March 3, 1931. L. ESPENSCHIED 1,795,204

ELECTRICAL WAVE FILTER

Filed Jan. 3, 1927 2 Sheets-Sheet 1

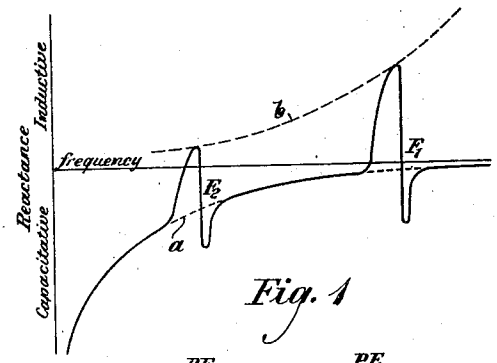


Fig. 1

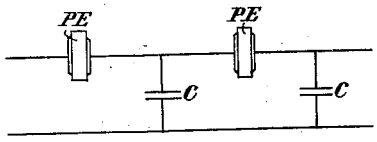


Fig. 2

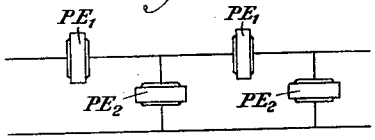


Fig. 4

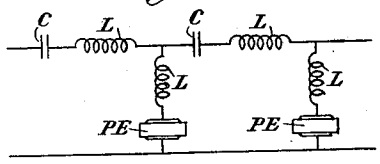


Fig. 6

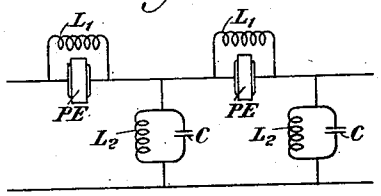


Fig. 8

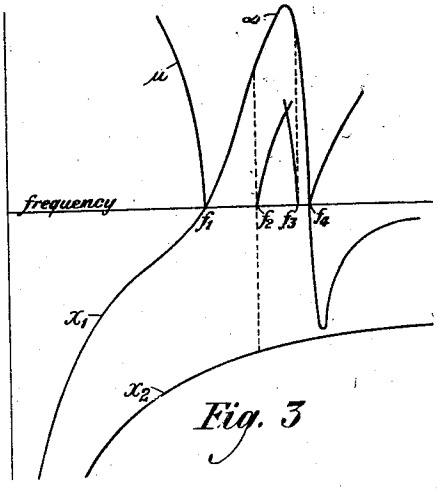


Fig. 3

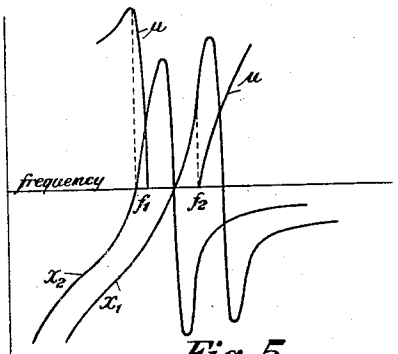


Fig. 5

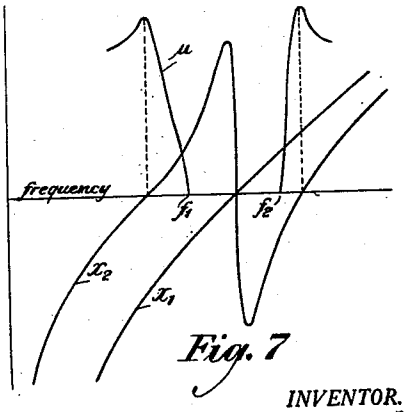


Fig. 7

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ELECTRICAL WAVE FILTER

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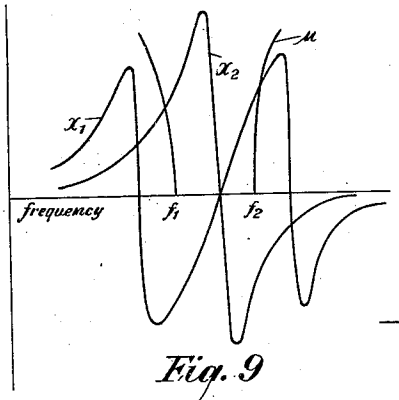


Fig. 9

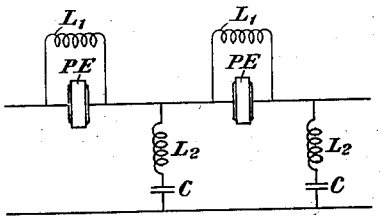


Fig. 10

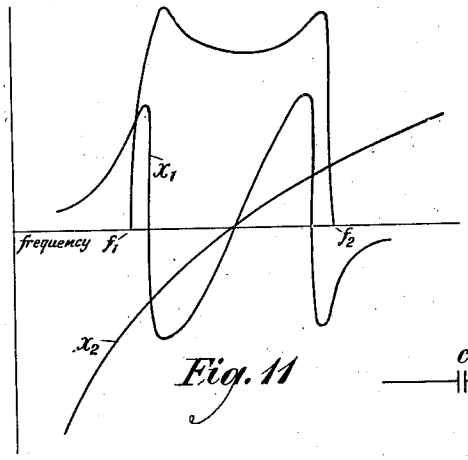


Fig. 11

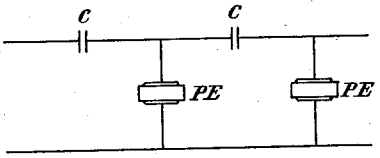


Fig. 12

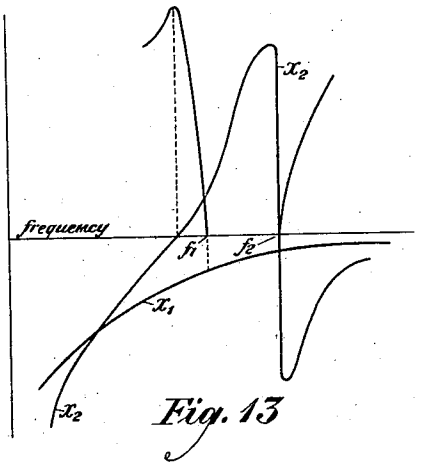


Fig. 13

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Patented Mar. 3, 1931 1,795,204

UNITED STATES PATENT OFFICE

LLOYD ESPENSCHIED, OF HOLLIS, NEW YORK, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK

ELECTRICAL WAVE FILTER

Application filed January 3, 1927. Serial No. 158,753.

This invention relates to electric wave filters, and more particularly to a wave filter adapted to transmit with small or negligible attenuation currents of all frequencies lying within a range or ranges of predetermined limiting frequencies while attenuating and substantially extinguishing current of frequencies lying outside the limits of the predetermined range or ranges.

While this invention may find expression in a great many embodiments, it has common to all of these embodiments the broad idea of a wave filter involving a plurality of piezo-electric structures, having an impedance element or elements in series with a line and an impedance element or elements in shunt across the line, the values of these impedance elements being so proportioned that the arrangement will transmit with small or negligible attenuation from a source of electromagnetic energy to some form of electrical receiving or translating device, currents of all frequencies lying within predetermined limits or ranges while attenuating and substantially suppressing currents of all frequencies lying outside the limits or ranges.

As is well known in the art, a simple electrical wave filter may consist of an electrical circuit network which has a negligible transmission loss over one or several frequency ranges while the loss is appreciable and may become very high over other ranges. It it is attempted to design an electrical wave filter for high impedance circuits with the elements heretofore employed therein, it will be found that the inductances required become impracticably large and that the capacities become very small, especially when the frequencies involved are high. It is an established fact that it is exceedingly difficult to wind an inductance of one henry or more which is to remain an inductive reactance over a wide range of frequencies, due particularly to the distributed capacities of the inductance. Furthermore, the electrical resistance of practicable coils tends to reduce the sharpness of the cut-off obtainable in an electrical wave filter and therefore, introduces another serious difficulty. These difficulties may in part be avoided by the introduction of step-up and step-down transformers to adjust the impedance to the requirements of filter design. Even in such transformers, however, difficulties arise if the impedance ratio is large, if a wide frequency range is to be covered and especially if the frequencies involved are high.

In order to overcome these difficulties, it is proposed herein to replace some or all of the circuit elements of the electrical wave filter by piezo-electric structures. The practicability of such a replacement may become apparent from the partial equivalence of the piezo-electric crystal to some form of electrical network consisting of suitable reactance elements. That this partial equivalence exists, will readily be seen from the following: If a piezo-electric crystal is connected in parallel with a tuned circuit of series inductance and capacity and the arrangement is fed with current from a source of variable frequency, and if, moreover, the current in the tuned circuit may be read on the meter as the frequency of the source is varied, it will be found that the current reaches a maximum value at the frequency of resonance of the tuned circuit. If the tuned circuit is so adjusted that its resonant frequency lies very close to the resonant frequency of natural vibration of the piezo-electric crystal and if the current in this tuned circuit is plotted as a function of frequency, it will be found that at the natural vibratory period of the piezo-electric crystal, the current in the tuned circuit will drop to a very low value, rising sharply thereafter as the resonant frequency of the crystal is passed. In other words, the piezo-electric crystal acts in some respects like a series resonant circuit of extraordinarily low decrement at its resonant frequency. At frequencies somewhat above the frequency at which current through the piezo-electric crystal is a maximum, the piezo-electric crystal acts like an anti-resonant circuit. Moreover, the crystal includes the equivalent of a resistance element representing energy dissipation due to its viscosity. A brief consideration of the characteristics of a piezo-electric crystal aids in a better understanding of the invention.

It is an object of this invention to produce an electrical wave filter which shall include a piezo-electric structure, in order that its transmission characteristic may become flatter within the transmitting band than has heretofore been possible with other electrical wave filters, so that all frequencies within a definite range or ranges may be transmitted substantially uniformly.

It is another object of this invention to provide an electrical wave filter of a plurality of recurrent sections, each of which includes substantially equal piezo-electric structures so that its attenuation characteristic will be steeper and its transmission characteristic flatter than the corresponding characteristics of electrical wave filters heretofore known.

While the invention will be pointed out with particularity in the appended claims, the invention itself, both as to its further objects and features, will be better understood from the detailed description hereinafter following, when read in connection with the accompanying drawing in which Figure 1 represents a simple reactance curve for a piezo-electric crystal; Figs. 2, 4, 6, 8, 10 and 12 represent recurrent structures of series and shunt elements of electrical wave filters involving piezo-electric crystals; and Figs. 3, 5, 7, 9, 11 and 13 represent the attenuation properties of the resultant electrical wave filters of this invention. Similar reference characters will be used to designate similar parts throughout the figures of the drawing.

Referring to Fig. 1 of the drawing, a characteristic reactance curve for a piezo-electric crystal is shown. The reference character a identifies a characteristic capacitative reactance curve such as might be obtainable when a condenser is connected to a source of variable frequency, the reactance decreasing as the frequency of a current impressed across the terminals of the condenser increases. The reference character b identifies a characteristic inductive reactance curve for an inductance connected to a similar source of variable frequency, the reactance increasing as the frequency of the current impressed across the terminals of the inductance increases.

A piezo-electric device may be considered to act like a condenser having a capacitative reactance at all frequencies substantially different from the resonant frequencies of the piezo-electric device. At or near a resonant frequency, the reactance differs substantially from that of a condenser, its reactance being then determinable from one of the loops shown in Fig. 1. For the particular piezo-electric device having the characteristic curve shown in Fig. 1, there are two frequencies, or, more accurately, there are two bands of frequencies at which the reactance differs substantially from the normal capacitative reactance of the condenser. These frequencies or bands of frequencies are designated by the reference characters F_1 and F_2, F_1 representing frequencies or a band of frequencies different from and higher than the frequencies or band of frequencies F_2. Moreover, at any one of the frequencies within either band F_1 or F_2, the reactance may be either capacitative or inductive, as will be apparent from an inspection of Fig. 1. Under ordinary conditions, the reactance may become inductive at frequencies slightly below those frequencies which correspond to natural frequencies of mechanical vibration of the crystal.

Referring to Figs. 2, 4, 6, 8, 10 and 12 of the drawing, each wave filter is composed of identical or substantially indentical sections, respectively, each including suitable elements in series with the line and suitable elements in shunt across the line. Thus, in Fig. 2, two sections of a plurality are shown, each including a piezo-electric crystal PE in series with the line and a condenser C in shunt across the line. The piezo-electric crystals PE are preferably identical, or substantially identical, in their structure and characteristics and accordingly vibrate at the same or at substantially the same frequencies. Fig. 3 shows the characteristic reactance curves of the series and shunt elements of each section, the curve identified by the reference character x_1 corresponding to the series element, the piezo-electric crystal PE, and the curve identified by reference character x_2 corresponding to the shunt element, the condenser C.

If the piezo-electric crystal PE were connected to a source of alternating current, the frequency of which varied as found desirable, the piezo-electric crystal would exhibit a capacitative reactance below the frequency f_1, the magnitude of the capacitative reactance decreasing as the frequency f_1 is approached. Beyond the frequency f_1, the reactance would become inductive rather gradually, and as the frequency approaches f_4, the inductive reactance would decrease very suddenly, becoming a capacitative reactance at and beyond the frequency f_4. The change from a high inductive reactance to a high capacitative reactance takes place about the frequency f_4 and within a very narrow range of the frequency spectrum. Thereafter the capacitative reactance decreases in magnitude with increase in frequency.

The curve x_2 is proportional to the capacitative reactance values of the shunt element, the condenser C. Obviously, as the frequency increases, the capacitative reactance correspondingly decreases. However, the curve x_2 exhibits magnitudes corresponding to four times the reactance values of the shunt capacity, and the reason for using four times the shunt reactance values will become

apparent from the description of the invention hereinafter following.

It is well known that the condition for unattenuated transmission in an electrical network exists when the ratio of the magnitude of the series reactance to four times the magnitude of the shunt reactance lies between zero and -1. Between these limits, the transmission takes place, while there is effective attenuation outside of these limits. Currents having frequencies lower than f_1 are considerably attenuated by the structure of Fig. 2, the attenuation decreasing as the frequency f_1 is approached. At the frequency f_1, the ratio of the series reactance magnitude to the shunt reactance magnitude is zero, so that transmission takes place at that frequency. With frequencies higher than f_1 and lower than f_2, the ratio of the series reactance magnitude to the shunt reactance magnitude is negative with increasing proportion as the frequency becomes nearer f_2. At the frequency f_2 however, the ratio of the series to shunt reactance magnitudes reaches the other limiting value for free transmission, i. e., -4, and beyond the frequency f_2, current is effectively attenuated. The range of free transmission lies between the cut-off points of the filter, f_1 and f_2. Outside of these limits, there is effective attenuation. The structure of Fig. 2 exhibits a flatter transmission characteristic and a steeper attenuation characteristic than have been heretofore obtainable with the ordinary and well-known electrical wave filters.

There is another very narrow frequency range between the frequency limits f_3 and f_4 which must be considered in connection with the structure of Fig. 2. The range of frequencies between f_3 and f_4 satisfy the conditions for free transmission, i. e., the ratio of the series reactance magnitude with the shunt reactance magnitude lies between zero and -4. However, the frequencies within this very narrow range are not freely transmitted by this structure, but are in effect attenuated. Between the frequencies f_3 and f_4, the piezo-electric crystal PE corresponds to an anti-resonant circuit which is receiving current of a frequency corresponding substantially to the natural frequency of the circuit. Accordingly, the resistance of the anti-resonant circuit is exceedingly high. This exceedingly high resistance effects attenuation in the structure even between the frequencies f_3 and f_4.

Fig. 4 represents another piezo-electric structure having similar series elements, the piezo-electric crystals PE_1, and similar shunt elements, the piezo-electric crystals PE_2. In Fig. 5, reference character x_1 shows the variation in reactance with frequency in the series elements, the piezo-electric crystals PE_1. Reference character x_2 represents reactance variation with frequency in the shunt elements, the piezo-electric crystals PE_2. The reference character u shows the filter characteristic of the structure corresponding to these series and shunt piezo-electric elements. This electrical wave filter freely transmits all currents having frequencies within the limits f_1 and f_2, and has a very sharply increasing attenuation characteristic at frequencies outside of this range. It is to be particularly noted that the attenuation is infinite at the frequency corresponding to the resonant point at which the shunt reactance is zero. It is also to be noted that at the frequencies f_1 and f_2, the ratios of the series reactance magnitude to the shunt reactance magnitude are both equal to -4, the ratio being zero at a point approximately midway between the frequencies f_1 and f_2.

Fig. 6 shows another piezo-electric filter structure having a plurality of sections only two of which are shown. The series element of each section comprises a condenser C and an inductance L in series relationship and the shunt element of each section comprises a piezo-electric crystal PE and an inductance L also in series relationship. The reactance curve for the series element of each section is designated in Fig. 7 by the reference character x_1. The curve x_2 is proportional to the reactance in the shunt element of each section of the filter. This piezo-electric filter transmits a band within the frequency limits f_1 and f_2, and substantially suppresses all frequencies outside of these limits. At the points f_1 and f_2, the ratio of series reactance to shunt reactance equals -4. It is to be noted that the attenuation is infinite at those points of the structure at which the shunt elements have zero reactance. Inasmuch as the shunt reactance curve x_2 indicates zero reactance at two points outside of the limits of free transmission of the filter, this filter has infinite attenuation at the frequencies corresponding to those points.

Fig. 8 shows another electric wave filter involving piezo-electric crystals. Each series element includes a piezo-electric crystal PE and an inductance L_1 in shunt therewith and each shunt element includes an inductance L_2 in shunt with a condenser C. The reactance curves for this piezo-electric filter are shown in Fig. 9 of the drawing, in which the reference character x_1 designates the series reactance-frequency variation, and in which reference character x_2 represents the shunt reactance-frequency variation, the latter being obviously the reactance curve of an anti-resonant circuit. This electrical wave filter has a very flat transmission characteristic between the frequencies f_1 and f_2, freely and uniformly transmitting currents of all frequencies within these two limits, and it has a very steep attenuation characteristic outside of the limits f_1 and f_2, substantially suppressing currents of all frequencies outside of

these limits, the attenuation increasing very rapidly with departures from the frequencies f_1 and f_2.

Fig. 10 shows another piezo-electric filter having a piezo-electric crystal PE in shunt with an inductance L_1 as the series element of each section and a series resonant circuit including an inductance L_2 and a condenser C as the shunt element of each section. In Fig. 11, the reference character x_1 designates the reactance variation with frequency for the series element, the piezo-electric crystal PE in shunt with the inductance L_1, and the reference character x_2 designates the reactance variation with frequency for the shunt element, the series resonant circuit comprising the inductance L_2 and the condenser C. This electrical wave filter is of the high-and-low pass class, freely transmitting currents of frequencies outside of the frequencies f_1 and f_2, while substantially suppressing all frequencies within these limits. At the frequencies f_1 and f_2, the ratio of the series reactance magnitude to the shunt reactance magnitude equals -4, so that currents of these frequencies are freely transmitted by the structure. At frequencies outside of the limits f_1 and f_2, the ratio of the series reactance magnitude to the shunt reactance magnitude lies between zero and -4, the range of free transmission of a filter structure, so that all frequencies outside of the limits f_1 and f_2 are freely transmitted by the arrangement. At frequencies between the limits f_1 and f_2, the ratio of the series reactance magnitude to the shunt reactance magnitude does not lie within the values accepted for free transmission, and accordingly all frequencies within these limits are effectively attenuated.

Fig. 12 represents another piezo-electric filter structure comprising a number of sections, each of which has a condenser C as a series element and a piezo-electric crystal PE as a shunt element. Curves x_1 and x_2 show the variations in the reactance magnitude of the condenser C and of piezo-electric crystal PE, respectively, with variations in frequency. In a structure such as Fig. 12, all frequencies between definite limits f_1 and f_2 will be freely transmitted, while all frequencies outside of these limits will be effectively attenuated. At the cut-off points f_1 and f_2, the ratio of the series reactance magnitude to the shunt reactance magnitude again equals -4, so that currents of these frequencies are freely transmitted by the system. At frequencies between these cut-off points, the ratio of series to shunt reactance magnitudes lies within the limits accepted for free transmission, and therefore, currents of frequencies within these limits are freely passed by the structure. At the resonant frequency at which the shunt reactance becomes zero, there is infinite attenuation in the arrangement.

By assigning suitable values to the elements employed in the various filter structures shown in the drawing, a system can be provided which will transmit from an input circuit to an output circuit sinusoidal currents having frequencies lying within a preassigned range or ranges, while at the same time effectively suppressing the transmission of currents of other frequencies lying outside of the preassigned range or ranges.

It will be understood that suitable impedance elements may be added to the filter structures to bring about any desirable transmission characteristics for these structures, the values of these additional elements being determined from convenience of design or may be made to satisfy some specified requirements, such as, for example, that the system shall have a definite and predetermined impedance at some certain frequency.

It will be further evident that while the filter structures shown in the drawing are either of the band pass or of the low-and-high pass classes, any desired high-pass or low-pass filter for a given frequency range or other circuit network may be designed, if the principles of this invention are properly carried out.

It will be obvious that where a plurality of piezo-electric elements are required, which shall have vibratory periods different from their natural periods, variations may be made in the elements associated with the piezo-electric crystals such, for example, as variations in the size of the gap existing between one or both of the metallic electrodes and the surfaces of the piezo-electric crystal, within the scope of this invention.

It will also be understood that the number of sections required for a particular wave filter will depend upon the degree to which it is desired to extinguish the currents to be filtered out. If the number of sections is increased, the ratio of the magnitude of the current of any particular frequency entering the filter to the magnitude of the current of that frequency leaving the filter will be greatly increased.

While this invention has been shown in certain particular embodiments merely for the purpose of illustration, it is to be distinctly understood that the principles of this invention may be applied to other and widely varied organizations without departing from the spirit and nature of the invention and the scope of the appended claims.

What is claimed is:

1. An electrical wave filter having a sharpened cut-off, comprising a piezo-electric element, and means co-operating therewith to render its attenuation characteristic very steep near its critical frequency and to render its transmission characteristic very flat throughout a plurality of frequencies.

2. An electrical wave filter having recur-

rent sections, comprising piezo-electric means to give it a steep attenuation characteristic and a flat transmission characteristic.

3. An electrical wave filter having a steep attenuation characteristic and a flat transmission characteristic, comprising a plurality of recurrent sections, each section including substantially equal piezo-electric structures of suitable impedances.

4. An electrical wave filter having a very sharp attenuation characteristic and a very flat transmission characteristic, comprising a plurality of similar recurrent sections in each of which there is a piezo-electric structure, said piezo-electric structures being substantially similar and of substantially the same impedances.

5. In combination, an input circuit, an output circuit, and an electrical band-pass filter interconnecting said input and output circuits, said electrical band-pass filter including a plurality of sections, each section comprising a reactive net work and a piezo-electric structure, the piezo-electric structure of each section acting to steepen the attenuation characteristic adjacent to the critical frequency of the band-pass filter.

6. In combination, an input circuit, an output circuit, and an electrical network interconnecting said input and said output circuits involving a plurality of piezo-electric elements and a plurality of reactive elements, one associated with each piezo-electric element, said net work flattening the transmission characteristic throughout a band occupying a definite portion of the frequency spectrum.

7. An electrical wave filter comprising a plurality of similar recurrent sections, all sections having similar piezo-electric devices of substantially equal vibratory periods and corresponding reactance elements for bringing the series portion of each section into a definite impedance relation to the shunt portion of each section.

8. An electrical wave filter comprising a plurality of sections each having a series element and a shunt element, a plurality of piezo-electric structures, and means to co-operate with said piezo-electric structures to bring about a predetermined impedance relationship between each series element and the corresponding shunt element.

9. An electrical wave filter comprising a plurality of recurrent sections, and a plurality of synchronous piezo-electric devices in said sections, each section having a series element and a shunt element, each series element bearing a definite and predetermined relation to each shunt element.

10. An electrical band-pass filter comprising a plurality of piezo-electric devices connected in tandem, and means whereby all of said piezo-electric devices may be rendered vibratory in response to currents impressed thereon having any of the frequencies within the limits of the band.

11. An electrical structure capable of freely transmitting currents of all frequencies lying within well defined limits of the frequency spectrum, including a plurality of substantially similar piezo-electric elements connected in tandem and operating in synchronism.

12. An electrical band-filter capable of freely transmitting currents of all frequencies lying within well defined limits of the frequency spectrum and for greatly suppressing currents of all other frequencies, including a plurality of piezo-electric devices which have substantially the same vibratory characteristics connected in tandem and means for operating said device so that they may exhibit substantially equal impedances.

13. An electrical wave filter comprising a plurality of sections including a plurality of substantially equal series piezo-electric elements and a plurality of substantially equal shunt piezo-electric elements.

14. An electrical wave filter including a circuit having a plurality of piezo-electric elements operating in synchronism at one frequency and connected in series relationship, and a plurality of piezo-electric elements operating in synchronism at another frequency and connected in shunt alternately between the series piezo-electric elements.

15. A band filter comprising a plurality of similar sections, each section including a series element and a shunt element, the series element of each section including a piezo-electric crystal and the shunt element a reactance, the various piezo-electric crystals operating in synchronism.

In testimony whereof, I have signed my name to this specification this 31st day of December, 1926.

LLOYD ESPENSCHIED.