June 26, 1956 D. M. LIPKIN 2,752,559

AMPLIFYING SYSTEM

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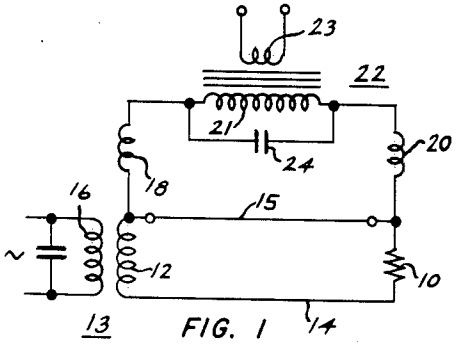


FIG. 1

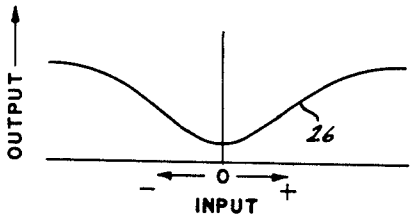


FIG. 4

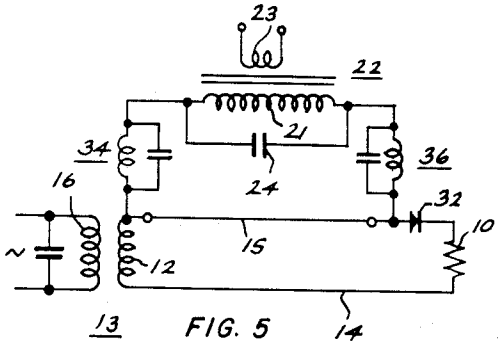
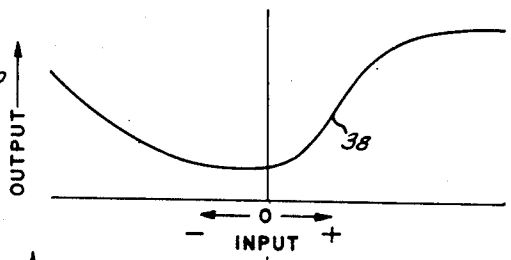


FIG. 5

FIG. 6



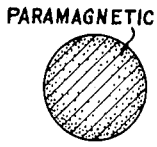


FIG. 2

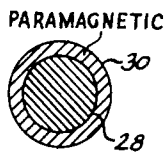


FIG. 3

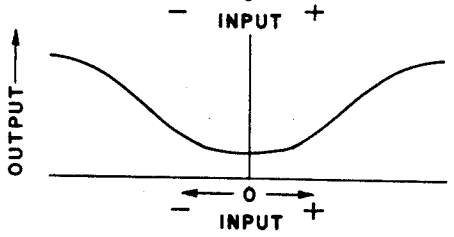


FIG. 8

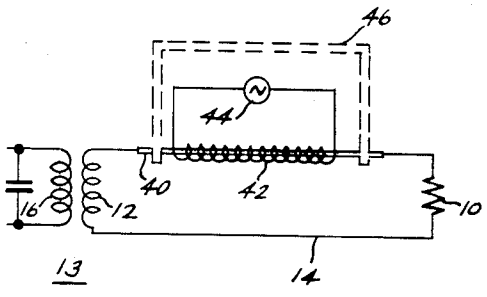


FIG. 7

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AMPLIFYING SYSTEM

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Application May 31, 1951, Serial No. 229,175

10 Claims. (Cl. 323—66)

This invention relates to amplifying devices and more particularly to an amplifying device utilizing magnetic phenomena for producing the desired amplification.

The prior art is familiar with amplifiers employing the valving action of a charged grid on an electron stream. Amplifiers of this type are characterized by rather limited life because of the perishability of the electron source, and many designs are relatively fragile. Other amplifiers are also known that make use of a change in impedance induced by change in permeability of a magnetic circuit. Such devices, known as saturable core reactors, are characterized by practically indefinite life and have, in the past, been restricted primarily by their relatively great weight and the rather low upper frequency limits at which they may be satisfactorily employed. Recently, contemporary developments in materials for use in magnetic amplifiers have permitted extension of the upper limits of the working frequency and considerably diminished the minimum weight. Nevertheless, the fabrication cost of such amplifiers is still considerable because of the need for independently fabricating the core and, by one means or another, winding the necessary coils thereon.

Accordingly, it is a primary object of the invention to provide new and novel amplifying apparatus.

A further object of the invention is to provide a new and novel amplifying system utilizing magnetic phenomena.

Another object of the invention is to provide a new and novel amplifying system wherein the amplification action is enhanced by the shifting current stream lines observed in response to skin effects appearing in magnetic conductors.

Other objects and advantages of the invention will in part be obvious and in part be described when the following specification is read in conjunction with the drawings in which:

Figure 1 is a schematic illustration of an amplifier circuit embodying the principles of the invention,

Figure 2 illustrates the cross-section of a solid magnetic conductor suitable for use in the apparatus of Figure 1.

Figure 3 illustrates a cross-section of a composite magnetic conductor which may be employed in the apparatus of Figure 1,

Figure 4 illustrates graphically the relationship between input stimuli and output signals in the apparatus of Figure 1,

Figure 5 illustrates schematically a modified form of the invention,

Figure 6 illustrates graphically the relationship between input and output stimuli in the arrangement of Figure 5,

Figure 7 illustrates schematically still another alternative arrangement incorporating the principles of the invention,

Figure 8 illustrates schematically the relationship between input and output signals in the apparatus of Figure 7.

Referring now to Figure 1 of the drawings, a load impedance at **10** is connected with the secondary of an air

core transformer at **12** by a conductor at **14** and a conductor at **15**. The conductor **14** may be nonmagnetic and constituted of copper, while the conductor at **15** is paramagnetic. The secondary **12** of the air core transformer **13** is magnetically associated with the primary **16**, which may form a part of the resonant anode circuit of any conventional oscillator or power amplifier structure; or may be fed from any other suitable source of auxiliary high frequency energy. The auxiliary frequency applied to the primary **16** of the transformer **13** and the dimensions of the paramagnetic conductor **15** are interrelated, as will be seen. The source and load ends of the paramagnetic conductor **15** are also connected, through isolating impedances **18** and **20**, with the ends of the secondary of a signal transformer **22** whose primary **23** is excited from the source of signal energy. The highest frequency applied to the primary **23** of the transformer **22** is lower than the auxiliary frequency impressed on the primary **16** of the transformer **13**. A capacitor **24** bypasses auxiliary frequency energy around the secondary **21** of the signal transformer **22**.

The dimensions of the paramagnetic conductor **15** and the frequency supplied to the primary **16** of the transformer **13** are so related that the impedance presented by the conductor **15** to energy at the auxiliary frequency is substantially greater than the direct current resistance of the conductor **15**. In a particular case, it may be assumed that the conductor **15** is of pure iron wire having a cross-section substantially similar to that appearing in Figure 2. The relatively high impedance to alternating currents of the relatively high auxiliary frequency is caused by skin effect, which concentrates the flow of current along the conductor **15** in a relatively thin film at its surface. Reference is made to "Electricity and Magnetism" by Norman E. Gilbert for a discussion of this skin effect phenomenon. The shading around the periphery of the conductor in Figure 2 illustrates this concentration. The film thickness may readily be determined from the relationship:

$$D=\frac{3.5}{\sqrt{f}}\sqrt{\frac{\rho}{\mu\rho_{cu}}} \text{ inches}$$

The resistance ratio is very nearly expressed by

$$\frac{R_{ac}}{R_{dc}}=0.0960d\sqrt{f}\sqrt{\frac{\mu\rho_c}{\rho}}+0.26$$

where "*d*" is the diameter of the conductor.

It will be immediately noted that both the depth of penetration and the resistance ratio are dependent upon the permeability of the conductor. The iron comprising the conductor **15** has a high permeability, but is characterized by sharply diminishing permeability in the presence of appreciable magnetic field strengths. The voltage supplied across the secondary winding **12**, the impedance of the conductor **15** and of the load **10** are so proportioned that the current flow through the conductor **15** from the source is never sufficient to saturate the outer periphery of the conductor in the absence of control signals. However, the control circuit extending from the secondary **21** of the transformer **22** through the isolating impedances **18**, **20** to the conductor **15** affords an arrangement for passing additional current through the conductor **15** to develop additional magnetic forces at its periphery. Such magnetic forces are great enough to drive the iron into that portion of its magnetic response characteristic where its permeability is greatly diminished, whereupon the impedance presented to energy at the auxiliary frequency delivered from the secondary **12** of the transformer **13** is also diminished, to increase the auxiliary frequency voltage appearing across the load **10**. Reference is made to "Reviews of Modern Physics," January 1947, pages 34 and 35, for a

discussion and showing illustrating the permeability variation utilized in this invention.

In a practical case, in which the conductor 15 may be a 0.003 inch of iron filament having a permeability of 56,000 and an auxiliary frequency of one megacycle per second, the resistance ratio observed may be of the order of thirty to one, permitting very substantial variation of the voltage appearing across the load impedance 10 in response to the control signals impressed on the primary 23 of the transformer 22. Under such conditions an output power about thirty times as great as the input power may be realized when the impedance of the load device 10 approximates the minimum impedance presented by the conductor 15.

The circuit of Figure 1 operates in essentially symmetrical fashion, as is apparent from an inspection of its input-output characteristic appearing in Figure 4. Here, input stimuli are indicated along the abscissa, while the output voltage across the load 10 is plotted as the ordinate. In the absence of control input stimulus, the conductor 15 presents a maximum impedance and the voltage across the load 10 is at its minimum value. As the input stimulus is increased in a positive direction, energy at the auxiliary frequency is delivered in increasing amounts to the load impedance 10, as shown by the right-hand portion of the curve 26. Conversely, if the input stimulus is increased in a negative sense, the output voltage appearing across the load 10 is also increased. Linear amplification may be obtained from the arrangement by the application of biasing current to the conductor 15 through other suitable isolating circuits. While high impedance chokes have been shown as isolating impedances at 18 and 20 in Figure 1, it will be understood that inductors of lesser impedance may be employed at these points with arrangements made to resonate them at the auxiliary frequency or that suitable low pass filters may be used.

Figure 3 illustrates an alternative cross-section for a conductor which may be employed at 15 in Figure 1. This conductor is composite in nature, consisting of an inner highly conductive core 28 which may be of copper, silver, or the like, and an outer paramagnetic portion 30 characterized by the highest conveniently attainable permeability. The paramagnetic substances usually have higher unit resistivity than copper or silver. The use of a conductor of the type illustrated in Figure 3 lowers the minimum impedance presented by the conductor 15, when its outer layers are magnetically saturated, by a factor of the order of five. This structure has the advantage of decreasing the signal power requirements which must be met for saturation of the outer portions of the composite conductor of Figure 3 and, consequently, substantially increases the power gain attainable from the arrangement of Figure 1. Considered qualitatively, it is apparent that when the skin depth reaches the thickness of the external magnetic coating 30, substantially the entire cross-section of the composite conductor of Figure 3 enters into the conduction process. The slope of certain portions of the curve of Figure 4 will be increased by the use of the composite conductor of Figure 3, but for many applications, particularly for pulse amplification, this is not a serious limitation.

The power gain obtainable with the symmetrically responsive arrangement of Figure 1 may be increased by the insertion of a unilateral conductor in series with the load 10 of Figure1; Figure 5 illustrates this mode of construction, in which the load impedance 10 is connected with the secondary 12 of the transformer 13 through a conductor 14, the unilateral conductor 32 and the paramagnetic conductor 15. Control energy is applied to conductor 15 from the secondary 21 of the transformer 22 through the anti-resonant circuits 34, 36, which are tuned to reject the auxiliary frequency present in the primary circuit of the transformer 13.

The unilateral conductor 32 of Figure 5 serves essentially to inactivate the amplifier circuit during half-cycles of the auxiliary voltage characterized by a selected polarity. The polarity of auxiliary voltage half cycles viewing the reverse impedance of the unilateral conductor 32 is chosen to be that polarity which tends to send current through the paramagnetic conductor 15 in a direction opposing the positive direction of signal current in 15. When the unilateral conductor 32 is oriented in the direction so defined, the remaining half cycles of the auxiliary voltage, which are not discriminated against by the presence of the unilateral conductor 32, always tend to send current through the paramagnetic conductor 15 in such a way as to aid any positive signal current which may already be flowing in that conductor. The result will be that, if positive signal current shall have been set up in the paramagnetic conductor 15 (tending to saturate the outermost portions of that conductor and therefore to decrease that conductor's skin effect and consequently as well its impedance to the auxiliary frequency current), the current that the auxiliary voltage will be able to set up in the conductor 15 will always aid this saturating effect of the signal current. The effect of the addition of the unilateral conductor 32 is to prevent alternate half cycles of the auxiliary voltage from tending to desaturate the outer portions of the paramagnetic conductor 15 once these have been saturated by the positive control current. The power gain obtainable with the modified circuit of Figure 5 will therefore be greater than that obtainable with the circuit of Figure 1.

In the circuit of Figure 5, if signal current flows in a negative sense through the paramagnetic conductor 15, its saturating effect on portions of this conductor will, on the contrary, always be opposed by the half cycles of the auxiliary frequency which are not discriminated against by the unilateral conductor 32, with the result that a lower power gain will be obtained than for positive control currents. The input-output response characteristic of the arrangement of Figure 5 will therefore be asymmetrical with a higher output for positive than for negative control currents, as depicted in Figure 6.

There may be circumstances where it is desirable to electrically isolate the control signal circuit and the controlled circuit. This condition is met and satisfied by the arrangement of Figure 7 in which the load impedance 10 may be connected with the secondary 12 of the auxiliary frequency transformer 13 through a conductor 14 and a second paramagnetic conductor 40. The paramagnetic conductor 40 may be surrounded by a concentrically disposed helical winding 42 supplied with energy from the control signal source 44. If additional magnetic circuit efficiency is desired, a yoke 46 may be added. The yoke 46 is provided with conductor-receiving apertures in its depending limbs and is characterized by good operating permeability at the maximum frequencies appearing at the control signal circuits. In connection with the previous circuits of Figures 1 and 5, it will be noted that the magnetic vectors have been disposed normal to the length of the wire, that is in the plane of the normal cross-section thereto. The magnetic vectors contributed by the control signal circuits have added directly to, or subtracted directly from, the magnetic vectors arising from the flow of auxiliary current through the control conductor. In the arrangement of Figure 7, however, the magnetic vectors developed by the auxiliary frequency current and by the control frequency current are normally disposed with respect to each other, the auxiliary frequency current developed vector lying, as before, in the plane of the normal cross-section to the conductor 40, while the magnetic vector developed by the control current flowing through the winding 42 is disposed along the length of the conductor 40 and normally disposed with respect to the auxiliary frequency current produced vector. The two vectors give rise to a resultant vector, as is well known which, when it is of sufficient magnitude, saturates the periphery of the conductor 40. The conductor 40, as before, may be either a solid paramagnetic conductor or a composite paramagnetic conductor as

shown in Figures 2 and 3, respectively. The control or input-output characteristic of the circuit of Figure 7 is depicted in Figure 8 and is symmetrical about the axis of zero excitation from the control signal circuits. In the absence of excitation in the control signal circuit, the conductor 40 presents its maximum impedance, its impedance diminishing progressively with increasing control signal circuit excitation either in the positive or in the negative sense. While the major amplification effect is due to current pulses flowing during half cycles of the auxiliary frequency energy in the circuits of Figures 1 and 5 characterized by one or the other polarities, the vectoral addition of normally disposed vectors in Figure 7 gives rise to an equal contribution from both positive- and negative-going half cycles of the auxiliary frequency energy.

It may be shown that the power which may be derived from circuits of the type shown in Figures 1 and 5 is expressed approximately by the relationship

$$\frac{1}{16}\frac{\rho_1}{2\pi}(a+1)^2H^2$$

where H is the magnetic intensity required to saturate the outer periphery of the paramagnetic conductor. The power gain for such a circuit is very nearly expressed by the relationship

$$\frac{1}{8}\left(\frac{a+1}{2}\right)^2$$

where a is the impedance ratio observed for alternating current and direct current energy. In the assumed case of a 0.003 inch conductor excited at an auxiliary frequency of one megacycle per second, the attainable power gain is of the order of thirty. Further improvement, as noted above, may be obtained by the use of composite structures for the control conductor and by the addition of a unilateral conductor in series with the amplifier's load.

A paramagnetic coating on a conductor having the composite structure of Figure 3 may be conveniently electrolytically deposited upon a copper base. Thicknesses of the order of a few ten-thousandths of an inch represent satisfactory plating depths.

Many other modifications and applications, not departing essentially from the principles of the invention, will be apparent upon further consideration to those skilled in the art.

What is claimed is:

1. In combination, a conductor at least partially paramagnetic, a load device, a first set of circuit connections adapted to connect said conductor and said load device with a source of periodic electric energy having a first frequency, whereby a current of said first frequency flows along said conductor, and a second set of connections adapted to impress electric energy of frequency lower than said first frequency on said conductor, whereby a current of said second frequency flows along said conductor, the dimensions and characteristics of said conductor and said first frequency being so related that the impedance presented by said conductor to energy at said first frequency in the absence of excitation of said second set of connections is at least twice the impedance presented by said conductor to direct current.

2. In electrical apparatus, a conductor at least partially paramagnetic, a load device, circuit connections adapted to connect said conductor and said load device with a source of periodic electric energy having a first frequency, whereby a current of said first frequency flows along said conductor, and a circuit producing a magnetic field at said conductor in response to energization from a source of signal stimuli characterized by a frequency less than said first frequency, the dimensions and characteristics of said conductor and said first frequency being so related that the impedance presented by said conductor to energy at said first frequency in the absence of excitation of said signal circuit is at least twice the impedance presented by said conductor to direct current.

3. In electrical apparatus, a paramagnetic conductor, a load device, first circuit connections adapted to link said conductor and said load device with a first source of periodic electric energy having a first frequency, second circuit connections adapted to link said conductor with a second source of electric energy characterized by a frequency less than said first frequency, and isolating devices restraining the circulation of energy at said first frequency in said second circuit, the dimensions and characteristics of said conductor and said first frequency being so related that the impedance presented by said conductor to energy at said first frequency in the absence of excitation of said second circuit connections is at least twice the impedance presented by said conductor to direct current.

4. In electrical apparatus, a paramagnetic conductor, a load device, a first circuit linking said conductor and said load device in series with a first source of periodic electric energy having a first frequency, and a second circuit linking said conductor with a second source of electric energy characterized by a frequency less than said first frequency, the dimensions and characteristics of said conductor and said first frequency being so related that the impedance presented by said conductor to energy at said first frequency in the absence of excitation of said second circuit is at least twice the impedance presented by said conductor to direct current while the impedance presented by said conductor to energy from said second source is substantially equal to the impedance presented by said conductor to direct current.

5. In electrical apparatus, a paramagnetic conductor, a unilateral conductor, a load device, a first circuit delivering energy at a first frequency to said load through said paramagnetic conductor and said unilateral conductor, and a second circuit delivering energy at a different lower frequency to said conductor.

6. In electrical apparatus, a conductor comprising a central conductive relatively nonmagnetic core sheathed in relatively magnetic material, a load device, a first circuit delivering energy at a first frequency to said load through said conductor, and a second circuit in parallel with the load and the conductor carrying energy at a different lower frequency through the conductor to influence the magnetic field in at least a portion of said conductor.

7. Apparatus according to claim 6 in which the specific conductivity of the material of said core exceeds the specific conductivity of the material of said sheath.

8. Apparatus according to claim 7 in which said core and said sheath are in electrical engagement.

9. Apparatus as in claim 2 including a unilateral conductor connected in series with said load.

10. In electrical apparatus, a paramagnetic conductor, a load device, a first circuit delivering energy at a first frequency to said load through said conductor, and a second circuit in parallel with the load and the conductor carrying energy at a different lower frequency through the conductor to influence the magnetic field in at least a portion of said conductor.

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