

Nov. 19, 1940.

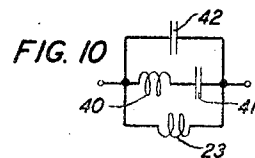
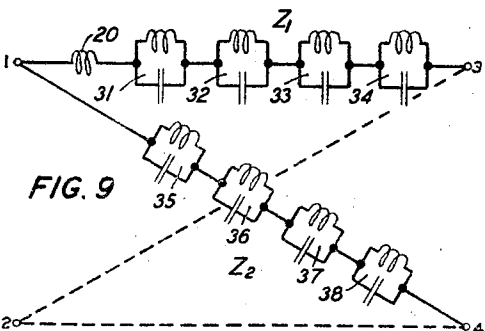
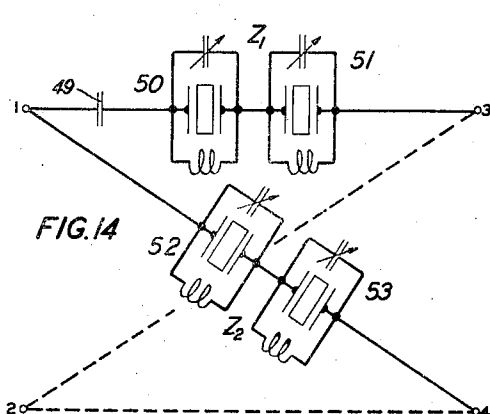
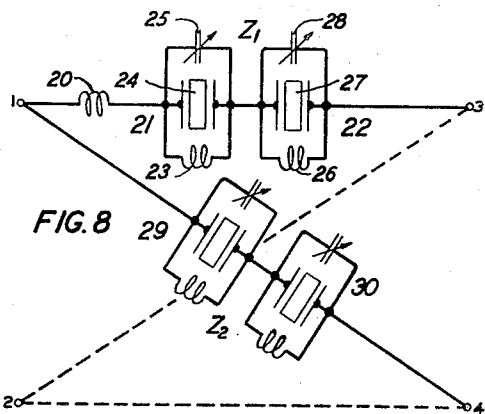
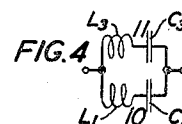
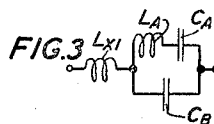
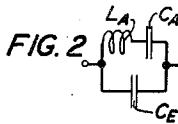
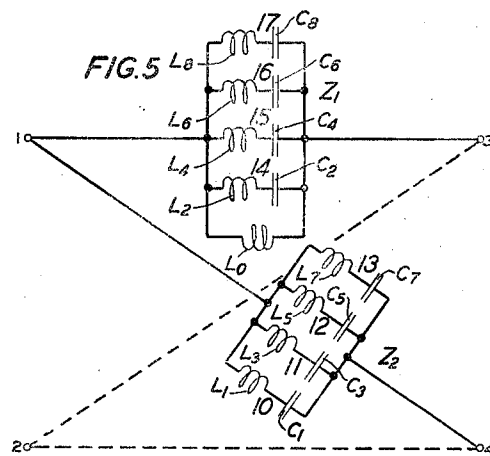
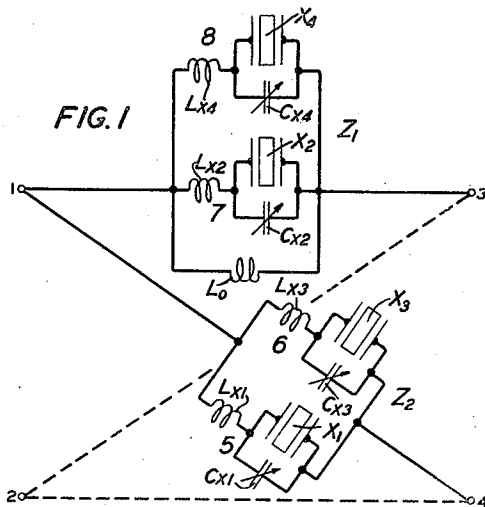
W. P. MASON

2,222,417

WAVE FILTER

Filed Sept. 24, 1938

2 Sheets-Sheet 1



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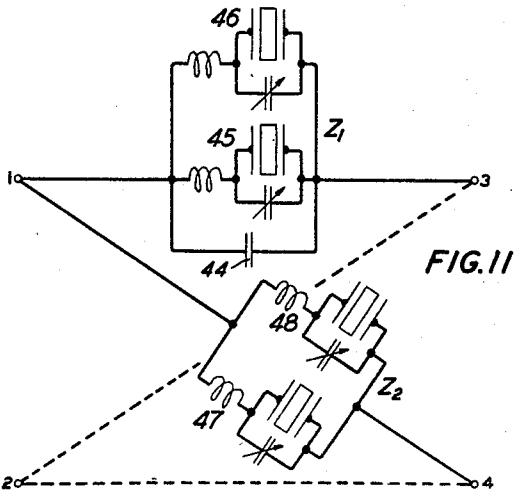
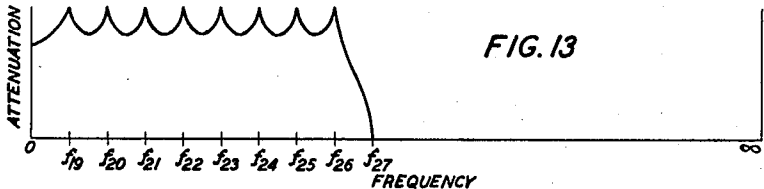
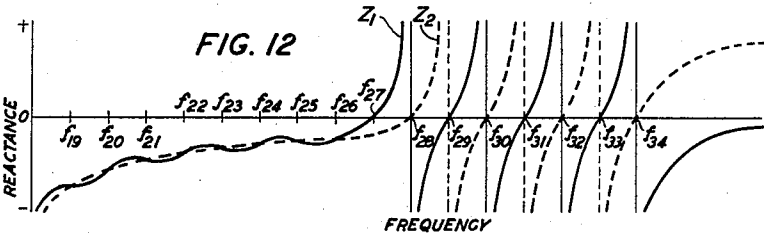
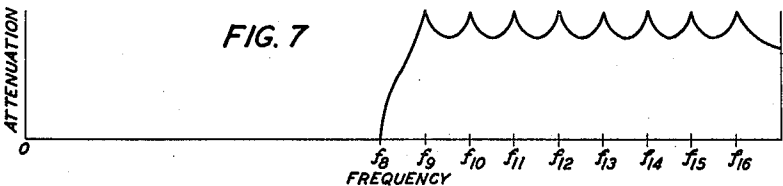
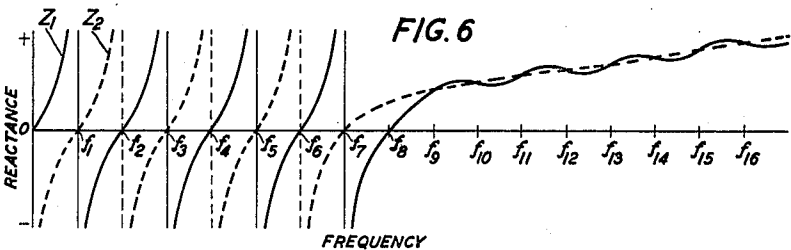
W. P. MASON

2,222,417

WAVE FILTER

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2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

2,222,417

WAVE FILTER

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Application September 24, 1933, Serial No. 231,493

25 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 which have a single transmission band and a single attenuation band.

The object of the invention is to increase the range of sustained high attenuation in a wave filter which uses piezoelectric crystals and has a single transmission band and a single attenuation band.

A feature of the invention is a single-section low-pass or high-pass crystal filter in which any desired number of arbitrarily placed attenuation peaks may be provided.

My prior United States Patent 1,921,035 issued August 8, 1933, discloses how to construct piezoelectric crystal filters of the low-pass type and of the high-pass type which are characterized by a single attenuation range and a single transmission range. The filters of that patent, however, have a maximum of three attenuation peaks and, therefore, the attenuation can be sustained at a high value over only a limited frequency range.

In accordance with the present invention there are provided crystal filters of the high-pass type and of the low-pass type which have any desired number of arbitrarily placed attenuation peaks. The filters are symmetrical lattice networks and each branch of the lattice comprises two or more piezoelectric crystals. An individual inductor is associated with each crystal. If the crystal and the inductor are connected in series, the combinations are connected in parallel, and if the crystal and inductor are connected in parallel, the combinations are connected in series. In the low-pass filter an additional inductor, and in the high-pass filter a capacitor, is associated with one of the impedance branches of the lattice. In order to facilitate the placing of the frequency of anti-resonance for the combination a capacitor, which may be made variable, is usually connected in parallel with the crystal.

If each lattice branch has two crystals, with associated inductors, the filter may be designed to have eight attenuation peaks which may be placed at any desired frequencies. In general, each additional crystal and inductor will provide four more peaks of attenuation. Some of the available critical frequencies may, of course, be utilized to improve the image impedance of the filter in the transmission band, in which case the number of attenuation peaks will be correspondingly reduced. However, by using a sufficient number of crystals and associated inductors,

any number of peaks may be provided, and these peaks may be distributed as required to keep the attenuation at a sustained high value over a wide frequency range.

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 shows one form of a low-pass wave filter in accordance with the invention in which the individual inductors are connected in series with the crystals;

Fig. 2 shows the equivalent electrical circuit for a piezoelectric crystal element;

Fig. 3 shows the equivalent electrical circuit for one of the impedance arms of Fig. 1;

Fig. 4 shows an electrical circuit which is equivalent to that shown in Fig. 3;

Fig. 5 shows a lattice network which is equivalent to the filter circuit of Fig. 1;

Fig. 6 shows the reactance-frequency characteristics for the branches of the lattice networks of Figs. 1 and 5;

Fig. 7 represents a typical attenuation characteristic for the low-pass filter of Figs. 1 and 5;

Fig. 8 shows an alternative circuit for the filter of Fig. 1 in which the inductors are connected in parallel with the crystals;

Fig. 9 shows a lattice network which is equivalent to the circuit of Fig. 8;

Fig. 10 shows a circuit which is equivalent to two of the anti-resonant loops of Fig. 9, and also to one of the combinations of Fig. 8;

Fig. 11 shows a high-pass filter following the circuit of the low-pass filter of Fig. 1;

Fig. 12 shows the reactance-frequency characteristics of the impedance branches of the lattice network of Fig. 11;

Fig. 13 shows a typical attenuation characteristic obtainable with the filter of Fig. 11; and

Fig. 14 shows an alternative circuit for the high-pass filter of Fig. 11 following the circuit of Fig. 8.

Fig. 1 is a schematic circuit of one form of the low-pass wave filter in accordance with the invention in which the individual inductors are in series with the crystals and the combinations are connected in parallel. The filter comprises two similar line impedance branches Z_1 and two similar diagonal impedance branches Z_2 disposed between a pair of input terminals 1, 2 and a pair of output terminals 3, 4 to form a symmetrical lattice network. For the sake of clarity in this figure and also in subsequent figures only one line branch and one diagonal branch are shown

in detail, the other corresponding line and diagonal branches being indicated by dotted lines connecting the appropriate terminals.

Each diagonal impedance branch Z_2 of the lattice comprises two parallel arms 5 and 6, one made up of a piezoelectric crystal X_1 in series with an inductor L_{X1} and shunted by a capacitor C_{X1} , and the other consisting of a crystal X_3 in series with an inductor L_{X3} and shunted by a capacitor C_{X3} . Each line branch Z_1 comprises three parallel arms, one being an inductor L_0 , another 7 consisting of a crystal X_2 in series with an inductor L_{X2} and shunted by a capacitor C_{X2} , and the third 8 made up of a crystal X_4 in series with an inductor L_{X4} and shunted by a capacitor C_{X4} . The capacitors may be made variable, as indicated by the arrows, so that the anti-resonances of the combinations may be readily adjusted.

The piezoelectric crystals may be of the type described in my aforementioned patent, or they may be of any other suitable type. The equivalent electrical circuit for such a crystal, as shown in Fig. 2, comprises a capacitance C_E shunted by a branch consisting of an inductance L_A in series with a capacitance C_A . The capacitance C_E is the simple electrostatic capacitance between the electrodes of the crystal. The values of the inductance L_A and the capacitance C_A depend upon the dimensions of the crystal and upon its piezoelectric and elastic constants. These elements may be evaluated from the formulae given in the patent mentioned above.

If Fig. 2 is taken as representing the equivalent circuit for the crystal X_1 , then the equivalent circuit for the arm 5 in Fig. 1 will be as shown in Fig. 3. The capacitance C_B is equal to the sum of the capacitances C_E and C_{X1} . The circuit of Fig. 3 may be transformed into the equivalent circuit shown in Fig. 4 by an application of the formulas given in connection with Fig. 13 in Appendix D of K. S. Johnson's *Transmission Circuits for Telephonic Communication* published by D. Van Nostrand Company. The circuit of Fig. 4 consists of two parallel arms, one comprising an inductance L_1 in series with a capacitance C_1 and the other made up of an inductance L_3 in series with a capacitance C_3 .

In like manner the remaining arms 6, 7 and 8 in Fig. 1 may be transformed into equivalent circuits of the type shown in Fig. 4. The complete lattice network equivalent to the lattice of Fig. 1 will then be as shown in Fig. 5. The diagonal branch Z_2 consists of the four resonant arms 10, 11, 12 and 13 connected in parallel, and the line branch Z_1 consists of the inductor L_0 and four other resonant arms 14, 15, 16 and 17 connected in parallel. The subscripts on the reference letters denoting the reactance elements indicate the frequencies of resonance for the various resonant arms.

The reactance-frequency characteristic for the line branch Z_1 of Figs. 1 and 5 will be as shown by the solid-line curve of Fig. 6, having zeroes at the frequencies zero, f_2 , f_4 , f_6 and f_8 , and poles at the frequencies f_1 , f_3 , f_5 and f_7 . The reactance of the diagonal branch Z_2 will have four zeroes and four poles as shown by the dotted-line curve. In order to provide a low-pass filter the zeroes of the diagonal branch are made to coincide with the poles of the line branch at the frequencies f_1 , f_3 , f_5 and f_7 , and the poles of the diagonal branch are made to coincide with the zeroes of the line branch at the frequencies zero, f_2 , f_4 and f_6 . The diagonal branch has no pole correspond-

ing to the zero of the line branch at f_8 and therefore this frequency determines the cut-off of the filter. In this illustrative case no critical frequencies are used for impedance correction.

Since there are seven critical frequencies and eight frequency intervals within the transmission band of the filter, there will ordinarily be eight peaks of attenuation in the attenuation range. These peaks occur where the two reactances Z_1 and Z_2 are equal, as indicated schematically by the crossings of the two curves at the frequencies f_9 , f_{10} , f_{11} , f_{12} , f_{13} , f_{14} , f_{15} and f_{16} . The location of the peaks is determined by the distribution of the critical frequencies within the transmission band and generally these are so chosen that the attenuation is maintained above some required minimum value over the desired frequency range. Fig. 7 shows a typical attenuation characteristic.

After the critical frequencies f_1 to f_8 within the band have been chosen, the values of the component elements in the equivalent lattice of Fig. 5 can be found from the resonant and anti-resonant frequencies of the Z_1 and Z_2 branches by a direct application of the reactance theorem given by R. M. Foster in the *Bell System Technical Journal*, vol. III, No. 2, April 1924, pages 259 to 267. The arm 10 consisting of L_1 , C_1 which has the lowest resonance in the diagonal impedance branch Z_2 , and the arm 11 comprising L_3 , C_3 , which has the next higher resonance, are now grouped together to form the circuit shown in Fig. 4. This circuit is then transformed into the equivalent circuit of Fig. 3 by means of the formulas given in Johnson's book mentioned above. The value of the inductance L_{X1} in the arm 5 of Fig. 1 is thus found. The values of the inductance L_A and the capacitance C_A in the equivalent electrical circuit representing the crystal x_1 , as given in Fig. 2, are also determined. The dimensions of the crystal X_1 having the required resonance frequency can thus be calculated. The value of the electrostatic capacitance C_E is next determined, and the capacitance C_{X1} found as the difference between C_B and C_E .

All of the elements X_1 , C_{X1} and L_{X1} in the arm 5 of Fig. 1 have thus been fixed, and this arm is equivalent to the two parallel arms 10 and 11 of Fig. 5. In like manner the remaining arms 12 and 13 in the diagonal branch Z_2 of Fig. 5 are converted into the equivalent arm 6 of Fig. 1. In the same way the arms 14, 15 and 16, 17 in the line branch Z_1 of Fig. 5 are converted into the equivalent arms 7 and 8, respectively, of Fig. 1. The values of all of the component elements in the circuit of Fig. 1 have thus been determined.

In the filter of Fig. 1 more arbitrarily placed attenuation peaks may be provided by adding more crystals, with associated inductors and capacitors. In general, the addition of a crystal to each impedance branch of the lattice will add four more peaks. When required some of the critical frequencies may be placed in the attenuating region of the filter in order to improve the image impedance in the transmission band. However, any number of attenuation peaks may be provided if a sufficient number of crystals are used, and there is thus provided a low-pass crystal filter in which the attenuation may be kept at a high value over any desired frequency range.

Fig. 8 shows an alternative circuit for the low-pass filter of Fig. 1 in which each inductor is connected in shunt with its associated crystal, and the parallel combinations are connected in series. Each line branch Z_1 consists of an in-

ductor 20 and two combinations 21 and 22. The combination 21 comprises an inductor 23, a crystal 24 and a variable capacitor 25, all connected in parallel, and the combination 22 is made up of an inductor 26, a crystal 27 and a capacitor 28 connected in parallel. The diagonal impedance branch Z_2 consists of the two series-connected combinations 29 and 30 each made up of an inductor, a crystal and a capacitor in parallel. The line and diagonal branches will have the same types of reactance characteristics as shown in Fig. 6 and the filter may be designed to have the type of attenuation characteristic shown in Fig. 7.

In designing the filter of Fig. 8 the equivalent line and diagonal branches in the form of groups of series-connected anti-resonant loops are first found from their critical frequencies by an application of Foster's reactance theorem mentioned above. The equivalent lattice structure is shown in Fig. 9. Each line branch consists of the inductor 20 and four anti-resonant loops 31, 32, 33 and 34 all connected in series. Each diagonal branch is made up of the four loops 35, 36, 37 and 38. The loops 31 and 32 are then transformed into the equivalent circuit of Fig. 10 by means of the formulas given in the above-mentioned book by Johnson in connection with Fig. 12 of Appendix D. This gives the value of the inductor 23 in the combination 21 of Fig. 8. The values of the inductor 40 and the capacitor 41 of Fig. 10 determine the resonance frequency of the crystal 24 of Fig. 8 and the dimensions of this crystal can then be calculated. The value of the capacitor 25 is found by subtracting the electrostatic capacitance of the crystal 24 from the value of the capacitance 42. All of the elements in the combination 21 of Fig. 8 are thus fixed, and this combination is equivalent to the two loops 31 and 32 of Fig. 9. In like manner the loops 33 and 34, 35 and 36, and 37 and 38 of Fig. 9 are converted into the combinations 22, 29 and 30, respectively, of Fig. 8.

In order to provide a high-pass filter the inductor L_0 of Fig. 1 is replaced by a capacitor 44 as shown in Fig. 11. The line impedance branch Z_1 consists of the capacitor 44 and the two arms 45 and 46 all connected in parallel. The diagonal branch Z_2 is made up of the two parallel-connected arms 47 and 48. The reactance characteristics of the line impedance branch Z_1 and the diagonal branch Z_2 will now be of the types shown respectively by the solid line and the dotted-line curves of Fig. 12. The line branch has zeroes at the frequencies f_{27} , f_{28} , f_{31} and f_{33} , and poles at f_{28} , f_{30} , f_{32} and f_{34} . The diagonal branch has zeroes at f_{28} , f_{30} , f_{32} and f_{34} , and poles at f_{29} , f_{31} and f_{33} . The cut-off will be at f_{27} and there will be eight peaks of attenuation, at the frequencies f_{19} , f_{20} , f_{21} , f_{22} , f_{23} , f_{24} , f_{25} and f_{26} , where the two reactance curves cross. A typical attenuation characteristic is given in Fig. 13. As in the case of the low-pass filter more peaks may be provided by adding more crystals, with their associated reactance elements, and certain of the critical frequencies may be utilized to improve the image impedance of the filter.

An equivalent circuit for the high-pass filter of Fig. 11, following the low-pass circuit of Fig. 8, is shown in Fig. 14 where the inductor 20 is replaced by a capacitor 49. The line impedance branch Z_1 consists of the two parallel combinations 50 and 51 connected in series with the capacitor 49. The diagonal branch Z_2 is made up of the two series-connected parallel combinations

52 and 53. The reactance characteristics of the line and diagonal branches will be as shown in Fig. 12 and the filter may be designed to have the type of attenuation characteristic shown in Fig. 13.

In any of the lattice structures shown the line and diagonal impedance branches may be interchanged without affecting the attenuation characteristic of the filter. Such a change will, however, alter the type of image impedance obtained. Also in the equivalent low-pass filter circuits of Figs. 1 and 8 a line branch of one may be interchanged with a line branch of the other, or a diagonal branch of one may be interchanged with a diagonal branch of the other, without affecting either the attenuation or image impedance characteristics. This same observation applies with respect to the equivalent high-pass filter circuits of Figs. 11 and 14.

What is claimed is:

1. A wave filter comprising four impedance branches equal in pairs and disposed between input terminals and output terminals to form a symmetrical lattice network, each of said branches comprising a plurality of impedance combinations, each of said impedance combinations including a piezoelectric crystal and a capacitor connected in parallel, and an associated inductor, each of one of said pairs of branches including one of a pair of equal additional reactance elements, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a single transmission band and a single attenuation band.
2. A wave filter in accordance with claim 1 in which each of said inductors is connected in series with its associated parallel-connected crystal and capacitor.
3. A wave filter in accordance with claim 1 in which each of said inductors is connected in parallel with its associated crystal.
4. A wave filter in accordance with claim 1 in which said additional reactance elements are inductors and said transmission band is on the lower side of said attenuation band.
5. A wave filter in accordance with claim 1 in which said additional reactance elements are capacitors and said transmission band is on the upper side of said attenuation band.
6. A wave filter in accordance with claim 1 in which each of said additional reactance elements is connected in series with the branch with which it is associated.
7. A wave filter in accordance with claim 1 in which each of said additional reactance elements is connected in parallel with the branch with which it is associated.
8. A wave filter in accordance with claim 1 in which each of said inductors is connected in series with its associated parallel-connected crystal and capacitor, and each of said additional reactance elements is connected in parallel with the branch with which it is associated.
9. A wave filter in accordance with claim 1 in which each of said inductors is connected in parallel with its associated crystal, and each of said additional reactance elements is connected in series with the branch with which it is associated.
10. A wave filter in accordance with claim 1 in which all of said impedance combinations in each of said branches are connected in parallel.
11. A wave filter in accordance with claim 1 in which all of said impedance combinations in

each of said branches are connected in series.

12. A wave filter in accordance with claim 1 in which in said one pair of branches each of said inductors is connected in series with its associated parallel-connected crystal and capacitor, and said additional reactance element is connected in parallel with said impedance combinations in the branch with which the additional reactance element is associated.

13. A wave filter in accordance with claim 1 in which in said one pair of branches each of said inductors is connected in parallel with its associated crystal, and said additional reactance element is connected in series with said impedance combinations in the branch with which the additional reactance element is associated.

14. A wave filter comprising four impedance branches equal in pairs and disposed between input terminals and output terminals to form a symmetrical lattice network, each of one of said pairs of branches comprising an inductor and a plurality of impedance combinations all connected in parallel, each of said impedance combinations including a piezoelectric crystal and an inductor in series and a capacitor in shunt with said crystal, each of the other of said impedance branches comprising a plurality of other impedance combinations, each of said other impedance combinations including a piezoelectric crystal and a capacitor in parallel and an associated inductor, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a transmission band extending from zero to a finite frequency.

15. A wave filter comprising four impedance branches equal in pairs and disposed between input terminals and output terminals to form a symmetrical lattice network, each of one of said pairs of branches comprising a capacitor and a plurality of impedance combinations all connected in parallel, each of said impedance combinations including a piezoelectric crystal and an inductor in series and a capacitor in shunt with said crystal, each of the other of said impedance branches comprising a plurality of other impedance combinations, each of said other impedance combinations including a piezoelectric crystal and a capacitor in parallel and an associated inductor, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a single attenuation band extending from zero to a finite frequency and a single transmission band.

16. A wave filter comprising four impedance branches equal in pairs and disposed between input terminals and output terminals to form a symmetrical lattice network, each of one of said

pairs of branches comprising an inductor and a plurality of impedance combinations all connected in series, each of said impedance combinations including a piezoelectric crystal, an inductor and a capacitor all connected in parallel, each of the other of said impedance branches comprising a plurality of other impedance combinations, each of said other impedance combinations including a piezoelectric crystal and a capacitor in parallel and an associated inductor, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a transmission band extending from zero to a finite frequency.

17. A wave filter in accordance with claim 14 in which in each of said other impedance branches said other impedance combinations are connected in parallel.

18. A wave filter in accordance with claim 14 in which in each of said other impedance combinations said associated crystal and inductor are connected in series.

19. A wave filter in accordance with claim 14 in which in each of said other impedance branches said other impedance combinations are connected in parallel and in each of said other impedance combinations said associated crystal and inductor are connected in series.

20. A wave filter in accordance with claim 15 in which in each of said other impedance branches said other impedance combinations are connected in parallel.

21. A wave filter in accordance with claim 15 in which in each of said other impedance combinations said associated crystal and inductor are connected in series.

22. A wave filter in accordance with claim 15 in which in each of said other impedance branches said other impedance combinations are connected in parallel and in each of said other impedance combinations said associated crystal and inductor are connected in series.

23. A wave filter in accordance with claim 16 in which in each of said other impedance branches said other impedance combinations are connected in series.

24. A wave filter in accordance with claim 16 in which in each of said other impedance combinations said associated crystal and inductor are connected in parallel.

25. A wave filter in accordance with claim 16 in which in each of said other impedance branches said other impedance combinations are connected in series and in each of said other impedance combinations said associated crystal and inductor are connected in parallel.

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