WAVE FILTER

Filed July 2, 1935

FIG. 1

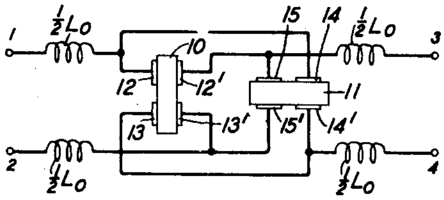


FIG. 2

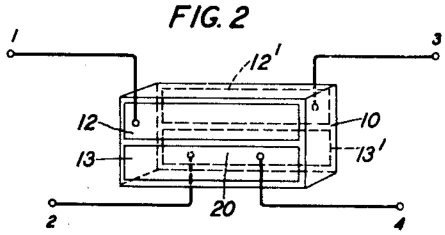


FIG. 3

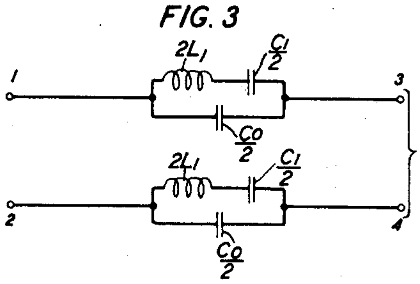


FIG. 4

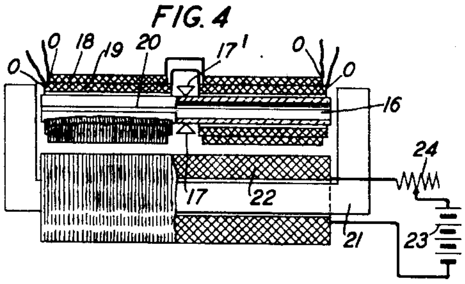


FIG. 5

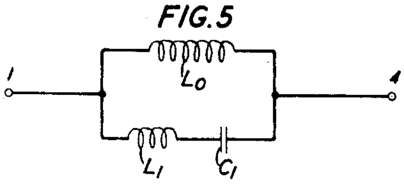


FIG. 6

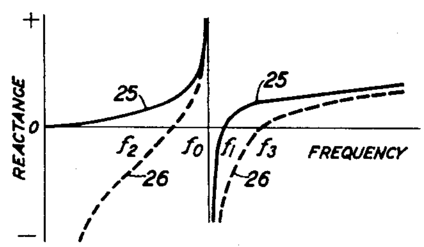


FIG. 7

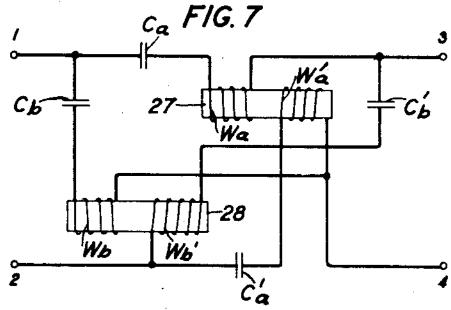


FIG. 8

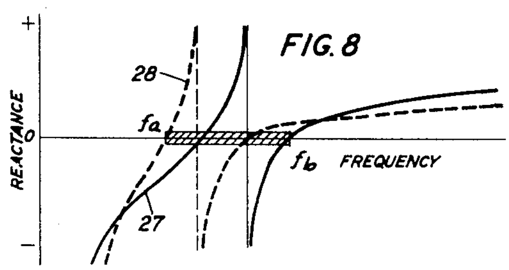
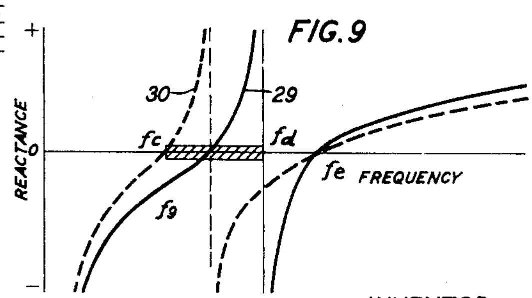


FIG. 9



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Patented Sept. 28, 1937

2,094,044

UNITED STATES PATENT OFFICE

2,094,044

WAVE FILTER

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Application July 2, 1935, Serial No. 29,463

7 Claims. (Cl. 178—44)

This invention relates to wave filters and more particularly to lattice type wave filters using electrically driven mechanical vibratory devices as impedance elements.

The principal objects of the invention are the reduction of the number of mechanical vibratory elements in a given filter structure and the simplification of the construction in the case of balanced types of circuit.

It is well-known that the lattice type wave filter possesses the advantage of complete generality in respect of the transmission characteristics it is able to provide. This advantage is accompanied, however, by the disadvantages of requiring a relatively large number of impedance elements and a high degree of balance between the impedances of certain of the branches. Where mechanical vibratory devices such as piezoelectric crystals or electromagnetically driven vibrators are included in the filter circuit to secure the advantages arising from their low energy dissipation, the cost of production and adjustment of these devices makes it desirable that their number be reduced to a minimum.

In accordance with the present invention, the number of vibratory elements required in a symmetrical lattice type filter is reduced by coupling a single element to each pair of similar branches in such manner that each vibratory element affects equally the impedance of the two branches to which it is coupled. The electromechanical coupling may be either electrostatic or electromagnetic, the former being suitable where piezoelectric crystals are used as the mechanical vibratory elements and the latter being better adapted for the coupling of metallic resonators, for example, tuning forks or vibrating rods.

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

Fig. 1 shows schematically a wave filter in accordance with the invention using piezoelectric crystals as electromechanical impedances;

Fig. 2 shows a form of piezoelectric crystal vibrator in accordance with the invention;

Fig. 3 illustrates characteristics of the device of Fig. 2;

Fig. 4 shows a magnetostrictive vibrator in accordance with the invention;

Figs. 5 and 6 illustrate characteristics of the device of Fig. 4;

Fig. 7 is a schematic arrangement of a filter in accordance with the invention using magnetostrictive vibrators; and

Figs. 8 and 9 illustrate characteristics of the filter of Fig. 7.

Referring to Fig. 1, the embodiment of the invention illustrated is a lattice type piezoelectric crystal filter comprising two piezoelectric crystals 10 and 11 which act as mechanical vibratory elements and which are so coupled to the electrical portion of the network that each crystal is included in two similarly disposed branches of the lattice. Thus, crystal 10 is included in each of the line branches and crystal 11 in each of the lattice branches. The input terminals of the filter are designated 1 and 2 and the output terminals 3 and 4.

The crystals may be rectangular plates cut with the plane of the rectangle perpendicular to the electric axis of the crystal and with the longer edge of the rectangle parallel to the mechanical axis of the crystal. Crystals cut in this fashion and provided with electrodes on the large faces of the rectangle vibrate longitudinally under electrical excitation and, when proportioned to produce resonances in the relatively low frequency range used in carrier telephony, have dimensions convenient for mechanical mounting. Other well-known types of crystal cut may also be used and under certain conditions these may be preferred. In the filter illustrated in Fig. 1 the crystals are of the rectangular type described above, but for convenience are shown in end elevation.

Crystal 10 is provided with two pairs of electrodes 12, 12', and 13, 13' on its opposite faces, electrodes 12 and 12' being directly opposite each other on the upper half of the crystal and electrodes 13 and 13' being similarly located on the lower half of the crystal. These electrodes may be of silver, plated directly on to the crystal, and may be applied by plating the two surfaces all over and afterwards removing a narrow strip of the plating along the center of each face. It is generally desirable also to remove narrow strips of the plating around the edges of the crystal. Crystal 11 is likewise provided with two corresponding pairs of electrodes 14, 14' and 15, 15'. The electrodes 12 and 12' of crystal 10 are connected respectively to terminals 1 and 3 and electrodes 13 and 13' to terminals 4 and 2 respectively. Electrodes 14 and 14' of crystal 11 are connected respectively to terminals 1 and 4 and electrodes 15 and 15' to terminals 3 and 2 respectively. The perspective drawing in Fig. 2 shows the form of crystal 10, the arrangement of the electrodes and their connections to the filter terminals.

While each crystal operates as a unitary vibratory structure their behavior in the filter circuit may be studied most conveniently by considering each as being equivalent to two crystals obtained by dividing the single crystal longitudinally along the gap between the adjacent electrodes. This would give two similar line branch crystals and two similar lattice branch crystals. If four separate crystals were used it would not be necessary to pay any attention to the manner of interconnecting the electrodes and the filter terminals, but when they are paired in accordance with the invention to form unitary structures it is necessary to ensure that the exciting voltages applied to each half will be so related that both halves will vibrate simultaneously in the same direction. Otherwise, the vibration of each half would tend to counteract that of the other and a bending along its longitudinal axis would result. By the system of interconnection described above and illustrated in Fig. 1 the proper relative polarities of the exciting voltages is obtained whereby the whole crystal is made to vibrate in the normal mode of each half. It will be observed that in the case of crystal 10 the lower electrodes 13 and 13′ are connected to the input and output terminals in reverse fashion to electrodes 12 and 12′ and that a similar reversal is present in the connections of the electrodes of crystal 11.

The electrical equivalent of crystal 10 is illustrated in Fig. 3. It comprises two similar impedances each consisting of a simple resonant circuit shunted by a capacity, the one impedance being connected between terminals 1 and 3 and the other between terminals 2 and 4. The two impedances in the electrical equivalent are free from mutual coupling although in the actual device the same mechanical resonator functions in each path.

The values of the inductances and the capacities appearing in the electrical equivalent may be determined from the crystal dimensions by first determining the electrical equivalent of the whole crystal on the assumption that the two electrodes on each surface are connected together to form single electrodes covering substantially the whole surface. The impedance of each half of the crystal will then be twice that of the whole crystal. In Fig. 3 each impedance comprises a resonant branch includes an inductance $2L_1$ and a capacity $C_1/2$, and a shunt capacity $C_0/2$. In terms of the dimensions of the crystal these quantities have substantially the following values:

$$2L_1 = \frac{212.2lt}{w} \text{ Henries}$$

$$\frac{C_a}{2} = \frac{.161wl10^{-14}}{t} \text{ Farads} \qquad (1)$$

$$\frac{C_0}{2} = \frac{20.1wl10^{-14}}{t} \text{ Farads}$$

where l, w, and t are respectively the length, width, and thickness of the crystal measured in centimeters.

The requirements for combining two pairs of similar piezoelectric crystals in a lattice type network to provide a single transmission band are disclosed in my earlier copending application Serial No. 653,622, filed January 26, 1933 wherein it is pointed out that the line and the lattice crystal impedances must have unlike frequency characteristics so related that the resonance of the line branches coincides with the anti-resonance of the lattice branches or vice versa. Equations (1) permit the crystal dimensions to be determined to meet this condition.

In the aforementioned copending application it is also shown that the use of inductances in series with each crystal or, alternatively, in series with each line external to the lattice, permits wider bands to be obtained without sacrifice of the sharpness of selectivity resulting from the low dissipation in the piezo-electric crystals. Fig. 1 shows four equal series inductances of value

$$\frac{1}{2}L_0$$

included in the lines external to the lattice for this purpose.

Another type of electromechanical impedance suitable for use in the filters of the invention is illustrated in Fig. 4. In this device the vibratory element is tubular member 16 of magnetostrictive material, supported at its mid-point by clamps 17 and 17′ and provided with exciting windings 18 and 19 for the alternating currents. These windings are shown each covering the whole length of the tube, but they may be arranged so that each extends over one-half of the tube. The vibration of the tube 16 is excited by magnetostrictive forces due to the currents in the windings and in order that these forces may have the same frequency as the exciting currents it is necessary that the tube be polarized magnetically by a undirectional magnetic field. For this purpose a polarizing magnet 21 is provided, the pole faces of which are brought close to the ends of the vibratory element forming therewith a substantially closed magnetic circuit. Small air-gaps must be left between the ends of tube 16 and the polarizing magnet to permit free vibration. A magnetizing winding 22 energized from battery 23, or other source of direct current, and controlled by rheostat 24, produces the polarizing magnetic field. To prevent eddy currents flowing under the action of the exciting currents it is desirable to have the tube 16 slotted longitudinally as indicated at 20 in the figure.

The electrical impedance of a magnetostrictive element of the type illustrated, measured at the terminals of one of the exciting windings corresponds to that of the network illustrated in Fig. 5 comprising an inductance L_0 shunted by a series resonant impedance L_1C_1. The inductance L_0 is that of the exciting winding in the absence of any magnetostrictive action or with the tube 16 fixed everywhere so that it cannot vibrate. The inductance L_1 and the capacity C_1 have values dependent on the physical dimensions and the mechanical constants of the tube 16 and on the magnetostrictive force factor. Expressions for their values in particular cases are given by Butterworth in the Proceedings the Physical Society, March 1, 1931 page 166. It may be noted that the resonance of L_1 and C_1 corresponds to the first mechanical resonance frequency of the tube to longitudinal vibrations.

The reactance-frequency characteristic of the impedance is illustrated by curve 25 of Fig. 6. It exhibits two critical frequencies one f_0, at which the impedance is anti-resonant, and a higher frequency f_1 corresponding to the resonance of L_1 and C_1, that is to the mechanical resonance of the vibrator. Due to the relatively small degree of electromechanical coupling provided by the magnetostriction effect the frequencies f_0 and f_1 are very close together thus tending to limit the use of the device to filters of very narrow band width. Increased separation of the critical frequencies can be obtained by the addition of a capacity in series with the exciting winding, the resulting reactance characteristic being of the type shown by curve 26 of Fig. 6. A new resonance frequency f_2 below f_0 is introduced and the higher resonance is moved upwards from f_1 to f_3 with respect to the anti-resonance frequency f_0 may be controlled by varying the value of the series capacity.

Fig. 7 illustrates the application of magnetostrictive vibrators of the type described above in a broad band filter in accordance with the invention. Two vibratory elements 27 and 28 are used, element 27 having two equal exciting windings W_a and W_a' which are connected respectively in the line branches of the lattice and element 28 having equal winding W_b and W_b' connected in the lattice branches. Equal capacities C_a and C_a' are connected in series with W_a and W_a' respectively, and a corresponding pair of equal capacities C_b and C_b' are included in the lattice branches. The vibratory members are shown in schematic form only, the polarizing magnets and their associated circuits being omitted.

Windings W_a and W_a' are so poled that the currents flowing therein will normally aid each other in exciting mechanical vibrations. These windings are included in series in the circuit from filter terminal 1 through capacity C_a, winding W_a to terminal 3 and thence through the filter load to terminal 4, winding W_a', capacity C_a' and terminal 2. The poling of windings W_a and W_a' must be such that a current traversing this circuit will magnetize the core in the same direction. The windings W_b and W_b' are poled in a similar manner. By virtue of the equality of the two windings on each of the vibrators equal impedances are introduced into the two line branches of the network and likewise into the two lattice branches.

To provide a single transmission band it is necessary that the lattice branch impedances have frequency characteristics different from those of the line branch impedances, but related thereto in such manner as to produce coincidences of the critical frequencies. As shown in U. S. Patent 1,828,454 of October 20, 1931, to H. W. Bode in connection with symmetrical lattice filters, the anti-resonance frequencies of the line branches must coincide with resonance frequencies of the lattice branches and vice versa, within the frequency range of the transmission band, whereas in the attenuation ranges the coincidences must be between critical frequencies of the same character. Two examples of possible arrangements of the critical frequencies in filters of the type shown in Fig. 7 are illustrated by Figs. 8 and 9. In Fig. 8 the full line curve 27 corresponds to the reactance of the line impedances and dotted curve 28 to the reactance of the lattice branches. In this case the transmission band extends from the lowest critical frequency f_a to the highest f_b. In Fig. 9 curves 29 and 30, which correspond respectively to the line and lattice branch impedances, have a direct coincidence of two resonances at frequency f_e and an inverse coincidence of a resonance and an anti-resonance of f_g. The band in this case extends from the lowest critical frequency f_c to the third critical frequency f_d, the frequency f_e being outside the band. In both figures the location of the band is indicated by a shaded horizontal area.

What is claimed is:

1. A broad band wave filter comprising two pairs of equal impedance branches connected between two input terminals and two output terminals to form a symmetrical lattice network, a mechanical vibratory element symmetrically coupled electromechanically to both branches of one equal pair and a second mechanical vibratory element similarly coupled to the other pair of equal branches, said vibratory elements having different resonance frequencies.

2. A broad band wave filter in accordance with claim 1 in which the mechanical vibratory elements are comprised of piezoelectric crystal plates.

3. A broad band wave filter in accordance with claim 1 in which the mechanical vibratory elements comprise piezoelectric crystals, each crystal being disposed symmetrically between two pairs of electrical plates to effect the electromechanical coupling to the pairs of equal impedance branches.

4. A broad band wave filter in accordance with claim 1 in which the mechanical vibratory elements are coupled electromagnetically to the respective pairs of branches.

5. A broad band wave filter in accordance with claim 1 in which the mechanically vibratory members comprise tubes of metal having magnetostrictive properties and in which the coupling to the respective impedance branches is effected by inductive windings extending over the length of the tubes.

6. A broad band electric wave filter comprising a plurality of connected impedance branches, two of said branches being of equal impedance and being subject to oscillations of like phase and amplitude when waves are transmitted through the filter, and a tuned mechanical vibratory element coupled electromechanically and in equal degrees to said two impedance branches whereby it modifies the impedances of said two branches equally.

7. In a broad band electric wave filter comprising a plurality of impedance branches, said branches having frequency dependent impedances the characteristics of which define a transmission band between definite frequency limits, two impedance branches having equal impedances and being subject to oscillations of like phase and amplitude when waves are transmitted through the filter, and a tuned mechanical vibratory element coupled electromechanically and in equal degrees to said two impedance branches whereby it modifies the impedances thereof equally.

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