

Jan. 2, 1940.

W. P. MASON

2,185,599

PIEZOELECTRIC APPARATUS

Filed Feb. 21, 1936

3 Sheets-Sheet 1

FIG. 1

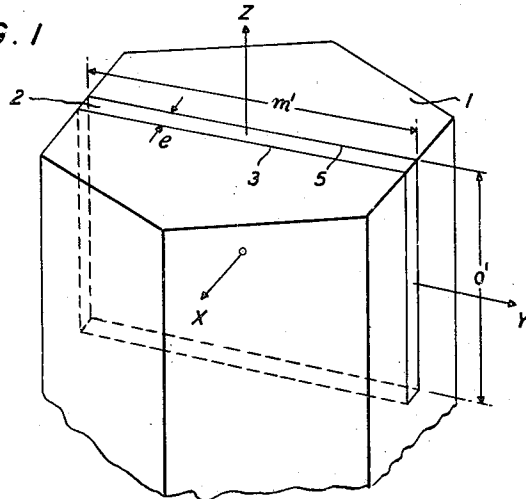


FIG. 2

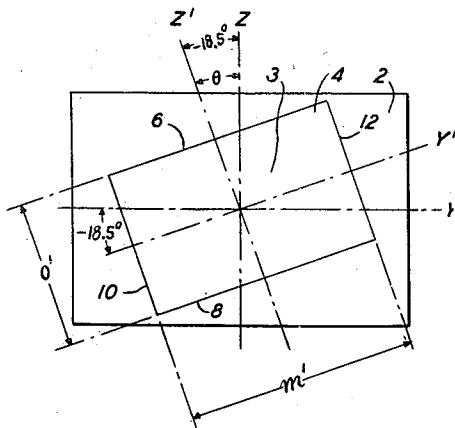


FIG. 3

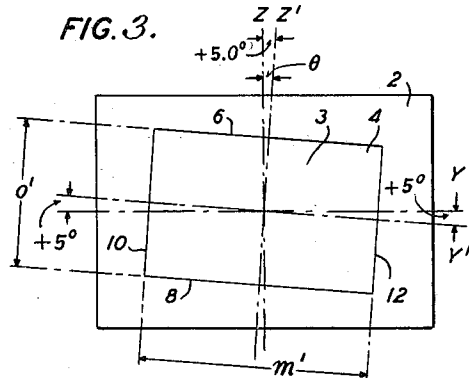
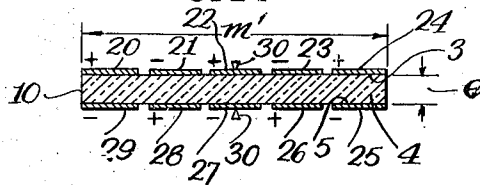


FIG. 4



INVENTOR
W. P. MASON
BY W. J. O'Neill
ATTORNEY

Jan. 2, 1940.

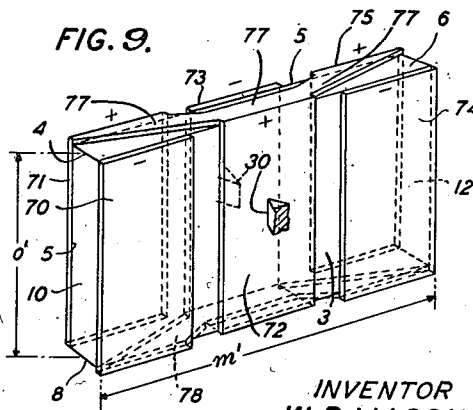
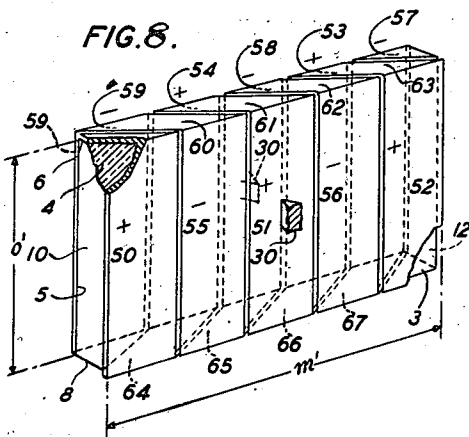
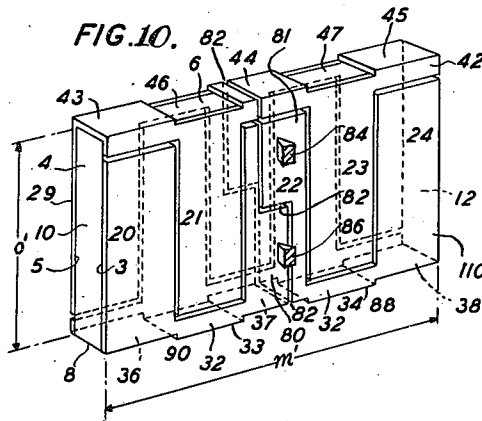
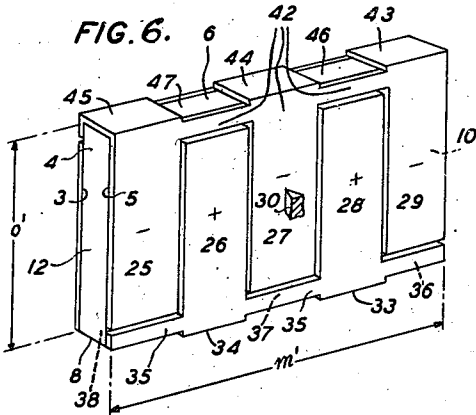
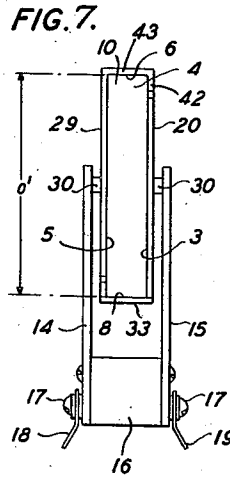
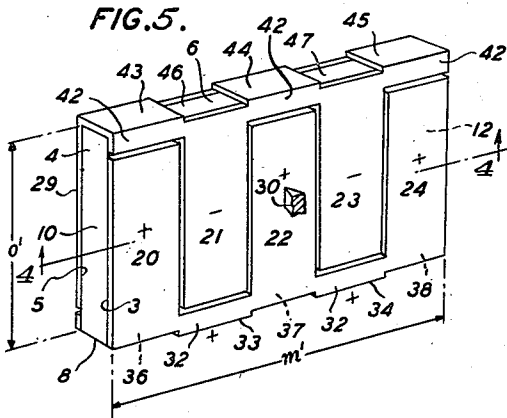
W. P. MASON

2,185,599

PIEZOELECTRIC APPARATUS

Filed Feb. 21, 1936

3 Sheets-Sheet 2



INVENTOR
W. P. MASON
BY
W. J. O'NEIL
ATTORNEY

Jan. 2, 1940.

W. P. MASON

2,185,599

PIEZOELECTRIC APPARATUS

Filed Feb. 21, 1936

3 Sheets-Sheet 3

FIG. 11.

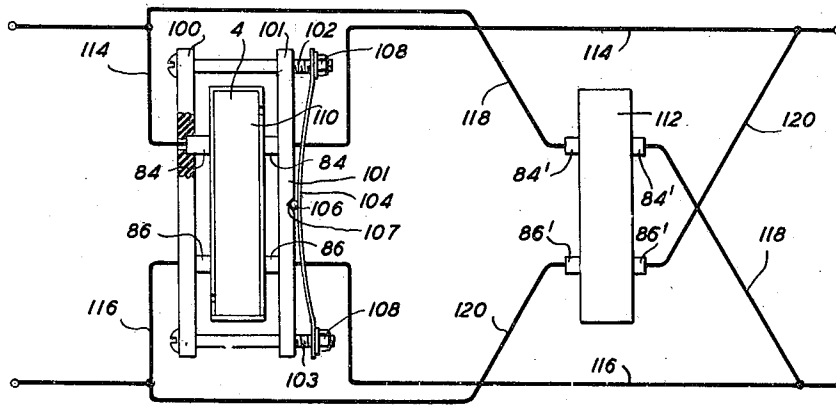


FIG. 12.

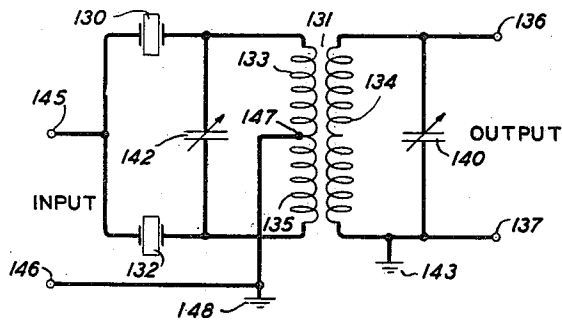


FIG. 14.

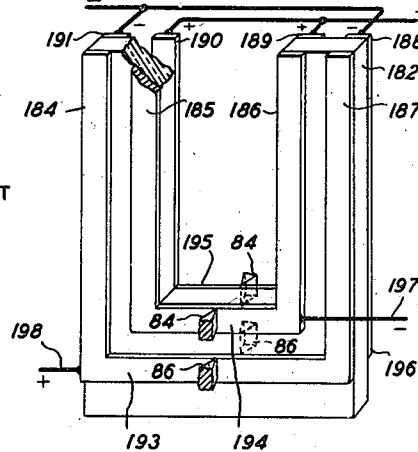
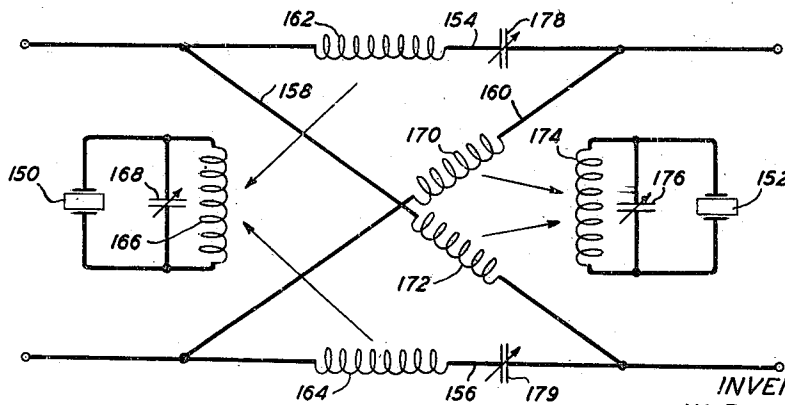


FIG. 13.



INVENTOR
W. P. MASON
BY
W. J. O'Neill
ATTORNEY

UNITED STATES PATENT OFFICE

2,185,599

PIEZOELECTRIC APPARATUS

Warren P. Mason, West Orange, N. J., assignor
to Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application February 21, 1936, Serial No. 65,022

24 Claims. (Cl. 171—327)

This invention relates to piezoelectric apparatus and particularly to piezoelectric crystal apparatus which may be utilized advantageously, for example, in electric wave filter systems such as in high frequency coaxial conductor filter systems or in radio filter systems for transmitters or receivers, for example, to separate bands of frequencies.

One of the objects of this invention is to obtain a substantially single frequency response from a piezoelectric crystal.

Another object of this invention is to extend the useful frequency range of piezoelectric crystals and electric wave filters up to and above three or four million cycles per second.

Another object of this invention is to dispense with soldered or wire connections or the like in connection with the electrodes of piezoelectric crystals.

Another object of this invention is to reduce the number of clamping devices associated with a piezoelectric crystal.

Another object of this invention is to reduce the number of piezoelectric elements employed in a circuit.

Another object of this invention is to reduce the impedance of a piezoelectric crystal.

Quartz crystal filter structures as heretofore constructed have been limited in their upper frequency range due either to the small size of the crystal with increasingly higher frequencies or to the large number of undesired extra or additional resonances that obtain near the main or desired frequency of the crystal.

In accordance with this invention, a piezoelectric quartz crystal for example, may be of moderately large size and may have such shape or relative dimensions and such orientation as to obtain substantially or effectively a single frequency response for a third, fifth, or any other desired harmonic frequency thereof without undesired extra or additional resonances near such main or desired harmonic frequency.

By utilizing such harmonic crystals cut to have certain shapes or ratios of axes to obtain single frequency responses for the selected harmonic frequency, the useful ranges of quartz crystals, for example, may be extended up to comparatively high frequencies such as, for example, up to three or four million cycles per second.

The crystal element may be an X-cut crystal element which is one that has its two parallel major or electrode faces or surfaces disposed perpendicular to the direction of the X or electric

axis of the natural crystal from which the element is cut.

The angular orientation of the axes or boundary surfaces of the crystal element with respect to the crystallographic axes of the natural crystal may vary over a range as to positive and negative directions and as to angular extent. One of the preferred ranges of angular orientations of the longest axis of an X-cut quartz crystal element about the electrical or X axis is from a negative (—) angle of about minus (—) 18.5 degrees to a positive (+) angle of about plus (+) 10 degrees with respect to the fundamental crystalline mechanical or Y axis of the natural crystal. Where a small coupling to the shear mode of motion of the crystal element is desired, the angular orientation of the principal axis or axis of greatest length of the X-cut quartz crystal element about the electrical or X axis may be substantially —18.5 degrees with respect to the direction of the mechanical or Y axis of the natural quartz crystal. Where a low or small value of temperature coefficient of frequency is desired, the angular orientation about the electrical or X axis of the axis of greatest length of the X-cut quartz crystal element may be substantially +5 degrees with respect to the mechanical or Y axis of the natural quartz crystal.

A piezoelectric crystal element may be driven at a harmonic longitudinal frequency by employing the same number of sets or pairs of oppositely disposed electrode platings as the number of the desired harmonic frequency. For example, to drive the crystal in longitudinal vibration at its third harmonic frequency, three sets or pairs of oppositely disposed electrode plates may be utilized. It will be understood that the number of sets or pairs of electrode plates may correspond to the odd or even number or order of harmonic frequency that may be desired. The odd harmonic crystal is of special interest because it has a node of its motion substantially at the geometrical center of the crystal element and accordingly may be conveniently nodally clamped and electrically connected there along the nodal line by any suitable clamping means such as, for example, by a pair of resiliently supported coaxial metallic prongs or projections each having a clamping area disposed in contact with the middle pair of oppositely disposed crystal electrode plates. The corners of the clamping areas of the clamping projections may be rounded to prevent stress concentrations.

By suitable interconnections between all positive plates and between all negative plates, but

not between the positive and negative plates, the electrode plates on one surface or face of the crystal may be made alternately positive and negative and of opposite polarity to the oppositely disposed electrode plates on the opposite surface or face of the crystal. By reason of the parallel circuit connections between the plurality of plates of the same polarity, a lower value of impedance in the crystal unit may be obtained.

The interconnections between the electrode plates as well as the electrode plates themselves may be formed by metallic coatings or platings associated or integral with the surfaces of the crystal thereby dispensing with soldered or wire connections. The connection platings may be formed, for example, on the side edges or on both the side edges and the major face margins of the crystal elements. The integral metallic platings or coatings may be of any suitable metal or metals such as, for example, aluminum, gold, platinum, chromium on top of the platinum, or other conductive material, and may be applied to or deposited on the surfaces of the crystal by any suitable method such as, for example, by sputtering, spraying, evaporation, cementing, rolling with a hot roller, or otherwise. Where the crystal has been first coated substantially over all its surfaces with the metallic material, undesired portions or parts of the original metallic coating may be removed to form the electrode plates and their interconnections in any suitable manner, such as, for example, by erasure, grinding, etching by suitable acid or otherwise removing undesired parts of the original plating. The corners of the crystal may be rounded off to remove sharp corners to prevent wear or damage to the metallic platings thereon by relieving stress concentrations, and to prevent chipping of the crystal when dividing the platings.

To obtain two separate circuits of equal impedance and equal frequency on one crystal, the crystal may be divided electrically into two halves by a construction wherein both middle electrode plates are divided into two parts by a plate division disposed centrally of the middle plates between two clamping points on the nodal line of the crystal and extending all the way around the crystal. The crystal may be nodally clamped and externally electrically connected by suitable clamping means such as by two pairs or sets of coaxial metal-coated clamping projections, one set of clamping projections making contact with one-half of the middle crystal electrodes and the other set making contact with the other half of the middle crystal electrodes. Such electrically divided crystal may be utilized, for example, in a balanced lattice type of electric wave filter with a resulting saving in the number of crystals and clamping devices employed for mounting the crystal.

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

Fig. 1 is a perspective view of an X-cut crystal element in relation to the natural quartz crystal;

Fig. 2 is a view of an X-cut crystal element having an orientation of -18.5 degrees;

Fig. 3 is a view of an X-cut crystal element having an orientation of $+5.0$ degrees;

Fig. 4 is a mid-cross-sectional side edge view

taken on the line 4—4 of the crystal element shown in Fig. 5;

Fig. 5 is a perspective view, greatly enlarged, of a fifth harmonic crystal embodying this invention;

Fig. 6 is a perspective view of the opposite side of the device shown in Fig. 5;

Fig. 7 is an end view of the device shown in Figs. 5 and 6 together with a holder therefor;

Fig. 8 is a partly broken and enlarged perspective view of another embodiment of the invention;

Fig. 9 is an enlarged perspective view of another embodiment of the invention;

Fig. 10 is an enlarged perspective view of another embodiment of the invention;

Fig. 11 is an end view of the device shown in Fig. 10, together with a holder and circuit connections therefor;

Fig. 12 illustrates another form of circuit connections;

Fig. 13 illustrates another form of circuit connections; and

Fig. 14 is a partly broken and enlarged perspective view of a tuning fork crystal embodying a feature of this invention.

Referring to the drawings, Fig. 1 is a perspective view of part of a "right-hand" natural quartz crystal 1. The three principal crystallographic axes thereof are, as indicated, the electrical or X axis, the mechanical or Y axis, and the optic or Z axis. A piezoelectric element or slab 2 having a length or longitudinal dimension m' , a width or breadth dimension o' , and a uniform thickness dimension e may be cut out of the natural crystal 1 in such manner that both of the widest or major surfaces 3 and 5 thereof are disposed perpendicular to an X or electrical axis of the natural crystal 1. Such cut of crystal element 2 is known as an X-cut crystal.

From the crystal slab 2, another piezoelectric element or slab 4 of rectangular surfaces may be sliced out, the edges 6, 8, 10, and 12 and axes o' , m' of which are oriented a negative angle θ of -18.5 degrees with respect to the Y or mechanical axis and the Z or optic axis, as illustrated in Fig. 2. The negative angle of orientation θ is defined hereinafter and in a paper published by applicant in the Bell System Technical Journal, volume XIII, No. 3, July 1934, at page 437. It will be understood that the slab 4 may be angularly oriented positively or negatively to any desired position such as, for example, anywhere within the region from $\theta = -18.5$ degrees, as shown in Fig. 2, to about $\theta = +10$ degrees or more. The -18.5 degree orientation of the quartz crystal element 4, as shown in Fig. 2 and as described and claimed in copending application Serial No. 702,334 filed December 14, 1933 by W. P. Mason and R. A. Sykes, now U. S. Patent No. 2,173,589, dated September 19, 1939, has a small value of coupling for the shear mode of motion thereof and hence any additional resonances due to that mode of motion will be at a minimum. The $+5$ degree orientation of the axes o' and m' of the quartz crystal element 4, as shown in Fig. 3, has the lowest value of temperature coefficient of frequency for orientations in the region from -18.5 degrees to $+10.0$ degrees.

Other alternative angular orientations may include the following: A piezoelectric quartz crystal element having its major plane and its opposite electrode surfaces substantially perpendicular to an electric crystallographic axis thereof as illustrated by the element 4 in Fig. 2, for ex-

ample, but having its major axis inclined at an angle θ —substantially —7.5 degrees with respect to the mechanical crystallographic axis thereof, instead of substantially —18.5 degrees as illustrated in Fig. 2, has a maximum value of piezoelectric constant d_{12} , and the greatest polarization for an applied stress and also the greatest expansions per unit length for a given applied voltage as shown from the following direct and inverse piezoelectric equations for a perpendicularly cut quartz crystal,

$$-P_x = -d_{12}Y; \quad y_y = -d_{12}E$$

and as shown in the appendix of applicant's paper, "Electrical Wave Filters Employing Quartz Crystals as Elements" published in the Bell System Technical Journal, Vol. XIII, pages 405 to 452, Fig. 35, July 1934; and such quartz element having such —7.5 degree orientation may be advantageously utilized where the largest expansion for a given applied voltage is desired as, for example, to mechanically operate a pivoted lever of a contact making relay, or where the largest polarization for a given applied force is desired as, for example, as a static or alternating stress measuring indicator where, when a force is applied to an end of such crystal, a polarization is generated in the electrode plates thereof, which may be measured by any suitable means, as an electrostatic voltmeter or by a vacuum tube voltmeter system, for example.

As another alternative orientation, a piezoelectric quartz crystal element having its major plane and its opposite electrode surfaces substantially perpendicular to an electric crystallographic axis thereof and having its major axis inclined at an angle θ —substantially +4, or from +4 to +5 degrees with respect to the mechanical crystallographic axis thereof, has, at such angular orientation, its maximum electromechanical or piezoelectric coupling and hence its lowest "r" or ratio of capacities occurring in the equivalent electrical network thereof and such element having such orientation may be utilized for obtaining wide frequency band wave filters, for the lower the value of such ratio of capacities, the wider will be the pass band of the filter.

As still another alternative orientation, a piezoelectric quartz crystal element having its major plane and its opposite electrode surfaces substantially perpendicular to an electric crystallographic axis thereof and having its major axis inclined at an angle θ —substantially —10 to —12 degrees with respect to the mechanical crystallographic axis thereof, may be utilized to obtain almost as good a result in respect to a single resonance response as may be obtained by an element having the —18.5 degree orientation as illustrated in Fig. 2, and has the advantage of a smaller temperature coefficient of frequency.

It will be noted that the quartz crystal element having an orientation of substantially —18.5 degrees, as illustrated in Fig. 2, is especially useful when it is desired to obtain a single resonance and it also has the advantage that a large tolerance is obtained for the angle of orientation, and that the quartz crystal having an orientation of substantially +5 degrees, as illustrated in Fig. 3, has a very small temperature coefficient of frequency and may be used advantageously, for example, in a wave filter subjected to large temperature changes or wherever the frequency cannot be allowed to vary much from a specified value.

It will be noted that the orientation of the axes o' and m' of the piezoelectric element 4 with respect to the fundamental crystallographic axes of the natural crystal 1 from which the element 4 is cut, may be selected as to both angular extent and direction. The direction of orientations with respect to the mechanical or Y axis and the optical or Z axis of the natural crystal 1 may be either positive (+) or negative (—) and since piezoelectric elements such as those of the quartz or tourmaline type occur in two forms, namely, either right-hand or left-hand, the positive direction of the angle may be either clockwise or counter-clockwise depending on whether the crystal is right-hand or left-hand.

The crystal is designated as right-hand if it rotates the plane of polarization of plane-polarized light traveling along the optic or Z axis in a right-hand direction and is designated as left-hand if it rotates the plane of polarization to the left. If a compression stress, as a squeeze, be applied to the crystal at the ends of the electric or X axis thereof, a charge will be developed which is positive at the positive end of the X or electric axis and negative at the negative end of the X or electric axis. The amplitude and sign of the charge may be measured with a vacuum tube electrometer. In specifying the orientation of a right-hand crystal, the angle which the axis of the piezoelectric element makes with the mechanical or Y axis and the optic or Z axis as the crystal element is rotated about the electrical or X axis is deemed positive when with the positive end of the X axis pointed toward the observer, the rotation is in a clockwise direction. A counter-clockwise rotation of such a crystal represents a negative orientation angle. Conversely, the orientation angle of a left-hand crystal is positive when with the positive end of the electric axis pointed toward the observer, the rotation is counter-clockwise, and is negative when the rotation is clockwise.

Stated differently, and as defined at pages 437 and 438 of applicant's article entitled "Electrical Wave Filters Employing Quartz Crystals as Elements", page 405, The Bell System Technical Journal, July 1934, Vol. XIII, No. 3, a positive angle of rotative orientation is a clockwise rotation of the principal or longest axis of a right-handed crystal about the electric or X axis when the electrically positive face of the crystal, as determined by a squeeze of the crystal is up. For a left-handed crystal, a positive angle is a counter-clockwise rotation.

The crystal material of Figs. 1 to 3 is shown as being of the right-hand type since a clockwise rotation there represents a positive (+) angle and a counter-clockwise rotation there represents a negative (—) angle.

The length or longitudinal dimension m' of the piezoelectric crystal element 4 is determined in a known manner by the frequency and the order of the harmonic that it is desired to employ. For example, if a 1000 kilocycle crystal vibrating longitudinally along the axis m' at its fifth harmonic is desired, the crystal element 4 may have a length dimension m' of approximately 1.27 centimeters. It will be understood that the crystal 4 may be ground to the proper length m' by any suitable mechanical method such as by carborundum dust. Either end 10 or 12 of the crystal element 4 may be ground to obtain the proper length dimension m' .

The thickness dimension e of the crystal ele-

ment 4 is determined by the impedance of the crystal 4. As used in an electric wave filter circuit, it is usually made quite thin in order to obtain a low or small value impedance but it will be understood that it may have a thickness dimension e to suit the impedance of the particular circuit with which it may be used.

In accordance with one feature of this invention, the width or breadth dimension of a crystal element as the dimension o' of the crystal element 4 may be within certain ranges or regions or ratios relative to the length dimension m' to obtain a substantially single response harmonic crystal. The proper width o' may be obtained by grinding either of the edges 6 or 8 or both to a suitable dimension for the width o' with respect to the length m' . For example, as determined by the measured resonances thereof, there are three preferred operating ranges of ratios of width o' to length m' for a -18.5 degree X-cut quartz crystal element 4 vibrating longitudinally at its third harmonic mode of motion, namely, the width o' may be between 0.0 and 0.23 of the length m' or between 0.255 and 0.275, or in the region between 0.46 and 0.6 to obtain a single prominent third harmonic frequency in the longitudinal mode of vibration thereof. This feature of the invention relating to the selected shape or ratio of the width o' to the length m' of a piezoelectric crystal to obtain substantially a single frequency response for a selected harmonic frequency thereof will be more fully described hereinafter.

A piezoelectric element such as the crystal 4 may be driven at a harmonic longitudinal frequency along the longitudinal axis or length m' , by employing the same number of sets or pairs of oppositely disposed metallic electrode platings as the number of the desired odd or even harmonic. A fifth harmonic crystal and its five sets or pairs of integral metallic electrode plates 20 to 29 are illustrated in Figs. 4 to 7 and 10, for example. The odd harmonic crystal, such as for example, the third or fifth harmonic crystals illustrated, is of special interest because it has a node of its motion substantially at the geometrical center of the crystal element and may be rigidly clamped and also electrically connected there along a nodal line substantially midway between the small ends thereof, by any suitable clamping means, such as for example, by resiliently supported pairs of coaxial projections 30, 34 and 36 as illustrated in Figs. 4 to 11.

Referring to Figs. 4 to 7, the five electrode plates 20 to 24 which are disposed on and made integral with one major surface or face 3 of the crystal 4 are made alternately positive and negative by suitable interconnections with the five electrode plates 25 to 29 which are disposed on and made integral with the opposite major surface 5 of the crystal 4 and which have opposite polarity to the electrode platings 20 to 24 disposed oppositely on the first-mentioned surface 3 of the crystal 4. To form the electrodes 20 to 29 and the connectors therebetween, the surfaces of the crystal 4 may be plated or coated in any suitable manner as by sputtering, evaporation, or spraying, with suitable metallic or conductive material, such as for example, with aluminum, platinum, or combination chromium on platinum, to form not only the integral electrodes 20 to 29 but also the connectors for connecting together all of the electrode plates of the same polarity as is illustrated in Figs. 5 to 7. This feature of interconnecting the electrode plates of a piezo-

electric element by means of the crystal plating itself permits dispensing with all soldered connections and all wire connections between the electrode plates 20 to 29 and does not require more than one pair of external connections and nodal clamping electrodes 30, as illustrated in Figs. 5 to 7, for mounting the crystal.

The combination platinum and chromium plated electrodes and the connections therebetween may be formed, for example, by first sputtering a layer of platinum onto the desired surface of the crystal and then depositing by vacuum distillation, for example, a thin film of chromium on top of the platinum. Where the aluminum plated electrodes and interconnections therebetween are utilized, the aluminum coating may be deposited on the desired surface of the crystal by vacuum distillation, for example, or by other suitable processes. An aluminum coating integral with the crystal provides a relatively small value of surface resistance for a given thickness of the aluminum film, has a relatively small effect on the natural frequency of a quartz crystal since the aluminum has very nearly the same density and Young's Modulus as the quartz and the thickness of the aluminum plating is accordingly relatively less critical, provides a good wearing surface and also good adherence to the crystal.

It will be understood that metallic coating may be applied to the surfaces of the crystal and that the undesired parts thereof may be afterwards removed as by grinding with carborundum dust, burning with an electric arc or by other suitable mechanical or chemical means removing the undesired parts of the plating to form the plated electrodes and the interconnections therebetween; or a screen or mask of suitable form as a narrow flat ribbon wire of suitable width may be held in contact with the crystal to prevent deposits of metallic plating on the surface of the crystal in contact with the wire and thereby provide the divided platings and interconnections therebetween.

As illustrated in Figs. 5 to 7, the metallic coating deposited on one side edge 8 of the crystal 4 interconnects all of the positive electrode plates 20, 22, 24, 26 and 28, and the metallic plating integral with the opposite side edge 6 of the crystal 4 interconnects all of the negative plates 21, 23, 25, 27 and 29. Part of the metallic coating between all negative plates 21, 23, 25, 27 and 29 and the margins at 32 and 35 is removed to form the positive connectors 32 and 35 and similarly the coating between all positive plates 20, 22, 24, 26 and 28 and the margins at 42 is removed to form the negative connectors 42. The metallic plating is rubbed off or otherwise removed from both ends 8 and 10 of the crystal 4. Hence, a complete connection exists between all positive plates 20, 22, 24, 26 and 28, and a complete connection exists between all negative plates 21, 23, 25, 27 and 29, but no connection exists between the positive and the negative plates.

More particularly, the metallic plating integral with the surfaces 3, 5, 6 and 8 of the crystal 4 may be divided into five sets or pairs of electrode plates 20 to 29 and interconnections therebetween by erasing or grinding or otherwise providing separation lines in the metallic plating on the surfaces of the crystal 4, as illustrated in Figs. 5 to 7. Such separations in the metallic plating may be of the order of 0.020 inch or other width to suit. The positive plates 20, 22 and 24 integral with the surface 3 of the crystal 4 are interconnected by the metallic plat-

ing on one side margin at 32 and are interconnected with the positive plates 26 and 28 on the opposite surface 5 of the crystal 4 by means of integral plating connections 33 and 34 on the side 8 and the margin plating 35 of the surface 5 of the crystal 4. The plating at 36, 37 and 38 on the side edge 8 may be erased or otherwise removed. Similarly, the negative plates 21 and 23 are interconnected by the metallic plating along the margin 42 and are interconnected with the negative plates 25, 27 and 29 on the reverse side 5 of the crystal 4 by means of plating connections 43, 44 and 45. On the side edge 6 at 46 and 47 and on the ends 10 and 12 the plating may be erased or otherwise removed.

The piezoelectric device, illustrated in Figs. 5 to 7 may be nodally clamped and externally electrically connected with other apparatus as a wave filter, for example, by the pair of coaxial metallic clamping projections 30 disposed in contact with the middle pair of crystal electrodes 22 and 27 of the crystal 4 at nodal points thereof which in the example shown are along a plane substantially midway between the ends 10 and 12 of the piezoelectric element 4. The clamping areas of the clamping projections 30 may be of any suitable shape to suit the nodal areas of the crystal 4; as illustrated in the several figures, they are shown in the shape of an elongated and very narrow rectangle. The clamping projections 30 may be constructed of any suitable material, such as for example, silver, brass or phenol fibre coated with tin and gold-plated. As shown in Fig. 7, the pair of clamping projections 30 may be secured to and supported by two metal cantilever springs 14 and 15, each fastened at one end thereof by screws 17 to an insulating block 16 of phenol fibre, Isolantite or other suitable insulating material. Terminals 18 and 19, secured to the springs 14 and 15, respectively, may form electrical connections with the crystal electrodes 27 and 22, respectively. The pressure exerted by the springs 14 and 15 may be of such value as to rigidly clamp the crystal element 4 between the clamping projections 30 to hold the crystal element 4 in place and establish electrical connections therewith.

While in Fig. 7 only one pair of clamping projections 30 are utilized to hold and connect with the piezoelectric crystal 4, it will be understood that one or more pairs of clamping projections, such as the clamping projections 30, may be utilized to nodally clamp the crystal 4 and that such clamping projections may be resiliently controlled by springs such as the cantilever springs 14 and 15 of Fig. 7 or the leaf spring 104 of Fig. 11, for example. Other examples of crystal holders which may be of the single or multiple crystal type suitable for holding any of the several piezoelectric crystal devices herein, are illustrated in United States Patent 1,978,188, to D. F. Ciccolella, granted October 23, 1934, and United States Patent No. 2,032,865, granted March 3, 1936 on application Serial No. 652,643, filed January 20, 1933 by Carl A. Bieling.

While the piezoelectric crystal device of Figs. 5 to 7 may include the crystal element 4 of Fig. 2 having an orientation of -18.5 degrees and having such ratio of width o' to length m' as to obtain substantially a single response at the fifth harmonic frequency thereof, it will be understood that the feature of interconnecting the crystal electrode plates by means of the plating itself may be utilized in connection with piezoelectric crystal elements having other orienta-

tions, such as for example, the $+5$ degree orientation shown in Fig. 3, and having other ratios of axes or dimensions o' , m' .

While the piezoelectric crystal device of Figs. 5 to 7 is illustrated as being driven, in the longitudinal mode of motion along the axis or length m' at the fifth harmonic frequency of vibration, by means of the five pairs of electrode plates 20 to 29 and the interconnections therebetween integral with the side margins and side edges of the piezoelectric element 4, it will be understood that three sets of integral crystal electrode platings similarly interconnected by means of the metallic plating integral with the side margins and side edges of the piezoelectric element 4 may be utilized to drive the element in the longitudinal mode of motion along the length m' at the third harmonic frequency of vibration or at any other harmonic frequency of vibration according to the number of pairs of crystal electrode plates utilized.

Fig. 8 illustrates an alternative method of forming and interconnecting crystal electrodes by means of metallic plating integral with a piezoelectric element such as the crystal element 4. As shown in Fig. 8, narrow strips are removed from the metallic plating on the side edges 6 and 8 and on the major surfaces 3 and 5 of the crystal element 4 in such manner that all of the positive electrode plates 50 to 54 are connected together and all of the negative electrode plates 55 to 59 are connected together by means of the transversely disposed metallic connectors 60 to 67 integral with the side surfaces 6 and 8 of the crystal element 4. The connectors 60, 62, 65 and 67 interconnect the negative electrodes 55 to 59. The connectors 61, 63, 64 and 66 interconnect the positive electrodes 50 to 54. All of the metallic plating is removed from both ends 10 and 12 of the crystal 4. A pair of metallic coaxial clamping members 30 disposed in contact with the electrodes 51 and 58 may nodally clamp the crystal 4 midway between the ends 10 and 12 thereof as shown in Fig. 8 and more fully described in connection with the modification illustrated in Figs. 5 to 7.

Fig. 9 illustrates another form of high frequency harmonically vibrating piezoelectric crystal device of moderate size having substantially a single resonance over the selected frequency range and which also may be utilized advantageously, for example, in high frequency coaxial conductor electric wave filter systems or in radio filter systems to separate bands of frequency in a small frequency space. As illustrated in Fig. 9, a piezoelectric element such as the crystal 4 is driven in longitudinal vibration along the axis or length m' at its third harmonic frequency. The driving mechanism consists in this case of three oppositely disposed sets or pairs of crystal electrode plates 70 to 75. The electrode plates 70, 72, 74 integral with one major face 3 of the crystal 4 are of alternate polarity and are of opposite polarity to the oppositely disposed electrode plates 71, 73 and 75 integral with the opposite face 5 of the crystal 4. The positive electrode plates 71, 72 and 75 and also the negative electrode plates 70, 73 and 74 are interconnected as shown in Fig. 9 without the use of soldered or wire connections. Any suitable method may be utilized to form the electrode plates 70 to 75 and the connections 77 and 78 therebetween; for example, the surfaces 3, 5, 6 and 8 of the crystal 4, by any suitable method such as by spraying, sputtering, evaporation,

cementing, or otherwise, may be covered over with a thin plating of platinum, aluminum or other suitable conductive coating. The undesired plating may be removed by suitable mechanical or chemical means. For example, the plated crystal may be dipped in melted paraffine wax or other acid resisting material which is allowed to solidify. Thin lines for the three sets of electrode plate separations may be scratched in the wax down to the surfaces of the crystal 4. Also, the wax on parts of both of the side edges 6 and 8 of the crystal 4 may be scraped off in order to leave blank the spots not covered by the connectors 77 and 78 of Fig. 9. With this arrangement, the positive plates 71, 72 and 75 of the crystal 4 are all connected together. On the opposite side edge 8, the wax is scraped off so that the negative plates 70, 73 and 74 will be connected together. The crystal is then dipped in any suitable acid and the metallic plating not covered by the wax is removed leaving a crystal 4 plated as shown in Fig. 9. Other suitable methods may also be utilized to establish the interconnections between the crystal electrodes by means of metallic platings, such as the platings 77 and 78 illustrated in Fig. 9. It will be noted that the same electrode connections as illustrated in Fig. 9, for example, may also be obtained by removing the plating merely at the upper corners of the negative plates 70, 73 and 74 to provide a separation from a positive connector corresponding to the connector 77, and by similarly removing plating at the lower corners of all positive plates to provide separation from a negative connector corresponding to the connector 78.

Where a piezoelectric element as the crystal 4 is provided with an odd number of sets or pairs of electrode plates 71 to 75, the center of the crystal 4 is a node where substantially no motion takes place and hence may be clamped and electrically connected there as by means of the pair of coaxial metallic projections 30 as illustrated in Fig. 9. Where a crystal as the crystal 4 has a -18.5 degree orientation as illustrated in Fig. 2, it has advantages for electric wave filter purposes because it then has a very small coupling to the shear mode of motion.

In accordance with a feature of this invention, a harmonic crystal has been found to be substantially free from additional resonances when the ratio of width axis o' to length axis m' is within certain limited regions. The preferred regions for such ratio of width to length for a third harmonic crystal as illustrated in Fig. 9 having a -18.5 degree orientation as illustrated in Fig. 2 are the following: When the ratio o'/m' is less than .23, the crystal has substantially only one resonance. When the ratio o'/m' is between .25 and .28, only small additional resonances are present. When the ratio o'/m' is between .46 and 0.6, only minor additional resonances are present. These three ranges constitute the preferred operating ranges for a third harmonic X-cut crystal 4 (Fig. 9) having an orientation of -18.5 degrees (Fig. 2).

These ranges of ratios of axes o'/m' mentioned in the preceding paragraph were obtained from the measured resonances of a particular piezoelectric quartz crystal having an orientation of $-18.25'$ as illustrated in Fig. 2, having a length dimension m' of 25.2 millimeters, a uniform thickness dimension e of 0.5 millimeters, and a breadth or width dimension o' which was varied by successive grindings from 25 millimeters to 5

millimeters (mm.) and in every case caused to vibrate longitudinally at its third harmonic mode of vibration by means of three sets or pairs of interconnected electrode plates such as are shown in Fig. 9. For each ratio of axes o'/m' , the number of frequencies present and the strength of vibrations may be noted and from these values, the regions of the ratios of axes o'/m' most free from coupling resonances are obtained.

The number of frequencies and strength of vibrations for any given dimensions of the crystal element may be observed in the following manner: The crystal may be put in a measuring circuit such as described on page 431 of the above-mentioned paper. When the frequency of the oscillator is varied, the current in the detector shows frequencies of maximum and minimum current output which are respectively the frequencies of resonance and anti-resonance of the crystal. In order to locate accurately the frequencies of anti-resonance, a stage of tuning may be inserted in the detector, in order to discriminate against the harmonics of the oscillator. For a given crystal the frequency of the oscillator may be varied over a wide range and the resonant and anti-resonant frequencies of the crystal measured. The strength of the vibration is proportional to the frequency difference between the resonant and anti-resonant frequencies divided by the frequency of resonance. Whenever a strong resonance is obtained with no other minor frequencies near it in frequency, a useful crystal is obtained.

The measured results agree quite well with the calculated results which follow.

The preferred ratios of width o' to length m' of any piezoelectric crystal element such as the crystal 4 vibrating in any harmonic mode of motion may be determined by calculation such as by calculating the various ratios of crystal element axes o'/m' for which other coupled frequencies exist and noting the regions therebetween where substantially no other coupled frequencies exist and where accordingly there is theoretically substantially only a single prominent harmonic response frequency for the crystal element as the element 4.

More particularly, the resonances of a harmonic crystal element as the element 4 may be calculated as follows:

Any X-cut piezoelectric crystal element, such as for example, the crystal element 4 of Figs 1 to 10 has four possible modes of motion, namely three modes of motion in compression and extension, one being longitudinally along the length axis m' , another being along the breadth or width axis o' , and a third along the thickness dimension e , and a shearing motion in the breadth-length plane. Each of these three extensional modes of motion may have harmonic frequencies while the shear mode of motion may have a double infinity of harmonics. By double infinity of harmonics is meant that the frequencies are governed by two sets of integers both of which may become indefinitely large, so that the number of combination frequencies increases as the square of the largest integers.

To find what frequencies occur near the frequency of the main extensional or longitudinal mode of motion along the axis m' of a crystal element as the element 4, and what shapes of crystals as to ratio of axes o'/m' will give essentially only one frequency response, the following calculations may be made:

The frequencies f_{33} , given by the width o' vibration are

$$f_{33} = \frac{h_{33}}{2o'} \sqrt{\frac{C_{33}}{\rho}} \quad (1)$$

where h_{33} indicates the number of the harmonic ($h_{33}=1, 2, 3$, etc.), o' is the width of the o' or optic axis, C_{33} is the modulus of elasticity along the o' axis and ρ is the density.

The frequency f_{22} , along the mechanical or m' axis is given by the equation

$$f_{22} = \frac{h_{22}}{2m'} \sqrt{\frac{C_{22}}{\rho}} \quad (2)$$

where h_{22} indicates the number of the harmonic as $h_{22}=1, 2, 3$, etc., C_{22} is the modulus of elasticity along the m' axis, and ρ is the density.

Suppose that it is desired to drive the crystal at its third harmonic vibration along the axis m' as shown for example in Fig. 9. This frequency will have coupling to that frequency along the axis o' , and when the two frequencies f_{22} and f_{33} are equal, a region of double resonance exists, and the crystal, theoretically, is not useful to obtain only one response frequency for that ratio of axes o'/m' which will be given by equating f_{33} to f_{22} , or

$$\frac{h_{33}}{2o'} \sqrt{\frac{C_{33}}{\rho}} = \frac{h_{22}}{2m'} \sqrt{\frac{C_{22}}{\rho}} \quad (3)$$

Hence

$$\frac{o'}{m'} = \frac{h_{33}}{h_{22}} \sqrt{\frac{C_{33}}{C_{22}}} \quad (4)$$

For example, for a -18.5 degree cut crystal, such as the crystal 4 of Fig. 2, for example, the value of

$$\sqrt{C_{33}/C_{22}} = 1.22 \quad (5)$$

Hence, for such third harmonic crystal ($h_{22}=3$), the ratios of axes o'/m' for which the crystal theoretically have resonance coupling between its mechanical and optical axes are given by taking $h_{33}=1, 2, 3, 4$ etc., giving by calculation:

$$\frac{o'}{m'} = .408; .814; 1.23; \text{etc.}$$

The frequency of a shear vibration is given by the equation

$$f_{44} = \frac{1}{2} \sqrt{\frac{C_{44}}{\rho}} \sqrt{\frac{n^2}{o'^2} + \frac{r^2}{m'^2}} \quad (6)$$

where n and r are integers, C_{44} is the shear modulus of elasticity, o' , m' are the lengths of axes of the crystal, and ρ is the density.

Equating f_{44} to f_{22} and solving for the resulting ratios of o'/m' gives

$$\frac{o'}{m'} = \frac{n/r}{\sqrt{\frac{h_{22}^2}{r^2} \left(\frac{C_{22}}{C_{44}} \right) - 1}} = \frac{n}{\sqrt{h_{22}^2 (C_{22}/C_{44}) - r^2}} \quad (7)$$

For a -18.5 degree X-cut crystal, such as the crystal 4 shown in Fig. 2, for example, the ratio C_{22}/C_{44} is equal to 1.264. Hence, the ratio of axes o'/m' for which coupling regions exist in such crystal will be, for a third harmonic crystal ($h_{22}=3$)

$n=1; r=0;$	$n=1; r=1;$	$n=1; r=2;$	$n=1; r=3$
$\frac{o'}{m'} = .296$	.3105	.368	.647
$n=2; r=0;$	$n=2; r=1;$	$n=2; r=2;$	$n=2; r=3$
.592	.621	.735	1.292
$n=3; r=0;$	$n=3; r=1;$	$n=3; r=2;$	$n=3; r=3$
.888	.931	1.102	1.94

etc. Limiting the calculated results to a square

crystal where the ratio of axes o'/m' equals 1, it appears from the foregoing calculations that the only region of any size for which the -18.5 degree third harmonic crystal is theoretically free from extraneous or coupling vibrations are when $o'/m' < .296$; and when $.41 < o'/m' < .592$.

The foregoing calculations determine theoretically the ratios of axes o'/m' at which maximum couplings exist for the extensional and shear modes of motion of X-cut crystals having an orientation of -18.5 degrees (Fig. 2) and longitudinally vibrating at their third harmonic frequencies along the axis m' . Similarly, calculations may be carried out for crystals driven at the higher orders of harmonics to determine the ratios of axes o'/m' for which maximum couplings exist. Between these regions of maximum couplings will be found regions of ratios of axes (o'/m') which have small couplings and which may be utilized to obtain substantially a single frequency response corresponding to the longitudinal mode of harmonic vibration along the m' axis. Of these, the preferred useful regions or ranges of ratios of axes o'/m' as determined by calculation are given as follows for the fifth, seventh and ninth harmonic modes of longitudinal vibration of crystals having in every case an orientation of -18.5 degrees, as shown in Fig. 2. Using these ratios of axes o'/m' , harmonic crystals reasonably free from coupling frequencies and having substantially a single frequency response may be obtained.

The preferred ranges of ratios of axes o'/m' include:

For a fifth harmonic -18.5 degree X-cut quartz crystal,

o'/m' under .1771
 o'/m' between .263 and .354
 o'/m' between .42 and .49

For a seventh harmonic -18.5 degree X-cut quartz crystal,

o'/m' under .1272
 o'/m' between .196 and .254
 o'/m' between .329 and .381

For a ninth harmonic -18.5 degree X-cut quartz crystal,

o'/m' under .0989
 o'/m' between .1615 and .1980
 o'/m' between .274 and .297
 o'/m' between .361 and .397

While the foregoing calculations have been based upon X-cut quartz crystals having an orientation of -18.5 degrees, as shown in Fig. 2, and longitudinally vibrating at the third, fifth, seventh, and ninth harmonics along the longitudinal axis m' , it will be understood that calculations and also actual measurements to determine the preferred regions may be similarly made for other harmonics and for orientations other than the -18.5 degree angular orientation (Fig. 2), such as, for example, the $+5.0$ degree orientation (Fig. 3) or other orientations therebetween or outside of such angular positions.

It will be understood that the particular examples of ratios of axes o'/m' given herein are merely illustrative of certain ratios of axes to obtain substantially a single response frequency in a piezoelectric element vibrating in a harmonic mode of motion, that certain useful ratios of axes o'/m' may exist outside these regions, and that within these regions specified certain ratios of axes o'/m' may exist which are more free of

extraneous coupling frequencies than others, as for example, in the example given for the third harmonic crystal, one of the regions reasonably free from extraneous vibrations included, by the calculations given hereinbefore, the region of o'/m' less than .296, while within this region, the measured results of regions o'/m' more free than others from such extraneous coupling vibrations included the regions o'/m' less than .23 and o'/m' within the range of .255 to .275.

Accordingly, it will be understood that calculations and measurements may be carried out in the manner described for piezoelectric elements of a desired angular orientation or harmonic mode of vibration and that the examples given are intended to be non-limitative illustrations of applicant's invention and discovery that certain shapes, dimensions or ratios of axes o'/m' exist which may be utilized to obtain a piezoelectric element having substantially a single response harmonic frequency characteristic for any selected harmonic vibration thereof or for any selected orientation thereof.

In accordance with another feature of this invention, two separate circuits on a single harmonic crystal may be obtained as illustrated in Fig. 10. This arrangement is useful in an electric wave filter structure of the balanced lattice type, for example, to permit a single crystal to be utilized in place of two separate equal frequency crystals. In this arrangement, each of the oppositely disposed middle electrode plates, such as for example the middle plates 51 and 58 of Fig. 8, or the middle plates 22 and 27 of Figs. 5 and 6, or the middle plates 72 and 73 of Fig. 9, may be divided into two parts such as the parts 80 and 81 of Fig. 10, by a separating line 82 of suitable width as .020 inch or less for example, in the metallic coating midway between the two coaxial pairs of metallic clamping projections 84 and 86 and extending symmetrically all the way around the crystal 4 as shown in Fig. 10 to thereby divide the crystal 4 electrically into two halves 88 and 90. While in Fig. 10, the dividing line 82 is illustrated as applied to a harmonic crystal having the type of integral plating shown in Fig. 6, it will be understood that harmonic crystals having platings as shown in Figs. 8 and 9 for example, may be electrically divided as shown in Fig. 10. To mount and connect such divided crystals, a double clamping arrangement as shown in Figs. 10 and 11 may be utilized. In this arrangement, one set of coaxial metallic projections 84 may make contact along a central nodal line with the upper half of the crystal 4 on the plating 81, and the other set of coaxial projections 86 may make contact with the lower half on the plating 80 as illustrated in Fig. 10. In this way, two separate circuits of equal impedance and equal frequency may be obtained on one harmonic crystal.

The metallic clamping connections 84 and 86 may be of any suitable form such as, for example, gold-plated phenol fibre or metal projections secured to two insulating blocks 100 and 101 (Fig. 11) which may be resiliently pressed toward each other by means of two bolts 102 and 103 cooperating with a leaf spring 104, for example. The contact areas of the clamping projections 84 and 86, like the clamping projections 30 hereinbefore described particularly in connection with Figs. 6 to 8, may be of suitable areas and shape to suit the nodal areas of the piezoelectric crystal element 4 which is clamped therebetween. To center the pressure of the spring 104 on the slid-

able insulating bar 101, a pressure centering pin or roller 106 of suitable diameter may be disposed in a transverse groove 107 in the insulating bar 101. The groove 107 is arranged midway between the clamping projections 84 and 86 secured to the insulating bar 101. The cylindrical roller 106 is disposed in contact with the center of the leaf spring 104. The tension of the spring 104 may be adjusted by screw threaded bolts 108 to a value to rigidly hold the crystal element 110 between the pairs of clamping projections 84 and 86. The insulating bars 100 and 101 may be constructed from high resistance insulating material such as Bakelite or Isolantite, for example. To reduce friction, the bolts 102 and 103 may be chromium plated and the openings in the bar 101 slidable thereon, may be coated with graphite lacquer.

It will be understood that the piezoelectric device 112 may be supported by a crystal holder like that supporting the element 110, or devices 110 and 112 may be supported by a multiple holder which may individually clamp the two piezoelectric devices 110 and 112 in a common supporting structure.

Fig. 11 further illustrates schematically an electric wave filter system of the lattice type in which a single piezoelectric crystal 110 divided as illustrated in Fig. 10 for example may serve for the two series arms 114 and 116 of the filter network and another piezoelectric crystal 112 similarly divided may serve for the two lattice arms 118 and 120 of the filter network in order to provide two separate circuits of equal impedance and equal frequency in connection with each of the crystals 110 and 112. The crystals 110 and 112 may be harmonic crystals of different frequencies but otherwise are of the same construction as shown in Fig. 10, for example. Each of the piezoelectric elements 110 and 112 may be divided electrically into two parts as shown in Fig. 10 by the line 82 which represents an erasure or removal of the metallic plating as indicated on the major surfaces and the side edges of each crystal.

Each of the crystals 110 and 112 may be nodally clamped at four points by the pairs of clamping projections 84 and 86 and 84' and 86'. Electrical connections may be made through the metallic clamping projections 84 and 86 associated with the crystal element 110 and through the clamps 84' and 86' associated with the crystal 112. The circuit connections may be for example as shown in Fig. 11. Referring to Fig. 11, the pair of clamping electrodes 84 are connected in series circuit relation with one series arm 114 of the filter network and the pair of clamping electrodes 86 are connected in series circuit relation with the other series arm 116 thereof. Similarly, the crystal element 112 having its plating divided in the same manner as that of the crystal 110 is connected in the two lattice arms 118 and 120 of the network by means of the pairs of metallic clamping members 84' and 86', respectively. Accordingly, this arrangement provides two equal series arms and two equal lattice arms in which each crystal 110 and 112 does the work of two, thereby reducing by half the number of crystals ordinarily required and providing an arrangement which permits a smaller number of crystals in a balanced lattice type of electric wave filter.

While the arrangement shown in Fig. 11 illustrates harmonic crystals of the divided plating type adapted to a particular circuit, it will be understood that such type of crystal may also be adapted to other circuits.

Fig. 12 illustrates a form of narrow band electric wave filter circuit employing two harmonic metallically coated piezoelectric crystals 130 and 132. The crystal elements 130 and 132 may be of the type shown in Figs. 5, 8 or 9, for example. In Fig. 12, a balanced hybrid coil type of transformer 131 has a secondary winding 134 connected with the output terminals 136 and 137 and has two primary coils 133 and 135 which are so connected in series aiding relation that the current flowing to one crystal 130 opposes that flowing through crystal 132 into the secondary winding 134 of the hybrid coil arrangement 131. Variable condensers 140 and 142 may tune respectively the secondary winding 134 and the primary windings 133 and 135 of the hybrid coil arrangement 131 at the mid-frequency of the filter. The secondary winding 134 of the hybrid coil arrangement 131 may be grounded at 143. The input circuit includes the terminals 145 and 146. The terminal 145 is connected with the windings 133 and 135 through the crystals 130 and 132. The terminal 146 is connected with the midpoint 147 of the primary windings 133, 135 of the transformer 134. Suitable clamping electrodes, such as the electrodes 30 of Figs. 5 to 9 may connect the crystals 130 and 132 in the circuit shown in Fig. 12. The input circuit associated with the terminal 146 may be grounded at 148. The harmonic crystals 130 and 132 may be identical in construction except that one may have a different frequency characteristic from the other to filter a suitable range or band of frequencies.

Fig. 13 illustrates a form of so-called lattice type electric wave filter circuit as described and shown at page 424. Fig. 16D of applicant's paper entitled "Electrical Wave Filter Circuits Employing Quartz Crystals as Elements", July 1934, Bell System Technical Journal, but herein provided with two harmonic crystals 150 and 152 of the type shown in Figs. 5, 8 or 9, for example. More particularly, the filter circuit shown in Fig. 13 consists of two series arms 154 and 156 and two lattice arms 158 and 160. Two transformers are utilized, each having two primary windings and one secondary winding. One primary winding 162 of one transformer is connected in series circuit relation with one series arm 154 of the filter; the other primary winding 164 of the same transformer is connected in series circuit relation with the corresponding series arm 156, and the secondary winding 166 of the same transformer is connected in parallel circuit relation with a condenser 168 and the piezoelectric harmonic crystal 150. As to the other transformer, one primary winding 170 thereof is connected in series circuit relation with one lattice arm 160 of the filter, another primary winding 172 thereof is connected in series circuit relation with another lattice arm 158 of the filter, and a secondary winding 174 thereof which is inductively coupled with the primary windings 170 and 172, is connected in parallel circuit relation with a condenser 176 and the piezoelectric harmonic crystal 152. Condensers 178 and 179 may be connected in circuit with the series arms 154 and 156, respectively. The harmonic piezoelectric crystals 150 and 152 may be of the type shown in Figs. 5, 8 or 9, for example, and are selected to have such difference in frequency characteristics as to provide a suitable range or band of frequencies for the filter. The condensers 168, 176, 178, and 179 may be variable

to tune the circuits to the mid-frequency value of the filter.

While Figs. 12 and 13 illustrate particular circuits in which the harmonic piezoelectric crystals disclosed herein may be utilized, it will be understood that such harmonic crystals may be utilized in other forms of circuits.

While in Figs. 5 to 10, the interconnections between the plated crystal electrodes by means of the metallic plating itself has been shown as applied to harmonic crystals vibrating in the longitudinal mode of motion, it will be understood that such plated crystal electrodes and such plated interconnections therebetween may be applied to other forms of crystals. For example, in Fig. 14, there is illustrated a tuning fork type of low frequency quartz crystal element 182 vibrating in flexure about a node in the yoke connecting the two forks thereof. The crystal 182 has four pairs or sets of metal plated electrodes consisting of eight plated electrodes 184 to 191 formed by metallic coatings integral with the surfaces of the two forks of the crystal 182. Metallic coatings or platings 193 and 194 integral with the yoke and nodal portion of the crystal 182 interconnect the positive electrodes 184 and 187 and interconnect negative electrodes 185 and 186, respectively. Similarly, metallic coatings or platings 195 and 196 disposed on the opposite side of the crystal 182 along the yoke and nodal portion thereof connect respectively the positive electrodes 189, 190 and the negative electrodes 188, 191. The electrodes 184 to 191 and their connections 193 to 196 are preferably integral metallic coatings as shown and may be formed as hereinbefore described in connection with Figs. 5 to 9 by depositing in a suitable manner suitable metallic plating on the surface of the crystal 182 and wherever necessary removing portions of the metallic plating to form the electrodes and their connections.

The wire connections shown in Fig. 14 are illustrative of circuit connections. The connection wires 197 and 198 may, for example, be omitted and individual external connections made with the connectors 193 to 196 by two pairs of metallic clamping means 84 and 86 disposed in contact with the metallic connectors 193 to 196 at the nodal points of the crystal 182.

It will be understood that in accordance with this invention, a piezoelectric element as the element 4, for example, may have such shape or dimensions (σ'/m') as to obtain substantially a single response at any selected harmonic frequency thereof as disclosed in connection with Figs. 1 to 10 particularly, that such piezoelectric element 4 may be driven in the longitudinal mode of motion at such selected harmonic frequency by a suitable number of pairs of crystal electrodes corresponding to the number of the selected harmonic, that the crystal electrodes and the interconnections therebetween may be formed by metallic coatings integral with the surfaces of the piezoelectric element 4 or 182 as illustrated in Figs. 5 to 10 or in Fig. 14, that such metallic coatings may be of any suitable metal or metals such as, for example, aluminum, platinum, or chromium on top of platinum deposited in any suitable manner such as, for example, by sputtering, evaporation in vacuum or by molten metal spray, that the piezoelectric element may be nodally clamped and electrically connected by a single pair of coaxial clamping projections as the projections 30 illustrated in Figs. 5 to 9 or by two pairs of such coaxial clamping projec-

tions 84 and 86 as illustrated in Figs. 10, 11 and 14, that any of the clamping projections may be of any suitable construction and may have contact areas suitable for the nodal zones of the piezoelectric element clamped therebetween, and that any of the clamping projections may be resiliently supported by suitable springs such as, for example, by the cantilever springs of Fig. 7 or the leaf spring of Fig. 11.

It will be further understood that any of the harmonically vibrating piezoelectric elements as illustrated in Figs. 5 to 9, for example, may be utilized in electric wave filter circuits as illustrated in Figs. 12 and 13, for example, or may be electrically divided by split platings as illustrated in Fig. 10 and utilized in an electric wave filter circuit as illustrated in Fig. 11, for example.

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 selective element for an electric wave filter comprising a piezoelectric element, means for driving said piezoelectric element in a selected odd harmonic frequency mode of vibration thereof, said piezoelectric element having electrode surfaces of such selected shape as to substantially eliminate coupling between said selected vibration and any other vibration in said element, said driving means including an odd number of pairs of plated electrodes integral with and oppositely disposed on said surfaces and corresponding in number of pairs with the order of said harmonic frequency, and metallic plating integral with said piezoelectric element for interconnecting said electrodes, means including divided portions of the middle pair of said pairs of electrodes for providing two separate circuits of equal impedance and equal frequency for said element, and means clamping and providing connections with said divided portions of said middle pair of electrodes.

2. A piezoelectric quartz crystal element having opposite substantially rectangular electrode surfaces disposed substantially perpendicular to an electric axis thereof, the length axis and the width axis of said surfaces being inclined substantially -18.5 degrees with respect to the mechanical and optic axes respectively of said element, and the ratio of lengths of said width axis with respect to said length axis being substantially within any of the ranges from 0 to .23, from .255 to .275 and from .46 to .6 to obtain a third harmonic frequency longitudinal mode of vibration substantially in the direction of said length axis and substantially mechanically uncoupled to any other mode of vibration in said element.

3. A piezoelectric quartz crystal element having opposite substantially rectangular electrode surfaces disposed substantially perpendicular to an electric axis thereof, the length axis and the width axis of said surfaces being inclined substantially -18.5 degrees with respect to the mechanical and optic axes respectively of said element, and the ratio of lengths of said width axis with respect to said length axis being substantially within any of the ranges from 0 to .177, from .263 to .354, and from .42 to .49 to obtain a fifth harmonic frequency longitudinal mode of vibration substantially in the direction of said

length axis and substantially mechanically uncoupled to any other mode of vibration in said element.

4. A piezoelectric quartz crystal element having opposite substantially rectangular electrode surfaces disposed substantially perpendicular to an electric axis thereof, the length axis and the width axis of said surfaces being inclined substantially -18.5 degrees with respect to the mechanical and optic axes respectively of said element, and the ratio of lengths of said width axis with respect to said length axis being substantially within any of the ranges from 0 to .1272, from .196 to .254, and from .329 to .381 to obtain a seventh harmonic frequency longitudinal mode of vibration substantially in the direction of said length axis and substantially mechanically uncoupled to any other mode of vibration in said element.

5. A piezoelectric quartz crystal element having opposite substantially rectangular electrode surfaces disposed substantially perpendicular to an electric axis thereof, the length axis and the width axis of said surfaces being inclined substantially -18.5 degrees with respect to the mechanical and optic axes respectively of said element, and the ratio of lengths of said width axis with respect to said length axis being substantially within any of the ranges from 0 to .0989, from .1615 to .1980, from .274 to .297, and from .361 to .397 to obtain a ninth harmonic frequency longitudinal mode of vibration substantially in the direction of said length axis and substantially mechanically uncoupled to any other mode of vibration in said element.

6. A piezoelectric quartz crystal element having opposite substantially rectangular electrode surfaces disposed substantially perpendicular to an electric axis thereof, the length axis and the width axis of said surfaces being inclined at a selected acute angle of substantially -18.5 degrees with respect to the mechanical and optic axes respectively of said element, and said width axis having such selected relative length with respect to and less than 0.6 the length of said length axis as to obtain a selected harmonic frequency extensional mode of vibration substantially in the direction of said length axis and substantially mechanically uncoupled to any other vibration in said element.

7. A piezoelectric element, means for driving said element in a selected harmonic frequency mode of vibration thereof, said element having such shape and relative dimensions as to reduce to an ineffective value the magnitude of mechanical coupling between said selected harmonic frequency vibration and any other vibration therein, and said driving means including electrodes formed integral with the opposite electrode surfaces of said element and conductive connections for said electrodes formed integral with boundary surfaces of said element other than said opposite electrode surfaces.

8. A quartz piezoelectric element, and means including electrodes integral therewith for driving said element in a selected harmonic frequency mode of vibration thereof, said element having such selected shape and relative dimensions as to reduce to an ineffective value the magnitude of mechanical coupling between said selected vibration and any other vibration therein, said electrodes comprising a plurality of pairs of aluminum coatings formed integral with opposite electrode surfaces of said element, conductive connections for said electrodes of similar

polarity comprising aluminum coatings formed integral with boundary surfaces of said element between said opposite electrode surfaces, and conductive members clamping said element therebetween and disposed in conductive contact with one of said pairs of electrodes.

9. A piezoelectric quartz crystal element of substantially rectangular parallelepiped shape having its largest surfaces disposed substantially perpendicular to an electric axis of the natural crystal and having its axis of greatest length disposed at an acute angle within a range of from substantially -18.5 degrees to $+10.0$ degrees with respect to the nearest mechanical axis of the natural crystal, and means including a plurality of sets of electrodes formed integral with said largest surfaces and connections for said electrodes formed integral with surfaces of said element between said largest surfaces for electrically driving said element at a selected odd harmonic mode of motion longitudinally along said axis of greatest length, the shape of said largest surfaces being such as to obtain effective vibration of said element in said harmonic mode of motion substantially uncoupled with any other mode of motion therein.

10. A piezoelectric body having metallic plating integral therewith, said plating comprising a plurality of electrodes and connections therebetween extending integrally with said body from one surface thereof to an opposite surface thereof.

11. A piezoelectric element having electrode surfaces and a side edge surface therebetween, a plurality of metallic electrodes disposed on said electrode surfaces, and means interconnecting said electrodes comprising metallic plating disposed on and integral with said side edge surface of said element.

12. A piezoelectric element having oppositely disposed major surfaces and oppositely disposed side edge surfaces, a plurality of metallic electrodes disposed on said major surfaces, means interconnecting some of said electrodes comprising metallic plating integral with one of said side edge surfaces, and means interconnecting others of said electrodes comprising metallic plating integral with another of said side edge surfaces.

13. A piezoelectric element having electrode surfaces and a side edge surface, said electrode surfaces having side margins, a plurality of metallic electrodes disposed on said electrode surfaces, and means connecting said electrodes including metallic plating integral with said side edge surface of said element and integral with said side margins of said electrode surfaces of said element.

14. A single piezoelectric element, means including an odd number of sets of oppositely disposed metallic platings operatively related to said element for vibrating said element at an odd harmonic frequency characteristic of said element, means including divided portions of the middle set of said metallic platings for obtaining two separate circuits of equal impedance and equal frequency for said element, and clamping connections disposed in contact with each of said divided portions of said metallic plating.

15. A piezoelectric element, means including a plurality of pairs of oppositely disposed electrodes formed integral with opposite electrode surfaces of said element for vibrating said element in a longitudinal mode of motion at a desired overtone frequency, and means including separated portions of one of said pairs of opposite elec-

trodes for obtaining two separate circuits of equal frequency for said element.

16. A piezoelectric element, a plurality of pairs of opposite electrodes formed integral with opposite electrode surfaces of said element, connections for said electrodes of similar polarity formed integral with a surface of said element between said opposite electrode surfaces, and conductive means disposed in contact with one of said pairs of opposite electrodes and clamping said element therebetween.

17. A quartz piezoelectric element, and electrodes therefor comprising aluminum coatings formed integral with said quartz element.

18. A quartz piezoelectric element, a plurality of aluminum electrode coatings formed integral with opposite electrode surfaces of said quartz element, and conductive connections for said electrodes comprising aluminum coatings formed integral with surfaces of said quartz element between said opposite electrode surfaces.

19. A quartz piezoelectric element having opposite electrode faces substantially perpendicular to an X axis, the shortest and longest axes of said faces being inclined to the Z axis and a Y axis respectively at an angle of substantially -18.5 degrees, and means including electrodes formed integral with said opposite electrode faces and connections for said electrodes formed integral with surfaces of said element between said opposite electrode faces for vibrating said element in a longitudinal mode of motion at a desired harmonic frequency which is a function of said longest axis dimension, said shortest axis being sufficiently smaller than said longest axis to obtain said desired frequency substantially uncoupled with other modes of motion therein.

20. A quartz piezoelectric element having opposite electrode faces substantially perpendicular to an X axis and substantially parallel to a Y axis and the Z axis, and means including electrodes formed integral with said opposite electrode faces and connections for said electrodes formed integral with surfaces of said element between said opposite electrode faces for vibrating said element in a longitudinal mode of motion at a desired harmonic frequency which is a function of the longest axis dimension, the shortest axis of said faces and said longest axis being inclined to said Z and Y axes respectively at an angle of substantially $+5$ degrees to produce the lowest temperature coefficient of frequency.

21. A quartz piezoelectric element having an electrode face substantially perpendicular to an X axis and substantially parallel to a Y axis, said element having its major axis inclined to said Y axis at such an angle of substantially $+5$ degrees as to produce its maximum electromechanical or piezoelectric coupling when subjected to an electric field in the direction of said X axis and vibrated in a longitudinal mode of motion at a frequency which is a function of said major axis dimension.

22. A quartz piezoelectric element having an electrode face substantially perpendicular to an X axis and substantially parallel to a Y axis, said element having its major axis inclined to said Y axis at an angle of substantially -7.5 degrees and being adapted for longitudinal vibration along said major axis at a desired harmonic frequency which is a function of said major axis dimension.

23. A quartz piezoelectric element having an electrode face disposed substantially perpendicular to an X axis and substantially parallel to a

Y axis, said element having its major axis inclined with respect to said Y axis at such an angle of substantially -10 to -12 degrees as to produce a substantially single resonance response when subjected to an electric field in the direction of said X axis and vibrated in a longitudinal mode of motion at a frequency which is a function of said major axis dimension.

24. A quartz piezoelectric element having opposite substantially rectangular shaped electrode faces disposed substantially perpendicular to an X axis, its length or longest dimension being along a Y' axis which is inclined with respect to the nearest Y axis at an acute angle of substantially -18.5 degrees, its thickness dimension being measured substantially along an X axis, and its width dimension as measured along the Z' axis having such a ratio of less than substan-

tially 0.6 with respect to said Y' axis dimension as to obtain substantially a single frequency resonance response, means for vibrating said element in a longitudinal mode of motion along said Y' axis at an harmonic frequency which is a function of said Y' axis dimension comprising a plurality of pairs of opposite electrodes formed integral with said electrode faces and corresponding in the number of pairs to the order of said harmonic frequency, interconnections for said electrodes of similar polarity formed integral with the surface of said element between said opposite electrode faces, and means including projections in contact with a part of some of said electrodes for clamping said element therebetween.

WARREN P. MASON.