

Jan. 25, 1927.

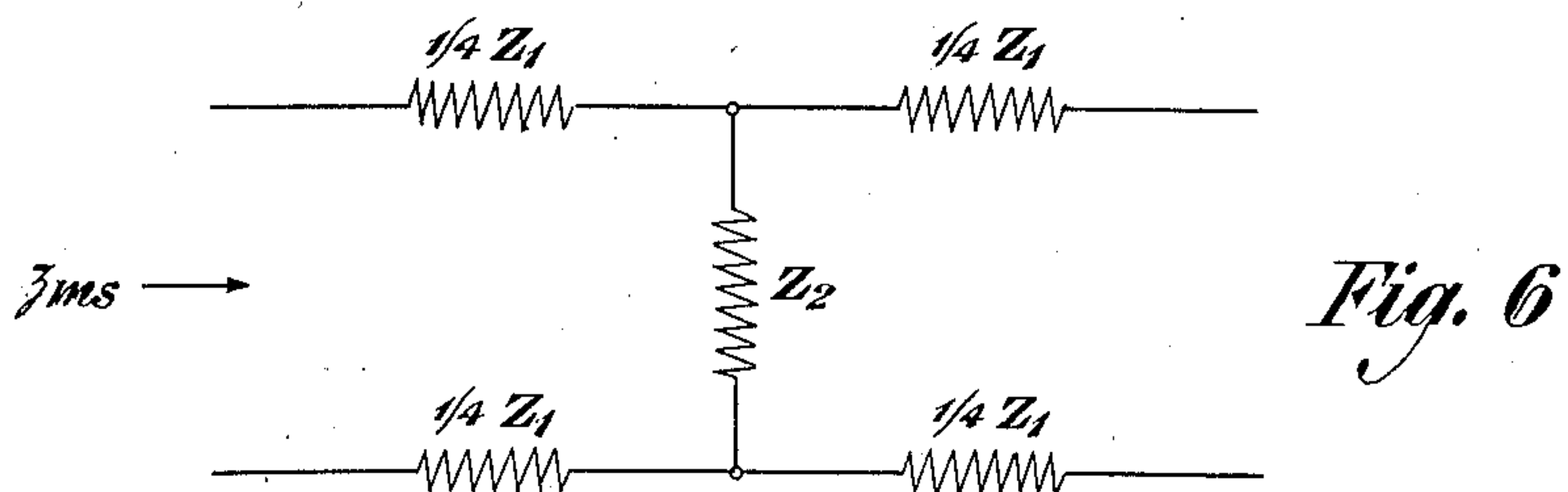
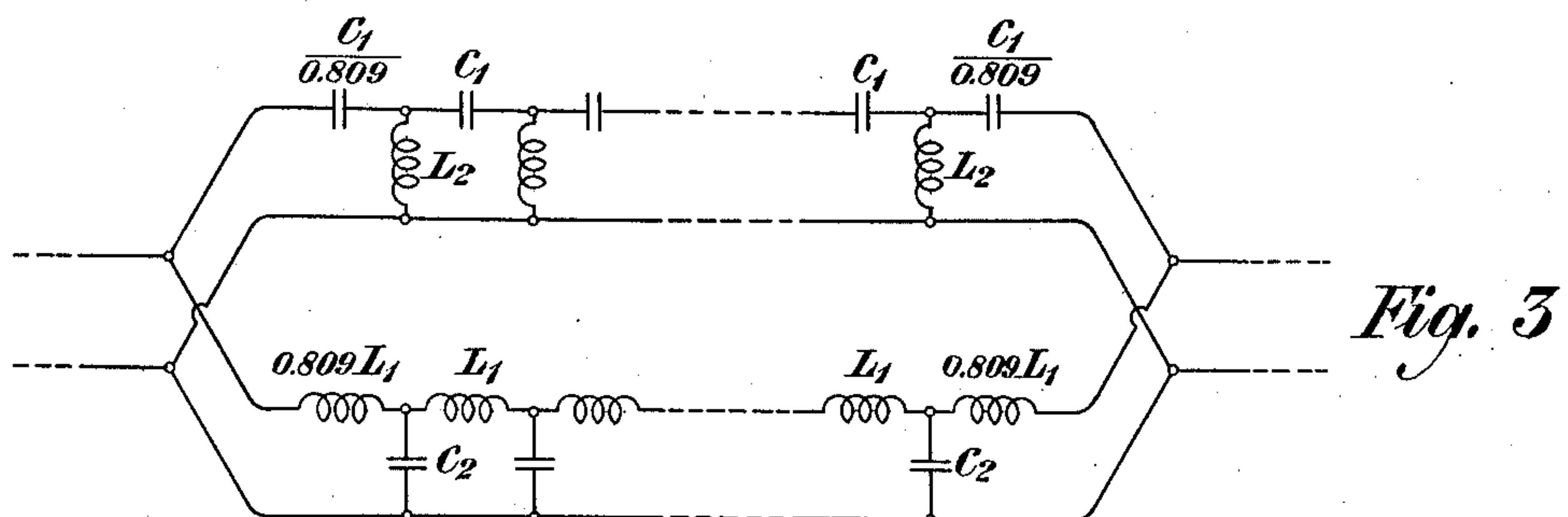
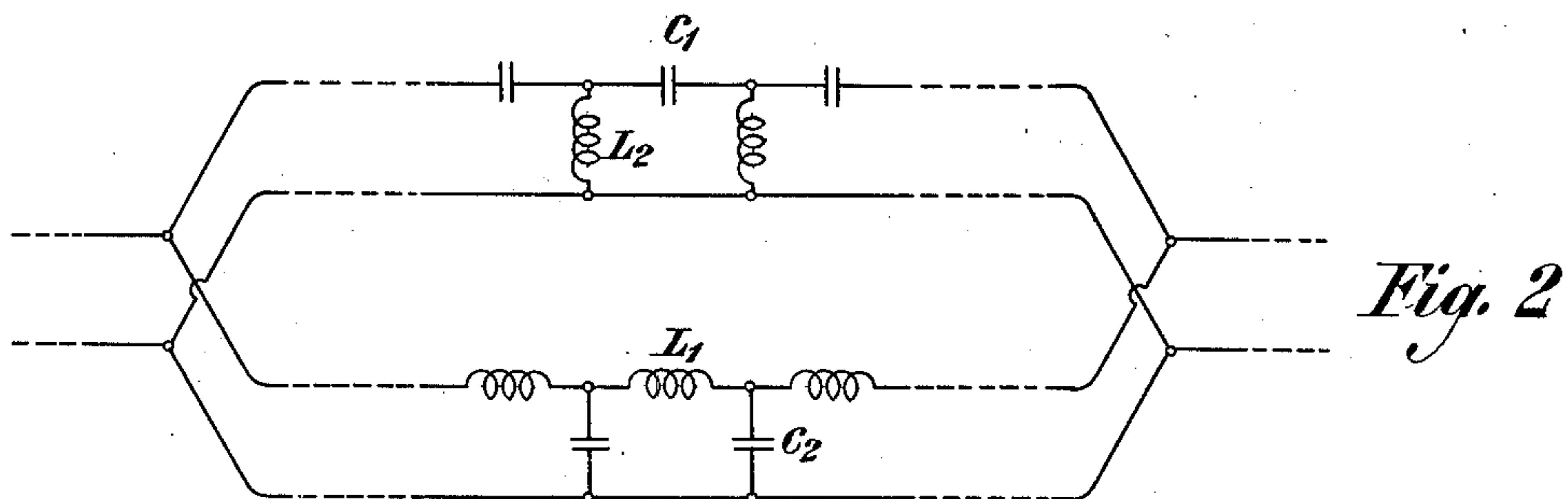
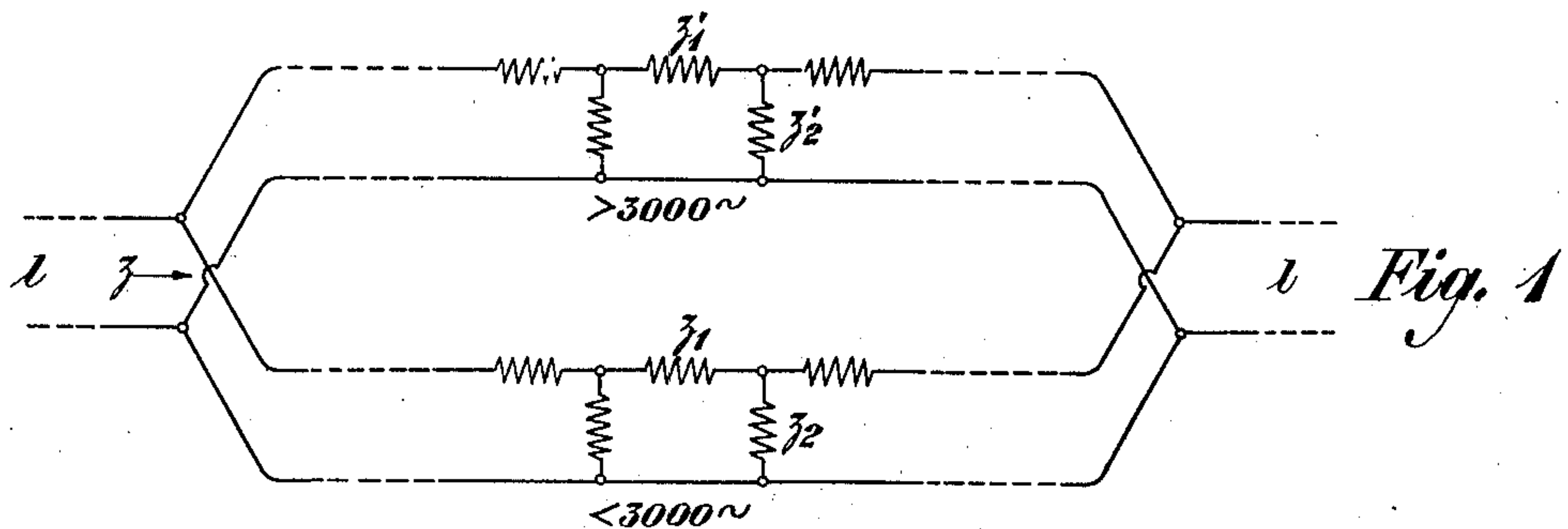
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1,615,252

ELECTRICAL WAVE FILTER

Filed June 9, 1923

3 Sheets-Sheet 1



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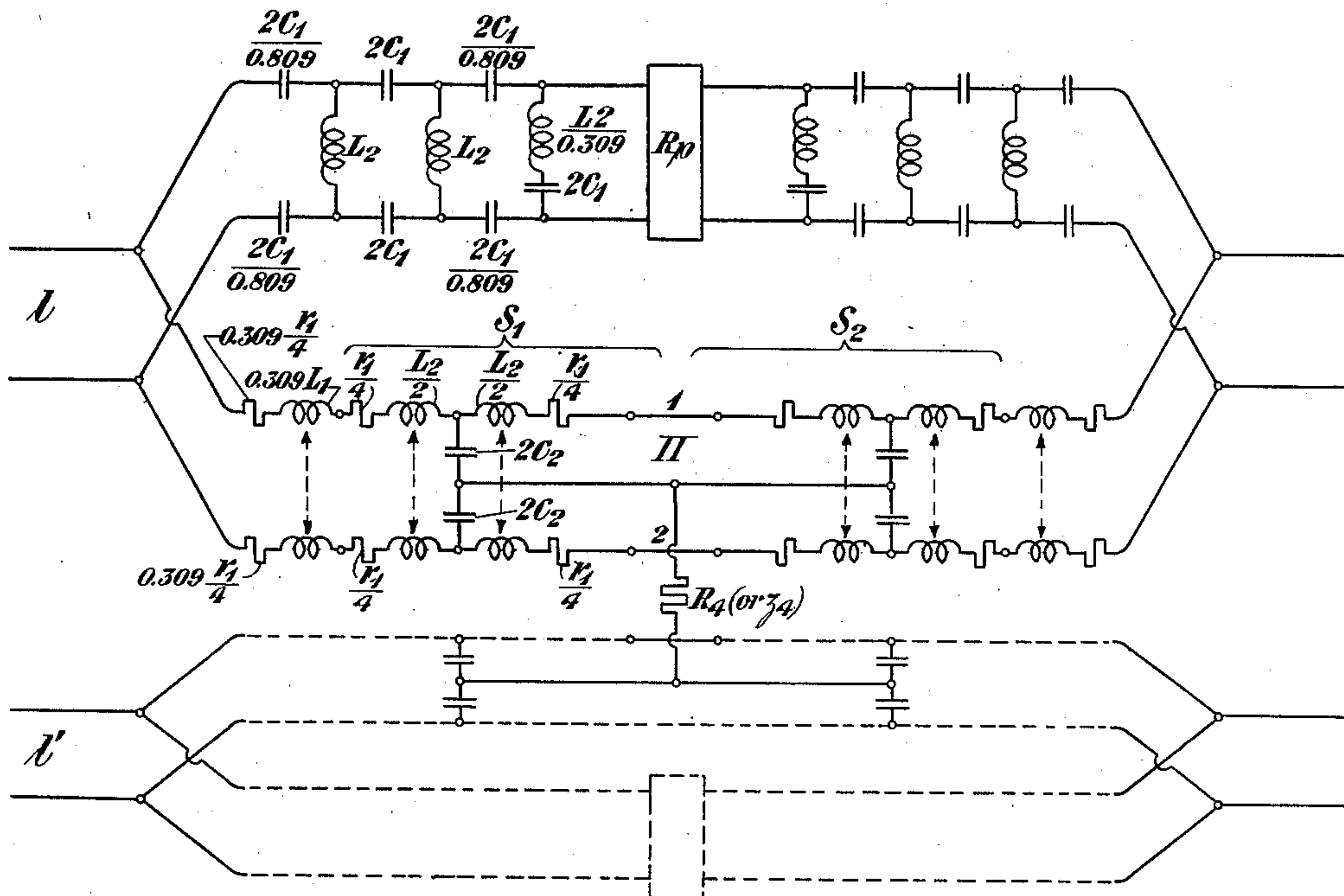


Fig. 4

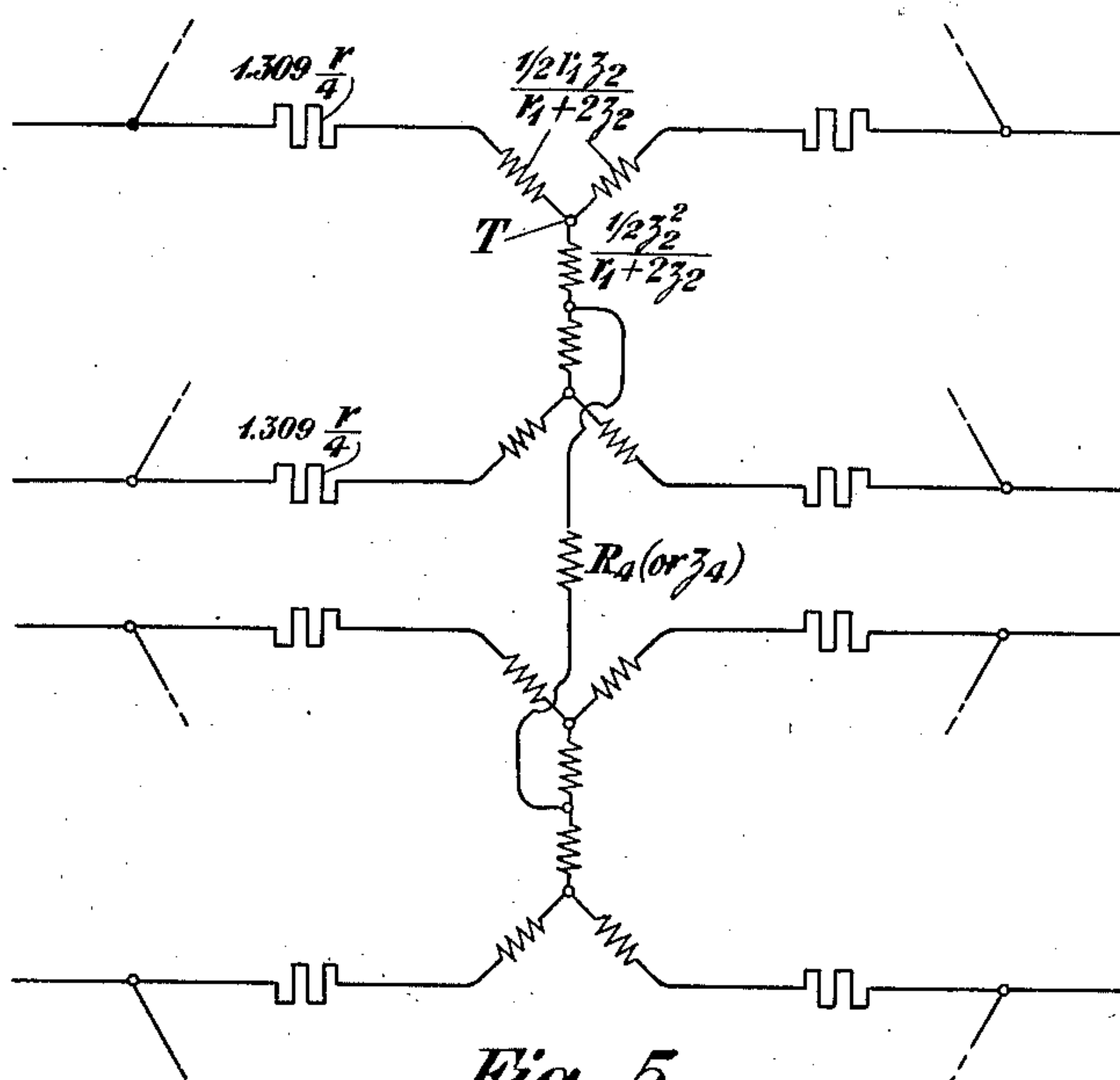


Fig. 5

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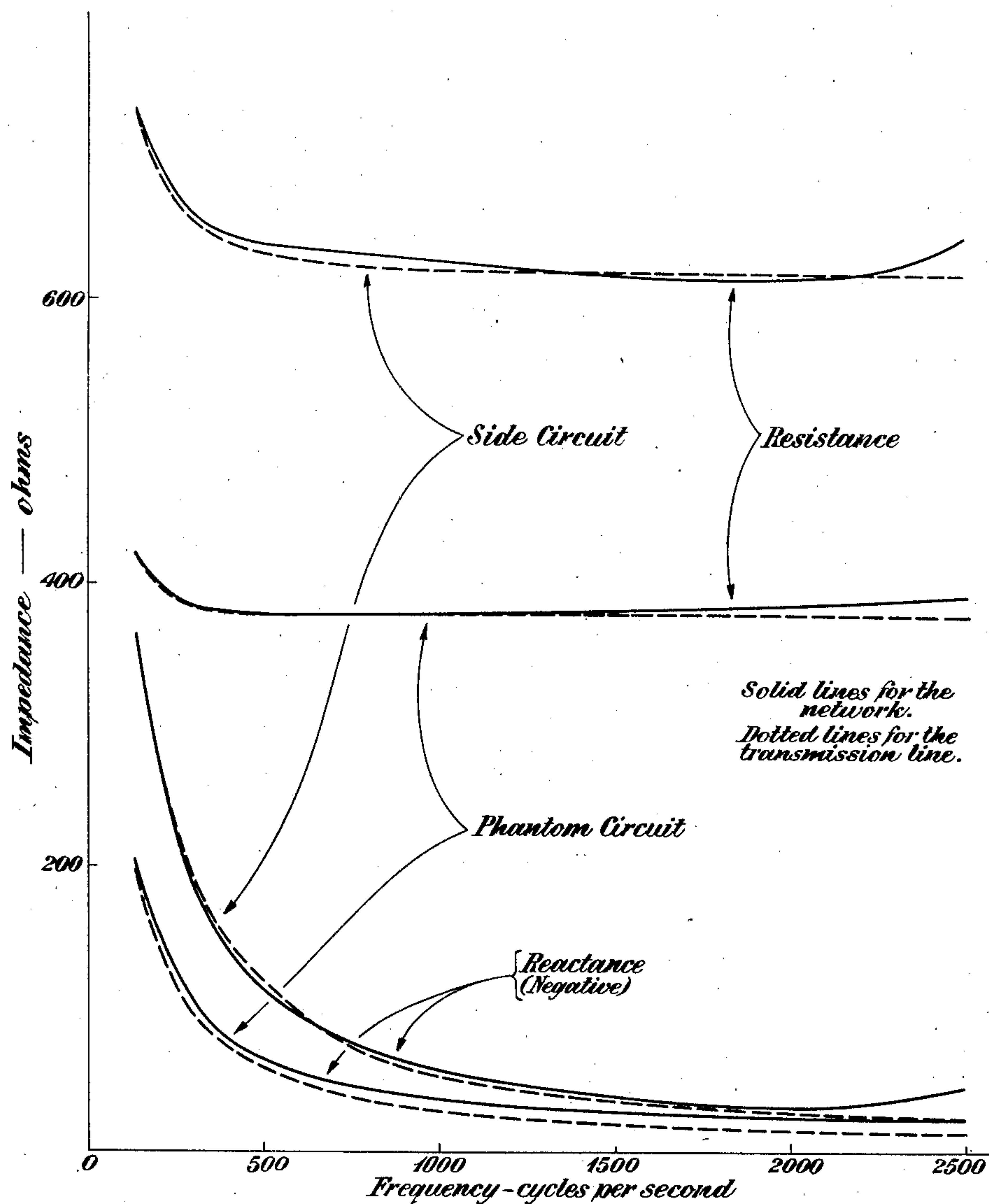


Fig. 7

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UNITED STATES PATENT OFFICE.

OTTO J. ZOBEL, OF NEW YORK, N. Y., ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

ELECTRICAL WAVE FILTER.

Application filed June 9, 1923. Serial No. 644,458.

A principal object of my invention is to provide an electrical wave-filter of the type having recurrent sections that shall simulate the impedance of a transmission line over a wide frequency range including low frequencies. Another object of my invention is to improve the characteristic impedance of a wave-filter by the introduction of resistances with its other impedance elements. Still another object of my invention is to provide a wave-filter of favorable characteristics for use in connection with phantom and side circuits. These and various other objects of my invention will be made apparent in the following specification and claims taken with the accompanying drawings, in which I have disclosed a single specific embodiment of the invention by way of illustration of the general principles involved. The following specification will relate to this particular example of the invention, leaving the invention to be defined in the appended claims.

Referring to the drawings, Figure 1 is a diagram showing a high pass filter and a low pass filter in respective parallel branches in a transmission line; Fig. 2 is a corresponding diagram showing the elements of the wave-filters more specifically; Fig. 3 is another diagram showing the terminal elements of the wave-filters; Fig. 4 is a diagram showing my invention embodied in a pair of side circuits and a phantom circuit; Figs. 5 and 6 are simplified diagrams corresponding to Fig. 4, which will be utilized in explaining the theory of Fig. 4; Fig. 7 is a diagram giving impedance-frequency characteristics for the side and phantom circuits of Fig. 4.

I will illustrate the principles involved in my invention by giving a specific example of design such as might easily arise in practical engineering work.

In an extended transmission line l , shown in Fig. 1, carrying currents of various frequencies, high and low, it is desired to provide parallel branches at a certain point, such that the high frequencies shall be transmitted through one branch and the low frequencies through the other branch. In the particular case under consideration, the critical dividing frequency is assumed to be at 3,000 cycles per second. It is well known

that high frequencies are attenuated more than low frequencies and one purpose of the separation of the currents into the two channels, as indicated, is to provide amplification by means of a "repeater" in the high pass branch.

The line l has a characteristic impedance of 620 ohms resistance at high frequency, but at 135 cycles per second its characteristic impedance is given by the complex number $720-i365$.

The general design for appropriate high pass and low pass filters is shown in Fig. 2, where the high pass filter is shown above and the low pass filter below. In accordance with well-known properties of such filters, we have the following equations, where f_c is the critical or cut-off frequency:

$$L_2 C_1 = \frac{1}{4} \left(\frac{1}{2\pi f_c} \right)^2, \quad (1)$$

$$L_1 C_2 = \left(\frac{1}{\pi f_c} \right)^2. \quad (2)$$

At high frequencies, the mid-series characteristic impedance or the mid-shunt characteristic impedance of the high pass wave-filter reduces to the expression

$$\sqrt{z'_1 z'_2},$$

where z'_1 is one of the series impedance elements and z'_2 is one of the shunt impedance elements. Accordingly we have as another equation of design

$$\sqrt{\frac{L_2}{C_1}} = 620. \quad (3)$$

The two wave-filters, one high pass and the other low pass, must be complementary to each other so that as nearly as practicable, at frequencies above or below the critical frequency, each one will be a reactance-nulling shunt for the other. The complementary relationship between the two filters requires that

$$z'_1 = 4z_2 \text{ and } z_1 = 4z'_2, \quad (4)$$

where z_1 is a series impedance element of the low pass filter and z_2 is a shunt impedance element of the low pass filter.

The foregoing equations (1), (2), (3) and (4) are sufficient to determine the capacities and inductances designated on Fig. 2

by the characters C_1 , L_2 , L_1 and C_2 . Their values work out as follows:

$$\begin{aligned} C_1 &= 0.0428 \times 10^{-6} \\ L_2 &= 16.4 \times 10^{-3} \\ L_1 &= 65.8 \times 10^{-3} \\ C_2 &= 0.1711 \times 10^{-6} \end{aligned}$$

The design of complementary wave-filters by which each becomes a reactance annulling shunt for the other at frequencies other than the critical frequency, involves so-called x -series initial termination where $x=0.809$. This means that the initial element of the wave-filter is a series element whose impedance value is 0.809 times that of the full series element. This gives the more definite showing of structure, as in Fig. 3.

The exact reactance annulling shunt for the low pass wave-filter of Fig. 1 with x -series ending, where $x=0.809$, would be

$$\frac{1}{2}z_1 + \frac{1}{0.309}z_2 \quad (5)$$

It can be shown that the complementary high pass wave-filter of Fig. 3 affords approximately such a shunt for the low pass wave-filter; indeed the x -series ending with $x=0.809$ is the optimum ending to make each wave-filter of Fig. 3 as nearly as practicable the best reactance annulling shunt for the other.

The impedance of the low pass wave-filter with x -series ending and with an ideal reactance annulling shunt is

$$z = \frac{z_1 z_2 + x(1-x)z_1^2}{\sqrt{z_1 z_2 + \frac{z_1^2}{4}}} \quad (6)$$

and in the particular case under consideration $x=0.809$. Accordingly equation (6) is an approximate expression for the impedance of the combined high pass filter and low pass filter as shown in Fig. 3, for frequencies transmitted by the low pass wave-filter.

At high frequency, the impedance of the low pass filter with x -series ending approaches infinity and the impedance of the high pass filter with x -series ending becomes substantially the same as its mid-series characteristic impedance which we have already taken as 620 ohms resistance in equation (3), the same as the high frequency impedance of the line l .

But at a frequency of 135 cycles per second, the impedance of the line l is known to be

$$z(135) = 720 - i365. \quad (7)$$

Giving to z_2 the value afforded at 135 cycles by the condenser C_2 , it works out that

$$z_2(135) = -i6880. \quad (8)$$

Applying this value in the equation ob-

tained by equating (6) and (7) and also giving to x its value 0.809, the result is obtained that

$$z_1(135) = 76.08 + i56.63. \quad (9)$$

The reactance expressed by the last term of the foregoing equation is almost exactly the same as the reactance of the inductance L_1 when it has the value obtained heretofore, namely 65.8×10^{-3} . Accordingly we see that having matched the impedance of the line l at high frequency, in order further to match it at 135 cycles per second, it needs only to put in series with each inductance L_1 the resistance

$$R_1 = 76.08 \text{ ohms.} \quad (10)$$

The addition of this resistance in the series elements of the low pass wave-filter will not affect the impedance at high frequency because then the impedance of the low pass filter approaches infinity in any case.

In Fig. 4, l and l' represent two side circuits comprised in a phantom circuit and it is desired first to provide high pass and low pass branches in each side circuit in accordance with the foregoing development and further to make whatever modification may be necessary to guard against reflection effects in the phantom circuit. We shall first give attention to the specific design of the side circuit l .

The repeater R_p is interposed in the high pass branch and on each side of it there is a high pass wave-filter consisting of two complete mid-series sections each with its terminal series impedance extended enough to give the 0.809-series ending. With this ending, the low pass filter gives approximately the proper reactance annulling shunt at the end of each high pass filter distant from the repeater R_p ; adjacent to the repeater R_p the more exact reactance annulling shunt is provided with the elements designated

$$\frac{L_2}{0.309} \text{ and } 2C_1 \text{ in series.}$$

The series impedance elements in Figs. 1, 2 and 3 have been shown on only one side of the line, but for line balance they should be disposed equally on the two sides of the line and this has been done throughout in Fig. 4. For example, two condensers in Fig. 4 each of capacity value $2C_1$ are equivalent to the single condenser C_1 in Fig. 3.

The low pass wave-filter is made with two complete mid-series sections designated S_1 and S_2 . The junction points 1 and 2 between these sections are midpoints of the low pass filter at which it can be opened, if that should be desired, for testing purposes or at which testing apparatus can be bridged across. The series inductance windings are on the same core and this is intended to be

indicated by the dotted lines connecting the adjacent arrowheads. In this way the inductance per turn is increased and, furthermore, as will be mentioned presently, the windings give zero inductance in the phantom circuit. The legends on the low pass filter giving the inductance of the series windings apply to the two opposite windings taken together. Thus $\frac{L_1}{2}$ means the inductance of the two windings in the side circuit.

In accordance with the principles that have already been stated, each end series impedance element has been adjusted so as to give 0.809-series ending and, as already explained, with this ending, the high pass wave-filter gives approximately the correct reactance annulling shunt.

Some resistance will inevitably be encountered in the inductance windings, and the computed value for the resistance R_1 , namely 76.08 ohms, includes such resistance in the inductance windings. This will generally be a small fraction, only a few per cent, but it will be understood that the resistances indicated in the series elements of the low pass filter in Fig. 4 reside principally in the resistance windings at those points and in small part in the inductance windings adjacent thereto.

Referring to Fig. 3, it will be seen that if each series inductance in the low pass filter were made to comprise equal windings on both sides of the line, each pair of equal windings on the same core, then if the line through the low pass filter be regarded as one side of a phantom circuit, these windings will offer no impedance, and low frequency currents on the phantom circuit will go through the low pass filter without meeting any impedance whatever. But the introduction of series resistances as shown in Fig. 4 puts resistance in each side of the phantom circuit even though the inductance windings can be ignored.

To arrive at a suitable modification to make correction in the phantom circuit for the resistances introduced in the low pass filter in Fig. 4, let each shunt condenser C_2 of Fig. 3 be represented by two condensers in series, each of value $2C_2$ as in Fig. 4. Let the points between these condensers be connected as shown in Fig. 4 with an unknown impedance at the element designated R_4 , which unknown impedance we will designate z_4 , for the present.

A convenient first step in arriving at a proper value for z_4 will be to replace the Π section, forming the mesh in which the character Π is placed, by an equivalent T section. This has been done in Fig. 5, in which also the high pass wave-filters have been omitted because of the high impedance of these branches at the low frequency of

135 cycles per second, in which we are at present interested; also the inductances of the low pass filter have been omitted because of no account on the phantom circuit. Each leg of the Π section in Fig. 4 is $2C_2$. Let the corresponding impedance be

$$\frac{1}{2}z_2.$$

With this understanding, the elements of the corresponding T section shown in Fig. 5 can easily be worked out to get the values given by the legends on the drawings.

Fig. 5 shows the two sides of the phantom circuit with a bridge across comprising the unknown impedance z_4 . In the ideal recurrent network of which this makes a mid-series phantom section, let a complete series element be Z_1 and let a complete shunt element be Z_2 , where Z_1 and Z_2 are as yet undetermined quantities. A comparison of Fig. 6 with Fig. 5 will make this apparent. By means of the values given in connection with Fig. 5, the following determinations are reached:

$$Z_1 = r_1 \left(0.809 + \frac{z_2}{r_1 + 2z_2} \right) \quad (11)$$

$$Z_2 = \frac{0.5z_2^2}{r_1 + 2z_2} + z_4 \quad (12)$$

Solving equation (12) and making use of the known formula for the mid-series characteristic impedance, namely

$$Z_{ms}^2 = Z_1 Z_2 + \frac{1}{4} Z_1^2, \quad (13)$$

we get

$$z_4 = \frac{Z_{ms}^2}{Z_1} - \frac{1}{4} (0.809r_1 + z_2) \quad (14)$$

Using the data of Fig. 7 and the formula of equation (14) for various frequencies from 135 to 2500 cycles per second gives z_4 a resistance component decreasing only slightly with frequency and approximately equal to 1340 ohms. This computation also gives z_4 a fairly constant and rather small positive reactance component which can be well enough neglected. It appears, therefore, that z_4 will be sufficiently well represented by a constant resistance.

$$z_4 = R_4 = 1340 \text{ ohms.} \quad (15)$$

Referring to Fig. 7, the components of the characteristic impedance of the phantom circuit are shown by the dotted lines and the impedance Z_{ms} is shown by the full lines. The close agreement shows that the value for z_4 obtained above, namely 1340 ohms, gives a very satisfactory simulation at the filters for the characteristic impedance of the phantom line over a suitable range of frequencies.

The introduction of the series resistances

in the lower pass filter and the further introduction of the shunt resistance R_4 which was entailed thereby, lead to a moderate amount of attenuation at the filters in the phantom circuit but the magnitude of this

I claim:

1. An electrical wave filter of the type having recurrent sections and in combination therewith apparatus to which the impedance of the wave filter is to be made to conform, each section of the wave filter having series and shunt reactance elements and each section also having added resistance elements.

2. An electrical wave filter of the type having recurrent sections and in combination therewith an extended transmission line, each section of the filter having series and shunt reactance elements and each section having added resistance elements whereby the impedance of the filter is matched to that of the said line over a wide frequency range.

3. A low pass electrical wave filter of the type having recurrent sections and in combination therewith an extended transmission line, each section of said filter having added resistance elements whereby the said line has its impedance matched to that of the filter at low frequencies.

4. In combination, a transmission line, high pass and low pass filters connected therewith, and resistance elements introduced in series in the low pass filter to match the

impedance of the two filters together to the line at low frequencies.

5. In combination, two transmission lines constituting two side circuits and a phantom circuit, a high pass and a low pass filter in each side circuit, and resistances associated with the two low pass filters to equalize the impedance looking into the filters from the line to the impedance looking into the line from the filters, both for the side circuits and the phantom circuit.

6. In combination, a line, a high pass filter and a low pass filter in parallel in said line, a repeater associated with said high pass filter, and said low pass filter comprising resistance elements in series.

7. In combination, two lines, a high pass filter and a low pass filter in parallel in each line, a repeater associated with each high pass filter, resistances in series in each low pass filter, and a cross-conductor comprising a resistance connecting central points of the low pass filters.

8. In combination, a line, a high pass filter and a low pass filter in parallel in said line and each having a terminal impedance value complementary to the other, said low pass filter also comprising resistance elements in series.

In testimony whereof, I have signed my name to this specification this 6th day of June, 1923.

OTTO J. ZOBEL.