

Feb. 3, 1942.

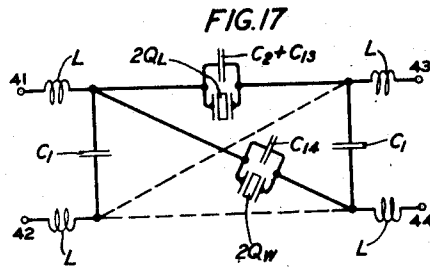
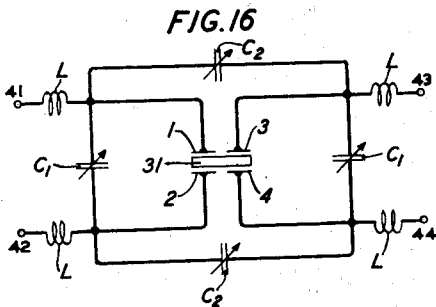
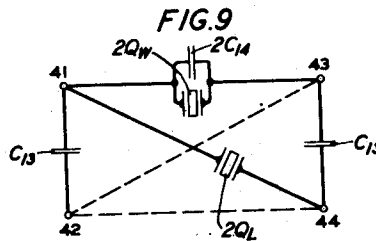
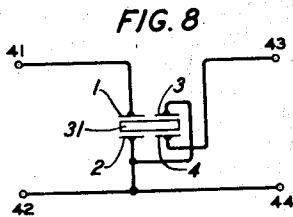
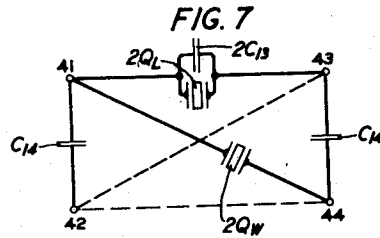
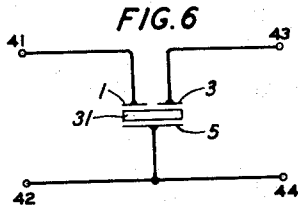
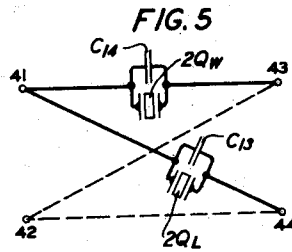
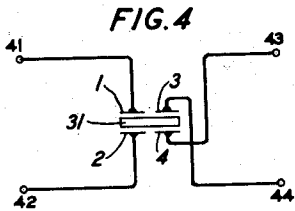
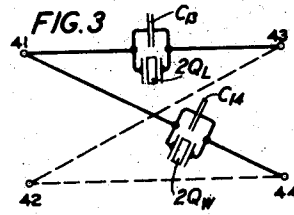
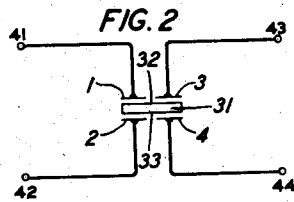
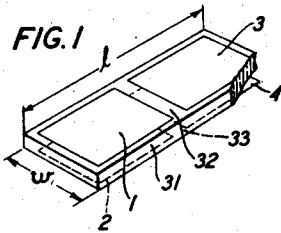
W. P. MASON

2,271,870

WAVE TRANSMISSION NETWORK

Filed Nov. 10, 1939

3 Sheets—Sheet 1



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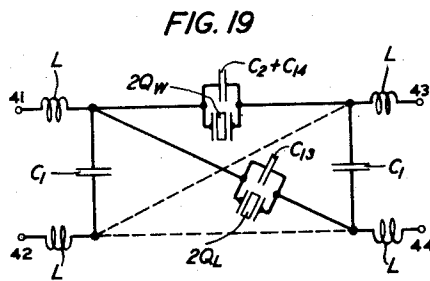
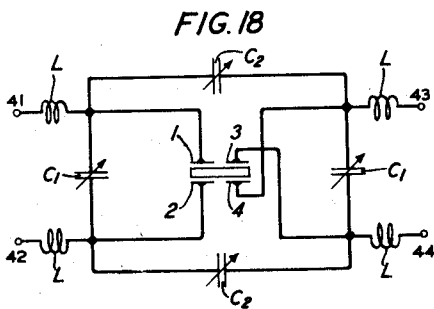
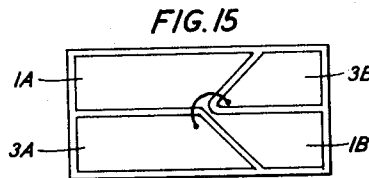
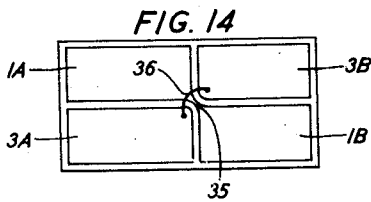
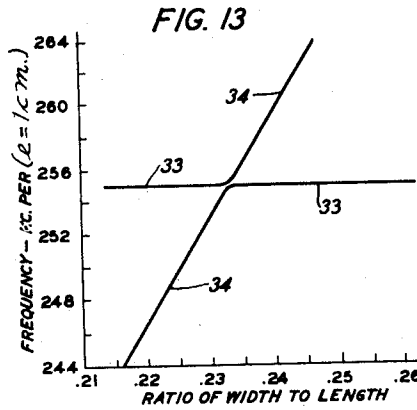
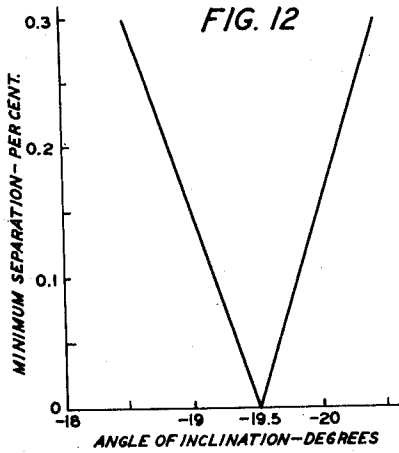
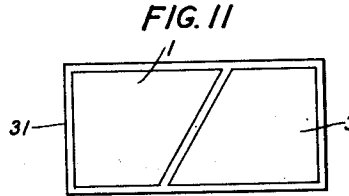
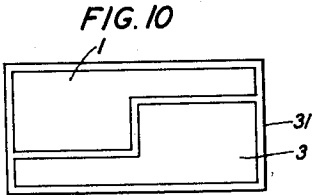
W. P. MASON

2,271,870

WAVE TRANSMISSION NETWORK

Filed Nov. 10, 1939

3 Sheets—Sheet 2



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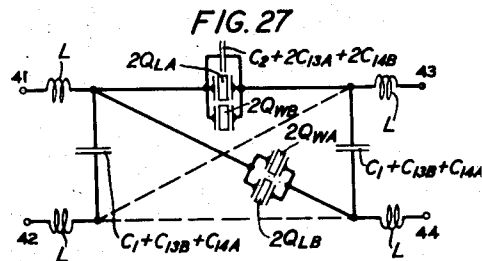
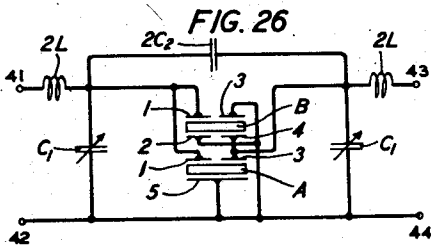
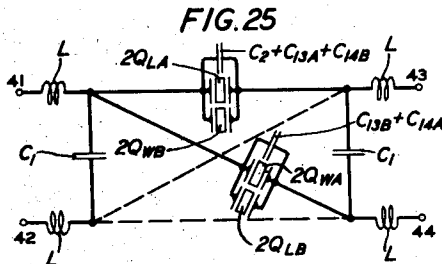
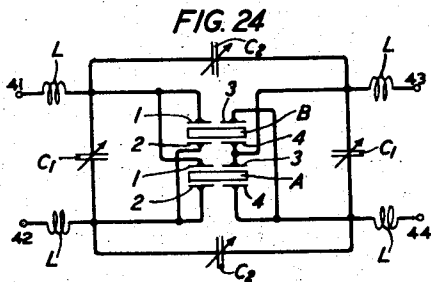
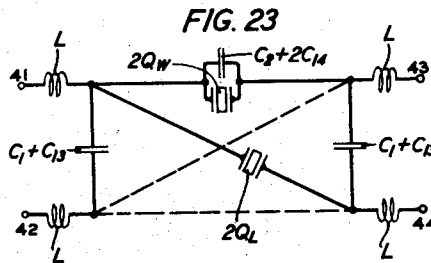
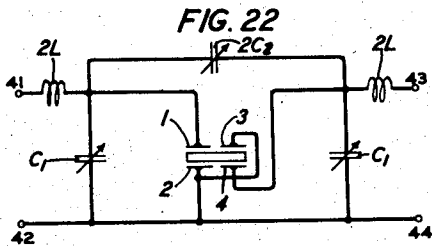
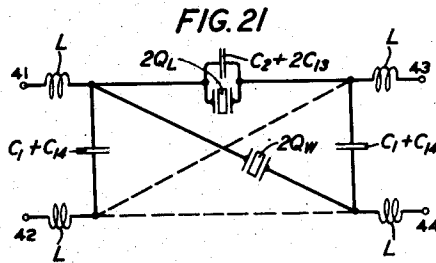
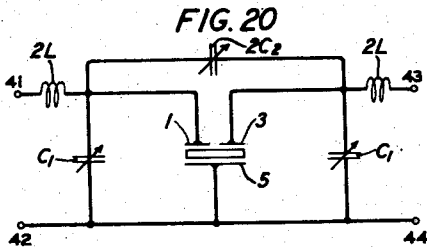
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2,271,870

WAVE TRANSMISSION NETWORK

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3 Sheets—Sheet 3



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UNITED STATES PATENT OFFICE

2,271,870

WAVE TRANSMISSION NETWORK

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Application November 10, 1939, Serial No. 303,757

17 Claims. (Cl. 171—327)

This invention relates to wave transmission networks and more particularly to wave filters which employ piezoelectric crystals as impedance elements.

The principal objects of the invention are to reduce the number of crystals required to build a wave transmission network meeting given requirements, to reduce the amount of piezoelectric material required for the crystals and to reduce the cost of such filters.

A feature of the invention is a wave filter comprising as a component element a single piezoelectric crystal adapted to vibrate in a plurality of substantially uncoupled modes of motion to provide a plurality of simultaneously effective resonances which may be independently placed at predetermined frequencies.

Heretofore a piezoelectric crystal when used in a wave filter has provided only a single usable resonance. Other resonances may be present but it has been the practice to keep them away as far as possible from the main resonance so that the transmission properties of the network will not be adversely affected. In accordance with the present invention, however, a single crystal element is made to provide a plurality of independent, simultaneously effective resonances which may be utilized in a wave filter or other wave transmission network.

As examples, two crystal cuts and the appropriate electrode arrangements are described. The crystal is in the form of a quartz plate having a substantially rectangular major face of specified orientation with respect to the axes of the mother crystal. One frequency of resonance is determined primarily by the length of the face and another primarily by the width. One crystal makes use of the fundamental longitudinal vibration in the direction of the width and a harmonic of the longitudinal vibration in the direction of the length. The other crystal makes use of the fundamental vibration in the direction of the length and a harmonic of the flexure vibration in the plane of the face. Since in both instances the modes of motion are substantially uncoupled, there are provided two resonances which are simultaneously effective in the filter circuit. Their frequencies are independent of each other and may be located as required by the filter design. In order to control the relative strengths of the two resonances special electrode arrangements are provided.

The crystal may be connected into the filter circuit in such a way that one resonance is effective in the line branch and the other is ef-

fective in the diagonal branch of the lattice portion of the equivalent network. There are disclosed filter circuits using only a single crystal which are electrically equivalent to former circuits requiring two crystals, and other circuits using two crystals which are equivalent to former circuits requiring four crystals. It is apparent, therefore, that the number of separate crystals required is cut in half. Also, the required amount of piezoelectric material is substantially reduced and the cost of building the networks is reduced. Both balanced and unbalanced structures are disclosed.

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

Fig. 1 is a perspective view of a piezoelectric crystal with associated electrodes suitable for use in the networks of the invention;

Figs. 2 and 4 show two types of balanced connections for the crystal of Fig. 1;

Figs. 3 and 5 represent the equivalent lattices for the circuits of Figs. 2 and 4, respectively;

Figs. 6 and 8 are the unbalanced structures for the circuits of Figs. 2 and 4, respectively;

Figs. 7 and 9 represent the equivalent networks for the circuits of Figs. 6 and 8, respectively;

Figs. 10 and 11 show modifications of the electrode arrangement shown in Fig. 1;

Figs. 12 and 13 present curves relating to a second type of doubly resonant crystal suitable for use in the networks of the invention;

Figs. 14 and 15 show suitable electrode arrangements for the second type of crystal;

Figs. 16 and 18 show balanced filter circuits using the electrode connections shown respectively in Figs. 2 and 4;

Figs. 17 and 19 represent the equivalent networks for the filters of Figs. 16 and 18;

Figs. 20 and 22 give the unbalance structures for the filters of Figs. 16 and 18, respectively, using the electrode connections shown in Figs. 6 and 8, respectively;

Figs. 21 and 23 represent the equivalent networks for the filters of Figs. 20 and 22, respectively;

Fig. 24 is a balanced filter circuit using two crystals with the connections shown respectively in Figs. 2 and 4;

Fig. 25 is the equivalent network for the filter of Fig. 24;

Fig. 26 shows the unbalanced structure for the filter of Fig. 24 using the electrode connections of Figs. 6 and 8; and

Fig. 27 represents the equivalent network for the filter of Fig. 26.

Taking up the figures in more detail, Fig. 1 is a perspective view of a piezoelectric crystal element, with its associated electrodes, suitable for use in the networks of the invention. The crystal is a quartz plate 31 having a substantially rectangular major face 32 substantially parallel to an electric or X-axis of the mother crystal and inclined at an angle of substantially +50 degrees with respect to the optic or Z-axis as measured in a plane perpendicular to said electric axis, the length dimension l being inclined at an angle of substantially 45 degrees with respect to said electric axis. This type of crystal orientation is disclosed in my copending application Serial No. 180,921 filed December 21, 1937, now Patent No. 2,204,762, issued June 18, 1940.

The crystal has four equal electrodes, symmetrically placed. On the face 32 are two electrodes 1, 3 with a transverse dividing line and on the other major face 33 are two other electrodes 2, 4 oppositely disposed, respectively, to the electrodes 1 and 3. If electrical connections are made between the four electrodes and the two pairs of terminals 41, 42 and 43, 44 as shown schematically in Fig. 2 the crystal will have the equivalent electrical circuit shown in Fig. 3. The equivalent network is a lattice in which each line impedance branch consists of a crystal 2Q_L shunted by a capacitance C₁₃ and each diagonal impedance branch consists of a crystal 2Q_W shunted by a capacitance C₁₄. The crystal 2Q_L has twice the impedance of the original crystal fully plated and vibrating longitudinally and a frequency of resonance equal to twice the frequency of the fundamental longitudinal vibration in the direction of the length. The crystal 2Q_W has twice the impedance of the original crystal fully plated and vibrating along its width and a frequency of resonance equal to the fundamental longitudinal vibration in the direction of the width.

It is seen, therefore, that these two frequencies of resonance are determined, respectively, by the length and the width of the original crystal. Furthermore, the two modes of motion are substantially uncoupled mechanically since for the harmonic of the length vibration the half of the crystal on one side of the transverse dividing line is expanding in the direction of its width while the half on the other side is contracting so that the net effect upon the width vibration is zero. The single crystal, therefore, provides two independent, simultaneously effective resonances which may be placed at any desired frequencies. The one appears in the line branch of the equivalent lattice and the other in the diagonal branch. Since in a wave filter these two frequencies are usually close together it follows that the ratio of the width of the crystal to its length will generally be in the neighborhood of 0.5.

The capacitance C₁₃ represents that effective between the electrodes 1 and 3 on the same side of the crystal and the capacitance C₁₄ represents that effective between the diagonally opposite electrodes 1 and 4. Due to the symmetry of the electrodes the other corresponding line and diagonal impedance branches will be the same as those described. For the sake of clarity in Fig. 3 and in subsequent figures only one line branch and one diagonal branch are shown in detail. The corresponding branches are indicated by dotted lines connecting the appropriate terminals.

If the connections between the electrodes 3, 4

and the terminals 43, 44 are reversed, as shown in Fig. 4, the line and diagonal impedance branches of the equivalent lattice network will be interchanged, as shown in Fig. 5. The crystal 2Q_W will now appear in the line branch and the crystal 2Q_L in the diagonal branch.

The balanced circuit of Fig. 2 may be converted to an unbalanced structure by interconnecting the two electrodes on one side, as for example electrodes 2 and 4. In this case the two electrodes may be replaced by a single electrode 5 as shown in Fig. 6. The equivalent balanced network is shown in Fig. 7. The crystal 2Q_L appears in the line branch of the lattice portion but the shunting capacitance is now equal to 2C₁₃. To reduce the magnitude of this capacitance a grounding strip may be run from one side of the crystal to the other between the electrodes 1, 3 and electrically connected to the electrode 5. The capacitance C₁₄ no longer appears in shunt with the crystal 2Q_W in the diagonal branch of the lattice but is shunted at each end of the circuit. In Fig. 7 the capacitance C₁₄ represents the capacitance effective between electrode 1 and the half of the electrode 5 which is diagonally opposite thereto.

The circuit of Fig. 4 may also be converted to the unbalanced form by connecting together two diagonally opposite electrodes, as for example electrodes 2 and 3, as shown in Fig. 8. Fig. 9 gives the equivalent balanced network in which the crystal 2Q_W in the line branch of the lattice portion is shunted by a capacitance 2C₁₄, the diagonal branch consists of the crystal 2Q_L and at each end of the lattice appears a shunt capacitance C₁₃.

As pointed out above, for the electrode arrangement of Fig. 1 the crystals 2Q_W and 2Q_L shown in the equivalent circuits of Figs. 3, 5, 7 and 9 will have substantially the same impedance, that is, their reactance characteristics as they pass through zero will have approximately the same slopes. These impedances are dependent upon the thickness of the crystal plate and to increase the impedance level the thickness is increased. However, in order to obtain more general filter characteristics it is desirable that means be provided for controlling the relative impedance levels of the two crystals. In accordance with the invention this may be done by extending the electrode 1, associated with the left half of the crystal face, to cover a portion of the right half, and extending the electrode 3 by the same amount to cover a portion of the left half, as shown in the plan view of Fig. 10. The electrodes 2 and 4 on the opposite face of the crystal are extended in a similar manner. This modification will not materially affect the impedance of the width mode but will decrease the electromechanical coupling for the harmonic of the length mode, thereby increasing the impedance level of the latter.

As seen in Fig. 10 the dividing line runs in a generally diagonal direction. A somewhat simpler electrode arrangement results if the dividing line is made straight, as shown in Fig. 11. The line makes an angle with the width dimension of the crystal and as this angle is increased the impedance level of the length mode is raised, without affecting the impedance of the width mode.

Another type of doubly resonant crystal suitable for use in transmission networks is a quartz plate having a substantially rectangular major face substantially perpendicular to an electric

or X-axis of the mother crystal with its length dimension inclined at an angle with respect to the nearest mechanical or Y-axis. This type of crystal orientation is disclosed in U. S. Patent No. 2,173,589, issued September 19, 1939. For a properly chosen angle of inclination the mechanical coupling between the two selected modes of motion can be reduced substantially to zero. These two modes are the fundamental longitudinal vibration in the direction of the length of the crystal plate and the second flexural vibration in the plane of the major face. This latter mode will have a frequency of resonance which is approximately four times that of the fundamental flexural vibration in this plane. A measure of the coupling is the minimum separation obtainable between these two frequencies of resonance. Fig. 12 shows the minimum separation, expressed in per cent of the mean frequency, plotted against the angle of inclination for the crystal plate. The curve indicates that the minimum separation falls substantially to zero when the above-mentioned angle is substantially -19.5 degrees. This, then, is the preferred angle for minimum mechanical coupling between the two modes of motion.

The curves of Fig. 13 give the frequencies of resonance for the two modes, in kilocycles per second, plotted against the ratio of width to length for a -19.5 degree crystal plate having a length l of one centimeter. For crystals having other lengths the frequencies of resonance are found by dividing the frequencies read from the curves by the actual length l . The two branches of the curve **33** relate to the length vibration and the two branches of the curve **34** relate to the second flexural vibration. It is seen that the length vibration has a frequency constant of about 255 kilocycles regardless of the width of the crystal. For a given length, however, the frequency of the flexural vibration is proportional to the width. The fact that there is a ratio, namely, 0.233, at which the two resonances occur at substantially the same frequency indicates that the two modes of motion are substantially uncoupled. When doubly resonant crystals of this type are used in wave transmission networks the ratio of width to length will usually fall between 0.20 and 0.26, depending upon the required separation between the resonances.

Fig. 14 shows a suitable arrangement of electrodes for the crystal cut just described. Each major face of the crystal has four equal electrodes, each of which is associated with one quarter. On the face shown the two diagonally opposite electrodes **1A** and **1B** are electrically connected by the strip **35** and the other two electrodes **3A** and **3B** are connected by the wire **36**. The connector **36** is soldered to the electrodes at points which are near the center of the crystal because these points are nearest to a node of motion in the crystal and the connections are less likely to work loose when the crystal vibrates. The other major face of the crystal has four other equal electrodes, namely, **2A**, **2B**, **4A** and **4B** oppositely disposed with respect to the electrodes **1A**, **1B**, **3A** and **3B**, respectively. Electrodes **2A** and **2B** are interconnected and electrodes **4A** and **4B** are interconnected.

The crystal of Fig. 14 may be connected between two sets of terminals, **41**, **42** and **43**, **44** as shown in Figs. 2, 4, 6 and 8 to provide the equivalent networks shown, respectively, in Figs. 3, 5, 7 and 9. In this case the electrodes **1A** and **1B**, connected together, take the place of electrode **1**,

electrodes **2A** and **2B** form electrode **2**, electrodes **3A** and **3B** form electrode **3** and electrodes **4A** and **4B** constitute electrode **4**. In the equivalent lattices **2Qw** now represents a crystal having twice the impedance of the original crystal fully plated and vibrating longitudinally and **2QL** represents a crystal having twice the impedance of the original crystal with full plating arranged to drive the second flexural mode only. The resonance frequency of **2Qw** will be that of the fundamental longitudinal vibration in the direction of the length and the resonance frequency of **2QL** will correspond to that of the second flexural vibration in the plane of the major face.

When the four electrodes are equal, as shown in Fig. 14, the flexural mode will have an impedance level approximately 1.6 times that of the longitudinal mode. In accordance with the invention this ratio of impedances may be increased, if desired, by extending two adjacent electrodes so that they cover portions of the other half of the crystal face. For example, as shown in Fig. 15, the electrodes **1A** and **3A** may be extended to the right by equal amounts so that they cover portions of the quarters with which electrodes **3B** and **1B** are associated. The electrodes **3B** and **1B** are reduced in area by the same amounts as the electrodes **1A** and **3A** are increased. The sum of the areas of the electrodes **1A** and **1B** is kept equal to the sum of the areas of the electrodes **3A** and **3B**. On the other major face of the crystal electrodes **2A** and **4A** are increased in area while electrodes **2B** and **4B** are reduced in area.

Specific filter circuits incorporating doubly resonant crystals will now be considered. The filters may employ one or more crystals and they may be of either balanced or unbalanced construction. In every case one crystal takes the place of two formerly required and, furthermore, there is a material saving in the amount of quartz used.

Fig. 16 is a schematic circuit of a filter using a single doubly resonant crystal **31** with the electrode connections shown in Fig. 2. Four equal inductances **L** are connected in series at the ends of the circuit, two equal capacitances **C₁** are connected in shunt at the respective ends of the crystal and two other equal series capacitances **C₂** are bridged across the crystal, one on each side. The capacitances may be made variable, as indicated by the arrows, to facilitate the adjustment of the filter characteristics. The equivalent network for the filter is shown in Fig. 17 wherein the crystal **31** is replaced by its equivalent lattice shown in Fig. 3. The circuit of Fig. 17 will be recognized as having the same configuration as the one using four singly resonant crystals disclosed in Fig. 13 of U. S. Patent No. 2,045,991, issued June 30, 1936. The crystal and other component reactance elements may be proportioned with respect to each other, in the manner set forth in the aforementioned patent, to provide a band pass or other desired transmission characteristic for the filter.

In the filter circuit of Fig. 18 the connections to one pair of electrodes have been reversed as shown in Fig. 4. Otherwise the circuit is the same as that of Fig. 16. The equivalent network is given in Fig. 19 in which the equivalent circuit shown in Fig. 5 has been substituted for the crystal.

The filter of Fig. 16 may be constructed in the unbalanced form, as shown in Fig. 20, wherein the electrodes are connected as shown in Fig. 6.

The filter requires only two series inductances, each having a value of $2L$, and one bridging capacitance having a value of $2C$. The equivalent balanced network is shown in Fig. 21. Also, the filter of Fig. 18 may be built as an unbalanced structure, as shown in Fig. 22, using the electrode connections shown in Fig. 8. Fig. 23 gives the equivalent balanced network.

The schematic circuit of Fig. 24 shows a balanced filter using two doubly resonant crystals A and B connected in parallel. The connections to crystal A are those shown in Fig. 2 and the connections to crystal B are those shown in Fig. 4. Series end inductances L , shunt capacitances C_1 and bridging capacitances C_2 are used in the manner shown in the filter circuits of Figs. 16 and 18. The equivalent network is shown in Fig. 25. In each impedance branch of the lattice portion are two crystals, one being furnished by crystal A and the other by crystal B. In the line branch the crystal $2Q_{LA}$ represents the harmonic vibration of crystal A and $2Q_{WB}$ represents the fundamental vibration of crystal B. In the diagonal branch the crystal $2Q_{WA}$ represents the fundamental vibration of crystal A and $2Q_{LB}$ represents the harmonic vibration of crystal B. Following the same notation the capacitances C_{13A} and C_{14A} represent interelectrode capacitances associated with crystal A and the capacitances C_{13B} and C_{14B} represent those associated with crystal B. With this filter a higher sustained attenuation and more peaks of attenuation may be obtained than with the filters using only a single crystal.

The filter of Fig. 24 may also be built in the unbalanced form, as shown in Fig. 26. The connections to the crystals A and B are those shown, respectively, in Figs. 6 and 8. The equivalent circuit is given in Fig. 27.

Two types of doubly resonant crystals suitable for use in the filters of the invention have been disclosed herein. Other suitable types of such crystals may, of course, be used in the circuits. Also, by way of illustration, a number of typical filter circuits employing doubly resonant crystals have been shown and described. It will be appreciated, however, that many other circuits making use of the principles of the invention may readily be devised by those skilled in the art. In particular similar band-pass filters of high impedance may be obtained by replacing the series inductances L by inductances connected in shunt at the respective ends of the network. Filters of the latter type, using singly resonant crystals, are disclosed in the aforementioned Patent No. 2,045,991.

What is claimed is:

1. Piezoelectric crystal apparatus comprising a single piezoelectric crystal adapted to vibrate in a plurality of substantially uncoupled simultaneously effective modes of motion to provide a plurality of resonances which may be independently placed at different predetermined frequencies, said crystal having associated therewith a plurality of functionally independent sets of electrodes for independently controlling said resonances, a dimension made of a value in accordance with the value of one of said frequencies and a different directional dimension made of a value in accordance with the value of another of said frequencies.

2. Piezoelectric crystal apparatus in accordance with claim 1 in which said crystal is a quartz plate having a substantially rectangular major face disposed substantially parallel to an electric

axis and inclined at an angle of substantially $+50$ degrees with respect to the optic axis as measured in a plane perpendicular to said electric axis, the length dimension of said face being inclined substantially 45 degrees with respect to said electric axis, one of said modes being a longitudinal vibration in the direction of the width of said face and another of said modes being a harmonic of a longitudinal vibration in the direction of said length.

3. Piezoelectric crystal apparatus in accordance with claim 1 in which said crystal is a quartz plate having a substantially rectangular major face disposed substantially perpendicular to an electric axis, the length dimension of said face being inclined substantially -19.5 degrees with respect to the nearest mechanical axis, one of said modes being a longitudinal vibration in the direction of said length and another of said modes being a harmonic of a flexure vibration in the plane of said major face.

4. Piezoelectric crystal apparatus in accordance with claim 1 in which means are provided for adjusting the electrostatic coupling for one of said modes of motion without materially affecting the electrostatic coupling for another of said modes of motion.

5. Piezoelectric crystal apparatus in accordance with claim 1 in which said crystal has a substantially rectangular major face, two of said electrodes being associated with said face and said two electrodes being separated by a line running in a generally diagonal direction with respect to said face.

6. Piezoelectric crystal apparatus in accordance with claim 1 in which said crystal has a substantially rectangular major face, four of said electrodes being associated respectively with the four quarters of said face, two diagonally opposite electrodes being electrically connected and the other two electrodes being electrically connected.

7. Piezoelectric crystal apparatus in accordance with claim 1 in which said crystal has a substantially rectangular major face, four of said electrodes being associated primarily with the four quarters of said face, two adjacent electrodes of said four being equal and each covering more than a quarter of said face, two diagonally opposite electrodes of said four being electrically connected and the remaining electrodes of said four being electrically connected.

8. Piezoelectric crystal apparatus comprising a single piezoelectric crystal adapted to vibrate in a plurality of substantially uncoupled simultaneously effective modes of motion to provide a plurality of resonances which may be independently placed at different predetermined frequencies, electrodes associated with said crystal for independently controlling each of said resonances and means for adjusting the electrostatic coupling for one of said modes of motion without materially affecting the electrostatic coupling for another of said modes of motion.

9. Apparatus in accordance with claim 8 in which said crystal is made of quartz.

10. Apparatus in accordance with claim 8 which includes a capacitor connected between two of said electrodes.

11. Piezoelectric crystal apparatus comprising a single piezoelectric crystal having a substantially rectangular major face, said crystal being adapted to vibrate in a plurality of substantially uncoupled simultaneously effective modes of motion to provide a plurality of resonances which may be independently placed at different prede-

terminated frequencies and having associated therewith electrodes for independently controlling each of said resonances, two of said electrodes being associated with said major face and separated by a line running in a generally diagonal direction with respect to said face.

12. Piezoelectric crystal apparatus comprising a single piezoelectric crystal having a substantially rectangular major face, said crystal being adapted to vibrate in a plurality of substantially uncoupled simultaneously effective modes of motion to provide a plurality of resonances which may be independently placed at different predetermined frequencies and having associated therewith electrodes for independently controlling each of said resonances, four of said electrodes being associated primarily with the four quarters of said major face, two diagonally opposite electrodes of said four being electrically connected and the remaining electrodes of said four being electrically connected.

13. Apparatus in accordance with claim 12 in which two adjacent electrodes of said four are equal and each covers more than a quarter of said major face.

14. Piezoelectric crystal apparatus comprising a single piezoelectric crystal having a plurality of independently controlled and simultaneously effective resonances of different predetermined frequencies, a plurality of functionally independent sets of associated electrodes for independently controlling said resonances, a dimension made of a value in accordance with the value of one of said frequencies and a different directional dimension made of a value in accord-

ance with the value of another of said frequencies.

15. Piezoelectric crystal apparatus comprising a single piezoelectric crystal having a substantially rectangular major face, a plurality of independently controlled and simultaneously effective resonances of different predetermined frequencies, and a plurality of functionally independent sets of associated electrodes for independently controlling said resonances, said face having its length made in accordance with the value of one of said frequencies and its width made in accordance with the value of another of said frequencies.

16. Apparatus in accordance with claim 15 in which said crystal is quartz, said major face being disposed substantially parallel to an electric axis and inclined at an angle of substantially +50 degrees with respect to the optic axis as measured in a plane perpendicular to said electric axis, the length dimension of said face being inclined substantially 45 degrees with respect to said electric axis and said length being in the neighborhood of twice the width of said face.

17. Apparatus in accordance with claim 15 in which said crystal is quartz, said major face being disposed substantially perpendicular to an electric axis, the length dimension of said face being inclined substantially -19.5 degrees with respect to the nearest mechanical axis and the ratio of width to length of said face falling within the range of 0.21 to 0.26.

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