

Oct. 17, 1939.

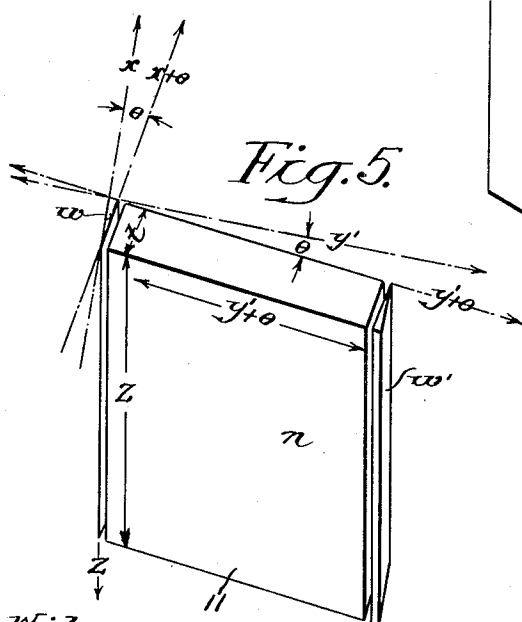
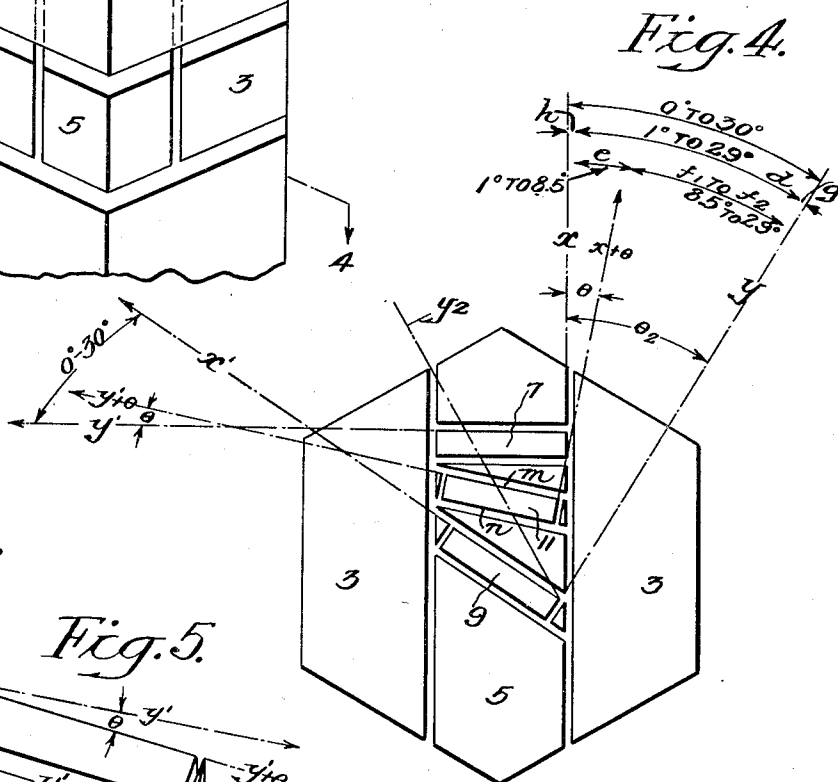
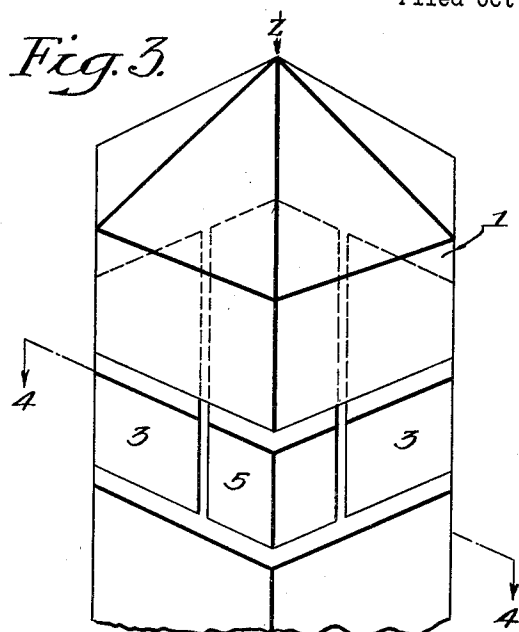
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2,176,653

TWO-FREQUENCY PIEZOELECTRIC ELEMENT

Filed Oct. 31, 1935

4 Sheets-Sheet 2



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TWO-FREQUENCY PIEZOELECTRIC ELEMENT

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4 Sheets-Sheet 3

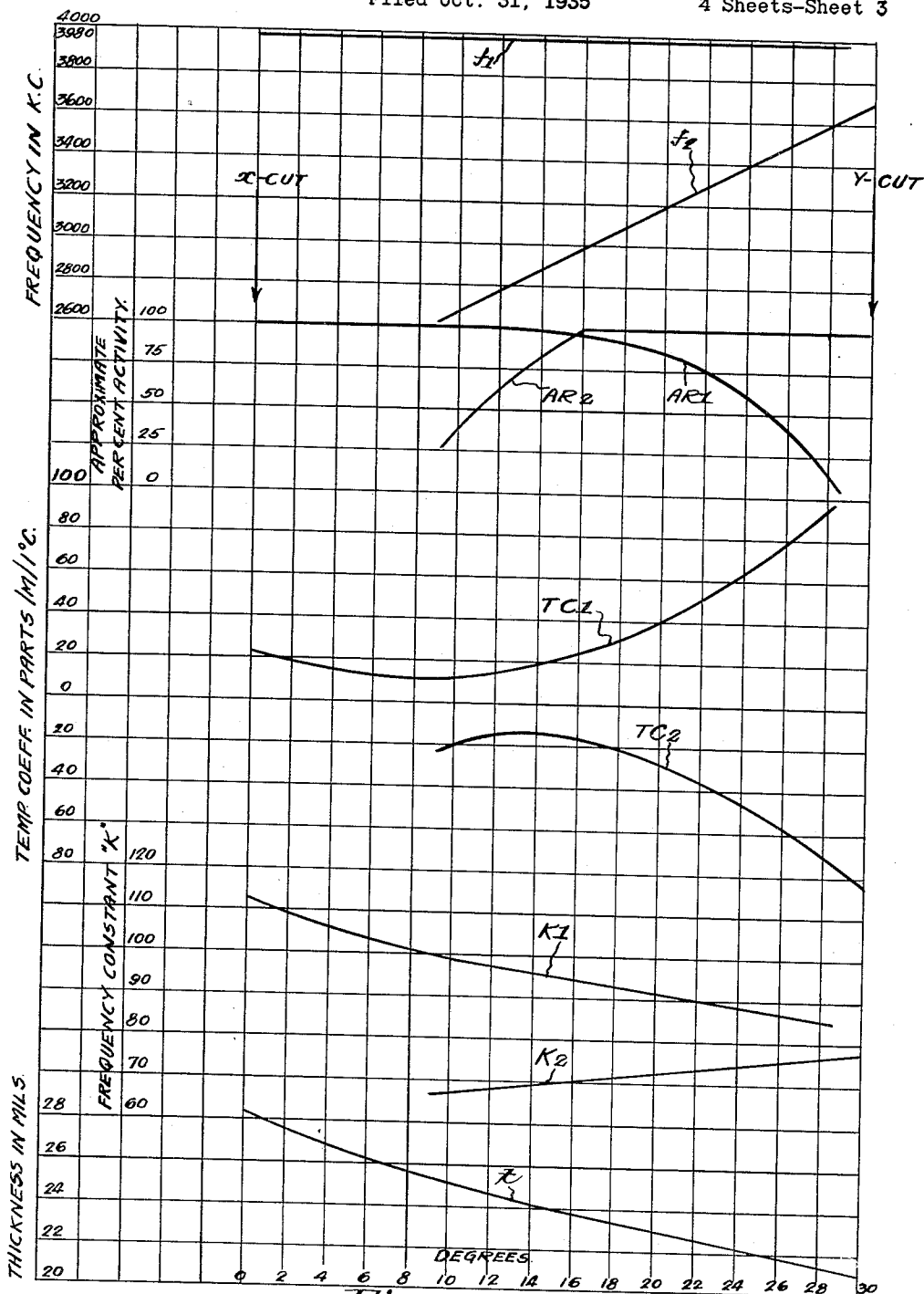


Fig. 6.

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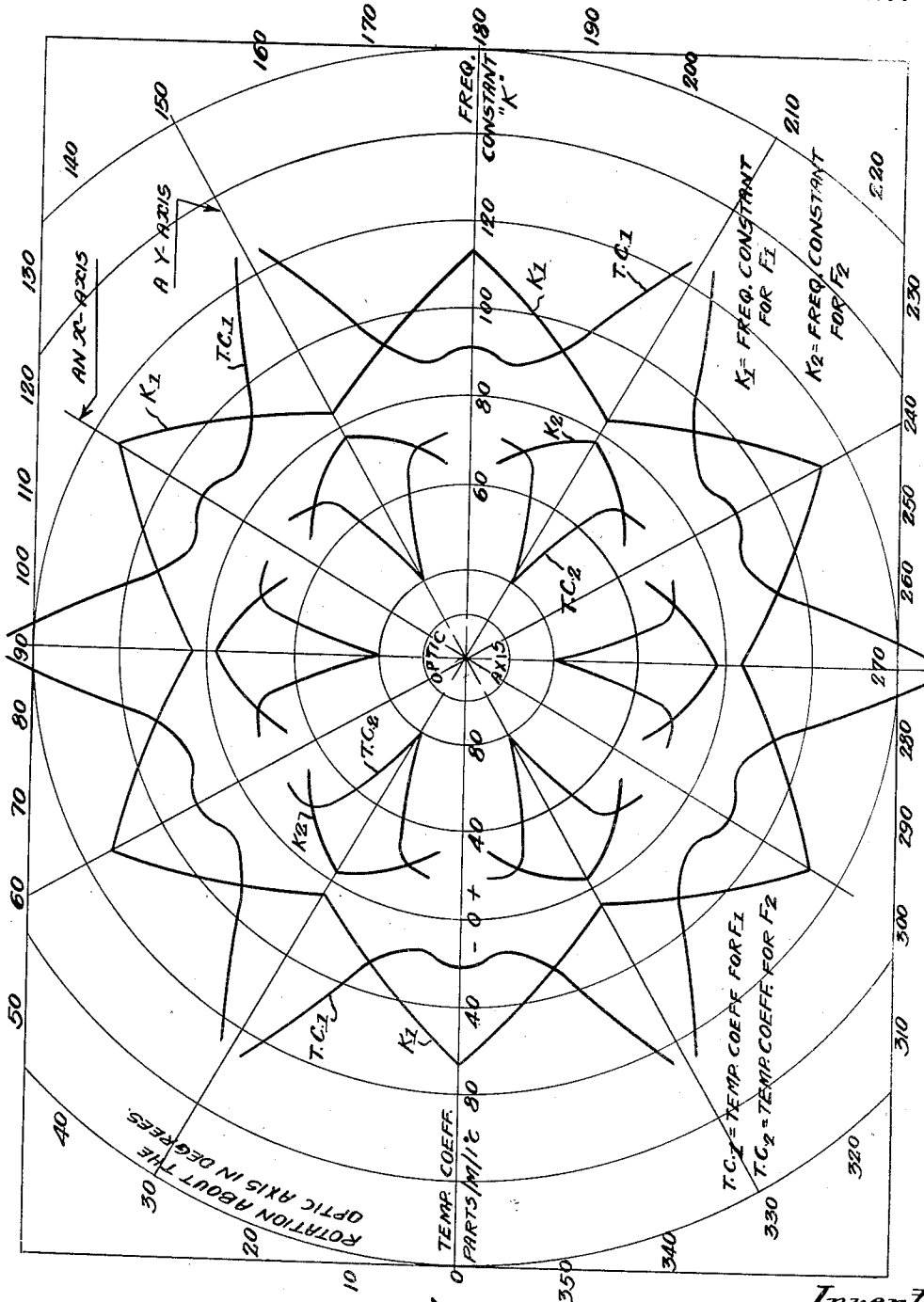
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TWO-FREQUENCY PIEZOELECTRIC ELEMENT

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4 Sheets-Sheet 4



CHARACTERISTICS OF QUARTZ PLATES ROTATED ABOUT THE OPTIC AXIS.

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Fig. 7.

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UNITED STATES PATENT OFFICE

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ELEMENTSamuel A. Bokovoy, Audubon, N. J., assignor to
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5 Claims. (Cl. 171—327)

This invention relates to the piezoelectric art and particularly to the cutting of quartz-piezoelectric elements.

It is known to those skilled in the art that when a quartz-crystal is "X-cut", that is to say, when it is cut in the form of a rectangular plate so oriented with respect to the mother crystal that its thickness dimension is along an electric (X) axis and its length or width along either the optic (Z) axis or a mechanical (Y) axis, several modes of vibration and, consequently, several fundamental frequency responses are possible of attainment. One of these modes of vibration, namely, the thickness-mode, is always present. In a given crystal there is but one useful fundamental frequency, characteristic of this mode of vibration. The same holds true if the crystal is "Y-cut", i. e., if the thickness dimension of the element is along a mechanical (Y) axis and its length or width along either an electric (X) axis or the optic (Z) axis.

In both X-cut and Y-cut crystals, the single useful fundamental frequency characteristic of the thickness-mode of vibration is usually considerably higher than any of the frequencies characteristic of the several width-length (contour) modes.

As noted by Hund, (Proceedings of The Institute of Radio Engineers, vol. 14, No. 4, August, 1926, at page 452) when rectangular quartz plates are cut with the electrode faces other than parallel with the X, or with the Y axes, but nevertheless parallel to the Z (optic) axis, two or more thickness-mode X-axis frequencies are present. These frequencies bear a random relation to each other and are not said to be predictable.

An object of the present invention is to provide a piezoelectric element that will respond to more than one fundamental thickness-mode frequency, said frequencies bearing a predetermined useful relation to each other.

Another object of the invention is to provide a piezoelectric element that will respond to two predetermined, correlated, fundamental thickness-mode frequencies, either frequency being achieved by simply tuning the L—C circuit with which the element is associated.

Another object of the invention is to provide a process for cutting a quartz-crystal to procure a piezoelectric element that will oscillate efficiently, without being "driven", at two desired thickness-mode frequencies.

Another object of the invention is to provide a simple, accurate and efficient mode of procedure in the cutting of quartz crystals, to eliminate as

far as possible any uncertainties with regard to the activity, the temperature coefficient of frequency and other operating characteristics of the finished element.

Other objects and advantages will be apparent and the invention itself will be best understood by reference to the following specification and to the accompanying drawings, wherein

Figure 1 is a chart showing the "weak" and the "strong" double frequency regions which lie between an X-axis and a Y-axis and the angle of rotation required to achieve a desired frequency response.

Fig. 2 is a pair of curves showing the upper and the lower frequency constants (K) for all angles of rotation about and parallel to the Z (optic) axis, between an X and an adjacent Y axis.

Fig. 3 shows in outline and in perspective a piece of natural quartz having a section cut and divided to provide a rough bar having top and bottom surfaces lying in a plane which is normal to the optic (Z) axis.

Fig. 4 is a cross-sectional view taken on the line 4—4 of Fig. 3 showing the relative position of a blank (cut in accordance with the invention from the bar of Fig. 3) with respect to a standard X-cut and a standard Y-cut blank.

Fig. 5 is a view in perspective of the center blank of Fig. 3 removed and trimmed. The Z (optic) axis marked on this figure is perpendicular to the plane of projection in Fig. 4.

Fig. 6 is a chart showing a family of curves indicative of certain characteristics of quartz plates of a specified thickness, cut in accordance with the invention, in the X—Y plane.

Fig. 7 is a chart illustrative of the uniformity of operating characteristics for all angles of rotation about the Z (optic) axis.

The present invention is predicated upon the discovery that a quartz element whose thickness dimension lies in a plane containing an X and a Y axis (i. e., in a plane normal to the Z axis) may be so orientated that it will respond to a thickness-mode fundamental frequency characteristic of an X axis and a second, lower, fundamental frequency characteristic of a Y axis which is 30° removed from said X axis. For certain angles of cut in an X—Y plane the amplitude or percent activity of one frequency response may be so small that unless the element is "driven" (as for resonator or electric filter work) it will not be readily apparent. For other angles of cut in this two frequency response region (i. e., in an X—Y plane) both responses may be of such mag-

nitude as to be readily discernible without driving the element.

In order to procure a piezoelectric element capable of responding to two independent fundamental frequencies it is preferable, first, to determine in terms of percent the relation that the desired lower frequency bears to the desired higher frequency. This is so regardless of the amplitude of the vibrations with which the finished element will respond. If one of the response frequencies need only be of an amplitude sufficient for resonator or electric-filter work the lower frequency should ordinarily be substantially no greater than 66% or no less than substantially 54.8% of the higher frequency. The lower limit obtaining when the element is X-cut. If, on the other hand, it is required that both frequencies be of an amplitude useful for oscillator work, the lower frequency should ordinarily be substantially no greater than 91.5%, or no less than substantially 66% of the higher frequency.

These limits are indicated in Fig. 1 wherein the frequency-ratio limits for the several response regions are shown in terms of percent by the perpendicular lines *a*, *b* and *c*.

In the chart of Fig. 1 an X (electric) and an adjacent Y (mechanical) axis are designated X and Y, respectively, and the space or region therebetween calibrated in degrees from the X axis. Horizontal line *d* extends from a point substantially 1° from the X axis to within 1° of the Y axis and marks the preferred limits within which piezoelectric elements may be cut in accordance with the present invention. An element cut within the limits defined by the arrows of line *e* and *h* will respond to two frequencies but to achieve the lower of the two frequencies the element needs to be driven. Area *e* extends from 1° to the line *b* corresponding substantially to 8.5° from an X-axis, and area *h* extends from the X-axis to the axis which is 1° therefrom.

That portion of the two frequency response region wherein both responses are of such amplitude as to be useful for oscillator work is shown by the line *f*¹—*f*² which extends from line *b*, 8.5° to line *d*, 29° removed from this X-axis.

An element cut within the limits of region *g* must be driven to achieve the higher of the two frequencies. Here the lower frequency is preferably no less than substantially 91.5% or no greater than substantially 93% of the higher frequency. Region *g* extends from line *c*, which is 29°, from an X-axis to a point 30° removed from the X-axis. The 30° line coincides with a Y-axis which is adjacent, in either direction, to the X reference-axis.

Assuming now that a piezoelectric element is required which shall be capable of oscillating selectively at two frequencies, say, 8000 kc. per second and 6000 kc. per second. The lower frequency is 75% of the higher and falls within the maximum two-frequency response region *f*¹—*f*². With this information, there remains to be determined

(a) The angle of rotation about the Z (optic) axis, in the X—Y plane, at which the element should be cut, and

(b) The thickness dimension required to achieve these independent frequencies.

As to (a), reference to Fig. 1 shows that for the 75% ratio the element should be so cut that its electrode faces are normal to an axis which is substantially 16° from an X axis.

As to (b), the exact thickness of the element is

determined in accordance with one or both of the following formulae:

$$(1) \quad t = \frac{K^1}{f^1}$$

or

$$t = \frac{K^2}{f^2}$$

Where *t* is the thickness of the element in mils of an inch, *f*¹ is the higher, and *f*² the lower, of the required frequencies expressed in megacycles. *K*¹ is a constant for the higher frequency, and *K*² for the lower frequency.

Referring to Fig. 2 from which these constants are derived and applying Formula 1:

$$t = \frac{93}{8} \text{ (megacycles)}$$

or, solved, the thickness of the finished element should be approximately 11.6 mils of an inch.

Checking by applying the lower frequency Formula 2

$$t = \frac{70}{6}$$

or, in substantial agreement with Formula 1, 11.6 mils of an inch.

The length-width ratio, as in prior art "thickness oscillators" is immaterial for all practical purposes.

It will be apparent upon an inspection of Fig. 2 that constance *K*¹ and *K*² are functions of the degree of rotation about the Z (optic) axis. These curves show the following range of constants:

	0°-1°	1°-8.5°	8.5°-29°	29°-30°
<i>K</i> ¹	113-111	111-101	101-85	85-84
<i>K</i> ²	62-62.5	62.5-67	67-77.5	77.5-78

The chart of Fig. 1 and the chart of Fig. 2 (from which the above table is taken) are useful in predetermining the angle of rotation and the thickness dimension required to sustain vibrations of a frequency from, say 400 kc., to say 15 megacycles. The upper frequency being limited only by the practical difficulties encountered in lapping or grinding thin plates.

The preliminary steps in the cutting of the crystal may proceed in the manner usual in the cutting of a standard X-cut blank. Thus, referring to Fig. 3, a section 3, say one inch thick, should first be sliced from the body of the mother crystal 1, and a bar 5 in turn cut from this section. As indicated in Fig. 3, the thickness dimension of this rough bar 5 is parallel to the Z axis, and as shown in Fig. 4, one of its greater dimensions is parallel to an X-axis, *x* and the other dimension is parallel to a Y axis, designated *y*¹, which is normal to the reference X axis, *x*.

In Fig. 4 a standard X-cut blank 7 and a standard Y-cut blank 9 are shown for the purpose of illustrating, relatively, the orientation of a blank 11 cut in accordance with the present invention. It will be observed that the X-cut blank 7 has its thickness dimension parallel to an X-axis, *x*, while the thickness dimension of the Y-cut blank 9 is parallel to a Y-axis *y* which is rotated a full 30° from *x*. One of the two greater dimensions of each of the blanks 7 and 9 is parallel to the Z (optic) axis. The Z axis is not shown in Fig. 4, it is perpendicular to the plane of projection.

As previously set forth and as clearly shown in

these drawings the piezoelectric element, 11, cut in accordance with the present invention, has its electrode faces *m* and *n* lying in planes parallel to a first reference axis, $Y^1 + \theta$, which is normal to a reference axis, $X + \theta$, which is normal to the Z (optic) axis and rotated, not less than 1° nor more than 29°, about the Z axis in a direction away from parallelism with an X axis and towards parallelism with an adjacent Y axis. In Fig. 4 the direction of rotation about the Z axis is in a clockwise direction, that is toward parallelism with that Y-axis which is designated *y*. However, as will hereinafter more fully appear in connection with Fig. 7, the direction of rotation may be in a counter-clockwise direction, that is, toward parallelism with that Y axis which is designated *y*².

As in Fig. 1, line *d* which extends between points 1° and 29° from an X axis indicates preferred angles of orientation within the invention. Similarly line *e* indicates the range 1° to 8.5° within which elements having a high frequency response of maximum amplitude are obtainable. Line $f^1 - f^2$ spans that portion of the two frequency response region, 8.5°-29°, wherein both responses may be of the same amplitude. Elements cut within the limits of line *g* and *h* will ordinarily respond to but a single frequency but may be driven to achieve a second frequency.

The blank 11 is ground and lapped to the required thickness and its edges preferably trimmed by removing the wedge shaped sections *w.w*¹. In accordance with the usual practice the crystal plate may be finished with its edges slightly beveled to avoid chipping. As previously set forth, the length-width ratio is not critical and may be of any convenient length-width dimensions and of any desired shape.

Fig. 6 shows the characteristics of several quartz elements having a thickness of 21 mils to substantially 28.3 mils of an inch at different angles of rotation about the Z (optic) axis in the X-Y plane. Referring to the bottom curve *t*, this curve shows the thickness required at all degrees (i.e., 0°-30°) in the X-Y plane to achieve the frequency response represented by the two top lines f^1 and f^2 . Line f^1 shows clearly that the higher frequency of 3980 k. c. may be achieved at substantially all angles from 0° to 29° in the X-Y plane, but that a second lower frequency f^2 will be of appreciable amplitude only when the crystal is cut between 8.5° and 30°. If the element is driven as a resonator, both frequencies may be achieved at any angle (including 0°) of rotation.

Curves AR1 and AR2 show that the amplitude response or "activity" of the upper and lower modes of vibration is a function of the angle of orientation about the Z (optic) axis and indicates that optimum response for both frequencies f^1 and f^2 is achieved when the electrode faces of the element lie in a plane substantially mid-way between an X and a Y axis. For other angles of rotation the amplitude response of one mode of vibration may be greater or less than that of the other, estimated, as indicated, in terms of percent, by these curves AR1 and AR2.

Curves TC1 and TC2 show, respectively, the temperature coefficient of frequency, in parts per million per degree C., exhibited by the crystal when vibrating at each of its two frequencies f^1 and f^2 .

Curves K1 and K2, which are indicative of the constants for each frequency, are similar in all respects with the curves of Fig. 2 and are included

in this figure to show at single glance all constructional and operating features of quartz crystal elements within the present invention.

Fig. 7 is a chart showing the characteristics of quartz plates rotated throughout the entire 360° scale about the optic axis. It will be noticed that there are twelve similar 30° segments each circumscribed by an X and a Y axis, and that the several curves within each segment are duplicates of corresponding curves in each of the other segments. The significance of this phenomena is, that in carrying the invention into effect, any X-axis and either of its two adjacent Y-axis may be employed as reference axes.

The temperature coefficient curves TC1-TC2 and the frequency constant curves K1-K2 are characteristic of frequencies f^1 and f^2 respectively, shown in Fig. 6, previously described.

The complete exploration of all angles of cut about and parallel to the optic axis, evidenced by the foregoing description, charts, table and formulae is considered to be a distinct contribution to the art. In carrying the invention into effect, frequent tests between successive stages of the grinding operation may dictate minor departures from the data and mode of procedure set forth. The invention, therefore, is not to be limited except insofar as is necessitated by the prior art and by the spirit of the appended claims.

What is claimed is:

1. A quartz piezoelectric element adapted to respond to two predetermined fundamental thickness-mode frequencies, the lower of said frequencies being at least substantially 66% and not more than substantially 91.5% of the higher of said frequencies, said element having its thickness dimension along an $X + \theta$ axis, said axis lying substantially 8.5° to substantially 29° removed from an X (electric) axis in a plane normal to the Z (optic) axis, the exact angle formed by the intersection of said X and $X + \theta$ axes being determined, in substantial agreement with the chart of Fig. 1, by the per cent relation which the lower of said frequencies bears to the higher of said frequencies.

2. The invention as set forth in claim 1 wherein the thickness of said element measured in mils of an inch along said $X + \theta$ axis is substantially equal to

$$\frac{K_1}{f_1} \text{ and to } \frac{K_2}{f_2}$$

where f_1 is the higher and f_2 the lower of said thickness-mode frequencies, K_1 is a constant of a value of from 101 to 85 and K_2 is a constant of a value of from 67 to 77.5.

3. A quartz piezoelectric element the thickness dimension of which is parallel to an $X + \theta$ axis which lies not less than 8.5° and not more than 29° removed from an X-axis in a plane normal to the optic (Z) axis.

4. Method of preparing and operating a quartz piezoelectric element adapted to respond to a thickness-mode frequency, characteristic of an $X + \theta$ -axis, and a second, preselected, lower thickness-mode frequency, characteristic of a $Y + \theta$ -axis which is 30° removed from said $X + \theta$ -axis, said lower frequency being at least 54.8% and not more than 93% of the higher of said frequencies, said method comprising: so cutting a blank from a quartz mother-crystal that its thickness dimension is along an $X + \theta$ axis which lies substantially 0° to 30° removed from an X-axis in a plane normal to the Z-axis, the exact angle formed by the intersection of said X and $X + \theta$

axes being determined in substantial agreement with the chart of Fig. 1 by the per cent. relation which the lower of said frequencies bears to the higher of said frequencies, then reducing the thickness of said blank to a thickness dictated by the formulae

$$t = \frac{K_1}{f_1}$$

and

$$t = \frac{K_2}{f_2}$$

where: t is the substantially exact required thickness of said element measured in mils of an inch along said $X+\theta$ axis, f_1 is the higher and f_2 the lower of said desired thickness-mode frequencies expressed in megacycles, and K_1 is a constant for the higher and K_2 a constant for the lower of said frequencies, the values of which constants are substantially those indicated in the chart of Fig. 2 and then vibrating said piezoelectric element, selectively, at the different frequencies peculiar to said constants K_1 and K_2 .

5. Method of preparing and operating a quartz piezoelectric element having substantially parallel electrode faces and adapted to respond selectively to a thickness-mode frequency which is

characteristic of that axis of the element which is normal to its said electrode faces and a second thickness-mode frequency which is characteristic of an axis which is 30° removed from said first mentioned axis, said method comprising: so cutting a crystal blank that its electrode faces are substantially parallel to a $Y+\theta$ axis which lies substantially 0° to 30° removed from a Y -axis, then reducing the thickness of said blank to a thickness dictated by the formulae:

$$t = \frac{K_1}{f_1}$$

and

$$t = \frac{K_2}{f_2}$$

where, t is the substantially exact required thickness of said element measured in mils of an inch along said first mentioned axis, f_1 is the higher and f_2 is the lower of said desired thickness-mode frequencies, K_1 is a constant of a value of from 84 to 113 and K_2 is a constant of a value of from 78 to 62, and then vibrating said piezoelectric element, selectively, at the different frequencies peculiar to the constants K_1 and K_2 .

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