

Oct. 15, 1935.

F. A. COWAN

2,017,180

COMMUNICATION AMPLIFIER WITH FEED-BACK

Filed Sept. 20, 1933

2 Sheets-Sheet 1

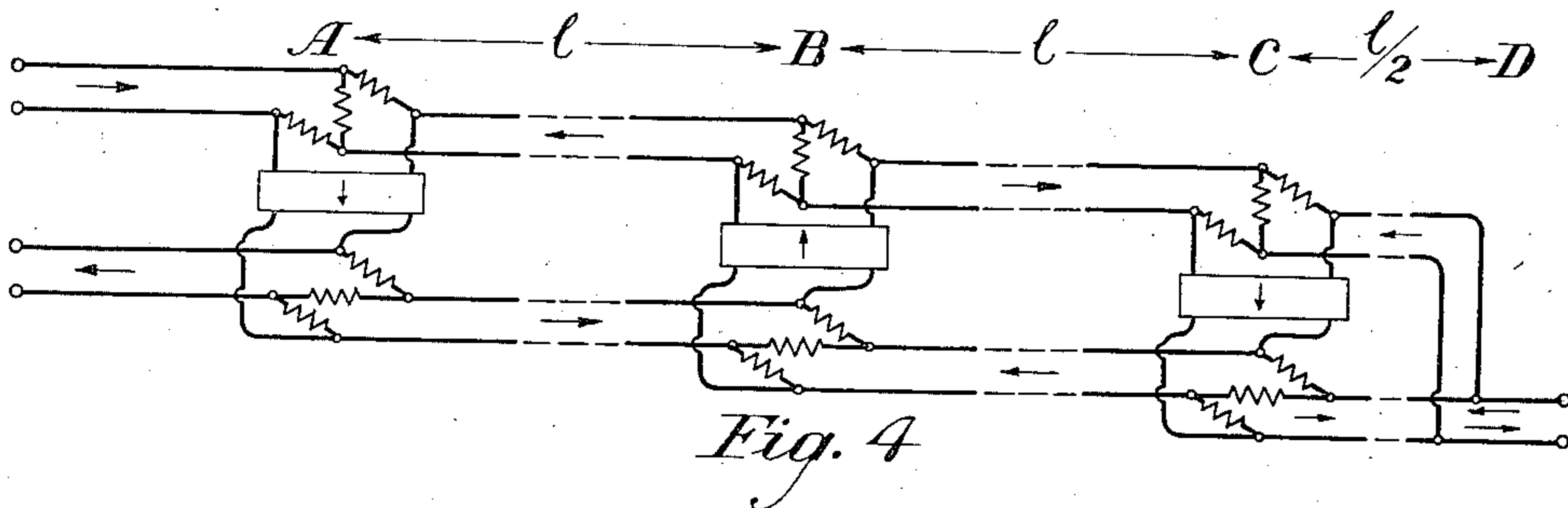
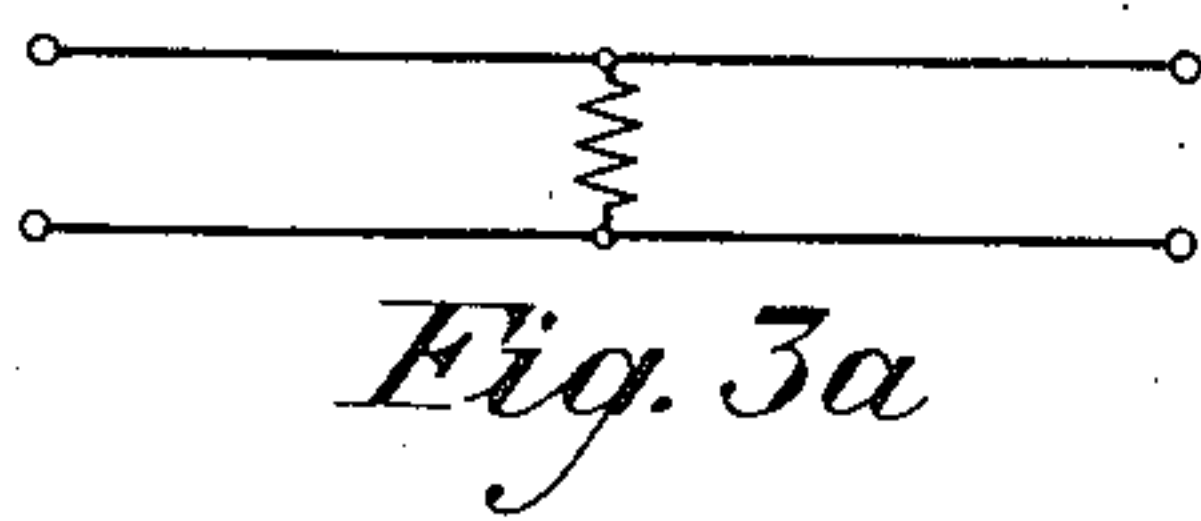
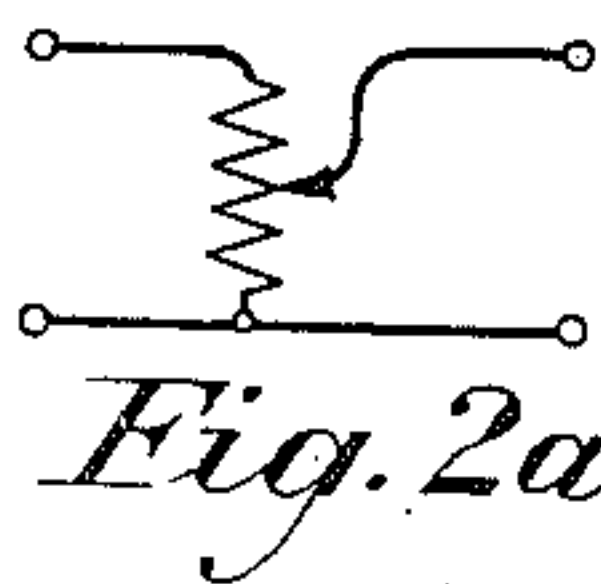
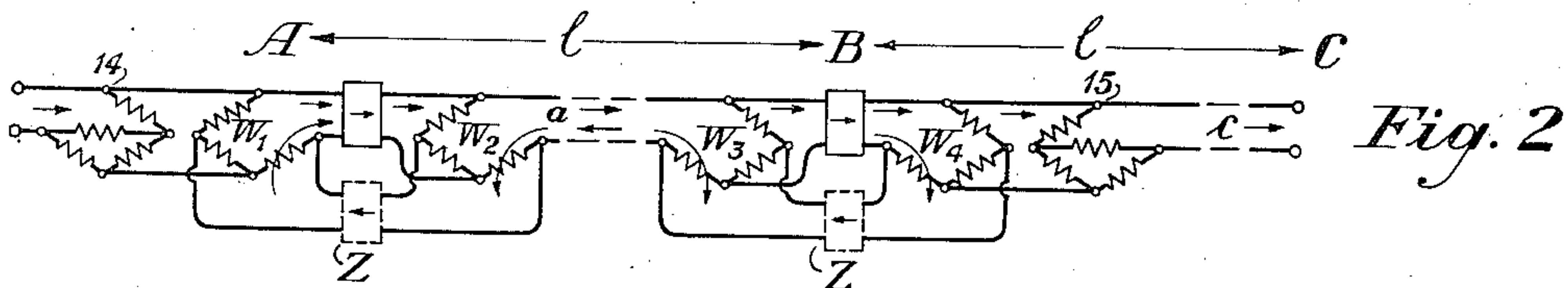
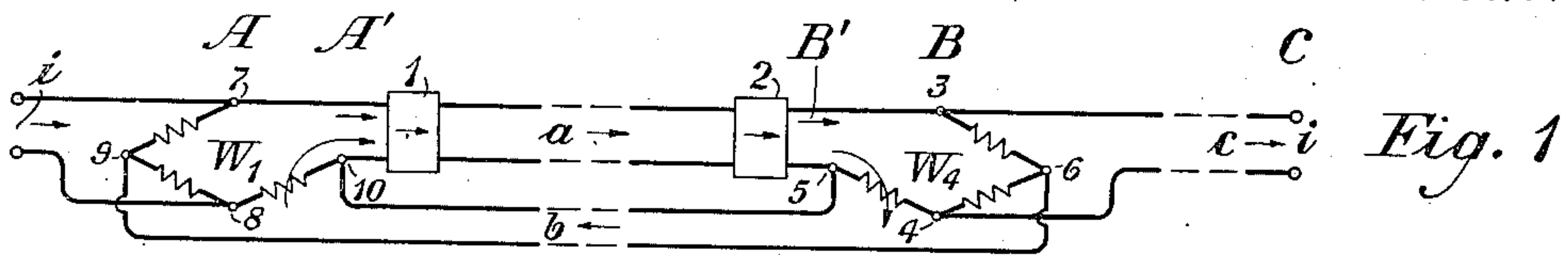
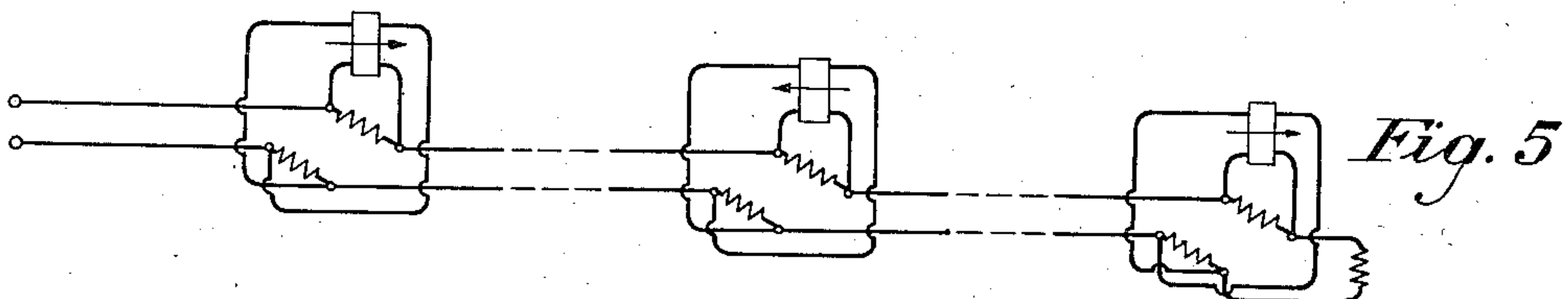
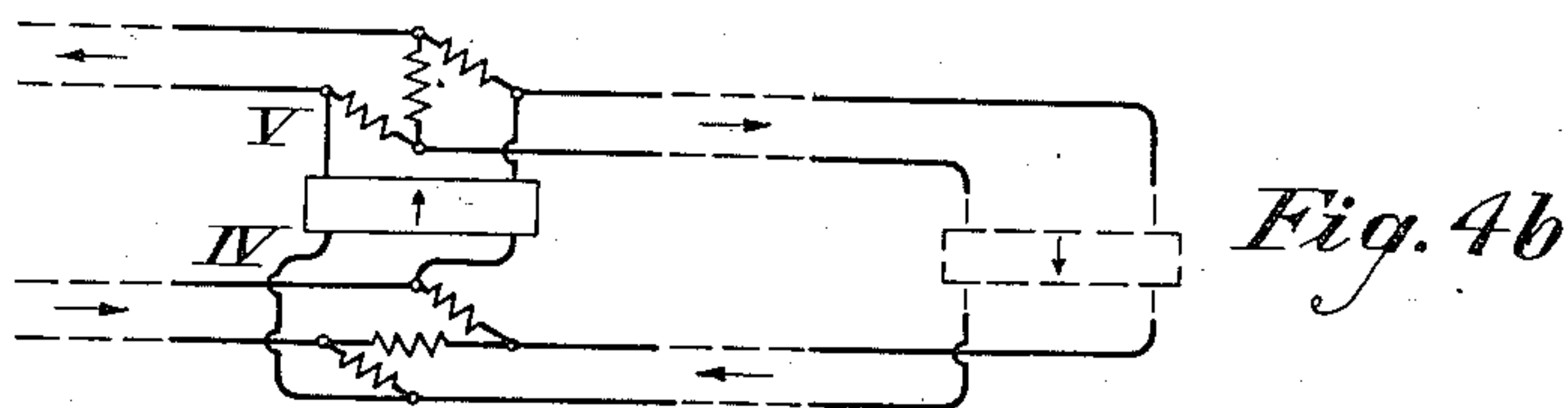
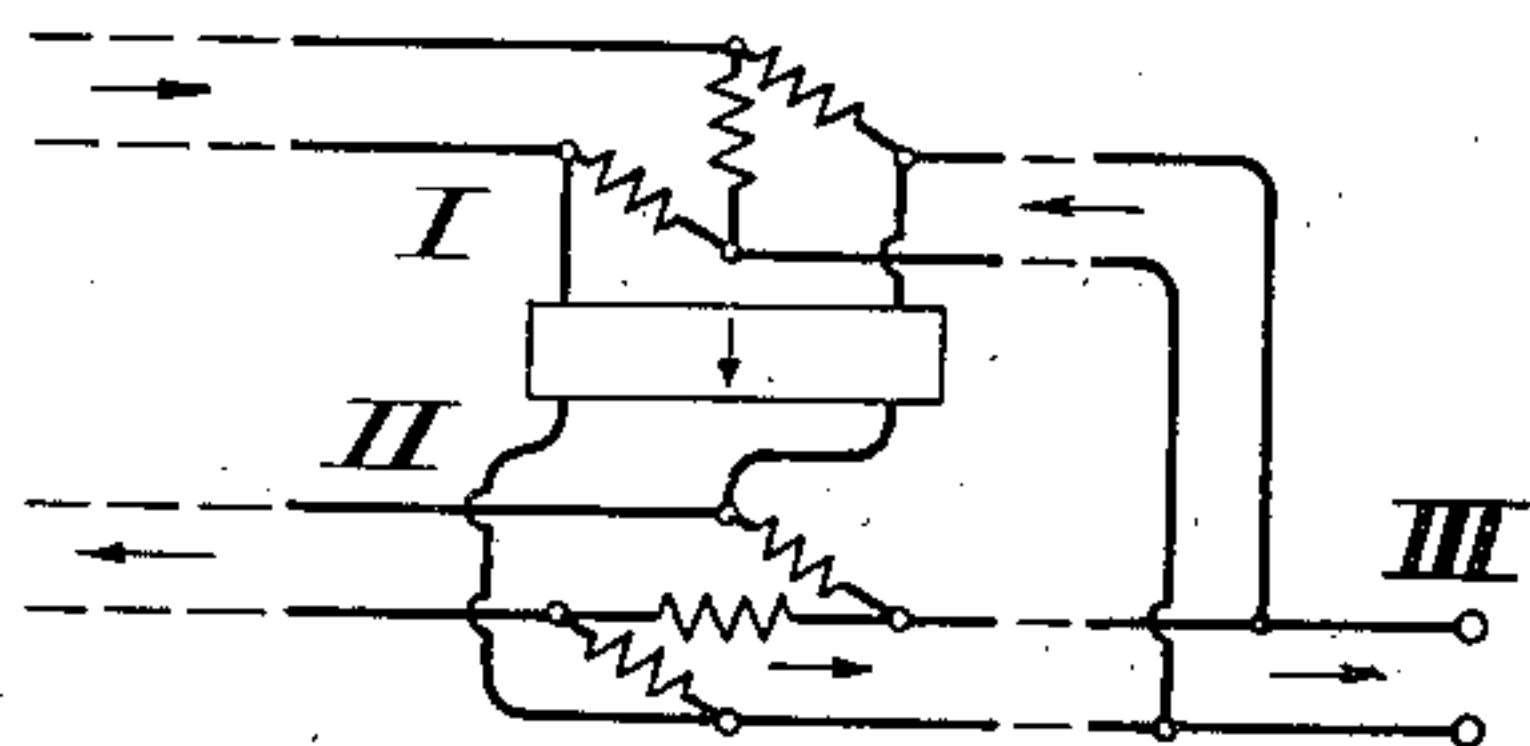


Fig. 4a



INVENTOR  
F. A. Cowan  
BY  
g. f. o. r. c.  
ATTORNEY



Oct. 15, 1935.

F. A. COWAN

2,017,180

COMMUNICATION AMPLIFIER WITH FEED-BACK

Filed Sept. 20, 1933

2 Sheets-Sheet 2

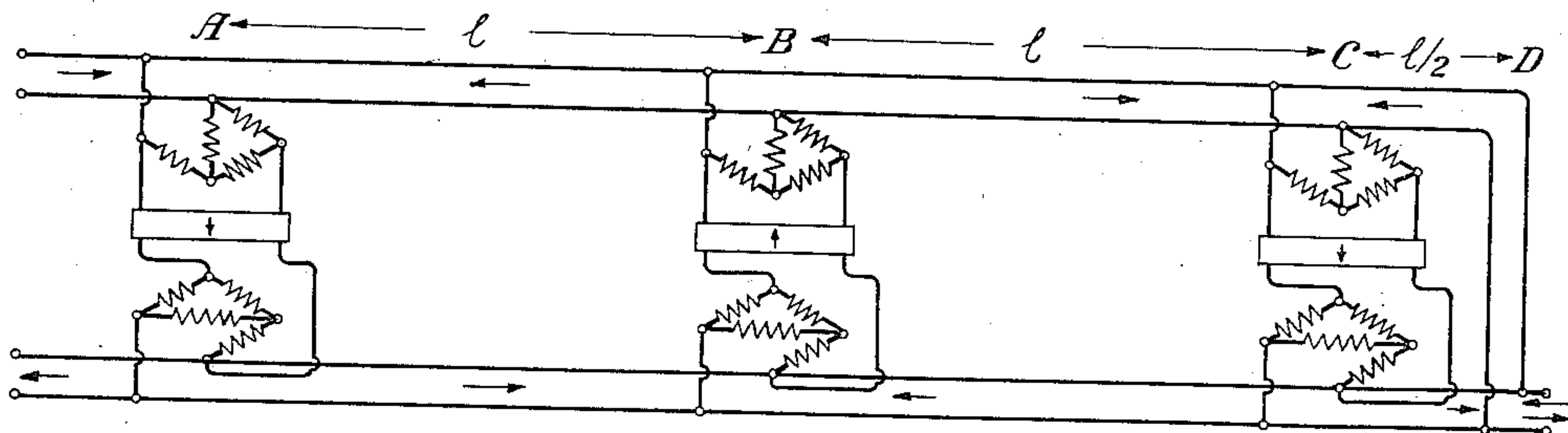


Fig. 6

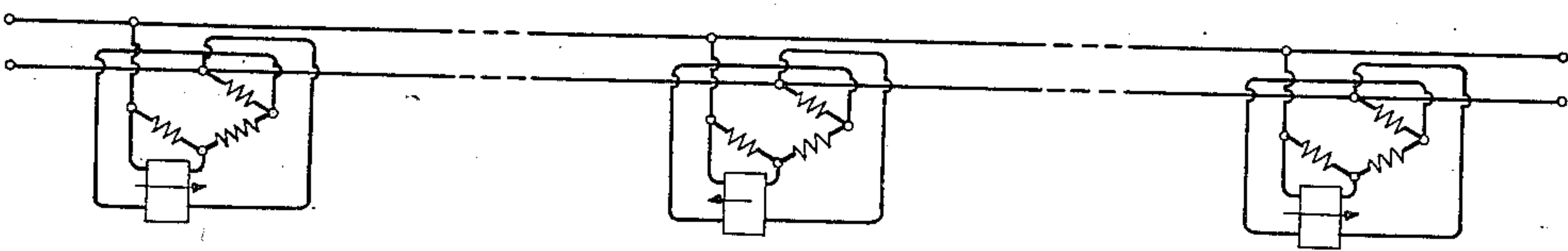


Fig. 7

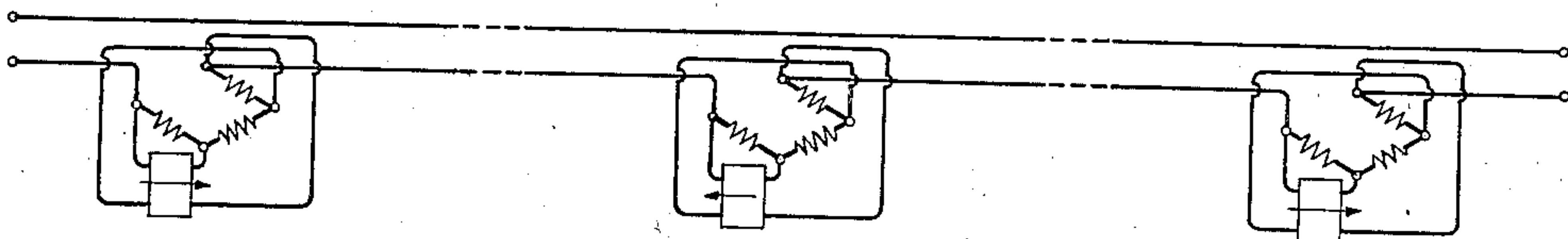


Fig. 8

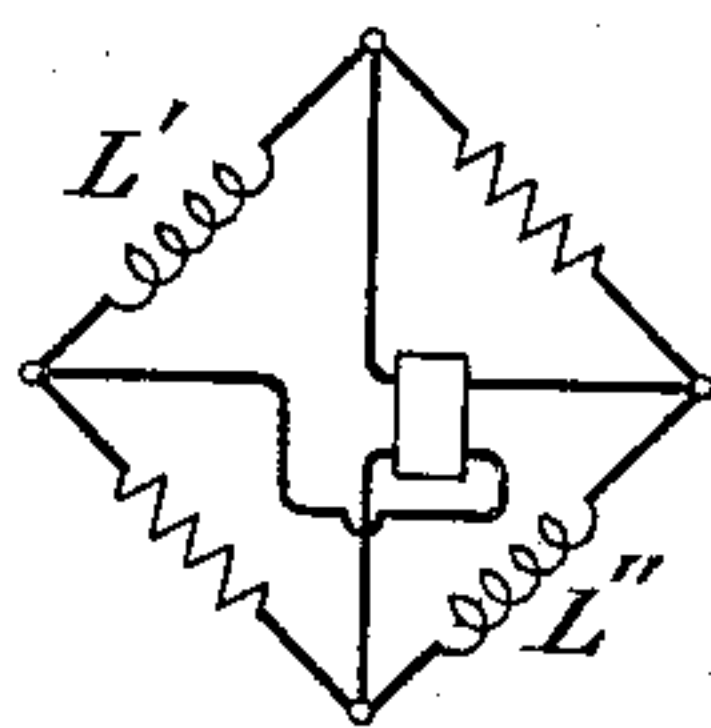


Fig. 5a

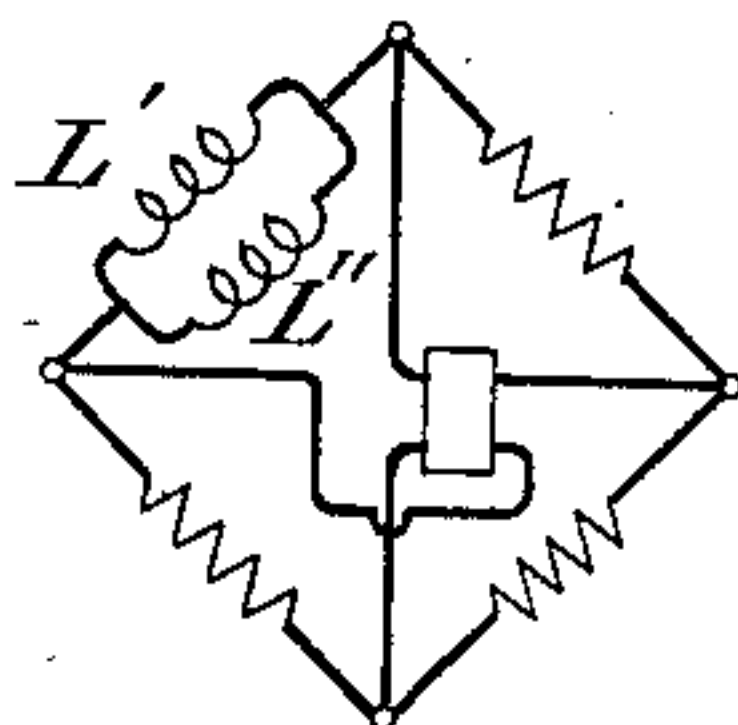


Fig. 7a

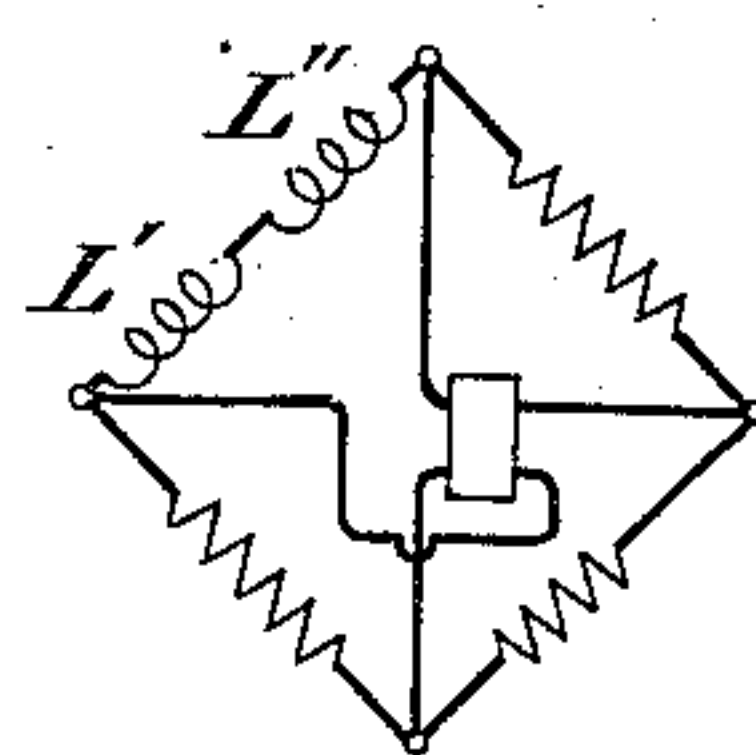


Fig. 8a

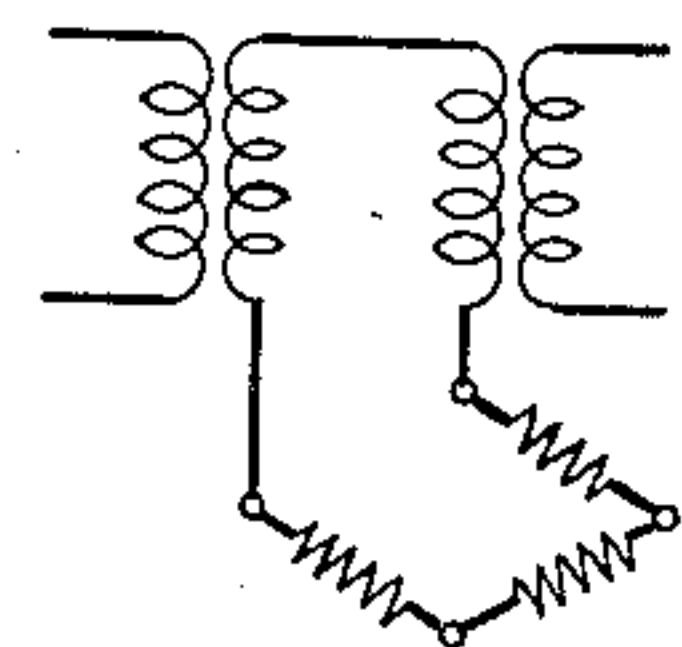


Fig. 8b

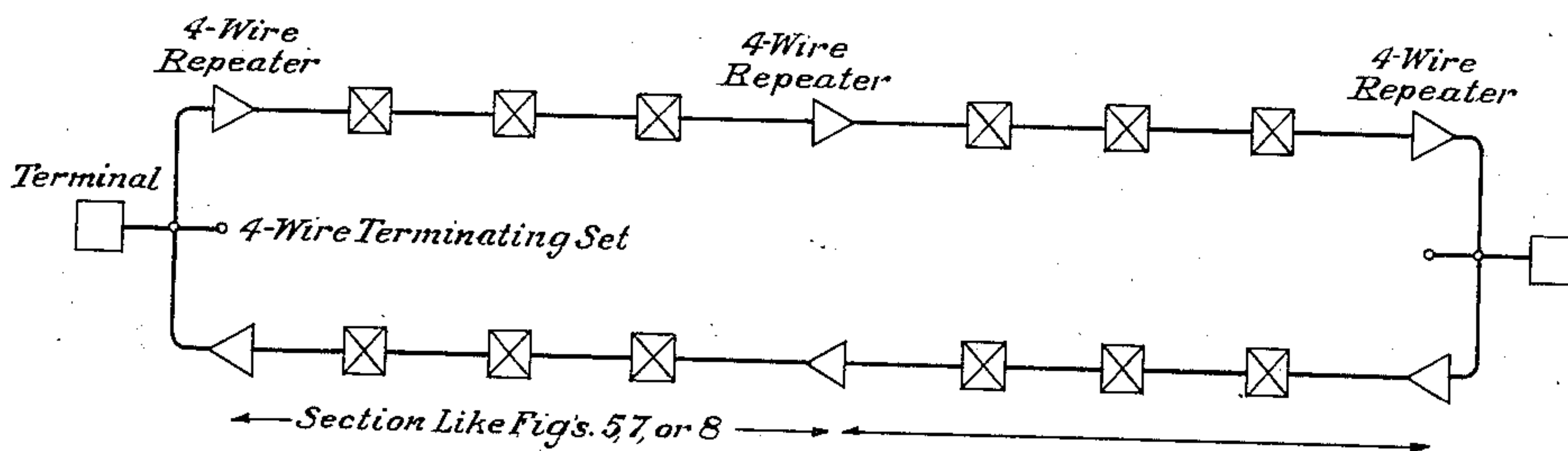


Fig. 9

INVENTOR  
F. A. Cowan  
BY *grator*  
ATTORNEY



## UNITED STATES PATENT OFFICE

2,017,180

COMMUNICATION AMPLIFIER WITH  
FEED-BACK

Frank A. Cowan, East Orange, N. J., assignor to  
American Telephone and Telegraph Company,  
a corporation of New York

Application September 20, 1933, Serial No. 690,283

16 Claims. (Cl. 178—44)

This invention relates to communication amplifier circuits with feedback and, more particularly, to long transmission lines in which a plurality of repeaters or amplifiers are used with feedback connections to each. The invention is an improvement in the use of amplifiers with feedback circuits, as disclosed in the application of Black, Serial No. 635,525, filed September 30, 1932.

Whereas, in that application transmission lines with repeaters are shown in which a pair of wires is used to feed back from one repeater to a previous repeater for the purpose of equalization and regulation, in this invention the primary purpose is to secure such suitable equalization and regulation by the use of feed-back without the necessity of employing separate pairs in the transmission and feedback paths.

The invention will be better understood by reference to the following specification and the accompanying drawings, in which Figure 1 shows a simple form of one of the Black circuits; Fig. 2 is one form of circuit embodying my invention and representing an extension of the Black circuit; Fig. 2a is a diagram of an alternative form of attenuator; Figs. 3a and 3b represent ways of obtaining line reflections for purposes hereinafter described; Fig. 4 is an extension of the circuit of Fig. 2 and is introduced for explanatory purposes; Figs. 4a and 4b are portions of the circuit of Fig. 4; Fig. 5 represents a consolidated circuit derived from Fig. 4; Fig. 6 is another explanatory circuit and 7 is derived therefrom; Fig. 8 is a modification of Fig. 7 and Fig. 8b shows a detail arrangement for application with the circuit of Fig. 8; Fig. 9 shows the invention as applied to a very long transmission line in which echo effects would ordinarily be excessive, and Figs. 5a, 7a and 8a are diagrammatic showings of Figs. 5, 7 and 8.

Referring more particularly to Fig. 1, there is shown a transmission line extending from A to C made up of two sections each of length  $l$  to be followed and preceded by similar sections. At A there is installed an amplifier 1, and at B there is an amplifier 2. In accordance with certain principles set forth in the Black application, it is desirable to have a feedback circuit from the output of the amplifier 2 to the input of amplifier 1, such feedback being obtained through a second pair of wires  $b$  which pair may be adjacent to the first pair  $a$ , as, for example, in the same cable. As pointed out in the Black application, it is desirable to maintain conjugate relationships between the feedback path  $b$  on the

one hand, and the input circuit  $i$  and the output circuit  $c$  on the other hand. Black points out that this may be obtained by means of a Wheatstone bridge arrangement after the amplifier 2 and a similar bridge in front of the amplifier 1, the bridge being normally balanced so that the points 3, 4 are conjugate with respect to the points 5, 6 and the points 7, 8 are conjugate with respect to the points 9, 10. It will be observed that the incoming line  $i$  in front of the amplifier 1 is conjugate with respect to the feedback circuit  $b$ . Also, that this feedback circuit  $b$  is conjugate with respect to the outgoing or load circuit  $c$ .

It has been shown by Black that in any such feedback circuit as the above, the voltage generated in the output of the amplifier 2 is given by

$$V = \frac{\mu}{1 - \mu\beta} V_1$$

where  $V_1$  would be the voltage at the input of the amplifier 1 from the incoming line.  $\mu$  is the over-all amplification factor of the amplifier circuits and path  $a$  taken in tandem from the input of amplifier 1 to the output terminals of amplifier 2, and  $\beta$  is the ratio of the voltage arriving at the input of amplifier 1 by feedback to the voltage developed at the output terminals of amplifier 2, and  $\beta$  would ordinarily be less than unity. If  $\mu\beta$  is considerably greater than unity, it will be seen that the above relation approximates to

$$V = -\frac{1}{\beta} V_1$$

which means that the output voltage is substantially independent of  $\mu$  and is dependent mainly on the degree of feedback coupling from the output to the input circuit. It is convenient to express the gain of the amplifier, as well as the degree of feedback, in terms of the transmission unit called the decibel, and the expression above states that the over-all gain of the amplifier and circuit from terminals 7 and 10 to terminals 3 and 5, is numerically equal to the loss in the feedback circuit from terminals 3 and 5 to terminals 7 and 10. From the above relation it is seen that there is an increase in energy level across the points 3 and 5 as compared with the points 7 and 10, and it will be noted, with equality ratio bridges, which are assumed in this particular circuit, the transmission loss from terminals 7 and 8 to 7 and 10, is equal to the loss from terminals 9 and 10 to 7 and 10. This means that the over-all gain from 7 and 10 to 3 and 5, is greater than the loss over the path  $b$  from 3 and



4 to 7 and 8 by the amount of the bridge losses. Transmission from the input  $i$  to point C will have a net loss or gain equal to the loss in transmission of the two bridges, plus the loss in line  $c$ , minus the gain between terminals 7 and 10 and 3 and 5. Since the bridge losses are equal, the above relationship simplifies to the loss of line  $c$  minus the loss of line  $b$ . It will readily be seen that if the sections  $b$  and  $c$  are of the same length  $l$  and of the same makeup, the energy level at the point C will be the same as at the point A, and all losses in the line will have been made up or equalized. It is apparent in this circuit that the amplifiers 1 and 2 may be separated as shown, or both may be located at the point A or both at the point B. Also, it is understood that each of these amplifiers may consist of one or a plurality of tubes connected in tandem or otherwise. If any increase occurs in the attenuation of the feedback line  $b$ , such as that due to an increase of temperature, there will be a corresponding increase of the gain from A to B. These will be numerically equal, and if the increase of attenuation in section  $c$  is the same as for section  $b$  then the increase in gain at B will be just sufficient to compensate for the added loss in section  $c$ .

Thus far the circuit described does not constitute a part of this invention. It will be observed that a separate pair of conductors  $b$  is used in the Black circuit for feedback, and Fig. 2 shows one method by which I obviate the use of this extra pair and still obtain the advantages of the feedback circuit. That is, I use one pair to perform the functions of the two pairs  $a$  and  $b$  of Fig. 1. This is obtained as shown in Fig. 2, by connection to this one pair, through conjugate branches for the two separate functions of additional Wheatstone bridges  $W_2$  and  $W_3$ , at each end of the pair. These bridges,  $W_2$  and  $W_3$ , serve the purpose of forcing the circulating path to follow the proper channel. It is seen that the conjugate properties of the Wheatstone bridge are so used in this circuit as to permit separation at the desired points of the direct transmission from the feedback.

The introduction of the two additional bridges, the first after amplifier 1 and the second in front of amplifier 2, has introduced additional loss in the feedback circuit so that the effective gain of the amplifier is higher. For this reason the gain losses must be introduced to keep the circuits compensating at the same energy levels as before, and I accomplish this by means of the additional bridges 14 and 15 which serve solely the purpose of attenuation. Other forms of attenuators may be used instead of these bridges, such as that shown in Fig. 2a, but I find it desirable that the attenuator shall simulate as closely as possible the characteristics of the circuits with which it is associated, and this may most readily be attained by using the bridge arrangements of 14 and 15.

In this condition the circuit from A to C is substantially equalized, for if any change occurs in the transmission channels  $a$  and  $c$ , for forward transmission, it affects correspondingly the return or feedback circuit, changing the net gain of the amplifiers in such manner that the energy level at C is substantially unaffected by changes in transmission losses.

In this circuit of Fig. 2 as well as of Fig. 1, the Wheatstone bridges  $W_1$  and  $W_4$  serve the double purpose of rendering the amount of feedback in-

dependent of external connections to the circulating paths at these points and of making the impedance as viewed by these external connections independent of the feedback. This means that the sections of circuit between A and B may be considered practically as a one-way amplifier having a gain and impedance independent of the lines to which it is connected. This condition, although desirable for some applications, is not a controlling requirement and the circuit could be successfully operated without the necessity of using Wheatstone bridges  $W_1$  and  $W_4$ . If these bridges are removed, then a point such as point B would, under certain conditions, be a point at which currents arriving from A would be transmitted through to C and be reflected back toward A. Currents arriving from C would be in part reflected back to C and in part transmitted into line section  $a$ . Such a condition could be secured and the apparatus at station B in Fig. 2 materially simplified by replacing it with a suitable discontinuity or a reflection point in the circuit. Two forms of such discontinuity or reflection devices are shown in Figs. 3a and 3b, it being understood that these are to take the place completely of the apparatus at station B of Fig. 2. The reflected wave from the discontinuity supplies the feedback which functions at station A in the same way as for Fig. 2. In order to keep the gains and losses correct this discontinuity should furnish a return loss equal to its transmission loss; that is, half the energy should be reflected, which corresponds to a transmission loss of 6 decibels.

If a circuit such as shown in Fig. 2 has bridges  $W_1$  and  $W_4$  removed, the effective gain of the section A to B is no longer independent of the conditions in the adjacent sections. If this dependence upon conditions in adjacent sections is not unacceptable the circuit may be so arranged as to not only simplify the apparatus required, but permit, with suitable terminal changes, transmission of signals in either direction over a single pair of wires without the necessity of changes at the intermediate points. A part of my invention then consists in modifying the circuits in accordance with such extension, and incidentally to effectively permit signaling in either direction. A circuit for this purpose is shown in Fig. 5. In order, however, to better understand the transition from Fig. 2 to Fig. 5, an intermediate stage is shown in Fig. 4, the connections of which are evident. Signals coming in from the west in the top pair of conductors follow a path indicated by the arrows pointing towards the east, and the arrows pointing towards the west show the feedback paths for such signals. On the other hand, signals coming from the east at the station D follow the path indicated by the arrows pointing towards the west, and the eastwardly pointing arrows show the feedback paths for such signals.

A better understanding of the operation of the circuit of Fig. 4 will be obtained by referring to Fig. 4a, which shows the last section of line from C to D only. Signal coming in at the point I is amplified and passes out over the line from C to D, the length of which is indicated as

$$\frac{l}{2}$$

A feedback path from the station D to the point I is provided for this amplifier, and at the same time a feedback path from the output of the amplifier at II returns to the previous amplifier.



For the present it will be assumed that any apparatus connected at point III is of high impedance so that it does not introduce any irregularity in the loop C—D—C. If again it is understood that  $\mu\beta$  is large compared to unity, then the net gain between points I and II (which may be taken as N decibels) is substantially equal to the loss in the loop C—D—C. Now consider Fig. 4b showing the loop B—C. The apparatus at C including the loop C—D—C, has been replaced by the box in the dotted lines. The feedback path for the amplifier of Fig. 4b may now be considered as extending from the point V to I, to II, to IV. The section of line from B to C will have a loss N, and the section from C to B will also have this same loss, whereas, the amplifier between I and II will introduce a gain of N units. Thus, the net loss in the loop B—C—B is N units. Consequently, the net gain between IV and V, due to the amplifier, is also substantially equal to N, and the net gain between IV and I is then substantially zero, which means that the energy level at the input point IV is the same as the energy level at the input point I. The same reasoning may be carried through any additional number of sections to the left of station B, Fig. 4 showing one more such. The overall gain of the circuit will be substantially zero for the reason that each amplifier introduces sufficient net gain to approximately compensate for the loss in the adjacent section. It will be noted that the Wheatstone bridge arrangements render the feedback path conjugate to the direct transmission path so that the amount of feedback is independent of the external connections to the circulating paths, and also render the impedances, as seen by the external connections, independent of the feedback, and therefore more stable.

The same line of reasoning which led from the circuit of Fig. 1 to that of Fig. 2, is applicable to that of Fig. 4, whereupon there is obtained the circuit of Fig. 5. This circuit has been obtained by consolidating the two bridges at any point, such as A, and using each section of line for both transmission and feedback, at the same time maintaining the conjugate relationship between these paths, as provided in Fig. 4. The consolidation may be looked upon as taking the output terminals of the repeater at A and connecting them to the input bridge, but at two points which are conjugate with respect to the input terminals. In this consolidation also, certain resistances become superfluous. The circuit of Fig. 5 functions in the same manner as Fig. 4, so far as the gains and losses in the various parts of the circuit are concerned, and the circuit is capable of transmission in both directions. The circuit for one section of Fig. 5 can be shown in simplified form by Fig. 5a, and from this, one may be able to recognize more readily the relationships between the different parts of the Wheatstone bridge.

Various modifications of the circuits thus far discussed, may be shown, which circuits possess certain advantages. For example, in the above description, it has been assumed that the impedance elements of the bridges, and the input and output impedances of the amplifiers, are each equal to the characteristic impedance of the line, at least throughout the utilized portion of the frequency range. In practice it would be desirable that as many as possible of these impedances should be pure resistances equal to some appropriate value such as the asymptotic value of the cable impedance. It is apparent, however, from Fig. 5a, that the bridge impedances in that circuit

or in that of Fig. 5, cannot be made pure resistances and still have the bridges balance. If the circumstances under which the line is operating are such that accurate conjugacy between certain different portions of the circuit are not important, that is, if one can remove from the bridges those functions which are performed by the bridges  $W_1$  and  $W_4$ , in Fig. 1, and Fig. 2, then only one impedance element in each bridge need be different from a pure resistance. On this basis the circuit of Fig. 4 may be changed to the arrangement of Fig. 6, and Fig. 5 to that of Fig. 7. In Fig. 6 the bridges now serve no useful purpose except to suggest the circuit of Fig. 7. This latter is obtained again by consolidation of the two bridges at such a point as A into a single bridge, the output terminals of the amplifier being brought around and connected to those two points of the input bridge which are conjugate to the input terminals. In Fig. 7, station D does not need a bridge. It is satisfactory instead to have a complete reflection of the wave, in which case the receiving element cannot absorb any appreciable amount of energy. Whether this reflection shall be obtained by means of an open or a short circuit depends upon whether a phase shift of  $180^\circ$ , to accompany the reflection, is or is not desired at this point. An open circuit gives no phase shift with reflection so far as the voltage wave is concerned, whereas a short circuit gives a  $180^\circ$  phase shift. Whether this phase shift is desired or not, depends upon the internal structure of the amplifier at station C, and its connection with the bridge at that point. There should be a net phase shift of approximately  $180^\circ$  in the complete circulating feedback path.

It will be seen that in Fig. 7 the two sections of line on each side of a repeater section, are connected in parallel to form an impedance member in the Wheatstone bridge, and a circuit diagram for a single section with its repeater circuit may be represented by Fig. 7a which points out clearly the relationships between the elements of the bridge. Since the two sections  $L'$  and  $L''$  of the line are in parallel, then the resistance or impedance of the other elements shown would be reduced by the factor 2 over the value which they have in Fig. 5 or Fig. 5a.

Instead of having the two sections of the line on each side of the repeater connected in parallel, it is possible to connect these in series, and such an arrangement is shown in Fig. 8. The corresponding simplified diagram is shown in Fig. 8a, and it will be evident that the resistance elements must be given double the value which they have in Fig. 5a. While the arrangement of Fig. 8 has certain advantages in some cases, it will be observed that the line is unbalanced and therefore more subject to disturbances. This, however, may be overcome by transformer connections between the amplifier and the line itself, as shown in Fig. 8b.

Nothing has been said as to the spacing between the repeaters, and it is not desired that any restriction should be placed on this so far as the scope of the invention is concerned. In general, the spacing will be limited by the phase shift which accompanies such circuits as those described, and these phase shifts can be controlled to a considerable extent by means of additional networks, of one nature or another, introduced at appropriate places such, for example, as indicated by Z in the feedback circuits of Fig. 2. It may also be advisable at times to make use of



certain supplementary feedback circuits, such as are known in connection with such circuits.

An interesting characteristic of all the systems proposed is, that a given section of cable is equalized by the similar adjacent section included in the feedback circuit. This implies that the section lengths should be uniform and the line characteristics substantially the same. Otherwise, for Figs. 1 and 2, the gain adjustments and equalization of the repeaters will not be wholly automatic. For the arrangements in Figs. 5, 7 and 8, however, the overall gain and equalization will still be automatically adjusted, although this will not be strictly true of the output levels along the circuit. Furthermore, its adjacent sections are not similarly exposed to the weather, that is, in the extreme case if one section were underground and the other aerial, the net gain and equalization would still be automatically adjusted, but the output levels may be only incompletely adjusted.

In the above description it has been assumed that the overall gain of a feedback repeater is equal to the loss in the feedback circuit. This is true only in the case where  $\mu\beta$  is very large compared to unity. Otherwise, the gain takes on the form

$$R = \frac{\mu}{1 - \mu\beta}$$

In the circuits of Figs. 5, 7 and 8, this departure from the simple relationship is substantially compensated in successive sections of line. For example, in Fig. 4a, the gain between points I and II will be slightly less than the loss in the loop C—D—C. Therefore, in Fig. 4b, the net loss in the loop B—C—B will be a corresponding amount greater than the loss of a single section B—C. The gain without this effect between points IV and V would therefore be greater than the loss in the section B—C. The effect, however, reduces this gain back to the loss. A similar compensation occurs in all the other sections of the line.

In the arrangements of Figs. 5, 7 and 8, it will be evident that irregularities in the cable circuit, or elsewhere, will cause reflections and therefore echo paths which are extraneous to those around which the system is designed, and these echo effects might become substantial in view of the fact that the circuit as a whole is adjusted for approximately zero gain or loss. To break up such echo paths the circuit as a whole may be sectionalized into moderate lengths by use of four-wire repeaters, as shown in Fig. 9. The four-wire repeaters would, of course, permit transmission in one direction only over any given pair of wires for through signaling, although within one of these larger sections two-way conversation may be carried on between points located between any two four-wire repeaters.

In the matter of the feedback, it is to be pointed out that the phase shift around the  $\mu\beta$  path should be such as to satisfy the conditions of stability, i. e., the phase shift of the signal waves over this path should not be zero for any frequency for which  $\mu\beta$  is equal to or greater than unity. This condition can be maintained by keeping the spacing between successive repeaters sufficiently small, or by the use of various types of networks in the circuit.

In a portion of the specification above, reference was made to the use of equality ratio bridges. This is the type of bridge which lends itself most readily to the explanation of the operation of the circuits, and is one which would com-

monly be used in practice. However, it will be apparent that bridges with other than equality ratios would be satisfactory and in some cases would be preferred.

It is evident that many modifications in addition to those described above, are possible, and all without departing from the spirit of the invention as defined by the following claims.

What is claimed is:

1. A wave transmission system comprising a direct wave transmission path over a circuit from one location to a location remote therefrom, an amplifier connected in said path, and an electromagnetically complete, non-singing feedback for said amplifier, said feedback path having a portion providing a path from one of said locations to the other, said portion being over the direct transmission circuit.

2. A wave transmission system comprising a direct wave transmission path over a circuit from one location to a location remote therefrom, an amplifier connected in said path, and an electromagnetically complete, non-singing feedback path for said amplifier, said feedback path having a portion providing a path from one of said locations to the other, said portion being over the direct transmission circuit, and means for maintaining the direct transmission path and the feedback path electrically separate.

3. A wave transmission system comprising a direct wave transmission path over a circuit from one location to a location remote therefrom, an amplifier connected in said path, and an electromagnetically complete, non-singing feedback path for said amplifier, said feedback path having a portion providing a path from one of said locations to the other, said portion being over the direct transmission circuit, and electrical networks to render the transmission path and the feedback paths conjugate with respect to each other.

4. A wave transmission system comprising a circuit having transmission characteristics subject to variations, an amplifier in said circuit, means for compensating for changes in the transmission characteristics of the circuit consisting of an electromagnetically complete, non-singing feedback for the amplifier, the path thereof including the said circuit.

5. The combination of claim 4 characterized by the fact that the direct transmission path and the feedback path while using the same physical path are electrically separate.

6. A wave transmission system comprising a transmission line and a plurality of repeater stations thereon, means for impressing a signal wave for direct transmission on the line, a negative feedback path from the output of one repeater to the input of an adjacent repeater, said feedback path being over the transmission line between these repeaters.

7. The combination of claim 6 characterized by the fact that the feedback path is around the first-named repeater, over the transmission line to the preceding repeater, and around this repeater to its input.

8. The combination of claim 6 characterized by the fact that the feedback path is around the first-named repeater, over the transmission line to the preceding repeater, and around this repeater to its input, the feedback path being maintained in conjugate relationship to the direct transmission path.

9. A wave transmission system comprising a circuit for direct transmission and subject to vary-



ing weather conditions which produce variations in transmission characteristics, an amplifier in said circuit, a feedback path over the same circuit, the feedback coupling provided thereby being adjusted for non-singing and such that changes in gain due to variations in direct transmission characteristics are substantially offset by changes in the feedback coupling.

10. A wave transmission system comprising a circuit, an amplifier connected in said circuit, and means for compensating for transmission changes in said circuit comprising a non-singing feedback path for said amplifier between the points of said circuit half the length of said circuit apart, the feedback path being over the circuit itself.

11. A wave transmission system comprising a circuit for direct transmission and including two gain sources having a feedback path connecting points remote from each other, the feedback path being adjusted for non-singing and extending over the circuit for direct transmission.

12. A wave transmission system comprising a circuit adapted for two-way signaling, a plurality of repeater stations on said circuit, a Wheatstone bridge circuit at each repeater station made up of the impedance of a section of the line and of supplemental impedances to form a substantially balanced bridge network, an amplifier at the station with its input terminals connected to the bridge at two points and its output terminals connected to the bridge at points conjugate to the first-named points.

13. A wave transmission system comprising a transmission line and a plurality of repeater stations along said line and adapted for two-way signaling, the circuit at each station constituting a balanced Wheatstone bridge with one arm made up of the two adjacent line sections in parallel and the other arms made up of supplemental impedances, an amplifier at each station with its input terminals connected across two points of the bridge and its output terminals connected across two points conjugate with respect to the first two.

14. A wave transmission system comprising a circuit adapted for two-way signaling, a plurality

of repeater stations on said circuit, a Wheatstone bridge circuit at each repeater station two opposite arms of which are made up of adjacent sections of the circuit and the other two arms are made up of supplemental impedances to form a substantially balanced bridge network, an amplifier at the station with its input terminals connected to the bridge at two points and its output terminals connected to the bridge at points conjugate to the first-named points.

15. A wave transmission system comprising a direct wave transmission path over a circuit from one location to a location remote therefrom, an amplifier connected in said path, and a feedback path for said amplifier, said feedback path having a portion providing a path from one of said locations to the other, said portion being over the direct transmission circuit, the characteristics of the feedback path being such that  $\mu\beta$  shall satisfy the conditions for stability,  $\mu$  being the overall amplification factor of the circuits of said amplifier,  $\beta$  being the ratio of the voltage at the input of said amplifier on the feedback path to the voltage at the other end of said path, and the conditions for stability being that the phase shift of the signal waves over the complete direct path from the amplifier input to where the return path begins shall not be zero for any frequency for which  $\mu\beta$  is not less than unity.

16. A wave transmission system comprising a direct wave transmission path over a circuit from one location to a location remote therefrom, an amplifier connected in said path, and a feedback path for said amplifier, said feedback path having a portion providing a path from one of said locations to the other, said portion being over the direct transmission circuit, the characteristics of the feedback path being such that the phase shift over the  $\mu\beta$  path shall not be zero at any frequency where  $\mu\beta$  is unity or greater,  $\mu$  being the overall amplification factor of the circuits of said amplifier,  $\beta$  being the ratio of the voltage at the input of said amplifier on the feedback path to the voltage at the other end of said path, and  $\mu\beta$  being the product of  $\mu$  and  $\beta$ .

FRANK A. COWAN.