Oct. 1, 1940. H. G. OCH 2,216,541

WAVE FILTER

Filed Sept. 24, 1938

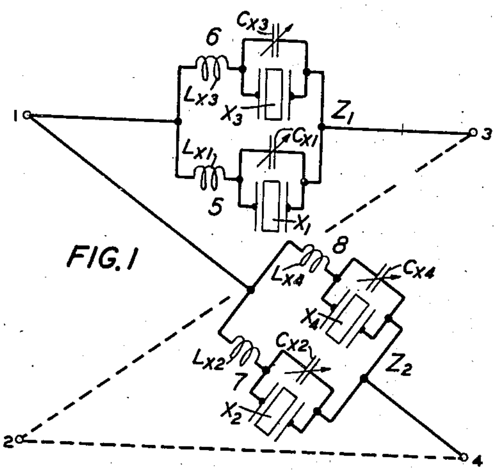


FIG. 1

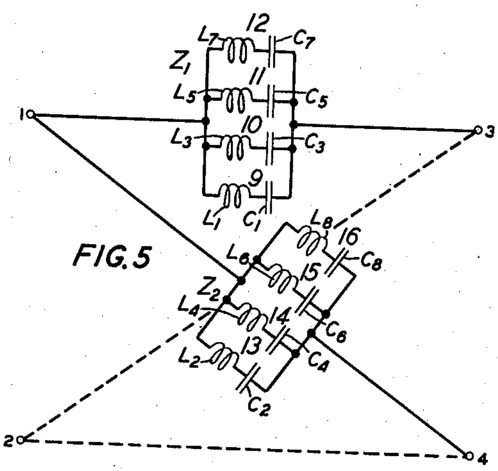


FIG. 5

FIG. 2

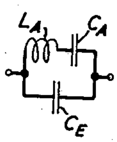


FIG. 3

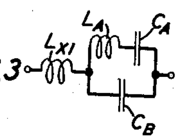


FIG. 4

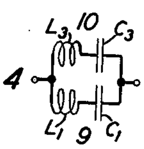


FIG. 6

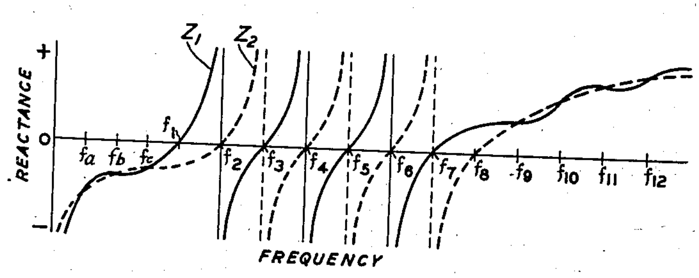
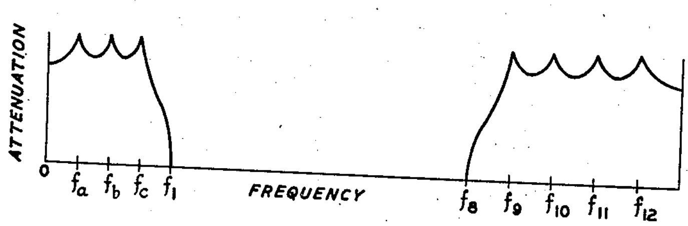


FIG. 7



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WAVE FILTER

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Application September 24, 1938, Serial No. 231,492

12 Claims. (Cl. 178—44)

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

An object of the invention is to increase the width of the transmission band in a wave filter employing piezoelectric crystals. Another object is to increase the range or ranges of sustained high attenuation in such a filter.

It is known how to build a band-pass wave filter which uses piezoelectric crystals and has a limited band width and a limited number of attenuation peaks. In accordance with the present invention there is provided a crystal band filter in which the band may be extended to any desired width and which has any desired number of arbitrarily placed attenuation peaks. By providing a sufficient number of peaks and by properly choosing their locations the attenuation of the filter may be kept at a sustained high value over any desired frequency range or ranges.

The filter is a symmetrical lattice network and each branch of the lattice comprises two or more piezoelectric crystals, with an individual inductor associated with each crystal. If the crystal and the inductor are connected in series, the combinations are connected in parallel. 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 branch of the lattice has two crystals the transmission band of the filter may be made more than twice the width heretofore attainable with crystal filters. Furthermore, the filter may be designed to have seven peaks of attenuation which may be placed at arbitrarily chosen frequencies, all on one side of the band or part below and part above the band. Additional peaks may be provided and the band may be further widened by using more crystals. In general each added crystal and its associated inductor will provide four more peaks of attenuation. Some of the available critical frequencies may 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 reactance elements any desired number of peaks may be provided.

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 a band-pass wave filter in accordance with the invention;

Fig. 2 represents an equivalent electrical circuit for a piezoelectric crystal element;

Fig. 3 shows an 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; and

Fig. 7 represents a typical attenuation characteristic for the filter.

Fig. 1 is a schematic circuit of a band-pass wave filter in accordance with the invention. The network 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 structure. Each impedance branch includes two piezoelectric crystals and their associated inductors and capacitors. For the sake of clarity in this figure and also in Fig. 5 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 line impedance branch Z_1 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 diagonal branch Z_2 is of the same structure as the line branches and comprises two parallel arms **7** and **8**, one made up of a crystal X_2 in series with an inductor L_{X2} and shunted by a capacitor C_{X2}, and the other consisting 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 crystal-capacitor combinations may be readily adjusted to the required frequencies.

As shown in Fig. 2, an equivalent electrical circuit representing a piezoelectric crystal element including its associated electrodes 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 formulas readily available.

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, in which the capacitance C_B is equal to the sum of the capacitances C_E and C_{X1}. Now the circuit of Fig. 3 may be transformed into the circuit shown in Fig. 4 comprising two parallel arms 9 and 10, one made up of an inductance L_1 in series with a capacitance C_1, and the other consisting of an inductance L_3 in series with a capacitance C_3. The formulas required for this transformation are 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.

In like manner the other arms 6, 7 and 8 of 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 line branch Z_1 consists of four resonant arms 9, 10, 11 and 12 connected in parallel, and the diagonal branch Z_2 comprises four other resonant arms 13, 14, 15 and 16 also connected in parallel. The subscripts on the reference letters denoting the reactance elements indicate the frequencies of resonance of the various arms.

The reactance-frequency characteristic for the line branch Z_1 will be as shown by the solid-line curve of Fig. 6, having zeroes at the frequencies f_1, f_3, f_5 and f_7, and poles at the frequencies f_2, f_4 and f_6. The diagonal branch will have a reactance characteristic of the same type, as shown by the dotted-line curve. In order to provide a band-pass filter the zeroes and poles of one branch are made to coincide with the poles and zeroes, respectively, of the other branch. Therefore, as shown in Fig. 6, the diagonal branch has zeroes at f_2, f_4, f_6 and f_8, and poles at f_3, f_5 and f_7. The diagonal branch has no pole at f_1 corresponding to the zero of the line branch at this frequency, and the line branch has no pole at f_8 corresponding to the zero of the diagonal branch. The frequencies f_1 and f_8 will therefore determine the limits of the transmission band, which will extend between these frequencies.

The filter shown will ordinarily have seven peaks of attenuation and these may be placed all on either side of the band, or part on one side and part on the other. The peaks occur where the two impedances Z_1 and Z_2 are equal, and in Fig. 6 three such frequencies, f_a, f_b and f_c, are found below the band and four, f_9, f_{10}, f_{11} and f_{12}, above. The location of these peaks is determined by the distribution of the critical frequencies within the transmission band and these are generally so chosen that the attenuation is maintained above some required minimum values over the desired frequency ranges on each side of the band. Fig. 7 shows a typical attenuation characteristic with the transmission band extending from f_1 to f_8 and attenuation peaks at the frequencies f_a, f_b and f_c below the band and at f_9, f_{10}, f_{11} and f_{12} above the band.

In designing the filter the following procedure is suggested. First the critical frequencies f_1 to f_8 are chosen and then the values of the component elements in the equivalent lattice of Fig. 5 are found from the zeroes and poles 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 9 consisting of L_1, C_1 having the lowest resonance and the arm 10 comprising L_3, C_3 having the next higher resonance in the line branch 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 then be calculated, and the value of the electrostatic capacitance C_E computed. The value of the capacitance C_{X1} to be added in shunt with the crystal will be 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 9 and 10 of Fig. 5. In like manner the remaining arms 11 and 12 in the line branch Z_1 of Fig. 5 are converted into the equivalent arm 6 of Fig. 1. In the same way the arms 13, 14 and 15, 16 in the diagonal branch Z_2 of Fig. 5 are converted into the equivalent arms 7 and 8 of Fig. 1. The values of all of the component elements in the circuit of Fig. 1 have now been determined.

The transmission band of the filter may be further widened and additional peaks of attenuation may be provided by adding more crystals, with their associated inductors and capacitors. In general the addition of a crystal and its associated reactance elements to each impedance branch of the lattice of Fig. 1 will add four more peaks. When required some of the critical frequencies may be placed outside of the transmission band and used to improve the image impedance of the filter, with a consequent reduction in the number of attenuation peaks. However, the transmission band may be widened to any desired extent and any number of peaks may be provided if a sufficient number of crystals and reactance elements are used.

What is claimed is:

1. A wave filter comprising four impedance branches equal in pairs and disposed between input terminals and ouput 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 an associated inductor, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a single transmission band.

2. A wave filter in accordance with claim 1 in which each of said inductors is connected in series with its associated crystal.

3. A wave filter in accordance with claim 1 in which all of said impedance combinations in each of said branches are connected in parallel.

4. A wave filter in accordance with claim 1 in which each of said inductors is connected in series with its associated crystal and all of said impedance combinations in each of said branches are connected in parallel.

5. A wave filter in accordance with claim 1 which includes added capacitors connected in shunt with certain of said crystals.

6. 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 plurality of impedance combinations connected in parallel, each of said impedance combinations including a piezoelectric crystal and an inductor connected in series, 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 an associated inductor, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a single transmission band.

7. A wave filter in accordance with claim 6 which includes added capacitors connected in shunt with certain of said crystals.

8. 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 parallel paths, each of said paths including a piezoelectric crystal and an associated inductor connected in series, and said pairs of branches having different reactance-frequency characteristics proportioned with respect to each other to provide a single transmission band.

9. A wave filter in accordance with claim 8 in which certain of said paths include added capacitors connected in shunt with said crystals.

10. A wave filter in accordance with claim 8 in which each of said paths includes an added capacitor connected in shunt with the crystal in said path.

11. A wave filter in accordance with claim 1, which includes added capacitors connected in shunt with certain of said crystals and in which each of said inductors is connected in series with its associated crystal.

12. A wave filter in accordance with claim 1, which includes added capacitors connected in shunt with certain of said crystals and in which all of said impedance combinations in each of said branches are connected in parallel.

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