Sept. 18, 1934. W. P. MASON 1,974,081

PIEZO ELECTRIC WAVE FILTER

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FIG. 1

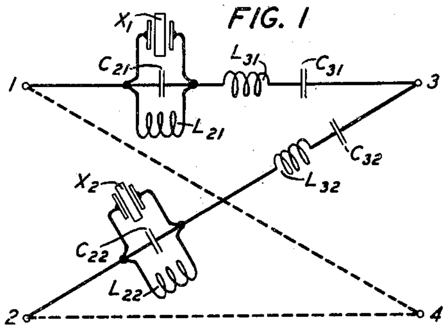


FIG. 2

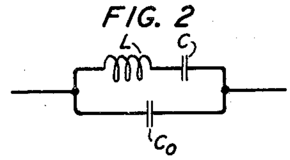
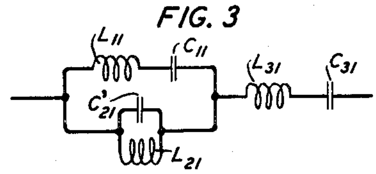


FIG. 3



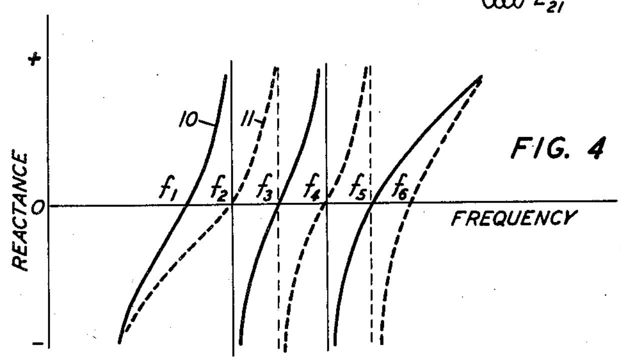


FIG. 4

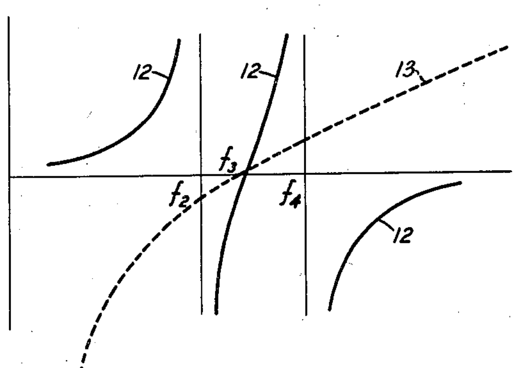


FIG. 5

FIG. 6

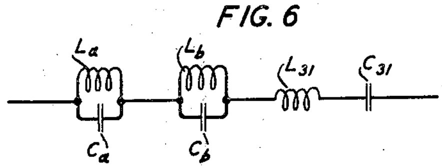


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FIG. 7

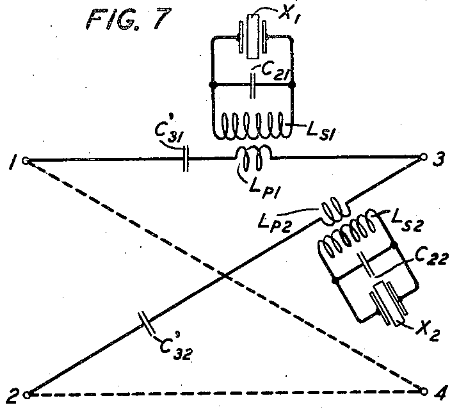


FIG. 8

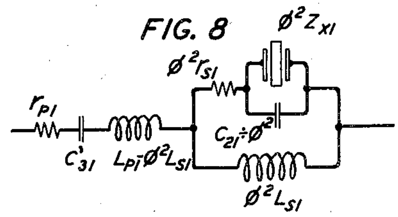


FIG. 9

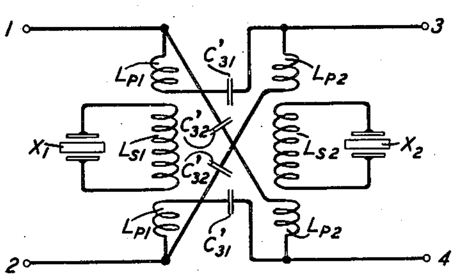


FIG. 10

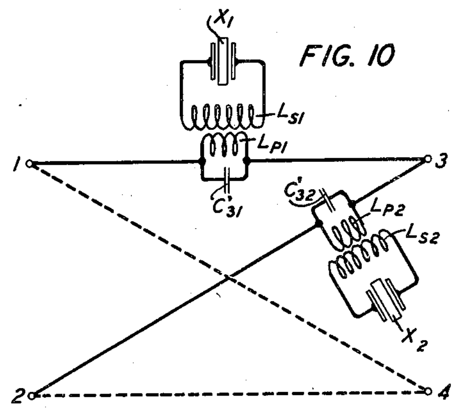


FIG. 11

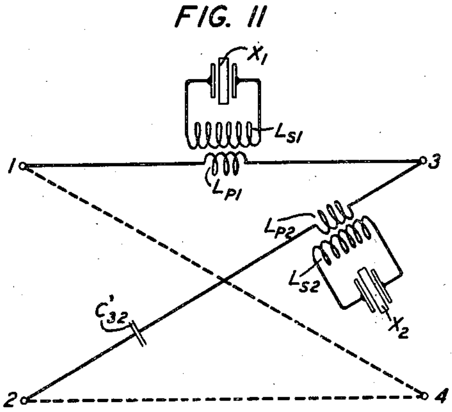
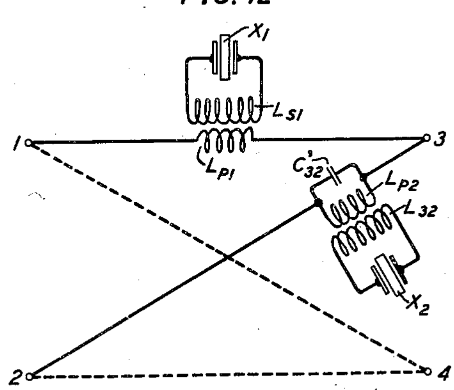


FIG. 12



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UNITED STATES PATENT OFFICE

1,974,081

PIEZO-ELECTRIC WAVE FILTER

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Application March 28, 1933, Serial No. 663,142

8 Claims. (Cl. 178—44)

This invention relates to broad band wave filters in which piezo-electric crystals are used as impedance elements and has for its principal object to extend the range of transmission characteristics that can be obtained with filters of this type. Another object is to reduce the number of crystals required for a desired selectivity.

The electrical impedance of a quartz piezo-electric crystal, as is well known, is characterized by a resonance and an anti-resonance at frequencies very close to each other and by a high capacitive reactance elsewhere. This characteristic makes it difficult to combine crystals in a filter circuit to obtain a reasonably wide transmission band and at the same time to provide a high attenuation level outside the band. The problem is discussed in my earlier application, Serial No. 653,622 filed January 26, 1933, wherein one arrangement is described for obtaining relatively wide transmission bands by combining an inductance in series or in shunt with each crystal of the filter. With this arrangement, band widths as great as 14 per cent of the mean frequency are obtainable without sacrifice of the attenuation level at frequencies remote from the cut-off.

In accordance with the present invention further extension of the band width consistent with a high attenuation level is made possible by the use of inductances connected both in series with and in shunt to each crystal of a filter. Two separate inductances may be associated with each crystal but in the preferred forms of the invention the inductances are arranged to form transformers through which the crystals are coupled to the filter branches. This arrangement has the advantage that in many cases the transformer ratios may be adjusted to permit the use of more practical crystal dimensions than would obtain with directly connected crystals. In one form of the invention the same crystal is coupled simultaneously into two branches of the filter network by means of a special transformer, thereby reducing the number of crystals required to a minimum.

As the number of inductance elements associated with the crystals of a filter is increased the effects of energy dissipation in the coil resistances become more important and the advantages arising from the substantially dissipationless character of the piezo-electric crystal tend to disappear. In the circuits of the invention the resistance of one of the added inductances in each branch can be completely compensated and that of the other partially compensated so that the filter selectivity is substantially that of a dissipationless network.

The invention will be more fully understood from the following detailed description of representative circuits and from the appended drawings, of which:

Fig. 1 shows in schematic form one embodiment of the invention;

Figs. 2 to 6, inclusive, are diagrams explanatory of the filter of Fig. 1;

Fig. 7 shows a preferred form of the invention;

Fig. 8 is explanatory of the filter of Fig. 7;

Fig. 9 shows a modified form of the network of Fig. 7, and

Figs. 10 to 12, inclusive, show additional examples of filters in accordance with the invention.

The filter shown schematically in Fig. 1 is of the symmetrical lattice type comprising two similar line impedances and two similar lattice impedances connected between input terminals 1, 2, and output terminals 3, 4. In this and in subsequent figures only one line impedance and one lattice impedance is shown in detail for the sake of clarity, the other corresponding branches having identical elements. The line impedances each comprise a piezo-electric crystal X_1 shunted by a small capacity C_{21}, preferably an adjustable air condenser, and an inductance L_{21}, and having in series with this combination an inductance L_{31} and a capacity C_{31}. The lattice impedances are of similar construction comprising a crystal X_2 shunted by an inductance L_{22} and a capacity C_{22} and including the series combination of inductance L_{32} and capacity C_{32}.

The crystals are preferably of quartz, cut and mounted in the manner described in my earlier co-pending application, Serial No. 653,622 filed January 26, 1933, in which case their electrical impedances correspond accurately to that of the electrical system of Fig. 2. This equivalent electrical impedance comprises a series resonant combination L, C, representing the piezo-electric properties of the crystal, shunted by a capacity C_0, representing the electrode capacity, which has a minimum value of about 125 times the capacity C.

The complete electrical equivalent of one of the line branches, obtained by substituting the impedance of Fig. 2 for the crystal, is shown in Fig. 3 in which the combination L_{11}, C_{11}, represents the piezo-electric resonance of the crystal and the shunting capacity C'_{21} is the crystal electrode capacity plus the external shunting capacity C_{21}. The other elements are designated to correspond to Fig. 1. Since the electrical equivalent contains six elements its reactance will be characterized by five critical frequencies of finite values, that is, there will be five frequencies at which the impedance is resonant or anti-resonant. The variation of the reactance with frequently is illustrated by curve 10 of Fig. 4, the critical frequencies being designated f_1 to f_5 in ascending order. The reactance of the lattice branches of Fig. 1 will have a similar frequency characteristic with the same number of critical frequencies.

The general rules for the proportioning of impedances in a symmetrical lattice with respect to each other to provide desirable transmission characteristics are described in U. S. Patent 1,828,454 issued October 20, 1931 to H. W. Bode and their application to piezo-electric crystal filters is discussed in my above mentioned co-pending application. In accordance with these principles one way of proportioning the lattice reactances in Fig. 1 is illustrated by curve 11 of Fig. 4, which shows the lattice branch reactance characteristic, the critical frequencies being allocated with respect to those of the line branch reactance to provide a single transmission band. In this arrangement the lattice branch has resonances coinciding with the anti-resonances of the line branch at frequencies f_2 and f_4 and anti-resonances coinciding with f_3 and f_5. The highest resonance occurs at an additional frequency f_6 and the transmission band extends from f_1 to f_6.

In my above mentioned co-pending application it is pointed out that in filters of simpler structure it is desirable that the several critical frequencies should form a geometric series or should approximate thereto, this type of spacing permitting the attenuation to be maintained high at frequencies outside the band. The same rule is applicable to the present types of filter, but in many cases it is preferable to modify the distribution of the frequencies somewhat particularly in the direction of spacing them closer together towards the edge of the band. For the case in which the critical frequencies form a geometric series the proportioning of the impedances is simple. Considering the structure of Fig. 3, the inductance L_{21} should be made to resonate with the capacity C'_{21} at the crystal resonance frequency. The combination of the crystal and the shunt inductance will then have a reactance characteristic of the type represented by curve 12 of Fig. 5. This curve exhibits a resonance at frequency f_3, which is the crystal resonance, and two anti-resonances f_2 and f_4 spaced geometrically above and below f_3. The separation between the anti-resonance frequencies is determined by the ratio of the capacities C_{11} and C'_{21} and is given by the formula

$$f_4-f_2=f_3\sqrt{\frac{C_{11}}{C'_{21}}} \qquad (1)$$

If the additional elements L_{31} and C_{31} are adjusted to resonate also at frequency f_3 their reactance will have a frequency characteristic of the type illustrated by curve 13 of Fig. 5. It is clear that the addition of such a reactance will not disturb the resonance at frequency f_3 or the anti-resonances at f_2 and f_4, but will simply introduce additional resonances above and below f_2 and f_4, which, due to the symmetry of the circuit will likewise be spaced geometrically about the frequency f_3. The proportioning of the crystal and shunt inductance combination thus determines three of the critical frequencies of the total impedance and also the ratio of the successive frequencies. To make the additional critical frequencies fall into the series, I find that the capacity C_{31} of the added resonant circuit should be given the value

$$C_{31}=C_{11}\left(3+\frac{C_{11}}{C'_{21}}\right) \qquad (2)$$

and the inductance L_{31} proportioned accordingly.

Since the ratio of C_{11} to C'_{21} determines the separation of the frequencies f_4 and f_2 it follows that, in the case described, the total band is controlled by this ratio. For crystals of the preferred type the electrode capacity has a minimum value about 125 times the piezo-electric capacity, corresponding to a value of the frequency interval f_4-f_2 equal to 9 per cent of f_3 for the case where the frequencies are in a geometric series. The addition of the external shunt capacity C_{21} permits the reduction of this interval as much as may be desired, thus making possible a band width range from about zero to 25 per cent of the mean band frequency.

In the more general case in which the critical frequencies do not lie in a geometric series the computation of the elements may be carried on as follows:

The impedance, Z_1, of the line branches may be expressed in terms of L_{31} and the critical frequencies as

$$Z_1=j\frac{L_{31}}{\omega}\,\frac{(\omega^2-\omega_1^2)(\omega^2-\omega_3^2)(\omega^2-\omega_5^2)}{(\omega^2-\omega_2^2)(\omega^2-\omega_4^2)} \qquad (3)$$

and the impedance Z_2 of the lattice branches as

$$Z_2=j\frac{L_{32}}{\omega}\,\frac{(\omega^2-\omega_2^2)(\omega^2-\omega_4^2)(\omega^2-\omega_6^2)}{(\omega^2-\omega_3^2)(\omega^2-\omega_5^2)} \qquad (4)$$

in which ω denotes 2π times frequency.

By the direct application of Foster's reactance theorem, described in the Bell System Technical Journal Vol. III, No. 2, April 1924, page 259, the elements of an impedance of the type shown in Fig. 6 may be calculated from the expression for Z_1 and a corresponding impedance for Z_2. The impedance shown in Fig. 6, while equivalent electrically to the filter line branch impedance is different from it structurally since it contains two series connected anti-resonant combinations L_aC_a and L_bC_b instead of the inductance shunted crystal. However, by means of an equivalence theorem described by O. J. Zobel, Bell System Techanical Journal Vol. II, No. 1, January 1923, page 46, designated transformation F, the pair of anti-resonant circuits can be transformed to the parallel combination in Fig. 3, giving the desired element values.

The inductances L_{31} and L_{32} may be determined from the characteristic impedance K which is found from equations 3 and 4 to be

$$K=\sqrt{L_{31}L_{32}}\frac{\sqrt{(\omega^2-\omega_1^2)(\omega^2-\omega_6^2)}}{\omega} \qquad (5)$$

and to have a value K_m at the mean frequency of the band given by

$$K_m=\sqrt{L_{31}L_{32}}(\omega_6-\omega_1). \qquad (6)$$

If L_{31} is made equal to L_{32} the common value is determined by Equation 6.

For the case in which the critical frequencies form a geometric series it will be noted that the external capacity C_{31} of the line branch is approximately three times the piezo-electric capacity of the crystal. Since the latter is frequently very small it may be found that the capacity C_{31} is inconveniently small and the inductance L_{31} is inconveniently great. Alternatively if C_{31} and

L_{31} are proportioned to give desirable values of the characteristic impedance it may be found that the crystal capacities are such that can be obtained only with excessively thin crystals. These difficulties are avoided in a modified form of the invention illustrated in Fig. 7 in which the crystals are coupled to the lattice branches through step-down transformers.

The line branches in the filter of Fig. 7 each comprise a capacity C_{31}' in series with an inductance L_{p1} to which is coupled a secondary inductance L_{s1}. Across the terminals of this inductance are connected the piezo-electric crystal X_1 and the band controlling shunt capacity C_{21}. The lattice branches are similar in structure comprising series capacity C_{32}' inductance L_{p2} and a secondary system made up of inductance L_{s2}, crystal X_2 and capacity C_2.

The branches of this filter differ structurally from those of the filter of Fig. 3, but, since they contain the same number of elements and since their reactances at zero and infinite frequencies are the same as for the branches of Fig. 3, the two filters are potentially equivalent. By known methods the line branch impedance of the filter of Fig. 7 may be transformed to the type shown in Fig. 8, which comprises the capacity C_{31}, unchanged in value, a series inductance of value $(L_{p1}-\phi^2L_{s1})$, and the parallel combination of an inductance $\phi^2L_s{}^1$, a capacity $C_{21}+\phi^2$, and a crystal of impedance ϕ^2Z_{x1}, where Z_{x1} is the impedance of crystal X_1. The factor ϕ^2 appearing in these values is an impedance transformation ratio having the value

$$\phi^2=\left(\frac{M_1}{L_{s1}}\right)^2$$

where M_1 is the mutual inductance between inductances L_{p1} and L_{s1}. The resistances of the inductance coils are shown in Fig. 8, the resistance r_{p1} being that of inductance L_{p1} and the resistance r_{s1} being that of inductance L_{s1}. The latter appears in series with the crystal and its shunt capacity, its value being modified in accordance with the transformation ratio.

Since the impedance shown in Fig. 8 corresponds, except for the location of the resistances, to the branch impedance of Fig. 1 it follows that the design procedures outlined above in connection with that figure can be applied to the circuit of Fig. 8 and hence to the filter of Fig. 7. The impedance ratio ϕ may evidently be made as small as may be desired by properly proportioning the coupling between the inductances. The effective impedance of the crystal may thus be brought to any desired value; so permitting the capacity C_{31} and its associated inductance $(L_{p1}-\phi^2L_{s1})$ to be kept within practical values.

The effects of the coil resistances may now be considered. The resistances of the series coils L_{p1} and L_{p2} may be made equal in which case their effects balance each other so that the selectivity of the filter is not disturbed. Equal series resistances in the four branches of a symmetrical lattice have the same effect as a resistance of the same value added in series external to the lattice at each end. That is, the effect is simply that which would arise from a slight change in the resistances of the impedances between which the lattice is connected. The secondary coil resistances cannot be made to balance each other completely but they do so partially. Since they appear in the branch impedances as part of an anti-resonant loop circuit they will produce effective series resistances which vary through a wide range of values, reaching maximum values at the anti-resonance frequencies of the impedance.

To maintain the sharpness of selectivity characteristic of dissipationless structures it is desirable principally that the effective resistance should be negligibly small at the cut-off frequencies and at frequencies in the attenuation range close thereto. In the filters of the types described above two factors help towards the realization of this condition. The first is that the anti-resonance frequencies lie within the band some distance from the cut-off frequencies so that the effective resistance at the cut-off frequencies tends to be fairly small and diminishes in the attenuation ranges. The second factor lies in the proportions of branch impedances due to inherent relationships of the effective capacities of the crystals which have a minimum ratio of about 125. In connection with the filter of Fig. 1 it was pointed out that for geometric spacing of the critical frequencies the series capacities C_{31} and C_{32} have values about 3 times the piezo-electric capacity of the crystal. Since the series inductances L_{31} and L_{32} are proportioned to resonate with these capacities at the crystal resonance and since the shunt inductances L_{21} and L_{22} are proportioned to resonate with the total shunt capacities of the crystals at the same frequency, it follows that the series inductances must be at least 40 times as great as the shunt inductances. This relationship is, of course, accurate only for the case of the geometric arrangement of the critical frequencies, but it holds substantially for most practical filter designs. The effective resistances due to the dissipation in the low inductance shunt coils therefore appear in series with the very large reactances of the series coils and condensers which represent the dominant part of the total impedance outside the band. The effect of the shunt coil dissipation thus becomes negligibly small at frequencies quite close to the cut-off. From experiment and calculation I have found that the unbalanced effective resistance corresponds to less than 20 per cent of the series coil resistance. Since similar relationships are involved in the filter of Fig. 7 the effects there are of like character and magnitude.

A modified form of the filter of Fig. 7 is shown schematically in Fig. 9, the feature of this network being that instead of having a separate crystal for each arm of the lattice only two crystals are used one of which is coupled by a double primary transformer to the two line branches, and the other of which is similarly coupled to the two lattice branches. The designation of the elements in Fig. 9 corresponds to the designations in Fig. 7. This circuit has the advantage that, besides reducing the number of crystals by half, the necessity for balancing the line and the lattice arms to secure symmetry is largely eliminated.

Additional examples of filter networks in accordance with the invention which are obtained by changing the location of the external capacities are illustrated by Figs. 10, 11 and 12, the elements being designated to correspond to Fig. 7. The filter of Fig. 10 is a band pass filter in which the primary coils are tuned by means of shunt condensers rather than series condensers. Fig. 11 represents a low pass filter obtained by omitting the series condensers from the line branches of the network of Fig. 7. Fig. 12 illustrates a high pass filter obtained by omitting the shunt tuning condensers from the line branches of the filter of Fig. 10. The capacities in shunt to the crystals are not shown in these figures, but it will be understood that such capacities may be employed as desired. It will be evident also that these networks may be modified in accordance with Fig. 9 to reduce the number of crystals.

What is claimed is:

1. A broad band wave filter comprising a plurality of impedance branches interconnecting a pair of input terminals and a pair of output terminals, said branches having reactances of diverse frequency characteristics proportioned with respect to each other to provide a single transmission band, each of said branches including a piezo-electric crystal, an inductance in parallel with said crystal, and a second inductance contributing a reactance effectively in series with said parallel combination.

2. A broad band wave filter comprising a plurality of impedance branches interconnecting a pair of input terminals and a pair of output terminals, said branches having reactances of diverse frequency characteristics proportioned with respect to each other to provide a single transmission band, each of said branches including a primary inductance, a secondary inductance coupled thereto and a piezo-electric crystal connected in parallel with said secondary inductance.

3. A broad band wave filter comprising two pairs of similar impedance branches connected between input terminals and output terminals to form a symmetrical lattice network, a primary inductance included in each of said branches, secondary inductances coupled to said primary inductances, and a piezo-electric crystal connected across the terminals of each of said secondary inductances, the impedances of said crystals co-operating with the reactances of said inductances to provide a continuous transmission band.

4. A wave filter in accordance with claim 3 in which the primary inductances are coupled in pairs to single secondary inductances.

5. A broad band wave filter comprising a plurality of impedance branches interconnecting a pair of input terminals and a pair of output terminals, said branches having reactances of diverse frequency characteristics proportioned with respect to each other to provide a transmission band between preassigned frequencies, at least one of said branches including an inductance which forms the primary winding of a transformer, a secondary inductance coupled to said primary winding, and a piezo-electric crystal connected across the terminals of said secondary inductance, the impedance of said crystal co-operating with the reactances of said inductances to provide the transmission band.

6. A broad band wave filter comprising a plurality of impedance branches similar in pairs connected between input terminals and output terminals to form a symmetrical lattice, a primary inductance and a tuning condenser therefor included in each branch, secondary inductances coupled to said primary inductance, and a piezo-electric crystal connected across the terminals of each of said secondary inductances, the impedances of said crystals co-operating with the reactances of said inductanes and said tuning condensers to provide a continuous transmission band.

7. A wave filter in accordance with claim 6 in which the said tuning condensers are connected in series with the said primary inductances.

8. A wave filter in accordance with claim 6 in which the said tuning condensers are connected in parallel with the said primary inductances.

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