

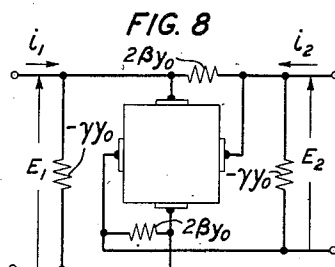
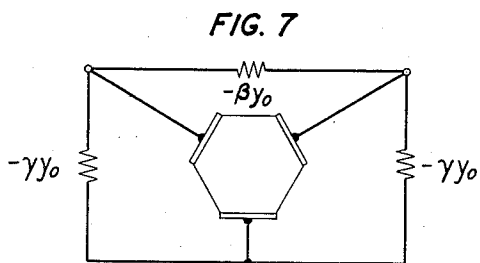
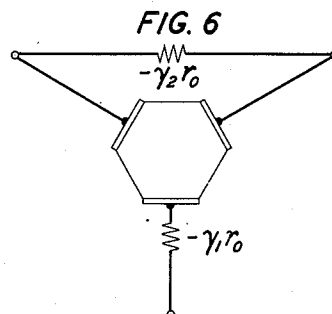
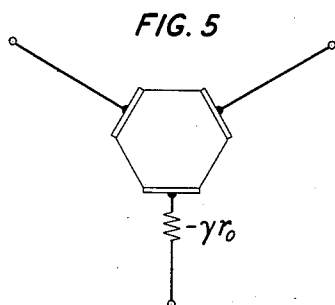
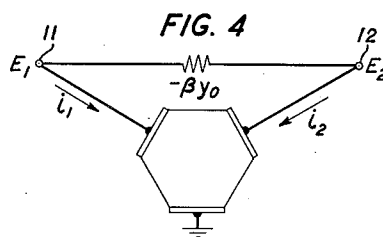
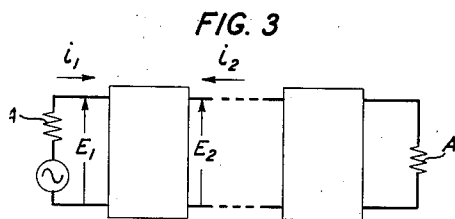
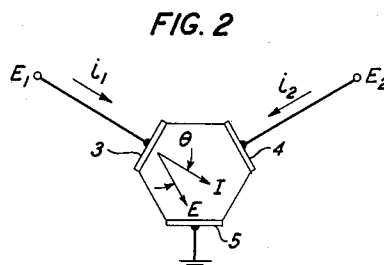
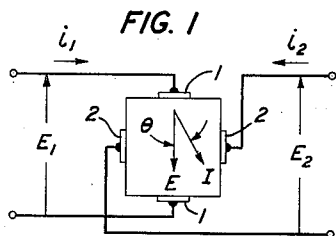
June 4, 1957

W. SHOCKLEY
NONRECIPROCAL CIRCUITS EMPLOYING
NEGATIVE RESISTANCE ELEMENTS

2,794,864

Filed Aug. 1, 1952

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

FIG. 9

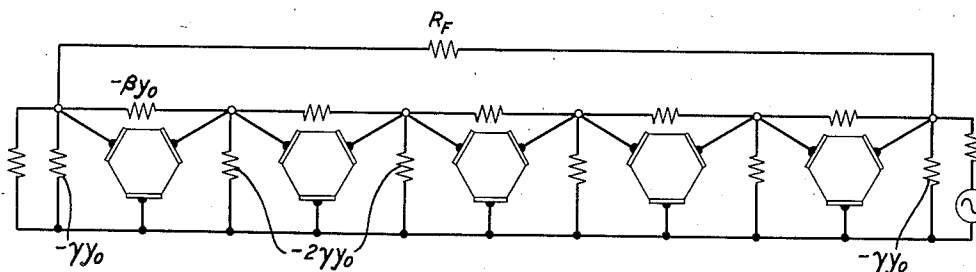


FIG. 10

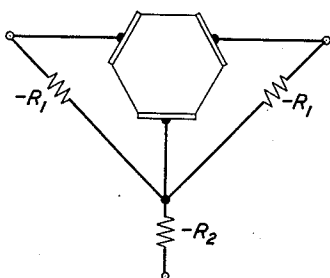


FIG. 11

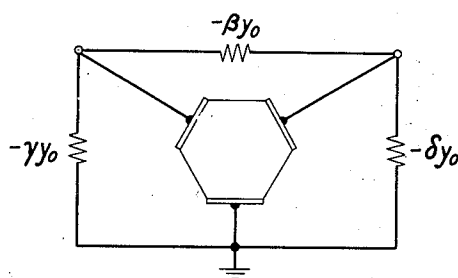


FIG. 12

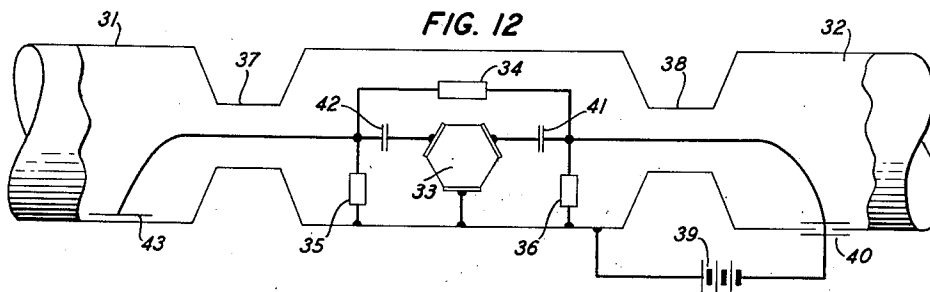
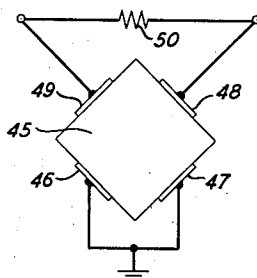


FIG. 13



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2,794,864

NONRECIPROCAL CIRCUITS EMPLOYING NEGATIVE RESISTANCE ELEMENTS

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Application August 1, 1952, Serial No. 303,642

12 Claims. (Cl. 179—171)

This invention relates to improvements in non-reciprocal transducers, and to their use in amplifiers or other circuits including negative resistance elements.

In the application of W. P. Mason and W. Shockley, Serial No. 302,278, filed concurrently with the instant application, now Patent 2,775,658, granted December 25, 1956, it has been proposed to use four-terminal non-reciprocal transducer units with negative resistance elements to obtain a one-way amplifier.

One object of the present invention is to provide a simpler, passive, non-reciprocal transducer than that heretofore known, and, more particularly, one which has phase reversal properties when used in a unilaterally conducting circuit component.

Another object of the invention is to increase the stability of negative resistance amplifiers.

The present invention in one of its aspects resides in a circuit combination of negative resistance and non-reciprocal elements which has directional transmission characteristics and which has phase reversal in the direction of better conduction. In another aspect, the invention resides in the use of circuits of this type in an inverse feedback amplifier.

A feature of the invention is a Hall effect plate having only three terminals which is a non-reciprocal transducer.

Other objects, advantages, and features will become apparent in the course of the following description of certain specific embodiments of the principles of the invention shown in the drawings.

In the drawings:

Fig. 1 illustrates a conventional four-terminal Hall effect unit or gyrator;

Fig. 2 shows a three-terminal Hall effect plate;

Fig. 3 is a schematic showing of a multistage amplifier;

Fig. 4 shows a unidirectionally conducting three-terminal Hall effect unit;

Figs. 5 and 6 illustrate alternative circuit arrangements;

Fig. 7 represents a single amplifying stage using a three-terminal non-reciprocal Hall plate;

Fig. 8 illustrates an amplification stage utilizing a four-terminal gyrator;

Fig. 9 depicts an amplifier having an odd number of stages and employing feedback;

Fig. 10 shows still another type of amplification stage of the three-terminal Hall plate type, which can be used with the amplifier of Fig. 9;

Fig. 11 indicates a three-terminal Hall plate and associated circuit components designed to simulate a general real quadruple;

Fig. 12 illustrates the use of a non-reciprocal circuit for coupling one wave-guide section to another; and

Fig. 13 shows a four-terminal device exhibiting non-reciprocal properties.

A discussion of negative resistances, and of gyrator and non-reciprocal elements, including four-terminal Hall

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plates and other polarized directional transducers, is set forth in the application of W. P. Mason and W. Shockley noted above. Illustrative examples of negative resistances are diodes, or high speed thermistors, which are biased by direct current to an operational point where slight increases of current result in a decrease of the voltage across the unit. The resistance presented to an applied alternating current signal is then effectively negative, and the signal may be effectively amplified.

The terminology developed in the application of W. P. Mason and W. Shockley noted above will also be found useful in the instant case, and is therefore set forth in this paragraph. Initially, a reciprocal transducer is one which obeys the theorem of reciprocity, and thus has equal transfer impedances for the two directions of transmission, as well as other known reciprocal properties. A non-reciprocal transducer is one which violates the theory of reciprocity and has transfer impedances which differ for the two directions of transmission. A directional phase shifter is a circuit element of the four-terminal type having a different phase shift for one direction of transmission than for the opposite direction of transmission. A gyrator has been defined as a circuit element in which the phase shifts differ by substantially 180 degrees for the two directions of transmission. In a directional transducer, the absolute magnitudes of transfer impedances differ for the two directions of transmission.

Considering the conventional symmetrical four-terminal Hall effect plate shown in Fig. 1, the matrix expressions for the current-voltage relationships are as follows:

$$E_1 = R_{11}i_1 + R_{12}i_2 \quad (1)$$

$$E_2 = R_{21}i_1 + R_{22}i_2 \quad (2)$$

$$i_1 = y_0(E_1 + \alpha E_2) \quad (3)$$

$$i_2 = y_0(-\alpha E_1 + E_2) \quad (4)$$

$$\alpha = \frac{R_{21}}{R_{11}} \quad (5)$$

where E_1 and i_1 , and E_2 and i_2 are the voltages and currents at terminals 1 and 2, respectively, where $R_{11} = R_{22}$ is the resistance between opposite terminals to voltages across the same terminals, and where $R_{12} = -R_{21}$ is the transfer resistance. With a permanent magnet applying a field of 17,500 gauss across the Hall effect plate of Fig. 1 perpendicular to the plane of the paper and using a Hall element .220 inch square and .045 inch thick, values of $R_{11} = 340$ ohms and $R_{21} = 78$ ohms have been obtained.

The significant quantity, which describes the characteristics of the four-terminal gyrator, is represented by the symbol α . The algebraic expression for α is given above. Physically it represents the transverse current which flows between two grounded terminals when unit current is passed in and out of the other two terminals of the gyrator as a result of the polarizing action of the magnetic field applied to the Hall plate. It is evident that α is a measure of the tendency of the current to flow sideways in the unit.

Proceeding to consider the specific improvements over the prior art represented by the instant application, Fig. 2 represents a simple three-terminal Hall effect plate of germanium having a magnetic field applied perpendicular to its surface. The dimensions and the magnitude of the applied magnetic field of the device of Fig. 2 are not critical and may be of the same order of magnitude as those set forth above with respect to Fig. 1. As may be seen from the following matrix expressions,

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the three-terminal Hall effect plate, like the four-terminal Hall effect plate, is not reciprocal:

$$i_1 = y_0 [E_1 - \frac{1}{2}(1-\alpha)E_2] \quad (6)$$

$$i_2 = y_0 [-\frac{1}{2}(1+\alpha)E_1 + E_2] \quad (7)$$

$$E_1 = r_0 [i_1 + \frac{1}{2}(1-\alpha)i_2] \quad (8)$$

$$E_2 = r_0 [\frac{1}{2}(1+\alpha)i_1 - i_2] \quad (9)$$

$$1/r_0 = y_0 [1 - \frac{1}{4}(1-\alpha^2)] \quad (10)$$

where E_1 and i_1 , and E_2 and i_2 in this case are the voltages and currents at terminals 3 and 4, respectively, of Fig. 2, and where y_0 and r_0 are conductance and resistance constants, respectively.

Use will be made subsequently of these characteristics in designing negative resistance amplifiers having gain in one direction and loss in the other. In the next paragraph, however, some general equations for an amplifier made by repeating certain similar units will be discussed.

Fig. 3 represents an amplifier terminated with an admittance A and a signal generator at one end and an equal admittance A at the other end. The amplifier consists of a sequence of identical units described by a matrix Y_{ij} , in which the admittance of the units is defined.

For each four pole the current matrix is:

$$i_1 = Y_{11}E_1 - Y_{12}E_2 \quad (11)$$

$$i_2 = -Y_{21}E_1 + Y_{22}E_2 \quad (12)$$

where Y_{11} and Y_{22} are the local conductances and Y_{12} and Y_{21} are the transfer conductances. If

$$Y_{11} = Y_{22} = Y_0 \quad (13)$$

then the admittance looking in either direction is

$$A = (Y_0^2 - Y_{12}Y_{21})^{1/2} \quad (14)$$

with sign such that $|Y_0 + A| > |Y_0 - A|$.

The current gain per stage from left to right is

$$\frac{Y_{21}}{Y_0 + A} \quad (15)$$

For the cases which will be discussed subsequently, the symmetry of the Hall effect plates considered is such that the diagonal elements of Y_{11} and Y_{22} of the matrices have the same value Y_0 . Under these conditions the input and output admittances will match the characteristics of the unit provided A has the value shown on the figure. In addition, our remarks will be chiefly restricted to the case of real admittances or conductances.

If the amplifier is open at any point and the conductance is measured looking into the two terminals, the conductance will be found to have the same value A . It is assumed in this analysis that the elements of the matrix are all real although both positive and negative values will be considered. The current gain per stage will thus evidently be the same for all stages and its formula is readily found to be that given above. The voltage gain has the same value so that the power gain is simply the square of the expression given.

One of the advantages stressed in the above-noted Mason-Shockley application in connection with gyrators is the possibility of using them to give transmission in one direction and zero transmission in the opposite direction. With the four-terminal gyrator, it is possible to achieve this effect by using direct resistance coupling between the input terminals and the output terminals so as to cancel the transmission due to the Hall effect. In the case of the three-terminal Hall plate with one terminal grounded, it is not possible to do this because the transmission characteristics are always positive. That is to say, the application of a voltage at the left-hand ungrounded terminal will produce a positive voltage at the right-hand ungrounded terminal if the latter is left open circuited. The same is true in the opposite direction so that bridging the input and output terminals with a positive resistance cannot result in zero transmission in one direction.

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It is possible, however, to obtain unidirectional transmission with the three-terminal Hall plate by connecting input and output terminals with a negative resistance element. This is accomplished as shown in Fig. 4 by means of the negative conductance $-\beta y_0$ between the input and output terminals 11 and 12.

The physical principle is evidently as follows: If terminal 12 is grounded and voltage is applied to terminal 11, then a current flow in terminal 12 will be produced in the opposite sense to that of terminal 11 due to conduction through the gyrator itself. If a negative resistance element, however, is connected between terminal 11 and terminal 12, it will produce a current flow in the opposite direction. By choosing this negative resistance properly it is possible to arrange that the application of voltage at terminal 11 produces no current flow to grounded terminal 12. Since the Hall effect plate is not symmetrical, this exact cancellation will not occur for transmission in the opposite direction.

It is evident, therefore, that choosing the negative resistance with either of one or the other of two values will result in complete loss of signal in one direction or the other. The formulae for these two cases are readily derived in terms of the equivalent circuit shown in Fig. 4:

$$i_1 = y_0 [(1-\beta)E_1 + [-\frac{1}{2}(1-\alpha) + \beta]E_2] \quad (16)$$

$$i_2 = y_0 [-\frac{1}{2}(1+\alpha) + \beta]E_1 + (1-\beta)E_2 \quad (17)$$

In order to obtain no transmission to the right, β is set equal to $\frac{1}{2}(1+\alpha)$ in which case

$$i_1 = Y_0 \left[\frac{1-\alpha}{2} E_1 + \alpha E_2 \right] \quad (18)$$

$$i_2 = y_0 \left[0 E_1 + \frac{1+\alpha}{2} E_2 \right] \quad (19)$$

and

$$\text{The current gain to the left} = -\frac{\alpha}{1-\alpha} \quad (20)$$

Similarly, to obtain no transmission to the left, β is set equal to $\frac{1}{2}(1-\alpha)$ in which event

$$i_1 = y_0 \left[\frac{1+\alpha}{2} E_1 + 0 E_2 \right] \quad (21)$$

$$i_2 = y_0 \left[-\alpha E_1 + \frac{1+\alpha}{2} E_2 \right] \quad (22)$$

and the current gain to the right in an iterated circuit $= \alpha/(1+\alpha)$.

Some remarks about the physical conditions of the two cases may perhaps be called for. The quantity α will be taken as positive as a convention in this analysis, the opposite case being equivalent to an interchange of the roles of left and right on the figure. For the case shown, the gyrator is itself a more effective transmitter from left to right than from right to left. This means that in order to prevent transmission to the right we must introduce a larger negative conductance between the two terminals than to prevent transmission to the left. When the negative conductance has this larger value, the transmission to the left is governed by the negative conductance and as a result, there is a reversal of phase in going across the gyrator. Since the negative conductance plays a larger role in this case of transmission to the left, the attenuation through the combination of Fig. 4 will be somewhat less than for the case of transmission to the right. These observations explain the appearance of plus and minus signs in the numerator and denominator of the expressions for current gain given above.

The circuit shown in Fig. 4 is mathematically similar in its properties to that shown in Fig. 5. Fig. 5 is better treated from the point of view of the resistance matrix rather than the conductance matrix, but entirely similar expressions are obtained for the conductance for the

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transmission properties. A combination of the two arrangements as shown in Fig. 6 may also be used to accomplish the same purpose.

In Fig. 7 we show a circuit which will give gain provided the parameters of the negative resistance are properly chosen. It consists of the circuit of Fig. 4 together with negative resistances at either side to give current gain. It is evident that when the circuits are placed in tandem, the negative resistances that come together in pairs may be replaced by single resistances. The negative resistances at the extreme right and left ends of the tandem units will, therefore, have one-half the conductance of those between the Hall plates.

The current matrix for this circuit may be readily written down by simply adding together the current contributions of the three negative resistances and the three-terminal Hall plates. The cases of no transmission in one direction or the other correspond to making the coefficients of the non-diagonal terms equal to zero. The values of the admittance A characterizing the repeated unit are shown in the table below together with the values for the current gain:

$$i_1 = y_0[(1-\beta-\gamma)E_1 + [-\frac{1}{2}(1-\alpha) + \beta]E_2] \quad (23)$$

$$i_2 = y_0[-\frac{1}{2}(1+\alpha) + \beta]E_1 + (1-\beta-\gamma)E_2] \quad (24)$$

For no transmission to right:

$$\beta = (1+\alpha)/2 \quad (25)$$

the

$$\text{Admittance} = y_0 \left[\frac{1-\alpha}{2} - \gamma \right] \quad (26)$$

and the

$$\text{Current gain} = \frac{-\alpha}{(1-\alpha-2\gamma)} \quad (27)$$

For no transmission to left:

$$\beta = (1-\alpha)/2 \quad (28)$$

the

$$\text{Admittance} = y_0 \left[\frac{1+\alpha}{2} - \gamma \right] \quad (29)$$

and the

$$\text{Current gain} = \frac{\alpha}{1+\alpha-2\gamma} \quad (30)$$

It is evident that current gain will result when the quantity 2γ lies in the range indicated below:

$$1-2\alpha < 2\gamma < 1$$

For $2\gamma = 1-\alpha$ the gain becomes infinite and for larger values it changes sign. From the point of view of stability it will be desirable to keep γ in the lower range so that a given percentage change in γ will make a smaller percentage change in the denominator. Introducing a value of .23 for α which has been determined for one specimen of germanium, we obtain for the limiting values for γ that bound the case for current gain with a reversal of sign for transmission to the left:

$$\gamma = \frac{1}{2} - \alpha = 0.27 \quad (31)$$

$$\gamma = \frac{1}{2}(1-\alpha) = 0.38 \quad (32)$$

If we take γ as equal to 0.35 or about 10 percent below the unstable value, the current gain will be

$$-0.23/(1-.23-.70) = -3.3 \quad (33)$$

corresponding to approximately 10 decibels per stage. For a difference of 20 percent the gain would be -1.5 or 3.6 decibels per stage.

It should be noted that there is a potential advantage in operating the unbalanced three-terminal amplifier with phase reversal between one stage and the next. This advantage is that it will be possible to make use of the phase reversal to give negative feedback across any odd

number of stages such as one, three, five, et cetera. In addition, when amplification stages not having phase reversal, such as are found in the Mason-Shockley application mentioned above, are used with stages having phase reversal, an odd number of stages of the latter type are employed, to obtain this over-all phase reversal property. By this means the gain characteristics of the amplifier can be still further stabilized. An example is discussed hereinafter.

In Fig. 8 a single amplification stage built around a four-terminal gyrator is illustrated. This is essentially the circuit considered in the Mason-Shockley application previously referred to. The quantities are expressed in terms consistent with the notation used above, however, and the current gains in two directions are considered. It will be observed that the formulae are substantially the same and consequently, the stability will also be the same:

$$i_1 = y_0[(1+\beta-\gamma)E_1 + (\alpha-\beta)E_2] \quad (34)$$

$$i_2 = y_0[-(\alpha-\beta)E_1 + (1+\beta-\gamma)E_2] \quad (35)$$

For no transmission to right:

$$\beta = -\alpha \quad (36)$$

$$\text{The admittance} = y_0(1-\alpha-\gamma) \quad (37)$$

and the

$$\text{Current gain} = \frac{-\alpha}{1-\alpha-\gamma} \quad (38)$$

For no transmission to left:

$$\beta = \alpha \quad (39)$$

$$\text{The admittance} = y_0(1+\alpha-\gamma) \quad (40)$$

and the

$$\text{Current gain} = \frac{\alpha}{1+\alpha-\gamma} \quad (41)$$

From the foregoing it will be noted that the three-terminal Hall plate amplifier involves less connections per stage than the four-terminal and somewhat less elements. In addition, in order to get the benefit of an increased stability corresponding to the case of transmission to the left in which there is an extra negative sign in the denominator, it is necessary to use negative resistance in the four-terminal gyrator in order to produce the zero of transmission.

In Fig. 9 an amplifier with a negative feedback loop is illustrated. This amplifier has the characteristics of formula 38 so that it has reversal in the sign of current and voltage gain across one unit. Such a non-reciprocal Hall effect unit which has reversal of sign in the direction of better transmission may be termed a "directional transducer having phase reversal." It corresponds to transmission to the left in Fig. 7. Feedback in the form of an ohmic resistance R_F can be used in this unit to stabilize the gain. This is an advantage over cases in which there is no phase reversal for in such cases it would be necessary to use a negative resistance to stabilize the voltage gain and it seems highly probable that such an active element will be inherently somewhat less easy to control in its characteristic than a purely passive element such as that shown in Fig. 9.

The individual stages of the amplifier of Fig. 9 may be of other form than shown in this figure. For example, the amplification stage of Fig. 10 is the full equivalent of those shown in Fig. 9; the four-terminal device of Fig. 8 could also be substituted into this amplifier circuit, provided the phase reversal constants are used.

With a minor modification, the circuits of Figs. 7, 8 and 10 may be modified so as to give the current voltage matrix for the general case in which the elements of the matrix are real. One such circuit is shown in Fig. 11. This circuit is described by five parameters, two of these being Y_0 and α which describe the Hall plate and three

others being β , γ and δ which describe the three conductances which, in our example, we take to be negative, although positive values may be desired in some cases. The relationship between current and voltage is illustrated below:

$$i_1 = y_0[(1-\beta-\gamma)E_1 + [-\frac{1}{2}(1-\alpha) + \beta]E_2] \quad (42)$$

$$i_2 = y_0[-\frac{1}{2}(1+\alpha) + \beta]E_1 + (1-\beta-\delta)E_2 \quad (43)$$

If we regard α as fixed at its largest value, then the remaining four parameters may be used to produce arbitrary values for the four matrix elements.

As an example of this choice, we show below the selection which will cause the circuit to simulate an ideal junction transistor with perfect collector saturation and a transistor current amplification factor, alpha, denoted by α' , of unity. Stating these conditions mathematically, the collector resistance $r_c = \infty$, $\alpha' = 1$, the resistance of the base $r_b = 0$, and the emitter resistance $r_e = 1/y_0\alpha$.

These conditions are satisfied by the three-terminal gyrator-type device and associated negative resistances of Fig. 11, when

$$\alpha = \beta = \frac{1}{2}(1-\alpha) \quad (44)$$

and

$$\delta = \frac{1}{2}(1+\alpha) \quad (45)$$

Substituting these values in Formulae 44 and 45,

$$i_1 = y_0[\alpha E_1 + OE_2] \quad (46)$$

$$i_2 = y_0[-\alpha E_1 + OE_2] \quad (47)$$

It is evident that the ability to simulate the equivalent circuits of tubes with this type of non-reciprocal transducer plus negative resistance as demonstrated in the foregoing example makes the field of conventional tube and transistor amplifiers accessible to these techniques. With the broad response band of the non-reciprocal component, this type of device appears to have substantial utility in the very high frequency range.

Because of the potentially small size of the elements considered here, it is quite practical to consider lumped circuit constant elements even in the millimeter wavelength range. This permits us to consider coupling from one wave-guide section to the next by aid of either three- or four-terminal Hall effect elements.

By way of example, in Fig. 12 the wave-guide sections 31 and 32 are coupled together by means of the non-reciprocal circuit, made up of the three-terminal Hall element 33 and the negative resistance elements 34, 35 and 36. These elements are introduced into the circuit after the wave guides are constricted to a coaxial line as at 37 and 38. In place of the wave guides as shown at 31, 32, extended coaxial lines may also be connected by this method. In Fig. 12, one method of supplying biasing current from any suitable source 39 to the negative resistance elements 34, 35 and 36 is shown. High frequency by-pass condensers 40, 41, 42 and 43 are suitably located to isolate the direct current circuit flowing through the negative resistances.

Fig. 13 illustrates a four-terminal rectangular Hall effect plate 45 which has very similar properties to those of the three-terminal plates described in some detail hereinbefore. More specifically, with two adjacent terminals 46 and 47 tied together and a negative resistance 50 between the two terminals 48 and 49, the device has much the same properties as that of Fig. 4.

It is to be understood that the foregoing arrangements are illustrative of the application of the principles of the invention and that numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A three-terminal Hall effect element having negative resistance elements interconnecting all three terminals.

2. A stabilized amplifier comprising a number of stages of amplification, each of an odd number of said stages including a phase reversing non-reciprocal gyrator unit comprising a non-reciprocal transducer and a two-

terminal negative resistance connected in such bridging relationship with respect to said transducer as to substantially cancel out alternating current signals applied to said non-reciprocal unit in one direction only, and a feedback circuit coupling a portion of the output of said amplifier to the input thereof.

3. A three-terminal Hall effect plate having three negative resistances connected between the three terminals.

4. In a stable amplifier, an alternating current signal circuit including an input circuit and an output circuit, a plurality of passive means including a magnetically polarized transducer for transmitting alternating current better in one direction than in the other successively interposed in said signal circuit between said input circuit and said output circuit, a first plurality of two-terminal negative resistance elements connected in such bridging relationship with respect to said magnetically polarized transducers as to substantially cancel out alternating current signals applied to said transducer in one direction only, a second plurality of two-terminal negative resistance elements connected and in amplifying relationship with said alternating current and spaced from each other by said magnetically polarized transducers signal circuit, and a feedback circuit interconnecting said input and output circuits.

5. An amplifying circuit as set forth in claim 4 wherein said feedback circuit is resistive and in which an alternating current signal is shifted 180 degrees between said input and said output circuits.

6. A stabilized amplifier comprising an alternating current signal circuit including an input circuit and an output circuit, an odd plurality of magnetically polarized three-terminal Hall effect elements successively interposed in said signal circuit between said input circuit and said output circuit, a plurality of two terminal negative resistances connected respectively in such bridging relationship with respect to said Hall effect elements as to cancel out alternating current signals applied to said elements from said output circuit toward said input circuit, and a feedback circuit interconnecting said input and output circuits.

7. A three-terminal Hall effect element having a first two-terminal negative resistance interconnecting two of said three terminals, and a second two-terminal negative resistance interconnecting one of said first two terminals and the third terminal of said Hall effect element.

8. In an alternating current signal circuit, a first two-terminal negative resistance, means for coupling said negative resistance in linear amplifying relationship with said alternating current signal circuit, and a directional transducer interposed in said signal circuit, said transducer including a three-terminal Hall effect device bridged across said alternating current circuit and having two terminals connected in series with one side of said alternating current signal circuit and circuit means connected between said two terminals including a second two-terminal negative resistance for substantially cancelling out alternating current signals transmitted through said Hall effect device in one direction only.

9. In an alternating current signal circuit, a first two-terminal negative resistance, means for coupling said negative resistance in linear amplifying relationship with said alternating current signal circuit, and a directional transducer interposed in said signal circuit, said transducer including a three-terminal Hall effect device bridged across said alternating current circuit and having two terminals connected in series with one side of said alternating current signal circuit and circuit means including a second two-terminal negative resistance for substantially cancelling out alternating current signals transmitted through said Hall effect device in one direction only, said second two-terminal negative resistance being connected to said Hall effect device symmetrically with respect to the portions of said alternating current circuit on either side of said Hall effect device.

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10. A circuit as defined in claim 9 wherein said second two-terminal negative resistance is connected between the third terminal of said Hall effect plate and the other side of said alternating current signal circuit.

11. A unilateral coupling circuit comprising a Hall effect element having at least three terminals, an alternating current input circuit connected to first and second of said terminals, an alternating current output circuit connected to second and third of said terminals, and means comprising a two-terminal negative resistance connected between said first and third terminals of said Hall effect element for substantially cancelling out alternating current signals applied at said second and third terminals and concurrently transmitting signals applied from said input circuit at said first and second terminals of said Hall effect element to said output circuit.

12. In an alternating current signal circuit, a first two-terminal negative resistance, means for coupling said negative resistance in linear amplifying relationship with said alternating current signal circuit, and a directional transducer interposed in said signal circuit, said transducer including a three-terminal magnetically polarized non-reciprocal device bridged across said alternating current circuit and having two terminals connected in series with

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one side of said alternating current signal circuit and circuit means including a second two-terminal negative resistance for substantially cancelling out alternating current signals transmitted through said nonreciprocal device in one direction only, said second two-terminal negative resistance being connected to said nonreciprocal device symmetrically with respect to the portions of said alternating current circuit on either side of said Hall effect device.

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