May 7, 1940. W. P. MASON 2,199,921

WAVE FILTER

Filed Sept. 28, 1938

FIG. 2

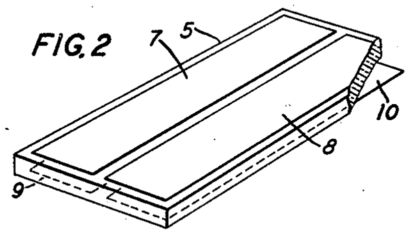
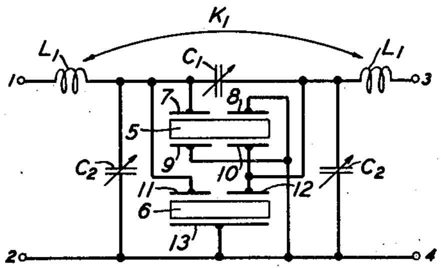


FIG. 1



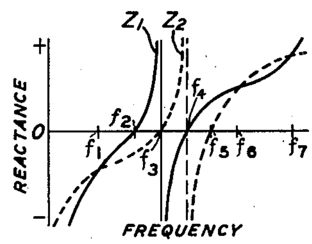
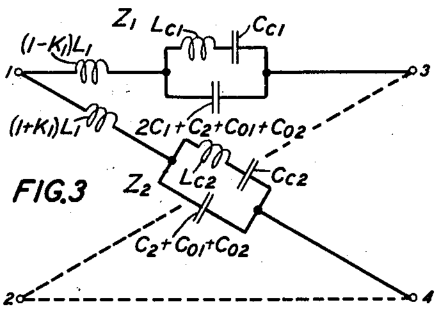


FIG. 4

FIG. 3



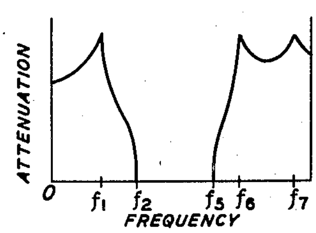
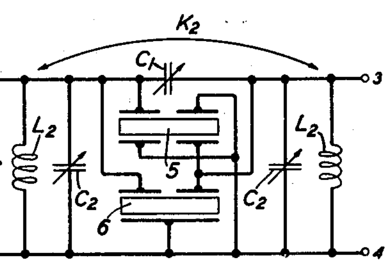


FIG. 5

FIG. 6



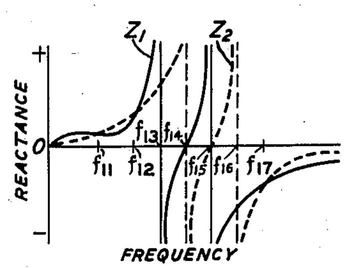


FIG. 8

FIG. 7

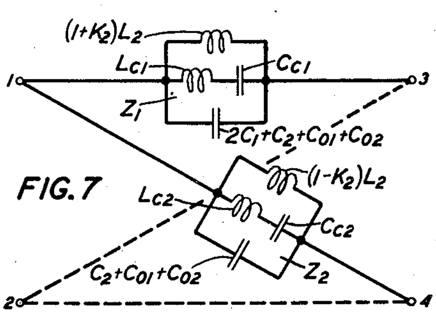


FIG. 9

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WAVE FILTER

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Application September 28, 1938, Serial No. 232,067

22 Claims. (Cl. 178—44)

This invention relates to frequency-selective wave transmission networks which employ piezoelectric crystals as impedance elements and more particularly to wave filters of the unbalanced type which use a plurality of such crystals.

An object of the invention is to improve the attenuation characteristics of unbalanced band-pass wave filters which employ piezoelectric crystals as impedance elements. Another object is to reduce the cost of filters of this type which have sustained high attenuation on each side of the transmission band.

The wave filter of the present invention is of the unbalanced, band-pass type one side of which may be grounded or otherwise fixed in potential. The filter comprises as impedance elements two or more piezoelectric crystals which have divided electrodes on one or both sides. One of the crystals has a single electrode on one side which is connected to the grounded side of the filter, and two electrodes on the other side which are connected, respectively, to the input terminal and the output terminal on the high side of the filter. Another of the crystals has two pairs of oppositely disposed electrodes. An electrode on one side and a diagonally opposite electrode on the other side of the crystal are connected together and to the grounded side of the filter. The remaining two electrodes are connected, respectively, to the input terminal and the output terminal on the high side of the filter. If these two crystals have different frequencies of resonance the filter may be designed to transmit a band lying between two preassigned frequencies while attenuating all other frequencies. The filter will have two peaks of attenuation which may be located one on the lower side of the band and the other on the upper side, both below the band or both above the band.

These two peaks of attenuation will be located at some distance from the transmission band but may be brought in closer to the band limits by the addition of a bridging impedance branch comprising a capacitance connected between the crystal electrodes associated with the high side of the filter. The larger the value of this capacitance the closer the peaks will be to the cutoff frequencies. The width of the transmission band will ordinarily be small on a percentage basis and can be made still narrower by the addition of capacitances connected in shunt at the ends of the crystals. The larger the values of these capacitances are made the narrower will be the band.

In order to widen the transmission band and improve the attenuation characteristic inductances may be added at the ends of the filter. If a filter having an inherently low image impedance is required these inductances are connected in series at the ends of the filter. If a high image impedance is desired the inductances are connected in shunt at the ends of the filter. The addition of the inductances materially widens the band and permits the location of an attenuation peak at infinite frequency or at zero frequency. These peaks at zero or infinite frequency may be moved in toward the band limits to any desired extent by adding an inductive coupling between the inductances. For the series-connected case the inductances are connected in the series-opposing relationship if the four-electrode crystal has the lower resonance frequency, and in the series-aiding relationship if the three-electrode crystal has the lower resonance frequency. For the shunt-connected case the inductances are connected series aiding if the four-electrode crystal has the lower resonance, and series opposing if the three-electrode crystal has the lower resonance.

Additional peaks of attenuation may be provided by employing more crystals in the filter circuit. The added crystals are connected in parallel with the two crystals, and in general each additional crystal permits the provision of one more arbitrarily placed attenuation peak. There is thus provided a crystal filter of the unbalanced type which has any desired number of attenuation peaks placed on either side of the transmission band and located at any arbitrarily chosen frequencies including zero and infinity. Due to the additional peaks the attenuation outside of the band may be sustained above any required minimum value over any desired frequency range. Considering the high discrimination obtainable the filter requires a minimum number of component elements and is therefore less expensive to build than the unbalanced crystal filters heretofore known.

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

Fig. 1 is a schematic circuit showing the embodiment of the wave filter of the invention in which the inductors are connected in series at the ends of the network;

Fig. 2 is a perspective view partially broken away of the piezoelectric crystal used in the filter showing the placing of the electrodes;

Fig. 3 shows the equivalent lattice network for the filter of Fig. 1;

Fig. 4 represents the reactance-frequency characteristics of the line and diagonal impedance branches of the lattice network of Fig. 3;

Fig. 5 shows a typical attenuation characteristic obtainable with the filter of Fig. 1;

Fig. 6 is a schematic circuit representing another embodiment of the invention in which the inductors are connected in shunt at the ends of the filter;

Fig. 7 shows the equivalent lattice network for the filter of Fig. 6;

Fig. 8 represents the reactance-frequency characteristics of the line and diagonal impedance branches of the lattice network of Fig. 7; and

Fig. 9 shows a typical attenuation characteristic for the filter of Fig. 6.

Fig. 1 is a schematic circuit of one form of the wave filter of the invention in which the inductances are connected in series at the ends of the network. The filter is a symmetrical four-terminal network having a pair of input terminals 1, 2 and a pair of output terminals 3, 4 to which terminal loads of suitable impedance may be connected. The network is unbalanced in structure so that the path connecting terminals 2 and 4 may be grounded or otherwise fixed in potential. The path connecting terminals 1 and 3 may be termed the high side of the filter.

The filter circuit includes two piezoelectric crystals 5, 6, a pair of equal inductors L_1, L_1 designated by their inductance and three capacitors C_1, C_2 and C_2 designated by their capacitances. The two inductors are connected in series between the input terminal 1 and the output terminal 3 on the high side of the filter and are inductively coupled by a mutual inductance equal to K_1L_1 where K_1 represents the coefficient of coupling. The crystal 5 is provided with two electrodes 7, 8 on one of its major faces and two oppositely disposed electrodes 9, 10 on the opposite face. The two diagonally opposite electrodes 8 and 9 are connected together and to the grounded side of the filter. The other two diagonally opposite electrodes 7 and 10 are connected, respectively, to the inner terminals of the inductors L_1, L_1. The second crystal 6 has a single electrode 13 on one face connected to the grounded side of the filter and a pair of electrodes 11, 12 on the opposite face connected, respectively, to the inner terminals of the inductors. The capacitance C_1 is connected between the inner terminals of the inductors, and the capacitors C_2, C_2 are shunted, respectively, between these terminals and the grounded side of the circuit.

The crystal elements 5 and 6 are preferably in the form of a relatively narrow rectangular plate cut perpendicular to the electrical axis of the mother crystal and with its length either in the direction of the mechanical axis or making a selected acute angle therewith. Such a crystal will vibrate longitudinally when an alternating potential is applied to electrodes placed on the larger surfaces. Other well-known types of crystal cut may be used and, under certain conditions, they may be preferred. The crystals shown in Fig. 1 are of the rectangular type described above but for convenience are shown in end elevation.

The placing of the electrodes on the crystals is shown more clearly in Fig. 2 which is a perspective view of the crystal 5 with a corner broken away. The crystal 6 is the same as crystal 5 except that the former has on one side a single electrode 13 instead of two electrodes. The electrodes may be of silver, aluminum or other suitable metal, plated directly onto the crystal, and may be applied by plating the two major surfaces all over and afterwards removing a narrow longitudinal strip of the plating along the center of the face when it is necessary to provide two electrodes on one face. It is generally desirable also to remove narrow strips of plating around the edges of the crystal. When the crystal vibrates in the longitudinal mode it is preferably supported between one or more pairs of oppositely disposed points or knife-edge clamps which contact the crystal in the nodal region near the center and along the optical axis. Connections to the electrodes may be made through these clamps or by attaching leads directly to the electrodes with soft solder.

Since the network of Fig. 1 is symmetrical with respect to its input terminals 1, 2 and its output terminals 3, 4 its properties may be investigated most conveniently from a consideration of the symmetrical lattice network to which it is equivalent. Each line branch of the equivalent lattice is equal to half of the impedance measured between the high-side terminals 1 and 3 of Fig. 1, and each diagonal branch is equal to twice the impedance measured between terminals 1 and 3 strapped together and the grounded side, that is, terminal 2 or 4. It is apparent that the mechanical vibration of the four-electrode crystal 5 will occur only in the first and the mechanical vibration of the three-electrode crystal 6 will occur only in the second measurement. Therefore, the impedance representing crystal 5 will appear only in the line branch of the lattice and the impedance of the crystal 6 will appear only in the diagonal branch. However, the electrode capacitance of both crystals will appear in each branch.

The equivalent lattice for the filter of Fig. 1 is shown in Fig. 3 in which the impedance of the crystal 5 is represented by its equivalent electrical circuit comprising a capacitance C_{O1} shunted by a branch consisting of an inductance L_{C1} in series with a second capacitance C_{C1}, and the impedance of the crystal 6 is represented by a similar circuit made up of the inductance L_{C2} and the two capacitances C_{O2} and C_{C2}. The capacitance C_{O1} represents the simple electrostatic capacitance between a pair of oppositely disposed electrodes such as 7 and 9 of the crystal 5. The values of the capacitance C_{C1} and the inductance L_{C1} depend upon the dimensions of the crystal and upon its piezoelectric and elastic constants. These elements may be evaluated, in terms of the dimensions of the crystal 5, from the following formulas, assuming that the crystal is of the X-cut variety described above and that the electrodes cover substantially the entire area of the two major faces:

$$L_{C1}=\frac{212.2lt}{w}\text{ henries} \tag{1}$$

$$C_{C1}=\frac{0.161wl10^{-14}}{t}\text{ farads} \tag{2}$$

$$C_{O1}=\frac{20.1wl10^{-14}}{t}\text{ farads} \tag{3}$$

in which l, w and t are, respectively, the length, width and thickness of the crystal 5 measured in centimeters. The values of the elements L_{C2}, C_{C2} and C_{O2} in the equivalent circuit for the crystal 6 may be found from the same formulas if the dimensions of the crystal **6** are substituted for those of the crystal **5**. It will be observed that these elements have twice the impedance of the corresponding elements in the equivalent circuit for a crystal of the same type having only a single electrode on each side.

As shown in Fig. 3 the equivalent lattice comprises two similar line impedance branches Z_1 and two similar diagonal impedance branches Z_2. It is assumed that the four-electrode crystal **5** has a lower resonance than the three-electrode crystal **6** and therefore, as pointed out above, the inductors L_1, L_1 of Fig. 1 are connected in the series-opposing relationship. Each line branch is made up of an inductance equal to $(1-K_1)L_1$ in series with a parallel combination consisting of a capacitance equal in magnitude to the sum of 2 C_1, C_2, C_{01} and C_{02} shunted by a branch comprising the inductance L_{C1} in series with the capacitance C_{C1}. Each diagonal branch consists of an inductance equal to $(1+K_1)L_1$ in series with a parallel combination comprising a capacitance equal to the sum of C_2, C_{01} and C_{02} shunted by an arm made up of the inductance L_{C2} in series with the capacitance C_{C2}. For the sake of clarity in this figure and also in Fig. 7 only one line branch and one diagonal branch are shown in detail, the corresponding line and diagonal branches being indicated by dotted lines connecting the appropriate terminals.

The image impedance Z_K of the lattice network of Fig. 3 is given in terms of the impedances of the line and diagonal branches by the expression

$$Z_K=\sqrt{Z_1Z_2} \qquad (4)$$

and the propagation constant P may be found from the expression

$$\tanh\frac{P}{2}=\sqrt{\frac{Z_1}{Z_2}} \qquad (5)$$

The filter will have a transmission band in the region where Z_1 and Z_2 are of opposite sign and will have attenuation bands where Z_1 and Z_2 are of the same sign, with peaks of attenuation occurring where these impedances are equal. By virtue of the equivalence of the two networks these expressions also give the impedance and propagation constant of the filter of Fig. 1. Due to the series end inductances L_1, L_1 the filter will have an inherently low image impedance.

Fig. 4 gives the reactance-frequency characteristics of the line and diagonal branches of the lattice network of Fig. 3. Each branch will have two resonances with an intermediate antiresonance. To provide a band-pass filter the lower resonance of the one branch is made to coincide with the anti-resonance of the other branch, and the anti-resonance of the one branch is made to coincide with the upper resonance of the other. Assuming that the line branch has the lower first resonance the two branches will have the reactance characteristics shown, respectively, by the solid-line and the dotted-line curves of Fig. 4. The line branch Z_1 has its resonances at the frequencies f_2 and f_4 and its anti-resonance at the frequency f_3, while the diagonal branch Z_2 has its lower resonance at f_3, its anti-resonance at f_4 and its upper resonance at f_5. The transmission band will be located between the frequencies f_2 and f_5 and peaks of attenuation will occur at the frequency f_1 below the band and the frequencies f_6 and f_7 above the band where the reactances are equal.

A typical attenuation characteristic is shown in Fig. 5. If the crystal **6** has a lower resonance than the crystal **5** the inductors L_1, L_1 should be connected series aiding to obtain the type of attenuation characteristic shown. If the coefficient of coupling K_1 is made zero the upper attenuation peak occurring at f_7 will be moved out to infinite frequency. If the end inductors are omitted entirely from the circuit the peak at f_7 will disappear, leaving only the peaks at f_1 and f_6. These peaks may be placed both on the lower side of the band or both on the upper side if desired. However, without the end inductors the maximum band width obtainable is of the order of 0.8 per cent of the mid-band frequency.

The chief function of the capacitor C_1 in the circuit of Fig. 1 is to permit the arbitrary location of the attenuation peaks occurring at f_1 and f_6. As the magnitude of C_1 is increased these peaks are moved in toward the transmission band limits f_2 and f_5. The function of the shunt capacitors C_2, C_2 is to decrease the width of the transmission band. The widest band is obtained when these capacitors are omitted. As their value is increased the band is narrowed.

The values of the various reactance elements in the lattice network of Fig. 3, including the electrical elements equivalent to the crystals, can be found from the resonant and anti-resonant frequencies of the Z_1 and Z_2 impedance branches by a direct application of R. M. Foster's reactance theorem given in the Bell System Technical Journal, vol. III, No. 2, April 1924, pages 259 to 267. The values of the component elements in the network of Fig. 1 are found by applying the numerical factors indicated.

If an inherently high image impedance is desired for the filter the inductors are connected in shunt at the ends of the network. In Fig. 6 the inductors L_2, L_2 are connected in this way and are inductively coupled with a coefficient of coupling K_2. It is assumed that the four-electrode crystal **5** has the lower resonance and therefore the inductors are connected in the series-aiding relationship. The arrangement of the other component elements is the same as in Fig. 1. The equivalent lattice network is shown in Fig. 7. It is the same as the lattice of Fig. 3 except that the inductances $(1-K_2)L_2$ and $(1+K_2)L_2$ are in parallel with the crystal impedances instead of in series with them, and the smaller inductance appears in the diagonal branch instead of in the line branch.

As shown by the reactance characteristics of Fig. 8 each branch of the equivalent lattice has two anti-resonances and an intermediate resonance. To provide a band-pass filter the lower anti-resonance of one branch is made to coincide with the resonance of the other, and the resonance of the one branch is placed at the upper anti-resonance of the other. If the line branch Z_1 has the lower first anti-resonance its reactance will be as shown by the solid-line curve with anti-resonances at the frequencies f_{13} and f_{15} and a resonance at f_{14}. As shown by the dotted-line curve the diagonal branch Z_2 will have anti-resonances at f_{14} and f_{16} and a resonance at f_{15}. The frequencies f_{13} and f_{16} mark the limits of the transmission band and attenuation peaks occur at f_{11} and f_{12} below the band and at f_{17} above the band where the reactances are equal.

Fig. 9 gives a typical attenuation characteristic. If the three-electrode crystal **6** has the lower resonance frequency the inductors are connected series opposing to obtain the type of characteristic shown. If the coefficient of coupling K_2 is zero the peak at f_{11} moves down to zero frequency. As in the circuit of Fig. 1, the function of the bridging capacitor C_1 is to determine the location of the peaks at f_{12} and f_{17}, and the function of the shunt capacitors C_2, C_2 is to regulate the width of the band. These capacitors may, of course, be made variable, both in the circuit of Fig. 1 and that of Fig. 6, as indicated by the arrows.

What is claimed is:

1. A wave filter comprising a pair of input terminals, a pair of output terminals, a bridging impedance branch including a capacitor connected between an input terminal and a corresponding output terminal, and two piezoelectric crystals, one of said crystals having two electrodes on one face and two other oppositely disposed electrodes on the opposite face, an electrode on one face and a diagonally opposite electrode on the opposite face of said one crystal being connected respectively to the terminals of said bridging branch, the other of said crystals having a pair of electrodes on one face and a single electrode on the opposite face, said pair of electrodes on said other crystal being also connected respectively to the terminals of said bridging branch, the remaining electrodes on said one crystal and said single electrode on said other crystal being connected to the remaining input and output terminals of said filter, and the dimensions of said crystals and the values of the reactance elements constituting said bridging branch being proportioned with respect to one another and with respect to two preassigned frequencies to provide a transmission band between said frequencies.

2. A wave filter comprising a pair of input terminals, a pair of output terminals, a bridging impedance branch including a capacitor connected between an input terminal and a corresponding output terminal, two inductors connected at the respective ends of said filter, and two piezoelectric crystals having different frequencies of resonance, one of said crystals having two electrodes on one face and two other oppositely disposed electrodes on the opposite face, an electrode on one face and a diagonally opposite electrode on the opposite face of said one crystal being connected respectively to the terminals of said bridging branch, the other of said crystals having a pair of electrodes on one face and a single electrode on the opposite face, said pair of electrodes on said other crystal being also connected respectively to the terminals of said bridging branch, the remaining electrodes on said one crystal and said single electrode on said other crystal being connected to the remaining filter terminals, the impedance measured between said first-mentioned input and output terminals having a different reactance-frequency characteristic from that of the impedance measured between said first-mentioned terminals strapped together and said remaining terminals strapped together, and said two measured impedances being proportioned with respect to each other and with respect to two preassigned frequencies to provide a transmission band between said frequencies.

3. A wave filter in accordance with claim 2 in which said inductors are connected in series at the ends of said filter.

4. A wave filter in accordance with claim 2 in which said inductors are connected in shunt at the ends of said filter.

5. A wave filter in accordance with claim 2 in which said inductors are inductively coupled.

6. A wave filter in accordance with claim 2 in which said inductors are inductively coupled in the series-aiding relationship.

7. A wave filter in accordance with claim 2 in which said inductors are inductively coupled in the series-opposing relationship.

8. A wave filter in accordance with claim 2 in which said four-electrode crystal has the lower frequency of resonance and said inductors are connected in series at the ends of said filter and are inductively coupled in the series-opposing relationship.

9. A wave filter in accordance with claim 2 in which said three-electrode crystal has the lower frequency of resonance and said inductors are connected in series at the ends of said filter and are inductively coupled in the series-aiding relationship.

10. A wave filter in accordance with claim 2 in which said four-electrode crystal has the lower frequency of resonance and said inductors are connected in shunt at the ends of said filter and are inductively coupled in the series-aiding relationship.

11. A wave filter in accordance with claim 2 in which said three-electrode crystal has the lower frequency of resonance and said inductors are connected in shunt at the ends of said filter and are inductively coupled in the series-opposing relationship.

12. A wave filter in accordance with claim 2 which includes two capacitors connected in shunt at the ends of said crystals.

13. A wave filter comprising a pair of input terminals, a pair of output terminals, a bridging impedance branch including a capacitor connected between an input terminal and a corresponding output terminal, two inductors connected in series with said bridging branch one on either side thereof, a pair of capacitors connected between the respective terminals of said bridging branch and the remaining filter terminals, and two piezoelectric crystals having different frequencies of resonance, one of said crystals having two electrodes on one face and two other oppositely disposed electrodes on the opposite face, an electrode on one face and a diagonally opposite electrode on the opposite face of said one crystal being connected respectively to the terminals of said bridging branch, the other of said crystals having a pair of electrodes on one face and a single electrode on the opposite face, said pair of electrodes on said other crystal being also connected respectively to the terminals of said bridging branch, the remaining electrodes on said one crystal and said single electrode on said other crystal being connected to said remaining filter terminals, and the dimensions of said crystals and the values of said inductors and capacitors being proportioned with respect to one another and with respect to two preassigned frequencies to provide a transmission band between said frequencies.

14. A wave filter in accordance with claim 13 in which said inductors are inductively coupled.

15. A wave filter in accordance with claim 13 in which said four-electrode crystal has the lower frequency of resonance and said inductors are inductively coupled in the series-opposing relationship.

16. A wave filter in accordance with claim 13 in which said three-electrode crystal has the lower frequency of resonance and said inductors are inductively coupled in the series-aiding relationship.

17. A wave filter comprising a pair of input terminals, a pair of output terminals, a bridging impedance branch including a capacitor connected between an input terminal and a corresponding output terminal, two inductors connected in shunt at the ends of said filter, a pair of capacitors also connected in shunt at the ends of said filter and two piezoelectric crystals having different frequencies of resonance, one of said crystals having two electrodes on one face and two other oppositely disposed electrodes on the opposite face, an electrode on one face and a diagonally opposite electrode on the opposite face of said one crystal being connected respectively to the terminals of said bridging branch, the other of said crystals having a pair of electrodes on one face and a single electrode on the opposite face, said pair of electrodes on said other crystal being also connected respectively to the terminals of said bridging branch, the remaining electrodes on said one crystal and said single electrode on said other crystal being connected to the remaining filter terminals, and the dimensions of said crystals and the values of said inductors and capacitors being proportioned with respect to one another and with respect to two preassigned frequencies to provide a transmission band between said frequencies.

18. A wave filter in accordance with claim 17 in which said inductors are inductively coupled.

19. A wave filter in accordance with claim 17 in which said four-electrode crystal has the lower frequency of resonance and said inductors are inductively coupled in the series-aiding relationship.

20. A wave filter in accordance with claim 17 in which said three-electrode crystal has the lower frequency of resonance and said inductors are inductively coupled in the series-opposing relationship.

21. A wave filter in accordance with claim 2 in which said inductors are connectors in series at the ends of said filter and said inductors are inductively coupled.

22. A wave filter in accordance with claim 2 in which said inductors are connected in shunt at the ends of said filter and said inductors are inductively coupled.

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