

Aug. 15, 1939.

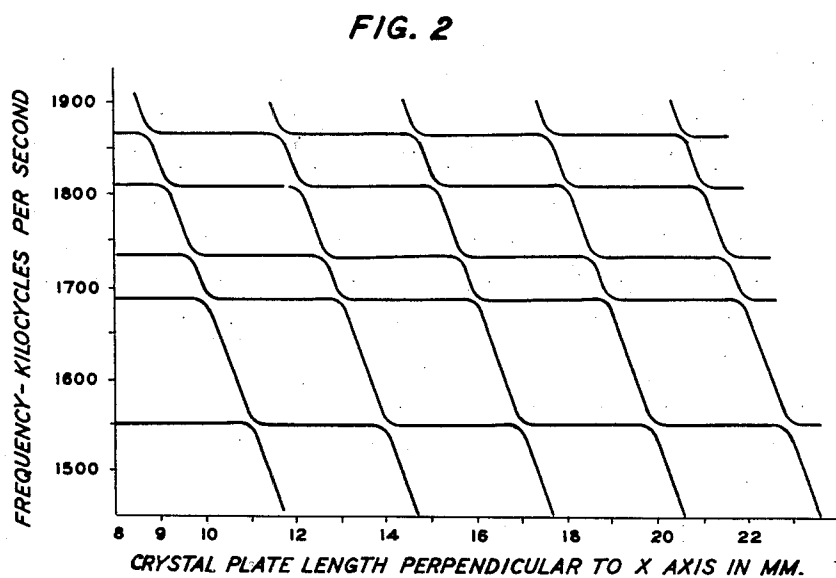
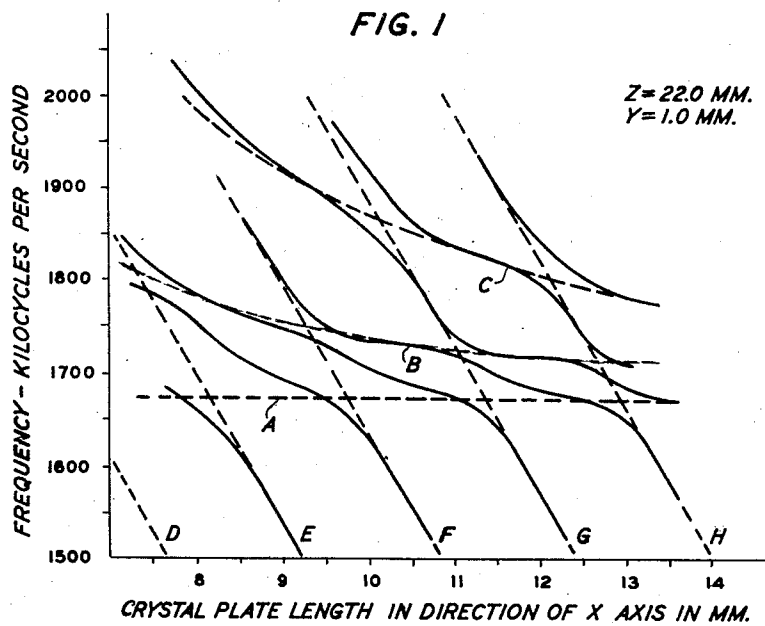
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2,169,301

WAVE FILTER

Filed Oct. 15, 1937

2 Sheets-Sheet 1



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FIG. 3

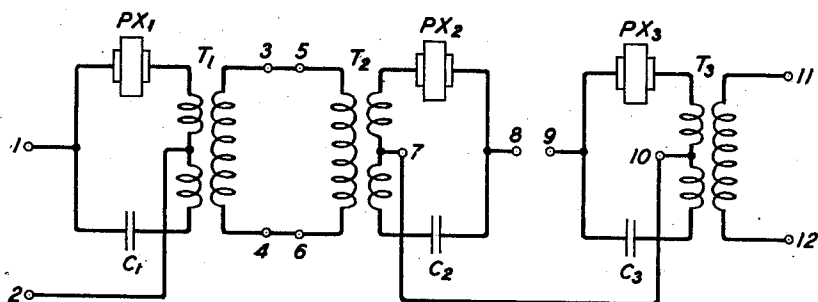
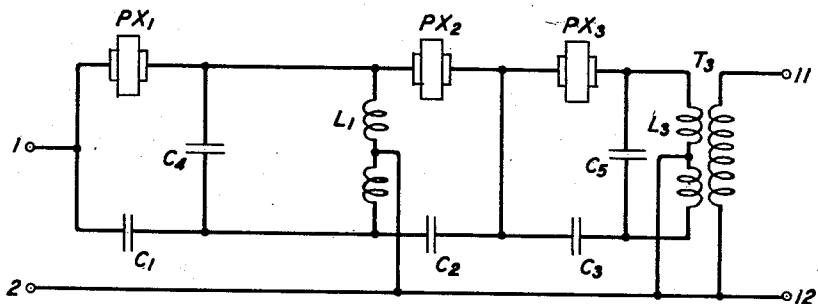


FIG. 4



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2,169,301

WAVE FILTER

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Application October 15, 1937, Serial No. 169,123

4 Claims. (Cl. 178-44)

This invention relates to wave filters and more particularly to high frequency filters in which piezoelectric crystal devices are used as impedance elements.

Heretofore it has been customary, in broad band wave filters employing piezoelectric crystal impedance elements, to use quartz plates of the Curie cut, or X cut, in which the major surfaces of the crystal plate are parallel to both the optical and mechanical axes. The principal resonance frequency of a plate of this type is determined mainly by its length in the direction of the mechanical axis and, by proper proportioning, it is possible to ensure that all of the other resonances of the crystal will occur at frequencies sufficiently remote to have no harmful effect upon the selective characteristic of the filter. However, for operation at frequencies of several megacycles per second, the X cut results in crystals of inconveniently small size and, to obtain crystals of practical dimensions it is therefore necessary to recourse to other types of cut in which the principal resonance is determined by the smallest dimension of the plate. For frequencies of the order mentioned above, Y cut crystal plates, in which the principal surface lies in the plane of the electric and optical axes, and the various modifications thereof are satisfactory. In plates of this type the principal resonance corresponds to a shear mode of vibration and its frequency is determined mainly by the thickness of the plate. Thin plates of relatively large surface area may therefore be used.

The problem of using Y cut crystal plates in electric wave filters is complicated by the fact that such plates exhibit multiplicities of resonances many of which occur at frequencies quite close to the principal resonance. These subsidiary resonances do not prevent the formation of a transmission band in a filter, but they tend to produce sharp diminutions of the attenuation at frequencies close to the band and thereby diminish the filter selectivity.

In accordance with the invention, the effect of the subsidiary resonances of the crystal plates upon the selectivity of a wave filter is diminished by constructing the filter of two or more tandem connected sections and using in the several sections rectangular crystal plates which have the same principal resonances but different subsidiary resonances. In this way any diminution of attenuation in one of the filter sections, because of a subsidiary resonance therein, is compensated by the high attenuation of the other sections at that frequency. I have found by extensive tests and mathematical analysis that the locations of the subsidiary resonances of a Y cut crystal, and crystals of related types of cut, are dependent upon the length and width of the crystal plate and that they may be systematically

controlled by proportioning the length and width of the plate with respect to the thickness. I have also determined for certain particular types of crystal cut, a series of optimum plate configurations which correspond to the most advantageous spacings of the subsidiary crystal resonances.

The invention will be more fully understood from the following detailed description and by reference to the attached drawings, of which:

Figs. 1 and 2 are illustrative of the resonance characteristics of a quartz crystal; and

Figs. 3 and 4 show in schematic form the circuits of wave filters embodying the invention.

For the purpose of illustrating the dependence of the resonance frequencies of a crystal plate in shear vibration upon the plate dimensions, the particular case of an AT cut crystal has been chosen. This type of cut, which is characterized by substantial independence of the resonance frequency upon temperature, is described in a paper by Messrs. Lack, Willard and Fair entitled "Some improvements in quartz crystal circuit elements", Bell System Technical Journal, Vol. XIII, No. 3, July 1934. It differs from the ordinary Y cut in that the plane of the crystal plate is inclined to the plane of the optic and electric axes at an angle of 35 degrees instead of being parallel thereto. The curves of Fig. 1 show the principal resonance frequencies of a rectangular AT cut plate as functions of the length of the plate in the direction of the X or electrical axis, the plate being assumed to have a thickness of one millimeter and a fixed length of 22 millimeters in the direction perpendicular to the X axis.

For any particular length of the crystal there is a plurality of resonances at somewhat irregularly separated frequencies. As the length in the X direction is varied, the frequencies follow variations that conform roughly to the pattern formed by the two sets of intersecting dotted lines. These sets of dotted lines represent the frequencies that the crystal would have under appropriate excitation if there were no coupling between the different vibrational modes. The dotted curves A, B and C represent related shear vibrations, the frequencies of which are given by the formula:

$$f = 1665 \sqrt{\frac{m^2}{b^2} + \frac{n^2}{a^2}} \quad (1)$$

wherein f denotes the frequency in kilocycles per second, a is the length of the plate in millimeters in the direction of the X axis, b is the thickness of the plate in millimeters, and m and n are integers. Curves A, B and C correspond to the values m equal to unity and n equal to 1, 3 and 5, respectively, curve A representing the fundamental shear vibration.

The diagonal dotted lines D to H represent harmonics of a low frequency flexural vibration of the plate along the X axis, the frequencies of these modes being likewise dependent upon the plate dimensions. The solid lines represent the actual measured resonance frequencies. These lines tend to coincide with the different portions of the several dotted lines, but do not intersect as do the latter. This is because of the mechanical coupling that exists between the shear and flexural modes of vibration. Near the points of intersection of the dotted lines the crystal exhibits pairs of resonances, the separation of which depends upon the degree of coupling between the vibrational modes.

If the dimension of the plate in the direction of the X axis were held fixed and its width perpendicular thereto were varied, the resonance characteristics would follow a somewhat similar set of curves to those of Fig. 1 corresponding to the interaction of a different set of shear and flexural vibrations. This is illustrated by the curves of Fig. 2 which show the principal characteristics of the principal resonances of the AT cut crystal as the dimension perpendicular to the X axis is varied, the ratio of the X dimension to the thickness being held fixed at the value 10.5 and the thickness having a value of one millimeter. The horizontal lines correspond to the resonances shown in Fig. 1 for the value of X equal to 10.5 and the diagonal lines represent harmonics of low frequency flexures propagated in the direction of the optic axis. A notable feature of the characteristics is that the two modes of vibration are very loosely coupled with the result that the resonances determined by the X dimension are displaced only at points very close to the intersections with the diagonal lines.

It thus appears that for an AT cut plate of rectangular shape and any given dimensions the frequencies of the principal resonances are determined by the interaction of the shear modes of vibration and coupled harmonic flexural modes, the frequencies of both modes and of the actual resulting resonances being systematically dependent upon the plate dimensions and being subject to control by alteration of these dimensions. Similar results obtain for the normal Y cut crystal and also for other modified forms thereof.

The general mathematical principles underlying the vibratory motion of a piezoelectric crystal are described in the paper noted above by Lack, Willard and Fair and also in the paper by W. P. Mason on "Electrical wave filters employing quartz crystals as elements", Bell System Technical Journal, Vol. XIII, No. 3, July 1934.

I have found that, besides the resonances discussed above, the crystals exhibit many other minor resonances due to the coupling of additional vibrational modes. In general, these additional resonances are not sharp enough to have a serious effect on the selectivity of a wave filter, but they produce irregularities in the transmission characteristic and for that reason it is desirable to avoid them. I have also found that by giving the crystal plates certain optimum dimensional relationships these minor resonances are removed from the neighborhood of the principal resonances by sufficient amounts to prevent their affecting the filter selectivity. For the AT cut crystal the most satisfactory dimensional ratios for rectangular plates are as follows: Denoting the thickness of the crystal plate by Y' , the length in the direction of the electrical axis by X and the length perpendicular thereto by Z' , the ratio

X/Y' should approximate to one or other of the values 9, 10.5, 12.5 and 13.8, and the ratio Z'/Y' should approximate to one or other of the values 10.8, 12.5, 14, 15.5, 17.5, 19.5, 21 and 22. This subject-matter relating to AT cut crystal plates of selected dimensional ratios including that shown in Figs. 1 and 2 is disclosed and claimed in my copending application Serial No. 278,237, filed June 9, 1939.

Fig. 3 shows a typical wave filter in which the invention may be used. This filter comprises three stages all of similar circuit configuration and all designed to have their principal pass bands at the same frequencies. Each stage is of the differential transformer type in which the transmission through a piezoelectric crystal impedance is balanced against the transmission through an impedance of different character, for example, a condenser, the two impedances being such that substantially complete balance is obtained except at frequencies in the transmission band. The first section, which lies between input terminals 1, 2, and output terminals 3, 4, comprises a three-winding transformer T_1 , piezoelectric crystal PX_1 and balancing capacity C_1 . The second section, between terminals 5, 6 and 7, 8, includes the corresponding elements T_2 , PX_2 and C_2 , and the third section, between terminals 9, 10 and 11, 12, includes the corresponding elements T_3 , C_3 and T_3 . Preferably the sections are connected back-to-back as illustrated, to facilitate impedance matching, and the transformers should have high inductance close coupled windings in order that they may approximate in their action to theoretically ideal transformers.

A simplified circuit arrangement is shown in Fig. 4 in which the two transformers T_1 and T_2 are replaced by a single divided inductance L_1 , the two halves of which preferably have a coupling coefficient as nearly as possible equal to unity. The total inductance of the coil should be relatively high, but its effect may be made negligibly small at the transmission band frequencies by the addition of a shunt capacity C_4 proportioned to resonate with the inductance of the mid-band frequency. A similar capacity C_5 is added to neutralize the inductance of output transformer T_3 at the same frequency.

Each of the sections of the filter of Fig. 3 is equivalent to a symmetrical lattice wave filter of the type disclosed in United States Patent 2,045,991, issued June 30, 1936, to W. P. Mason, in which one pair of equal impedances comprises similar piezoelectric crystals and the other pair comprises equal capacities. If desired, inductances may be added in series with each of the crystals and each of the balancing capacities in the manner disclosed in the above-mentioned patent for the purpose of increasing the effective transmission band width. This may also be done in the filter shown in Fig. 4.

The crystal elements PX_1 to PX_3 are preferably of the AT cut mentioned above and are proportioned to provide the main transmission band at the frequency of the basic shear vibration resonance, that is at the frequency closest to the dotted curve A of Fig. 1. Evidently if all of the three crystals were alike in their dimensions, they would all have the same extra resonances and a plurality of pass bands quite close together would result. In accordance with the invention the unwanted bands are suppressed by proportioning the crystals to have the same basic resonance frequency but giving them different rectangular proportions so that the extra resonances

do not coincide. For example, all of the crystals may be made to have their Z' dimensions equal to twenty-two times their Y' dimensions, or thicknesses, but may have their X dimensions respectively equal to 9, 10.5 and 12.5 times the thicknesses. From the curves of Fig. 1, the relationship of the extra resonance frequencies to that of the basic resonances is readily determined. For an X/Y' ratio of 9 the nearest significant resonances are at frequencies 1.032 and 1.065 times the basic resonance. For a ratio of 10.5 the values are 1.025, 1.061, and 1.102, and for a ratio of 12.5 the values are 1.020, 1.040 and 1.075. The basic resonance frequency is inversely proportional to the thickness of the crystal, but since it is also dependent on the other plate dimension, it is evident from Fig. 1 that plates having the different proportions noted above must all have slightly different thicknesses if their basic resonance frequencies are to be equal. While the extra resonances appear at frequencies differing only by a small percentage from the basic resonance, the actual frequency difference at high frequencies is quite large. For example, at a frequency of 2,000,000 cycles per second, a difference of 1 per cent represents a frequency interval of 20,000 cycles per second, and the minimum separations indicated by the figures given above represent intervals of 40,000 cycles per second or more. This permits the formation of adequate bands for speech transmission purposes.

Instead of holding the Z'/Y' ratio the same for all of the crystals and varying only the X/Y' ratio, it will generally be preferable to vary both ratios from crystal to crystal, but in all cases the optimum values given above should be used. Another method of proportioning which also gives satisfactory results consisting in making the X/Y' ratios for all of the crystals approximately equal to one of the optimum values, e. g., 10.5, but making the ratios for the several crystals differ slightly from each other so that a sufficient relative displacement of the extra resonances is obtained.

In the appended claims the expression "AT cut" is used to define the particular orientation of a quartz crystal plate with respect to the principal crystal axes for which the major surfaces of the plate lie in a plane inclined at an angle of 35 degrees to the plane of the optic and electric axes of the crystal.

What is claimed is:

1. In a wave filter comprising a plurality of

tandem sections having transmission bands at the same frequencies, piezoelectric crystal impedances individual to each section, said impedances comprising rectangular crystal plate vibrators cut with similar orientations to the principal crystal axes, each of said plates being proportioned to have a principal shear vibration resonance at a common frequency, and the several plates having different rectangular shapes whereby their secondary resonances occur at respectively different frequencies for each plate.

2. In a wave filter comprising a plurality of tandem sections having transmission bands at the same frequencies, piezoelectric crystal impedances individual to each section, said impedances comprising rectangular crystal plate vibrators cut with similar orientations to the principal crystal axes, each of said plates being proportioned to have a principal shear vibration resonance at a common frequency determining a desired transmission band, and the several plates having different rectangular shapes whereby the formation of unwanted additional transmission bands in the filter is prevented.

3. In a wave filter comprising a plurality of tandem sections having transmission bands at the same frequencies, piezoelectric crystal impedances individual to each section, said impedances comprising rectangular AT cut quartz crystal plate vibrators, each of said plates being proportioned to have a principal shear vibration at a common frequency determining a desired transmission band and the several plates having ratios of their lengths in the direction of the crystal electrical or X axis to their thicknesses respectively equal to different ones of the numbers in the series 9, 10.5, 12.5, and 13.8.

4. In a wave filter comprising a plurality of tandem sections having transmission bands at the same frequencies, piezoelectric crystal impedances individual to each section, said impedances comprising rectangular AT cut quartz crystal plate vibrators, each of said plates being proportioned to have a principal shear vibration at a common frequency determining a desired transmission band and the several plates having ratios of their lengths in the direction perpendicular to the crystal electrical or X axis to their thicknesses respectively equal to different ones of the numbers 10.8, 12.5, 14, 15.5, 17.5, 19.5, 21, and 22.

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