rochelle salt or sodium potassium tartrate 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 in effect by a single rotation of the Rochelle salt crystal element, the rotation being in effect substantially about the thickness dimension axis X, Y or Z of the piezoelectric body as illustrated in Figs. 1, 2 and 3, respectively, the orientation angles, respectively, α =substantially 49° 56', θ =42° 26', and ϕ =an angle of substantially 45 degrees between the X and Y axes, designate in degrees the effective angular position of the length axis dimension L of the crystal plate as measured from one of the other two X, Y and Z axes. The relation of the X, Y and Z axes to the outer faces of a grown Rochelle salt crystal body are illustrated in W. P. Mason U. S. Patent 2,178,146, dated October 31, 1939. Rochelle salt belongs to the rhombic hemihedral class of crystals and has three orthogonal or mutually perpendicular axes generally designated as the *a*, *b* and *c* axes or the X, Y and Z axes, respectively.

Referring to the drawing, Figs. 1, 2 and 3 represent perspective views of thin bare piezoelectric Rochelle salt type crystal elements 1, 2 and 3 cut from crystalline Rochelle salt free from defects and made into a plate of substantially rectangular parallelepiped shape with its major surfaces having a length or longest dimension L and a width dimension W which is perpendicular to the length dimension L, the thickness or thin dimension T between the major surfaces being perpendicular to the other two dimensions L and W. In accordance with the particular mode or modes of motion selected, the final width dimension W of the Rochelle salt crystal element 1, 2 or 3 of Figs. 1, 2 and 3 may be made of suitable value according to the desired resonant frequency. The width dimension W also may be related to the length dimension L in accordance with the value of the desired 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, 2 or 3 of Figs. 1, 2 and 3 may be utilized.

As shown in Fig. 1, the length dimension L of the X-cut type crystal element 1 illustrated in Fig. 1 lies along a Y' axis in the plane of the mechanical axis Y and the optic axis Z of the Rochelle salt 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 49 degrees 56 minutes (49° 56'). The major surfaces and the major plane of the Rochelle salt crystal element 1 of Fig. 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 Y' is accordingly the result of a single rotation of the length dimension L about the X axis α degrees. It will be noted that the crystal element 1 of Fig. 1 is in effect an X-cut Rochelle

salt crystal plate rotated α degrees about the X axis.

Fig. 2 is a perspective view of a Y-cut Rochelle salt piezoelectric crystal element 2 having its longest or length dimension L along the X' axis and inclined at an angle of θ =substantially $42^\circ 26'$ with respect to the X axis, the major surfaces of the crystal element 2 being parallel or nearly parallel to the plane of the Z axis and the X axis.

Fig. 3 represents a Z-cut type Rochelle salt crystal element 3 having its length or longest dimension L along the X' axis and inclined at an angle θ which may be any angle intermediate the X and Y axes, the major surfaces of the crystal element 3 being parallel or nearly parallel to the plane of the X and Y axes.

The orientations illustrated in Figs. 1, 2 and 3 accordingly represent X-cut, Y-cut and Z-cut type Rochelle salt piezoelectric crystal elements 1, 2 and 3, respectively, which may be adapted for independently controlled longitudinal length L and longitudinal width W mode vibrations, and also other low frequency or face mode vibrations, which may be utilized either alone or simultaneously, according to the arrangement of the electrodes and connections that are used therewith, and the dimension-frequency constants that are selected therefor.

Suitable conductive electrodes, such as the crystal electrodes of Fig. 4, 5 or 6, for example, may be placed on or adjacent to or formed integral with the opposite major surfaces of the crystal plate 1, 2 or 3 of Figs. 1, 2 and 3 in order to apply electric field excitation to the Rochelle salt plate 1, 2 or 3 which may be vibrated alone or simultaneously in a desired width W fundamental longitudinal mode of motion and/or the length L longitudinal fundamental or harmonic mode of motion at independently controlled resonant response frequencies which depend upon different sets of dimensions involving the width dimension W and the length dimension L, the fundamental longitudinal length and width mode frequencies being roughly from 117 to 186 kilocycles per second per centimeter of the width dimension W, and of the length dimension L, or n times that value where n is the numerical order of the longitudinal mode harmonic frequency such as $n=2, 3$, etc. for the second, third, etc. harmonic longitudinal mode frequency along the length dimension L or the width dimension W.

The crystal electrodes and interconnections therebetween when formed integral with the major surfaces of any of the crystal elements of Fig. 1, 2 or 3 may consist of thin coatings of colloidal carbon, silver, gold, platinum, aluminum or other suitable metal or metals deposited upon the surfaces by painting, spraying, or evaporation in vacuum for example, or by other suitable process.

When the Rochelle salt crystal plate 1 or 2 has an orientation angle of α =substantially $49^\circ 56'$ with respect to the Y axis as illustrated in Fig. 1, or $\theta=42^\circ 26'$ with respect to the X axis as illustrated in Fig. 2, the length L longitudinal fundamental mode of motion or harmonic thereof is mechanically uncoupled to other modes such as the fundamental longitudinal or extensional mode of motion along the width dimension W of the crystal plate 1 or 2 and the latter may be used simultaneously, without coupling to, for example, the second harmonic extensional mode along length dimensional L.

To obtain the two longitudinal modes of mo-

tion simultaneously, one along the length dimension L and the other along the width dimension W, it is necessary that the crystal element have a piezoelectric constant which will generate a longitudinal motion along the width dimension W and also another piezoelectric constant that will generate a longitudinal motion along the length dimension L.

In the case of the X-cut type Rochelle salt crystal element 1 illustrated in Fig. 1, the requirement of suitable piezoelectric constants d'_{12} and d'_{13} may be met when the length dimension L is inclined at any suitable angle α between the Y and Z axes in the YZ plane, the YZ plane being parallel or nearly parallel to the major plane and the major surfaces of the Rochelle salt crystal element 1 of Fig. 1.

As indicated by Equations 31 and 32 of my paper "A dynamic measurement of the elastic, electric and piezoelectric constants of Rochelle salt" published April 15, 1939, in Physical Review, volume 55, page 775, the piezoelectric constants d'_{12} and d'_{13} involved in the longitudinal or extensional mode vibrations along the length dimension L and along the width dimension W, respectively, of the X-cut Rochelle salt crystal element 1 illustrated in Fig. 1 are equal to:

$$d'_{12} = \frac{d_{14}}{2} \sin 2\alpha; d'_{13} = \frac{d_{14}}{2} \sin 2\alpha \quad (1)$$

The constants d'_{12} and d'_{13} are of equal value as shown by Equation 1 and reach their maximum values when the angle $\alpha=45^\circ$ or when the length dimension L of the X-cut type Rochelle salt crystal element 1 of Fig. 1 is inclined 45° with respect to the Y and Z axes thereof, the major surfaces thereof being parallel to the plane of such Y and Z axes.

When it is desired to independently use these two desired modes, the angle α may be made $49^\circ 56'$ to provide for a zero or no coupling between either the length or the width longitudinal modes and the face shear mode, and thereby to avoid a resulting mechanical coupling between the desired second, or other harmonic, of the length longitudinal mode along the length axis L and the desired fundamental of the width longitudinal mode along the width axis dimension W. Since any coupling directly between the second harmonic longitudinal mode along the length dimension L and the fundamental longitudinal mode along the width dimension W cancels itself out, it is not necessary to provide for a zero coupling directly between these two modes.

When the length dimension L of the X-cut type Rochelle salt crystal element 1 of Fig. 1 is inclined at an angle of α =substantially $49^\circ 56'$ with respect to the Y axis, the coupling coefficient S'_{24} representing the coupling between the face shear mode and both the length L and width W longitudinal modes becomes zero.

As indicated by Equation 33 of my Physical Review paper hereinbefore referred to, the equation for the value of S'_{24} is:

$$S'_{24} = \sin^2 2\alpha \left[\left(S_{23} + \frac{S_{44}}{2} - S_{22} \right) \cos^2 \alpha + \left(S_{33} - S_{23} - \frac{S_{44}}{2} \right) \sin^2 \alpha \right] \quad (2)$$

where

$$S_{23} = -1.03 \times 10^{-12}$$

$$S_{27} = 3.495 \times 10^{-12}$$

$$S_{33} = 3.34 \times 10^{-12}$$

$$S_{44} = 7.98 \times 10^{-12}$$

α =the angle between the Y' length axis L and the Y axis, as illustrated in Fig. 1.

Substituting these values in the above Equation 2, the angle α for which S'_{24} becomes zero and vanishes is $\alpha=49^\circ 56'$, α being the angle between the length dimension L and the nearest Y axis, as illustrated in Fig. 1.

While the maximum values for the piezoelectric constants d'_{12} and d'_{13} occur when the angle $\alpha=45^\circ$, the angle of $\alpha=49^\circ 56'$ is near enough thereto to obtain good values of piezoelectric constants d'_{12} and d'_{13} and, moreover, at the same time obtain the desired longitudinal modes along the length dimension L and the width dimension W without interference or coupling with each other. Such an X-cut type Rochelle salt crystal element 1 of Fig. 1 also has a strong electromechanical coupling which varies somewhat with temperature change, and is easily driven by suitable electrodes in the two desired longitudinal modes of motion, one being along the length dimension L and the other along the width dimension W.

As illustrated in Fig. 2, a Y-cut type Rochelle salt piezoelectric crystal element 2 having its length dimension L along the X' axis and inclined at an angle of $\theta=42^\circ 26'$ with respect to the X axis also may be used as a doubly resonant crystal element. Such an element has an electromechanical coupling that does not vary much with temperature, and with the θ angle equal to substantially $42^\circ 26'$, the length L longitudinal mode of motion and width W longitudinal mode of motion are substantially free from coupling with each other and with any other modes of motion therein.

For the Y-cut type Rochelle salt crystal element 2 illustrated in Fig. 2, the piezoelectric constants controlling the longitudinal mode vibrations along the length dimension L and along the width dimension W are:

$$d'_{21} = -\frac{d_{25}}{2} \sin 2\theta; d'_{23} = \frac{d_{25}}{2} \sin 2\theta \quad (3)$$

The coupling coefficient or constant S'_{15} for the longitudinal length mode is:

$$S'_{15} = \sin^2 2\theta$$

$$\left[\left(S_{11} - S_{12} - \frac{S_{55}}{2} \right) \cos^2 \theta + \left(S_{13} - S_{33} + \frac{S_{55}}{2} \right) \sin^2 \theta \right] \quad (4)$$

where

θ = the angle between the length axis L along the X' axis and the X crystallographic axis.

$$S_{11} = 5.18 \times 10^{-12}$$

$$S_{33} = 3.34 \times 10^{-12}$$

$$S_{13} = -2.11 \times 10^{-12}$$

$$S_{55} = 32.8 \times 10^{-12}$$

Substituting these values in Equation 4, the angle θ for which S'_{15} becomes zero and vanishes is $\theta=42^\circ 26'$ as illustrated in Fig. 2.

When the angle $\theta=42^\circ 26'$, as illustrated in Fig. 2, there is substantially no coupling between either the longitudinal mode along the length axis dimension L or the longitudinal mode along the width axis dimension W and the face shear mode in the XZ plane of the Rochelle salt crystal element 2.

A Z-cut type Rochelle salt crystal element 3, as illustrated in Fig. 3, having its major surfaces perpendicular to the Z axis also may be used to generate fundamental and harmonic longitudinal mode width W and length L vibrations of the kind useful for a doubly resonant crystal element. However, in such a Z-cut type crystal element 3, the zero coupling angles of $\phi=0$ or 90 degrees involved in the two modes of longitudinal

motion referred to cannot be used since the piezoelectric constants d'_{32} and d'_{31} controlling these modes are both of zero value at the zero coupling angles of $\phi=0$ degrees or $\phi=90$ degrees, the angle ϕ being measured between the length or longest dimension L of the crystal element 3 and the nearest X axis thereof, as illustrated in Fig. 3.

For the Z-cut type Rochelle salt crystal element 3 of Fig. 3, the piezoelectric constants d'_{32} and d'_{31} are:

$$d'_{32} = -\frac{d_{36}}{2} \sin 2\phi; d'_{31} = \frac{d_{36}}{2} \sin 2\phi \quad (5)$$

and the coupling constant S'_{26} for the length or width longitudinal mode of motion and the face shear mode of motion is:

$$S'_{26} = \sin^2 2\phi$$

$$\left[\left(S_{22} - S_{12} - \frac{S_{66}}{2} \right) \cos^2 \phi + \left(S_{12} - S_{11} + \frac{S_{66}}{2} \right) \sin^2 \phi \right] \quad (6)$$

where ϕ is the angle between the length axis dimension L and the X crystallographic axis, as illustrated in Fig. 3.

$$S_{11} = 5.18 \times 10^{-12}$$

$$S_{12} = -1.53 \times 10^{-12}$$

$$S_{22} = 3.495 \times 10^{-12}$$

$$S_{66} = 10.08 \times 10^{-12}$$

Inserting these values in Equation 6, the S'_{26} coupling constant vanishes only at $\phi=0$ degrees and $\phi=90$ degrees. Since the piezoelectric constants d'_{32} and d'_{31} are both zero at both of these angles, a Z-cut type Rochelle salt crystal element 3 having its length or longest dimension L disposed or inclined at an angle of $\phi=0$ or 90 degrees with respect to its major plane X axis is not useful at these particular angles as a doubly resonant crystal element involving the second harmonic of the length L longitudinal mode of motion and the fundamental of the width W longitudinal mode of motion. However, such a Z-cut type Rochelle salt crystal element 3 may be utilized at ϕ angles other than those of 0 or 90 degrees and particularly at the angle of $\phi=45$ degrees for a single longitudinal mode of motion.

The principal modes of interest that are particularly considered herein in connection with the X-cut, Y-cut and Z-cut type crystal orientations illustrated in Figs. 1, 2 and 3 are the width longitudinal mode of motion along the width W axis and also the length longitudinal mode of motion, fundamental and harmonic, along the length dimension L of the crystal elements 1, 2 and 3 illustrated in Figs. 1, 2 and 3. The longitudinal width W mode vibration, fundamental or harmonic, operates to alternately extend and shorten the width dimension W of the crystal element 1, 2 or 3 about a nodal line which for the fundamental vibration extends along the center line length dimension L of the crystal element 1, 2 or 3. Similarly, the longitudinal length L mode of motion, fundamental or harmonic, operates to alternately extend and shorten the length dimension L of the crystal element about a nodal line which for the fundamental mode vibration is located on the center line width dimension W of the crystal element 1, 2 or 3. The broken lines and arrows shown in Fig. 2 of the H. J. McSkimin and R. A. Sykes application hereinbefore referred to represent, in greatly enlarged scale, the general configuration of the edges of a crystal element operating in the type of motion involved in the width W longitudinal mode. The

length L longitudinal motion is of a similar nature.

Since the nodes involved in the length L longitudinal mode of motion are located on the nodal line involved in the width longitudinal mode of motion, the crystal elements of Fig. 1, 2 or 3 may be mounted there or near the nodal point or points without damping or interfering with the simultaneous operation of either the width W longitudinal mode vibration or the length L longitudinal mode vibration. In the case of the second harmonic of the length L longitudinal mode vibration, the two nodal point regions on each of the major surfaces would be located on the center line length dimension L of the crystal element at points spaced about 0.25 of the length dimension L from each end thereof. Accordingly, at such nodal points the crystal element of Fig. 1, 2 or 3 may be mounted by rigidly clamping it there between two pairs of oppositely disposed clamping projections of small contact area which may be there placed or inserted in very small indentations or depressions cut or provided at the four nodal points of the crystal element. Such small depressions may be cut in the major surfaces of the crystal element at the nodal points thereof and may have a depth of about 0.05 millimeter and a diameter of about 0.4 millimeter as measured on the major surfaces of the crystal element.

The relative values of the resonance frequencies associated with the width W longitudinal mode vibration and with the length L longitudinal mode vibration in a crystal element having an orientation illustrated in Fig. 1, 2 or 3 may be controlled by the dimensional ratio of width W with respect to length L . For the X-cut, Y-cut, and Z-cut crystal elements 1, 2 and 3 having orientation angles of $\alpha=49^\circ 56'$, $\theta=42^\circ 26'$ and $\phi=45^\circ$ respectively, as illustrated in Figs. 1, 2 and 3, the fundamental of the width W longitudinal mode frequency has a frequency-dimension constant respectively of 160, 118 or 186 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 fundamental of the length L longitudinal mode vibration of such X-cut, Y-cut, and Z-cut crystal elements 1, 2 and 3 having the particular orientation angles mentioned and illustrated in Figs. 1, 2 and 3, has a frequency-dimension constant of the same value, namely 160, 118 or 186 kilocycles per second per centimeter of length dimension L independent of the value of the selected dimensional ratio of width W with respect to length L , and two times that value for the second harmonic frequency thereof. The frequencies of these two modes of motion, namely the second harmonic of the longitudinal length L mode, and the fundamental of the longitudinal width W mode approach each other when the ratio of the width dimension W with respect to the length dimension L is in the region of about 0.5; and in this region of special interest, the resonances of these two modes are substantially uncoupled or only very loosely coupled when the α angle of the Rochelle salt crystal element 1 has a value of substantially $49^\circ 56'$ as illustrated in Fig. 1 or the θ angle of the crystal element 2 of Fig. 2 has a value of substantially $42^\circ 26'$.

Accordingly, when the dimensional ratio of W/L is in the region of 0.5 and the orientation is that of Fig. 1 or 2, the frequencies of these two independent modes of vibration may be placed close together but remain sufficiently uncoupled

to provide simultaneously two independently controlled frequencies from the same Rochelle salt crystal element, 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 50 or less to 500 or more kilocycles per second.

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

$$f = \frac{160}{W}; f = \frac{117.5}{W}; f = \frac{186}{W}$$

respectively, for the crystal elements 1, 2 and 3 where W is the length value of the width dimension W of the crystal element 1, 2 or 3 of Fig. 1, 2 or 3 expressed in centimeters.

The fundamental frequency in kilocycles per second of the longitudinal length L mode vibration is given by the same relation:

$$f = \frac{160}{L}; f = \frac{117.5}{L}; f = \frac{186}{L}$$

for the crystal elements 1, 2 and 3 respectively, where L is the length dimension L of the crystal plate expressed in centimeters. The foregoing frequency-dimension constants respectively represent values that obtain when the X-cut, Y-cut and Z-cut crystal elements 1, 2 and 3 have the orientation angles of $\alpha=49^\circ 56'$, $\theta=42^\circ 56'$ and $\phi=45^\circ$, as illustrated in Figs. 1, 2 and 3.

Figs. 4, 5 and 6 illustrate forms of electrode arrangements which may be utilized to drive any of the crystal elements of Fig. 1, 2 or 3. As illustrated in Fig. 4, a single pair of electrodes 9 and 15 may be used to drive the crystal element 1, 2 or 3 in either the width W longitudinal fundamental mode vibration or the fundamental of the longitudinal length L mode of motion to obtain separately, but not simultaneously, either of two independently controlled longitudinal fundamental mode resonance frequencies of a desired value.

More particularly, Fig. 4 is a perspective view of the crystal element 1, 2 or 3 of Figs. 1, 2 and 3 provided with a pair of opposite electrodes 9 and 15 which may be utilized to usefully operate separately, but not together, in the crystal element 1, 2 or 3 of Figs. 1 to 3, the fundamental of the longitudinal length L mode of motion or that of the longitudinal width W mode of motion at a frequency of 117 to 186 kilocycles per second per centimeter of length dimension L or width dimension W . For this purpose the electrodes 9 and 15 may partially or wholly cover the major surfaces of the crystal element 1, 2 or 3 and may be supported and connected in circuit by means of suitable conductive members disposed in contact with each of the electrodes 9 and 15. It will be understood that Rochelle salt crystal elements of the type having the orientation angles $\alpha=49^\circ 56'$ or $\theta=42^\circ 26'$ illustrated in Figs. 1 and 2, for example, and provided with a pair of electrodes of the type illustrated in Fig. 4 may be utilized to obtain a desired fundamental length L longitudinal mode vibrational frequency that is substantially uncoupled with any other mode of motion therein. Where a harmonic of such fundamental longitudinal mode is used, the harmonic frequency is likewise free from coupling to other modes of motion. The harmonic frequency may be of any desired order and may be obtained by the use of electrode arrangements known in the art in connection with quartz longitudinal

mode crystal elements, such as, for example, those shown in Mason U. S. Patent 2,185,599 dated January 2, 1940.

As shown in Fig. 5, the second harmonic of the longitudinal length L mode of motion may be driven by means of two pairs of electrodes 10, 11, 12 and 13 placed on both of the major surfaces of the crystal element of Fig. 1, 2 or 3; and also with suitable connections, the fundamental of the longitudinal width W mode of motion may be driven at the same time by one set of the connected sets of electrode platings 10 to 13, with the result that the two useful and independently controlled resonance frequencies of the crystal element may be made to appear simultaneously. More particularly, as illustrated in Fig. 5, the Rochelle salt crystal element 1, 2 or 3 of Fig. 1 2 or 3 may be provided with four equal-area electrodes 10, 11, 12 and 13, two of the electrodes 10 and 11 being placed on one major surface 20 of the crystal element with a centrally located narrow transverse split, gap or dividing line 7 therebetween, and the other two electrodes 12 and 13, being oppositely disposed and placed on the opposite major surface of the crystal element and separated with a similar narrow and oppositely disposed split or dividing line 7 therebetween, the dividing lines 7 extending generally in the direction of the width W axis of the crystal element according to the value of the angle selected between the direction of the dividing line 7 and the direction of the length dimension L . The gap or separation between the electrode coatings or platings on each of the major surfaces of the crystal element may be of the order of about 0.3 millimeter, with the center line of such splits 7 in the platings 10 to 13 on the opposite sides of the crystal plate 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 arrangement of Fig. 5 in order to obtain a filter system comprising a single Rochelle salt crystal element having two independently controlled and simultaneously effective resonances which may be placed at desired frequencies, one of which may appear in the line branch of the equivalent lattice and the other in the diagonal branch thereof, as described more fully in connection with Figs. 2 and 3 of the Mason application Serial No. 303,757 referred to hereinbefore.

The balanced circuit of Fig. 5 may be converted into an unbalanced filter structure by interconnecting the two electrodes 12 and 13 on one of the major surfaces of the crystal element. In this case, the two electrodes 12 and 13 of Figs. 5 and 7 may be replaced by a single electrode 15 as shown in Fig. 6, and the electroded crystal element of Fig. 6 may be connected as shown schematically in Fig. 8 and as described more fully in connection with Figs. 6 and 7 of the Mason application Serial No. 303,757 hereinbefore referred to.

As illustrated in Fig. 8, to reduce the magnitude of the shunting capacitance appearing in the line branch of the lattice portion, a narrow grounding strip 14 of metallic or conductive coating or plating may be placed on one major surface of the crystal element between the electrodes 10 and 11. The strip 14 may extend around one edge of the crystal element 1 to the opposite major surface thereof where it may be electrically connected to the large electrode 15. The ground strip

14 may be approximately 1 millimeter in width and may be placed between and separated from the two electrodes 10 and 11 on the same major surface of the crystal element 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 15 on that surface. It will be noted that in order to drive the electroded crystal element of Fig. 5 or 6 in the second harmonic of the longitudinal length mode of motion, one half of the crystal plate is made of opposite polarity to that of the other half, as indicated by the + and - signs in Figs. 5 and 6, and that this may be accomplished by utilizing a crystal element 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. 8. Inductance coils may be added in the usual manner in series or in parallel with the network of Fig. 8 to produce broad band low or high impedance filters, for example. In order that the crystal impedance may appear in both arms of the lattice structure of Fig. 8, one mode is driven when the terminals 21 and 23 are both of same polarity, and the other mode is driven when these terminals 21 and 23 are of opposite polarity. Since both modes are substantially uncoupled they may produce simultaneously two independently controlled resonances of predetermined frequencies of desired values.

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, 2 or 3 of Figs. 5 and 6 may be extended to cover a portion of the other half thereof. This may be done, for example, by adjustment of the angular position of the electrode dividing line 7 with respect to the length dimension L . The angle may be any desired value over a wide range of angles. This adjustment does not materially affect the impedance of the longitudinal width W mode resonance, but with decreasing values for the 90-degree angle shown in Figs. 5 and 6 will increase the impedance level of and cut down the drive on second harmonic length L mode resonance, without materially affecting the impedance of the width W 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 length dimension L of the crystal element illustrated by a 90-degree angle in Figs. 5 and 6, the internal capacity associated with the second harmonic of the longitudinal length L mode of motion, which is nearly a maximum value when the angle equals 90 degrees as shown in Figs. 5 and 6, may be varied and adjusted to a desired value without changing the internal capacity associated with longitudinal width W mode.

It will be understood that the circuits illustrated in Figs. 7 and 8 represent particular circuits. These and other forms of filter circuits, in which a doubly resonant crystal element may be utilized, are described in W. P. Mason application Serial No. 303,757 hereinbefore referred to. 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 2,198,634, granted April 30, 1940,

to R. A. Sykes on application Serial No. 230,775, filed September 20, 1938.

The electroded doubly resonant crystal elements of Figs. 4, 5 and 6 may be mounted in any suitable manner, such as by nodal clamping, or otherwise. Where the clamping form of mounting is used, opposite conductive clamping projections may resiliently contact the electroded crystal element at its nodal points only in order to support and to establish individual electrical connections therewith.

Alternatively, instead of being mounted by clamping, the electroded crystal plate may be mounted and electrically connected by cementing or otherwise firmly attaching fine conductive supporting wires directly to a thickened part of the electrodes of the crystal element at its nodal points only. Such fine supporting wires may be secured to the electroded crystal element by conductive cement and may extend horizontally from the vertical major surfaces of the crystal element and at their other ends be attached by solder, for example, to 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 in order to limit the bodily displacement thereof when the device is subjected to mechanical shock. In a suitable mounting of this type for the crystal element, the horizontal supporting wires may be spaced along the vertical rods to suit the nodal points of the electroded crystal elements. 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 may be utilized for mounting the crystal element.

Although this invention had 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 face mode piezoelectric Rochelle salt type crystal element having its substantially rectangular major surfaces substantially parallel to 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 $49^{\circ} 56'$ 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 0.20 and 1.0.
2. A face mode piezoelectric Rochelle salt type crystal element having its substantially rectangular major surfaces substantially parallel to the plane of an X axis and the Z axis, the major axis length dimension of said major surfaces being inclined at an angle of substantially $42^{\circ} 26'$ with respect to said X 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 0.2 and 1.0.
3. A piezoelectric Rochelle salt type crystal element having its substantially rectangular major surfaces substantially parallel to the plane of

two of the three mutually perpendicular X, Y and Z axes thereof, the major axis length dimension of said major surfaces being in said plane and intermediate said two of said three X, Y and Z axes, 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 0.2 and 1.0, and means including a plurality of sets of functionally independent electrodes adjacent said major surfaces for operating said element simultaneously at a plurality of independently controlled frequencies dependent upon different sets of said major surface dimensions, one of said frequencies being dependent upon the fundamental of the longitudinal or extensional mode vibration along said width or length dimension.

4. A piezoelectric Rochelle salt type crystal element having its substantially rectangular major surfaces substantially parallel to the plane of two of the three mutually perpendicular X, Y and Z axes thereof, the major axis length dimension of said major surfaces being in said plane and intermediate said two of said three X, Y and Z axes, the dimensional ratio of the width dimension of said major surfaces with respect to said length dimension thereof being one of the values substantially in the region of 0.5, and means including a plurality of sets of functionally independent electrodes adjacent said major surfaces for operating said element simultaneously at a plurality of independently controlled frequencies dependent upon said major surface 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 second harmonic of the longitudinal or extensional mode vibration along said length dimension.

5. A piezoelectric Rochelle salt type crystal element adapted to vibrate simultaneously at a plurality of desired independently controlled longitudinal mode frequencies one of which is dependent mainly upon the length dimension and another of which is dependent upon the width dimension 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 $49^{\circ} 56'$ 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 0.50.

6. A piezoelectric Rochelle salt type crystal element adapted to vibrate simultaneously at a plurality of desired independently controlled longitudinal mode frequencies one of which is dependent mainly upon the length dimension and another of which is dependent upon the width dimension of its substantially rectangular major surfaces, said length dimension being substantially in the plane of an X axis and the Z axis and inclined at an angle of substantially $42^{\circ} 26'$ with respect to said X axis, said major surfaces being substantially parallel with respect to said XZ 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 region of substantially 0.50, said width dimension expressed in centimeters being a value of substantially 118 divided by said another of

said frequencies expressed in kilocycles per second.

7. A piezoelectric Rochelle salt type crystal element adapted to vibrate simultaneously at a plurality of independently controlled frequencies dependent mainly upon different sets of 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 $49^{\circ} 56'$ 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 0.2 to 1.0, said width dimension and said length dimension being a set of corresponding values in accordance with the values of said frequencies.

8. A piezoelectric Rochelle salt type crystal element adapted to vibrate simultaneously at a plurality of desired independently controlled frequencies dependent mainly upon different sets of the length and width dimensions of its substantially rectangular major surfaces, said length dimension being substantially in the plane of an X axis and the Z axis and inclined at an angle of substantially $42^{\circ} 26'$ with respect to said X axis, said major surfaces being substantially parallel with respect to said XZ 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 0.2 to 1.0, said width dimension and said length dimension being a set of corresponding values in accordance with the values of said frequencies.

9. A piezoelectric Rochelle salt type crystal element and means including two functionally independent pairs of opposite electrodes cooperating with said element for vibrating said element simultaneously at two independently controlled desired frequencies dependent mainly upon different sets of the length and width dimensions of the rectangular 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 substantially $49^{\circ} 56'$ with respect to said Y axis, said major surfaces being substantially parallel with respect to said YZ plane.

10. A piezoelectric Rochelle salt type crystal element and means including two functionally independent pairs of opposite electrodes cooperating with said element for vibrating said element simultaneously at two independently controlled desired frequencies dependent mainly upon different sets of the length and width dimensions of the rectangular major surfaces of said element, said length dimension being substantially in the plane of an X axis and the Z axis and disposed at an angle of substantially $42^{\circ} 26'$ with respect to said X axis, said major surfaces being substantially parallel with respect to said XZ plane.

11. A Rochelle salt type piezoelectric crystal element adapted to vibrate at a desired longitudinal or extensional mode frequency, said crystal element having substantially rectangular shaped major surfaces, said major surfaces having a length or longer dimension and width or shorter dimension, said length dimension being made of a value in accordance with the value of said desired frequency, said major surfaces and said length and width dimensions being sub-

stantially parallel to the plane of a Y axis and a Z axis thereof, and said length dimension being inclined at an angle of substantially $49^{\circ} 56'$ with respect to said Y axis to obtain said desired longitudinal mode frequency substantially free from coupling with other modes of motion in said crystal element.

12. A Rochelle salt crystal element in accordance with claim 11 wherein said desired longitudinal mode frequency is a fundamental mode frequency, and said length dimension expressed in centimeters is equal to substantially 160 divided by said desired frequency expressed in kilocycles per second.

13. A Rochelle salt crystal element in accordance with claim 11 wherein said desired longitudinal mode frequency is a harmonic mode frequency, and said length dimension expressed in centimeters is equal to substantially 160 divided by said desired frequency expressed in kilocycles per second, and multiplied by the numerical order of said harmonic frequency.

14. A Rochelle salt type piezoelectric crystal element adapted to vibrate at a desired longitudinal or extensional mode frequency, said crystal element having substantially rectangular shaped major surfaces, said major surfaces having a length or longer dimension and width or shorter dimension, said width dimension being made of a value in accordance with the value of said desired frequency, said major surfaces and said length and width dimensions being substantially parallel to the plane of a Y axis and a Z axis thereof, and said length dimension being inclined at an angle of substantially $49^{\circ} 56'$ with respect to said Y axis to obtain said desired longitudinal mode frequency substantially free from coupling with other modes of motion in said crystal element.

15. A Rochelle salt crystal element in accordance with claim 14 wherein said desired longitudinal mode frequency is a fundamental mode frequency, and said width dimension expressed in centimeters is equal to substantially 160 divided by said desired frequency expressed in kilocycles per second.

16. A Rochelle salt type piezoelectric crystal element adapted to vibrate at a desired longitudinal or extensional mode frequency, said crystal element having substantially rectangular shaped major surfaces, said major surfaces having a length or longer dimension and width or shorter dimension, said length dimension being made of a value in accordance with the value of said desired frequency, said major surfaces and said length and width dimensions being substantially parallel to the plane of an X axis and a Z axis thereof, and said length dimension being inclined at an angle of substantially $42^{\circ} 26'$ with respect to said X axis to obtain said desired longitudinal mode frequency substantially free from coupling with other modes of motion in said crystal element.

17. A Rochelle salt crystal element in accordance with claim 16 wherein said desired longitudinal mode frequency is a fundamental mode frequency, and said length dimension expressed in centimeters is equal to substantially 118 divided by said desired frequency expressed in kilocycles per second.

18. A Rochelle salt crystal element in accordance with claim 16 wherein said desired longitudinal mode frequency is a harmonic mode frequency, and said length dimension expressed in centimeters is equal to substantially 118 di-

vided by said desired frequency expressed in kilocycles per second, and multiplied by the numerical order of said harmonic frequency.

19. A Rochelle salt type piezoelectric crystal element adapted to vibrate at a desired longitudinal or extensional mode frequency, said crystal element having substantially rectangular shaped major surfaces, said major surfaces having a length or longer dimension and width or shorter dimension, said width dimension being made of a value in accordance with the value of said desired frequency, said major surfaces and said length and width dimensions being substantially parallel to the plane of an X axis and a

5 Z axis thereof, and said length dimension being inclined at an angle of substantially $42^{\circ} 26'$ with respect to said X axis to obtain said desired longitudinal mode frequency substantially free from coupling with other modes of motion in said crystal element.

20. A Rochelle salt crystal element in accordance with claim 19 wherein said desired longitudinal mode frequency is a fundamental mode frequency, and said width dimension expressed in centimeters is equal to substantially 118 divided by said desired frequency expressed in kilocycles per second.

WARREN P. MASON.