Sept. 24, 1940. F. E. TERMAN 2,215,672

HIGH-EFFICIENCY AMPLIFIER

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Fig. 1.

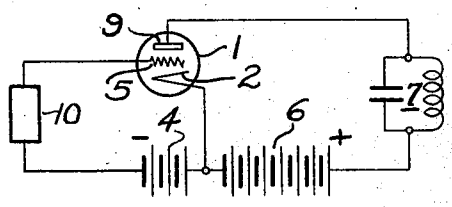
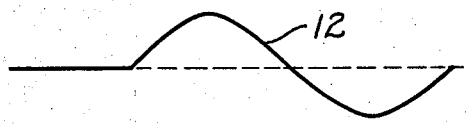
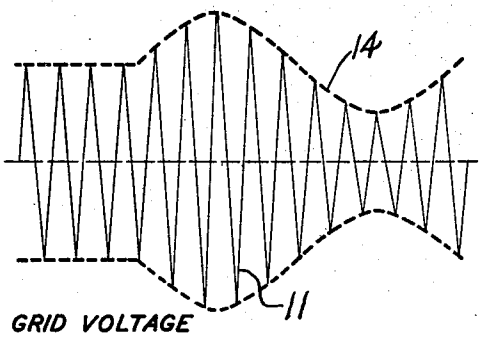


Fig. 2.



SIGNAL VOLTAGE

Fig. 3.



GRID VOLTAGE

Fig. 6.

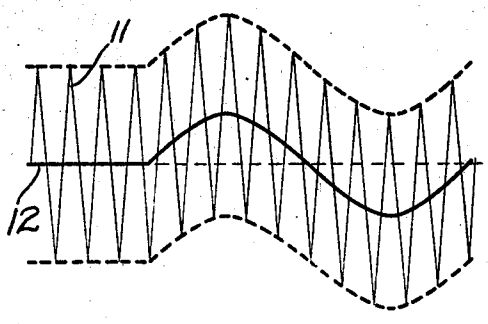


Fig. 4.

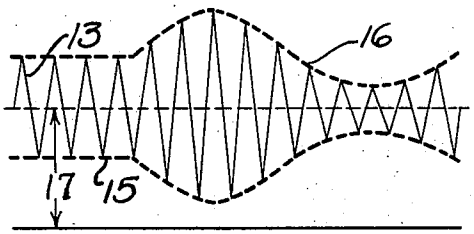


PLATE VOLTAGE

Fig. 7.

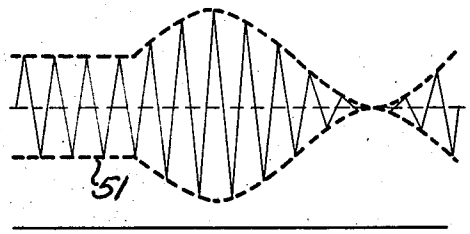


Fig. 5.

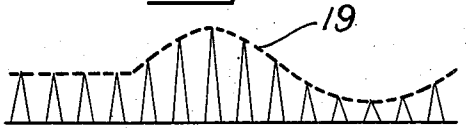
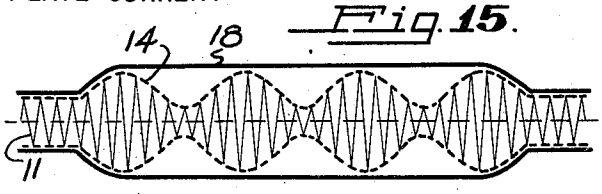


PLATE CURRENT

Fig. 8.



Fig. 15.



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Fig. 9.

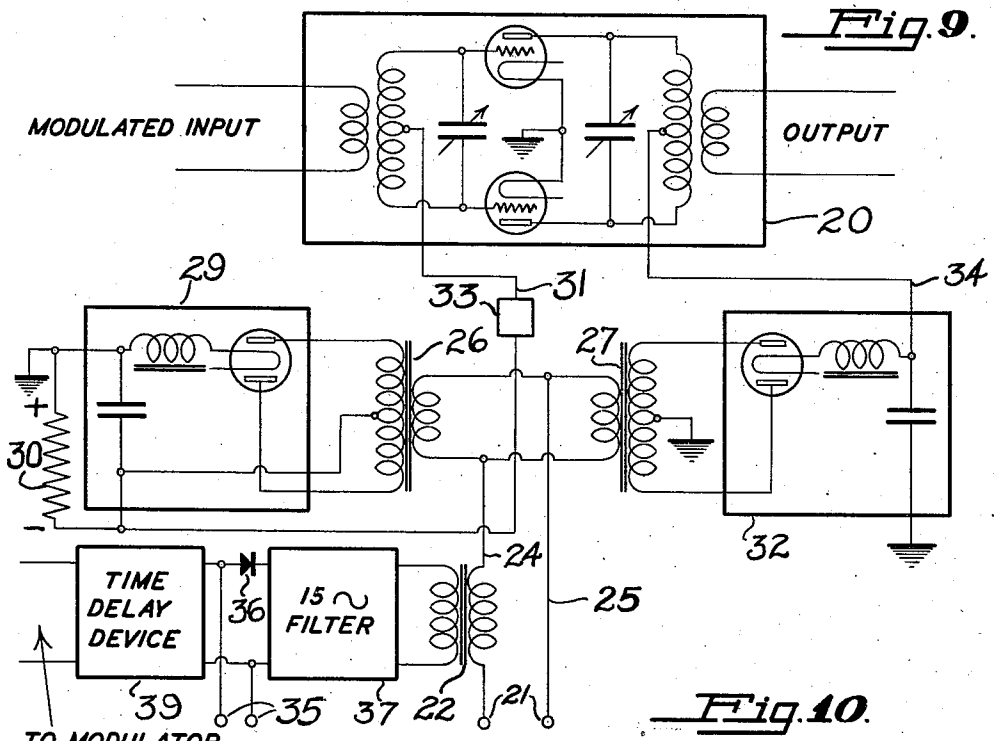
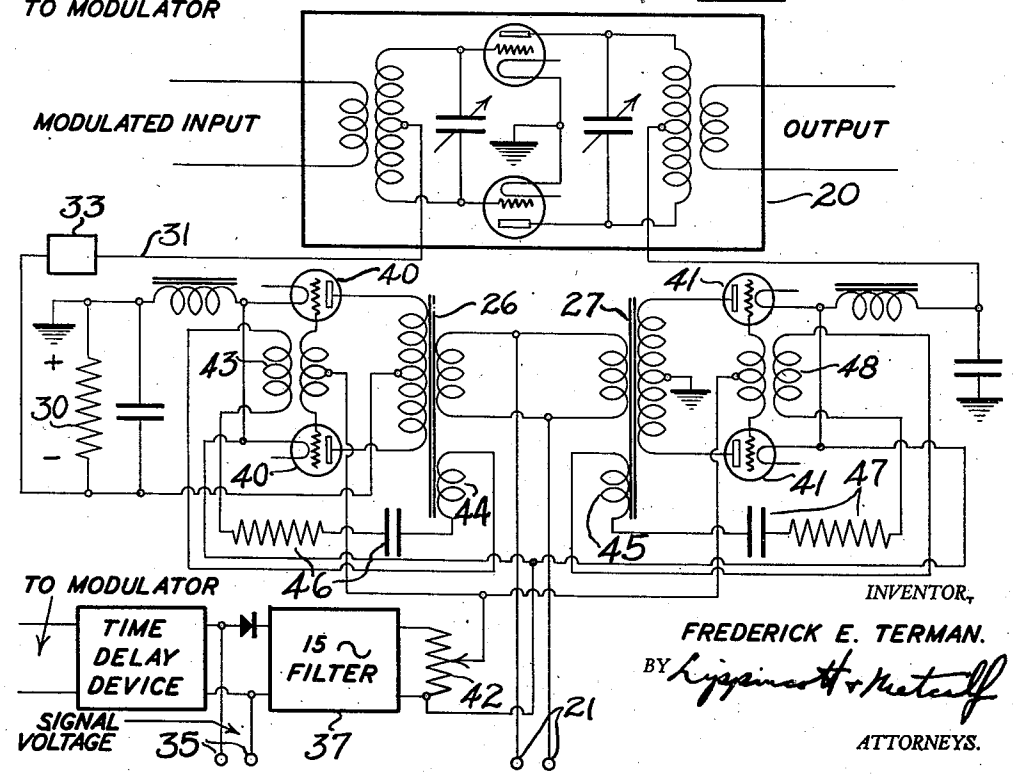


Fig. 10.



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Fig. 11.

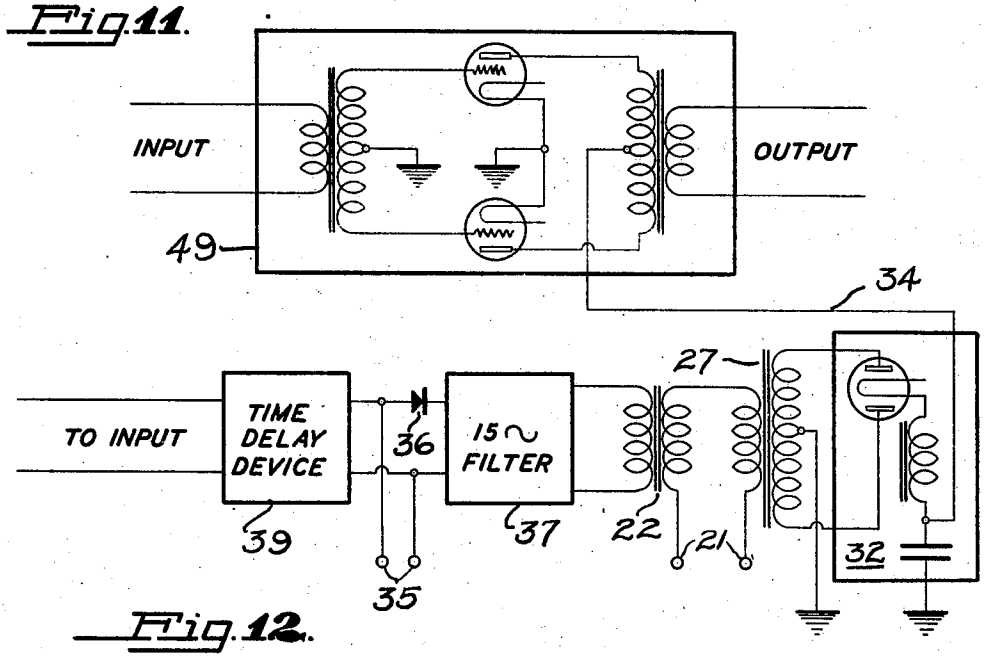


Fig. 12.

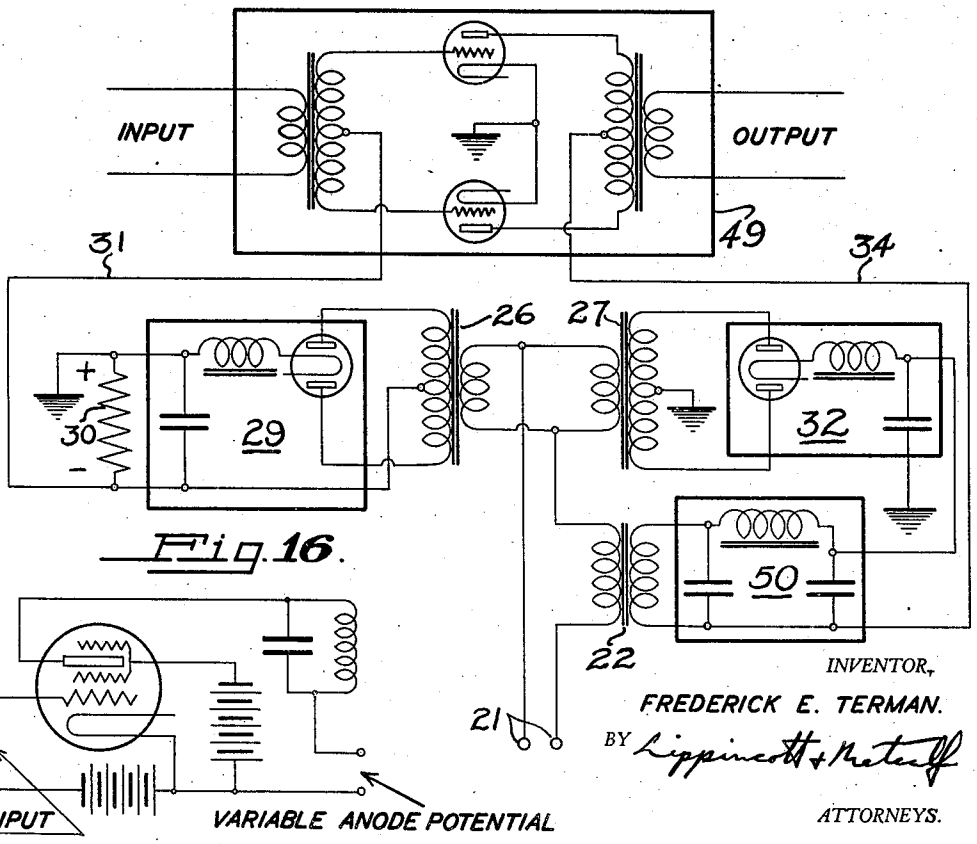


Fig. 16.

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Fig. 13.

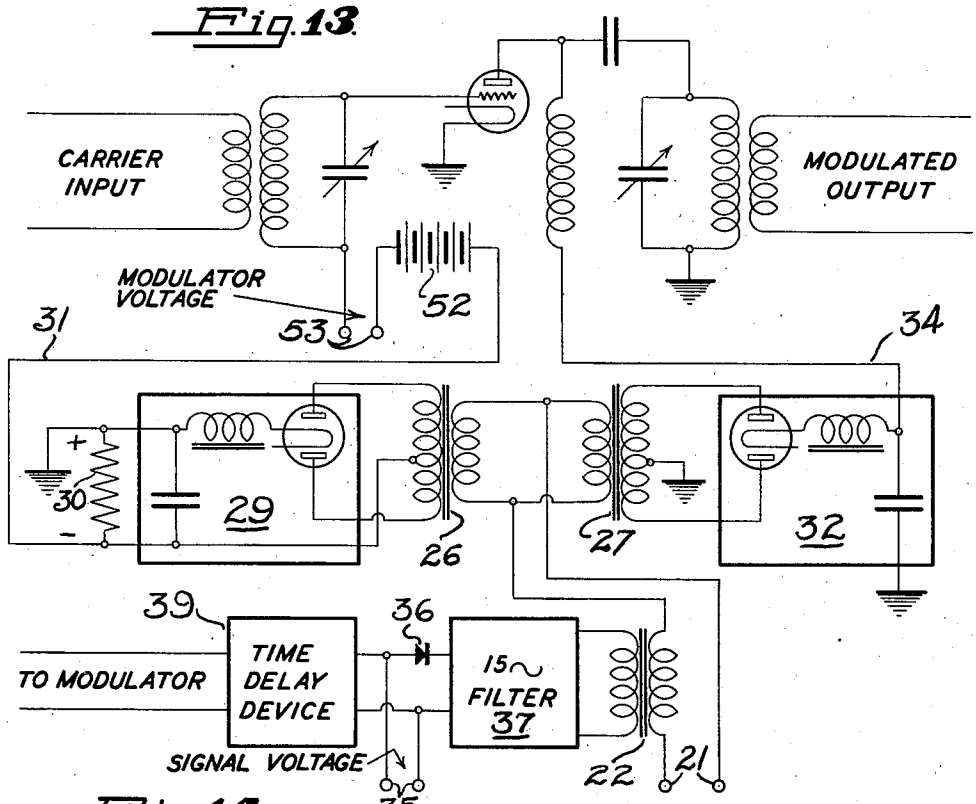
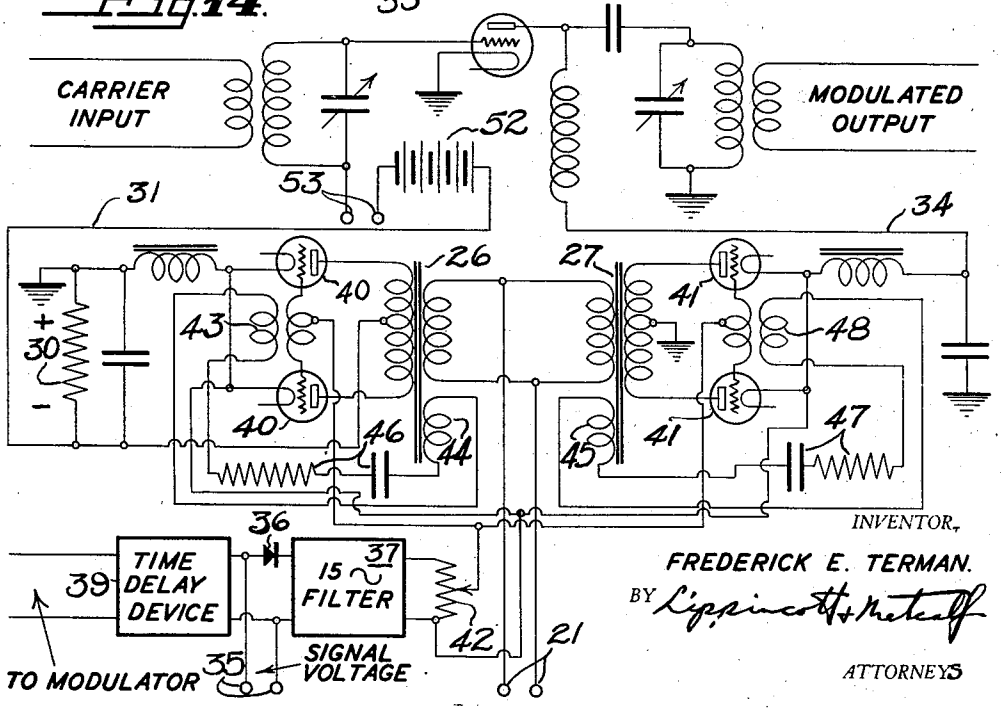


Fig. 14.



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UNITED STATES PATENT OFFICE

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HIGH-EFFICIENCY AMPLIFIER

Frederick E. Terman, Stanford University, Calif.

Application August 4, 1936, Serial No. 94,150

8 Claims. (Cl. 179—171.5)

My invention relates to vacuum tube amplifiers, and particularly to high-efficiency amplifiers of the class-B and grid-modulated class-C types.

Among the objects of my invention are: To improve the plate efficiency of class-B linear amplifiers and of grid-modulated class-C amplifiers; to provide a method of operating class-B amplifiers always at or near cut-off; to produce larger outputs from tubes of given power ratings, to reduce tube size and power requirements for the production of given output currents, and to provide economy of operation due to decreased power and tube replacement costs; to provide a method of varying anode potential and preferably, control electrode potential, in accordance with the degree of modulation of a signal impressed upon an amplifier or to be modulated upon a carrier; to provide a method of maintaining the ratio of control electrode bias to anode potential constant with variable anode potentials; to provide a method of varying the anode potential without changing the anode current angle of flow; and to make high-level grid-modulated amplifiers commercially practical.

My invention possesses numerous other objects and features of advantage, some of which, together with the foregoing, will be set forth in the following description of specific apparatus embodying and utilizing my novel method. It is therefore to be understood that my method is applicable to other apparatus, and that I do not limit myself, in any way, to the apparatus of the present application, as I may adopt various other apparatus embodiments, utilizing the method, within the scope of the appended claims.

Briefly, my invention comprises a method of operating vacuum tube amplifiers at high efficiency, wherein the anode and control electrode potentials are varied in consonance with the envelope of the modulation envelope.

Referring to the drawings:

Figure 1 is a diagram showing a generalized amplifier circuit.

Figure 2 shows a sine wave representing an audio-frequency signal which has previously been modulated upon a carrier to be amplified in the circuit of Figure 1, operating as a class-B amplifier; or is to be modulated upon a carrier in the circuit of Figure 1, operating as a grid-modulated class-C amplifier.

Figure 3 is a curve showing the voltage applied to the grid when a carrier previously modulated by the audio current of Figure 2 is impressed upon the circuit of Figure 1, operating as a class-B amplifier.

Figure 4 shows the effective plate voltage in the circuit of Figure 1 under class-B operation when the modulated carrier shown in Figure 3 is applied to the control electrode.

Figure 5 is a graphical representation of the plate current in the circuit of Figure 1 for class-B operation.

Figure 6 is a graph showing the voltage applied to the grid by modulating the audio-frequency signal of Figure 2 upon a carrier current, when operating the circuit of Figure 1 as a grid-modulated class-C amplifier.

Figure 7 is a graph showing the effective plate voltage in the circuit of Figure 1, when operating as a grid-modulated class-C amplifier.

Figure 8 is a graph showing the anode current flowing in the circuit of Figure 1 for grid-modulated class-C amplifier operation.

Figure 9 is a circuit diagram showing my method of controlling grid and plate voltages, applied to a conventional linear push-pull amplifier.

Figure 10 is a circuit diagram showing a modification of Figure 9 wherein the potentials supplied to the tube electrodes are varied by means of a grid-controlled gas rectifier, such as a "Thyratron."

Figure 11 is a circuit diagram showing my invention applied to a class-B audio-frequency amplifier using high-mu tubes.

Figure 12 is a circuit diagram showing a class-B audio amplifier, using conventional tubes, wherein the reactor-saturating current is supplied by the direct current flowing in the plate circuit of the class-B audio tube.

Figure 13 is a circuit diagram illustrating my invention, applied to a conventional grid-modulated class-C amplifier.

Figure 14 is a circuit diagram illustrating an alternative arrangement to Figure 13, wherein the grid and plate potentials are controlled through "Thyratron" tubes.

Figure 15 is an extension of the curve shown in Figure 3, illustrating the envelope of the modulation envelope.

Figure 16 is a schematic diagram illustrating the use of a screen-grid tube as a class-B amplifier controlled in accord with my invention.

Briefly, my invention comprises a method of operating vacuum tube amplifiers at high efficiency, wherein the potential applied to the anode, and preferably the biasing potential applied to the control electrode are varied in consonance with the envelope of the modulation envelope, so that the electrode potentials are at all times sufficient to handle the input to the tube

without distortion, without introducing needless loss while the input is unmodulated. This may be accomplished by using a saturable reactor, in which the degree of saturation is controlled by the degree of modulation of the current to be amplified, connected in series with the alternating-current source and the rectifier-filter system supplying the control electrode and anode voltages; or, alternatively, utilizing grid-controlled gas rectifier tubes, such as "Thyratrons," to control these voltages in accordance with the amplitude of the input current.

The principles involved are equally applicable to many types of tubes and amplifiers, class-A, class-B, and grid-modulated class-C amplifiers may be controlled in accord with my invention, and various types of three-element vacuum tubes, screen-grid tubes, and pentodes may be more efficiently operated by the method to be described, while the controlling means and method may be used in various embodiments.

Consider first the case of conventional three-element vacuum tubes operated as class-B linear amplifiers and as grid-modulated class-C amplifiers.

Linear amplifiers have, as is well known, a maximum theoretical efficiency of 78.5 per cent with full excitation, which is reduced in direct proportion as the exciting voltage is reduced. In practice, the maximum efficiency obtained is about sixty per cent with full excitation, and so if provision is made for amplifying a completely modulated signal, the efficiency is of the order of thirty per cent when the carrier is unmodulated.

In grid-modulated class-C amplifiers, the minimum instantaneous plate potential is large except at the crest of the modulation cycle, and when sufficient plate voltage is provided to handle the crest of a completely modulated wave, there is a high voltage drop across the tube when the carrier is unmodulated, and the consequent low efficiency is of the order of that in class-B amplifiers, as above.

In both cases, the result is excessive plate loss, high power cost, and high installed tube capacity in proportion to the power output. These losses are so high that prior to this invention, high-level grid-modulated amplifiers have never been commercially practical. However, these disadvantages may be overcome by causing both anode potential and, preferably, control electrode bias, to vary simultaneously in accordance with the envelope of the modulation envelope, thus materially reducing the plate loss during the time the carrier is unmodulated, raising the over-all efficiency and reducing the rated tube capacity necessary to produce a given power output.

The more detailed operation of my invention may better be understood by reference to the drawings.

Figure 1 shows a generalized circuit for a three-element vacuum tube amplifier. A three-element vacuum tube envelope 1 contains a cathode 2, heated by a source of electricity not shown in the diagram. A battery 4, or an equivalent source of constant direct current, maintains a negative potential upon the control electrode 5 of tube 1. A battery 6, or an equivalent source of constant direct current, maintains a constant positive potential through output impedance 7 upon anode 9. Current source 10 supplies, in the case of class-B amplifier operation, a modulated carrier to be amplified by tube 1. When operating as a grid modulated class-C amplifier, source 10 supplies a radio-frequency carrier current, and an audio-frequency signal current to be modulated thereon.

Figure 3 represents the potential impressed upon grid 5 of tube 1 by source 10 when supplying thereto a modulated carrier. The instantaneous potential 11 is shown bounded by the modulation envelope 14.

The effective plate voltage is the resultant of the constant potential of battery 6, less the load impedance drop. Figure 4 shows the instantaneous value of the effective plate voltage as curve 13, varying about a battery potential of amplitude 17. The variations of the minimum instantaneous plate potentials are shown graphically by dotted line 15, while dotted line 16 indicates the corresponding maximum instantaneous potentials.

For class-B operation, the grid bias is adjusted to cut-off value, and consequently, plate current is permitted to flow only during the positive half-cycles of the modulated carrier impressed on the grid. This half-cycle flow is shown in Figure 5, with the envelope 19 of the maximum instantaneous values shown as a dotted line.

The low efficiency obtained with ordinary class-B amplifiers of modulated radio waves results from the fact that the plate-supply voltage must be large enough to care for the modulation crests, so that during the periods when there is no modulation, or the modulation is very slight, the minimum instantaneous plate voltage is larger than necessary and causes needless plate loss. This may be seen by inspecting the minimum instantaneous plate potential curve 15 of Figure 4. My invention avoids this loss by controlling both the grid-bias and plate supply potentials simultaneously in such a way that they vary in accordance with the envelope of the modulation envelope. It is not desirable to cause these potentials to vary as rapidly as the modulation frequency, and, as will be explained later, it is sufficient that they vary with the average syllabic power of voice-modulated currents. Figure 2 shows a circuit diagram of a linear class-B amplifier 20, adapted to accomplish this purpose by obtaining both grid-bias and plate-supply potentials from a common source and then controlling this common source by a saturated reactor operated by rectified voice-frequency current.

Line terminals 21 are provided, through which the alternating current power may be introduced to the circuit. One of line terminals 21 is connected to one side of a saturable reactor 22, and through leads 24 and 25, the line potential is applied through reactor 22 to the parallel primaries of transformers 26 and 27.

A full-wave rectifying and filtering unit 29 is connected across the secondary of transformer 26. A high resistance 30 is shunted across said rectifying and filtering unit 29 with its positive end grounded. From the negative side of resistance 30, a negative bias is placed on the grids of amplifier 20 through lead 31. This method of obtaining the grid bias is, of course, conventional. A small fixed bias 33 may be inserted in lead 31 for a purpose to be explained later.

A suitable rectifying and filtering unit 32 is connected across the output side of transformer 27, and a positive potential is applied to the plates of the tubes in amplifier 20 through lead 34 from said rectifying unit.

Since the same initial source supplies both plate and grid potentials to the amplifier, it is apparent that any voltage variation across the

primaries of transformers 26 and 27 will affect both equally, in ratio depending on the constants of the transformer and rectifier-filter circuits involved, and that, regardless of the magnitude of the supply voltage change, the ratio between the plate and grid potential variations will remain constant.

Terminals 35 are connected to a rectifier 36 and across the input side of a low-pass filter 37, shown schematically. The output side of filter 37 is connected with the saturating winding of reactor 22.

As the audio-frequency signal is impressed upon terminals 35, rectifier 36 and filter 37 will cause a direct current to flow in the saturating winding of the reactor 22, increasing the degree of saturation of the core and thereby reducing the impedance. This reduction of the reactor impedance permits the potential supplied to the primaries of transformers 26 and 27, and by said transformers to the appropriate rectifier-filter units, to increase to a point where said amplifier 20 can handle the modulated carrier current to be amplified without distortion. It will be noted that if the class-B tubes are originally biased to cut-off and have a substantially constant amplification factor, then the bias will always be at cut-off, irrespective of the amount of saturation in the saturated reactor. The result is, therefore, that regardless of the voltage upon the amplifier-tube electrodes, the tube is always kept in a condition corresponding to class-B operation, with a constant angle of flow of the plate current. However, when the reactor is saturated, both grid-bias and plate-supply potentials become greater, and the tube can handle an increased signal voltage without distortion.

It is frequently found that class-B amplifiers may be operated with a bias slightly less than cut-off, and a gain in linearity secured. For this purpose an additional fixed bias 33 may be inserted in the grid bias lead 31, and used to neutralize a small portion of the variable bias provided by the rectifier filter unit 29.

The initial adjustment is preferably such that the amplifier grid- and plate-supply potentials are normally about ten to twenty per cent greater than the values needed for amplification of the unmodulated carrier. This condition would normally correspond to operating the reactor 22 unsaturated, and represents a voltage roughly fifty-five to sixty per cent of the voltage applied to the class-B tubes when the reactor 22 is fully saturated. The plate efficiency under practical conditions can then be expected to be of the order of fifty to fifty-five per cent, as contrasted with the thirty per cent normally obtained when amplifying only the carrier.

With such potentials on the tube it is possible, however, to accommodate a degree of modulation of only ten to twenty per cent. In order to amplify higher degrees of modulation without distortion it is possible to raise the voltages applied to the tube, as explained above, by rectifying a portion of the audio-frequency signal current and using this rectified current to saturate the reactor. By proper adjustment and proportions it is possible for the saturable reactor 22 to control the supply voltage over the necessary range with relatively little direct-current power, since the saturable reactor is equivalent to an amplifier having a very large gain.

The result is high plate efficiency coupled with constant carrier amplitude. The plate efficiency is high because the plate voltage supplied to the tube is never very much greater than the smallest value necessary to accommodate the exciting voltage. The carrier amplitude is constant because the tube always operates with the same angle of current flow irrespective of the amount of saturation of the reactor. This also results in distortionless amplification.

It is to be noted that non-linearity between the output voltage of the saturated reactor 22 and the direct current saturating current from filter 37 introduces no distortion. It is merely necessary that the voltage applied to the tube electrodes always be sufficient to accommodate the degree of modulation present at the moment. Any excess in supply voltage merely reduces the efficiency slightly without introducing distortion.

For proper operation with voice-modulated waves the saturation of the reactor should follow the syllabic power of the voice. This means that the filter-circuit 37 supplying the saturating current, and also the rectifier-filter systems for the plate and grid voltages, should be proportioned so as to follow variations of average voice power up to perhaps fifteen cycles per second, while discriminating rather sharply against more rapid variations. This can be accomplished with the aid of a suitable low-pass filter 37 and by attention to the filter circuits of the power rectifiers, so that tube potentials will follow average voice power without following the modulation, and vary with the envelope of the modulation envelope. Figure 15 shows graphically the envelope 18 of the modulation envelope 14.

In order that there be absolutely no distortion introduced by the action of the saturated reactor it is desirable to introduce a time delay 39, shown schematically, between terminals 35 and the modulator (not shown) in order that the tube voltages will have time to adjust their amplitude to the degree of modulation by the time this modulation arrives at the grid of the class-B tubes in amplifier 20. However, if the initial adjustment is such as to provide for about twenty per cent modulation before distortion starts, and if the circuit arrangements are such that the saturated reactor tends always to provide sufficient voltage at the tube to handle about twenty per cent higher degree of modulation than required to produce the rectified audio-frequency current in the saturated reactor, then distortion will be very small even if the time delay is omitted. This is because the average degree of modulation in ordinary radio transmitters is usually relatively small, and furthermore does not ordinarily increase with extreme suddenness because audible sounds tend to build up gradually to their full amplitude. If the adjustment is such as to provide this twenty per cent margin, the time required for an increasing amplitude to use up this margin will normally be sufficient to enable the reactor to operate and increase the margin.

The net result obtainable with an arrangement such as illustrated in Figure 9 is therefore a plate efficiency exceeding fifty per cent at all times, as contrasted with the usual average plate efficiency of approximately thirty per cent. The importance of this saving can be seen by considering what it means in connection with a fifty thousand watt broadcast transmitter. With the conventional class-B system having thirty per cent efficiency, the tube dissipation is one hundred seventeen thousand watts; with fifty per cent efficiency the tube dissipation is only fifty thousand watts. This net saving of sixty-seven thou-

sand watts represents a reduction of at least one third in the transmitter power bill, and a halving of the tube capacity required in the output stage. When it is realized that in a five hundred thousand watt transmitter, such as that used in Station WLW, the cost of power and tube replacements is approximately one hundred seventy thousand dollars per year, the dollars and cents value of such economies is obvious.

This high-efficiency system of class-B amplification has all the advantages of a controlled-carrier system of modulation, and in addition provides a constant-carrier power. The automatic volume control and detector problems at the receiver that tend to reduce the desirability of the controlled-carrier transmitter are thereby avoided.

Figure 10 shows a modification of Figure 9. In the circuit of Figure 10, the potentials supplied to the tube electrodes of amplifier 20 are varied by means of grid-controlled gas rectifiers such as "Thyratrons" 40 and 41. A resistance 42, across the low-pass filter 37, provides the voltage drop necessary to control the grids of "Thyratrons" 40 and 41 when a signal current is passed through terminals 35. Additional windings 44 and 45 are provided on transformers 26 and 27 respectively, together with suitable phase-splitters 46 and 47 and transformers 43 and 48 to provide proper control potentials for the grids. Arrangements for using "Thyratrons" to produce controlled direct-current voltages are well known and need not be further elaborated upon.

The same principles discussed above in reference to Figure 9 may be applied to a class-B audio-frequency amplifier as shown in Figures 11 and 12. The fundamental ideas here are essentially the same as above, and need not be repeated in detail. The principal difference is that with class-B audio amplifiers there is no exciting voltage applied during the quiescent periods, while in the case of the class-B radio-frequency amplifier handling modulated waves, there is always at least the carrier present. The result is that the range of control which can be exerted to advantage by the saturated reactor 22 is greater in the case of the class-B audio amplifier. Thus a reasonable arrangement would be to supply, during the quiescent periods, a potential of about one-third the plate potential required during moments when the tube is fully excited. This means that the saturated reactor 22 would give about one-third as much voltage when unsaturated as when fully saturated.

Figure 11 shows an audio amplifier 49 for the use of class-B tubes designed to operate with zero bias, i. e., with tubes having very high amplification factors. This permits simplifying the general layout by the omission of the grid-bias source, leaving merely a variable plate voltage which is increased and decreased as necessary to accommodate the exciting potential.

Figure 12 shows an arrangement similar to that of Figure 9, for use as an audio amplifier, in which the current for saturating the reactor is supplied by the direct-current flowing in the plate circuit of the class-B audio tube.

The current flows from the plates of amplifier 49 through lead 34, through a by-pass filter 50 and the saturating winding of reactor 22 before returning to the positive side of rectifier unit 32. The direct current passing through the reactor performs the same function as that received from the low-pass filter 37 of Figure 9. This current increases with the exciting voltage applied to the tubes, and hence varies in exactly the way necessary to obtain the desired control.

It is of course understood that many variations of the circuit arrangement can be used to carry out the general principles which have been described above. Thus other means of controlling the tube electrode potential source may be employed and the controlling methods may be adapted to polyphase rectifier systems. Under circumstances where several stages of linear amplification are employed, it is possible to simultaneously vary the plate-supply and grid-bias voltages of two or more linear stages with the same saturated reactor. These and other modifications represent minor details as far as this disclosure is concerned. The essential novel idea is the arrangement of class-B amplifiers in such a way that the grid-bias and plate-supply voltages are simultaneously varied by the envelope of audio-frequency in such a way as to maintain the class-B tube always at or near cut-off with the same angle of flow.

Considering now the operation of class-C grid modulated amplifiers; the basic circuit is again that of Figure 1, but source 10 now supplies a carrier current, and an audio-frequency signal current to be modulated thereon. The audio signal is represented in Figure 2 by curve 12, and is shown in Figure 6 superimposed upon a carrier whose instantaneous potential is indicated by curve 11.

Figure 7 shows the instantaneous effective plate potential existing as a result of imposing the varying grid voltage of Figure 6 upon a grid-modulated class-C amplifier tube. This voltage is the resultant, analogous to the case of Figure 4, of the constant potential from battery 6, less the drop in impedance 7. Curve 51 shows the minimum instantaneous effective values of this plate potential.

Figure 8 shows the plate current flow, with the envelope 52 of the maximum instantaneous values. Since the grid bias is greater than cut-off, the current will flow only during the more positive portions of the positive half cycles of the voltage applied to the grid.

An inspection of curve 51 in Figure 7 will show that as in the case of class-B operation, the minimum instantaneous plate potential is relatively large except at the crest of the modulation cycle. This again results in high average plate losses because of the high average voltage drop across the tube and is the result of the fact that sufficient plate voltage must be provided to handle the crest of modulation.

Figure 13 shows a conventional grid-modulated class-C amplifier except for the means of obtaining grid-bias and plate-supply voltage. The grid-bias is here obtained from two separate sources. A battery 52, or other suitable source of constant direct current potential, provides a fixed bias while an additional bias is provided varied in accordance with the degree of modulation as described below. The variable parts of the grid-bias and the plate-supply voltage are derived from the common line voltage applied to terminals 21, using suitable transformers 26 and 27 and rectifier-filter units 29 and 32, as explained for class-B operation. This arrangement insures that these two voltages always have a constant ratio to each other. By making the ratio of voltages supplied through leads 34 and 31 equal to the amplification factor of the tube, variations in the voltage applied to the pri-

maries of transformers 26 and 27 will not alter the angle of current flow in the plate circuit and will have no effect upon the plate-current impulses, provided that the plate voltage is always at least sufficient to accommodate the amount of excitation present. The term "angle of current flow" represents the number of electrical degrees, in terms of the radio frequency grid-exciting voltage, during which the plate current flows, and is a function of the grid-biasing and plate potentials. Altering the voltage applied to terminals 21 merely affects the minimum instantaneous plate voltage and hence the plate losses. For highest efficiency the plate-to-filament voltage should be no larger than necessary to accommodate the exciting and modulating voltages acting on the grid of the modulated amplifier. When this condition is realized the minimum instantaneous plate potential will always be small, the plate efficiency will be high (normally fifty to seventy percent), and yet there need be no distortion.

In the grid-modulated amplifier of Figure 13, the plate-to-filament voltage is varied in accordance with the degree of modulation in such a way that said voltage is raised or lowered as the degree of modulation becomes more or less. In this way the minimum instantaneous plate voltage can be kept small while at the same time insuring adequate plate voltage for all conditions.

Figure 13 illustrates means of accomplishing the necessary voltage control utilizing a saturated reactor 22, in series with the alternating current power source terminals 21. This reactor 22 operates the grid-bias and plate-supply rectifier-filter units 29 and 32, in the same manner as explained in connection with Figure 9. The saturation, and hence the impedance, of this reactor 22 is controlled by the direct current obtained by rectifying and smoothing a portion of the modulating frequency energy impressed upon terminals 35. This gives a saturation that increases with the modulation and hence increases the voltage across primaries of transformers 26 and 27 as the modulation comes on. This in turn increases both grid and plate potentials and thereby enables the tube to handle the increased modulation without distortion when the modulating voltage is applied to the input terminals 53, provided in the grid-circuit of the class-C amplifier.

For proper operation of this arrangement, rectifier-filter systems 29 and 32 should have identical time constants, so that when the voltage across the primaries of 26 and 27 is varied the grid-bias and plate potentials will vary proportionately to each other even during the transient period. It it also desirable that rectifier 36, which operates the saturated reactor 22, be provided with a low-pass filter circuit 37 which will pass frequencies up to about ten or fifteen cycles, but will cut off higher frequencies. This permits the voltage across the primaries of transformers 26 and 27 to vary in accordance with average syllabic power of the voice-modulated waves, but at the same time prevents the system from operating rapidly enough to follow the modulation frequency, just as in class-B operation.

For perfect functioning it is desirable that a time delay 39 be provided, as indicated schematically in Figure 13. This gives the voltages on the tube time to change to accommodate changes in modulation by the time these changes reach the grid of the amplifier through terminals 53. The effect of omitting this time delay will be to introduce momentary distortion when very rapid increases in the amplitude of the modulated voltage occur.

However, if the initial adjustment is such that with no modulation about twenty per cent more plate voltage is present than is required to handle the unmodulated carrier, and if the control for the voltage across the primaries of transformers 26 and 27 is proportioned so that there is always a tendency for the plate voltage of the tube to be about twenty per cent greater than the minimum actually required, then the distortion will be negligible even if the time delay 39 is omitted. The reason is that ordinarily sounds, such as represented by speech, take a small but definite period to build up from zero to maximum intensity, and a twenty per cent margin, in conjunction with a control system having reasonably small time constants, will normally be able to increase the plate voltage fast enough to prevent momentary distortion.

Figure 14 shows an alternative arrangement to Figure 13 wherein "Thyratrons" 40 and 41 are used to control the plate-supply voltage and the variable part of the grid-bias voltage, as explained in connection with Figure 10. The explanation need not be repeated.

With an initial adjustment such that the plate voltage is twenty per cent greater than that required to handle the carrier, one will have about sixty per cent normal plate voltage when the carrier is unmodulated. When sufficient modulating voltage is available to modulate the carrier completely the adjustments should be such that the plate voltage will rise to one hundred, or, better yet, one hundred twenty per cent of the normal value that would be used in a conventional type of grid-modulated amplifier. It is to be noted that the relationship between the plate voltage and the rectified modulating voltage used for control need not be linear. It is merely necessary that the plate voltage increase rapidly enough with increased modulation always to provide ample plate voltage to handle the modulation at the moment.

The benefits to be gained by the use of this high-efficiency grid-modulated amplifier as compared with the conventional grid-modulated amplifier are apparent when a specific example is considered. Assume that the plate efficiency at the crest of the modulation is sixty per cent in the conventional amplifier. Then the plate efficiency during intervals of no modulation is thirty per cent and the average plate efficiency with ordinary speech modulation is barely higher than thirty per cent. In a high-efficiency system in which a twenty per cent margin is allowed in the initial adjustment, the efficiency without modulation will be approximately fifty per cent and will rise slightly with modulation. Hence, in order to obtain one kilowatt carrier power it is necessary to provide two and one-third kilowatts of plate dissipation when a conventional grid-modulated system is used, while the plate dissipation will be only one kilowatt when the high-efficiency circuit is used. The saving that results in the installed tube capacity and hence in the tube costs is obvious, and there is a similar reduction in the power bill and in the cost of the rectifier-filter system required. These economies make high-level grid-modulated power amplifiers entirely practical for the first time.

It is obvious that a variety of alternative arrangements to Figures 13 and 14 are possible.

For example, other control systems can be employed for varying the plate-supply and grid-bias potentials. In particular, where three-phase power is used, a control system operating symmetrically upon each phase can be employed.

It will be noted that the operation of the class-C grid-modulated system is identical, except for the additional constant component of grid-bias used to maintain the tube always under the same class-C conditions, with that of the class-B amplifier, wherein this constant component may be omitted in many circumstances. The essential difference between the two is that in the grid-modulated amplifier only a portion of the total grid-bias is varied as the plate voltage is varied, and the class-C grid-modulated amplifier has been described as associated with a modulation system rather than acting as a simple amplifier.

The essential novelty of my invention in relation to grid-modulated class-C amplifiers lies in: (1) The discovery that by varying the plate voltage, and a portion of the grid-bias, in such a way that the ratio between said plate voltage and said variable grid-bias equals the amplification factor of the tube, the angle of flow of the plate current pulses is unaffected; (2) The use of this principle to increase the efficiency of grid-modulated amplifiers by varying the plate potential and part of the grid-bias in accordance with the degree of modulation.

The common novelty is the operation of the tubes in such a way that all or part of the grid-bias and plate-supply voltages are simultaneously varied by the envelope of the modulation envelope in such a way as to maintain the amplifier in distortionless operation of the type desired; the discovery that if the ratio of the plate voltage to the variable grid-bias is kept equal to the amplification factor of the tube, the plate current angle of flow of the tube is unaffected by the plate voltage variations; and the use of this principle in operation as above to increase class-B and grid-modulated class-C amplifier efficiency by varying the plate potential and grid-bias in accordance with the degree of modulation of impressed signals.

The methods described for three-element vacuum tubes are applicable, with similar gains in efficiency, to circuits using screen-grid tubes as shown in Fig. 16.

In a screen-grid class-B amplifier, the modulated carrier input is impressed upon the control grid; the screen-grid bias is constant, as is that on the control grid, and the anode voltage is varied in accord with the degree of modulation, using a circuit analogous to that of Figure 11.

For grid-modulated class-C amplifier operation, the carrier is applied to the control grid, and the signal to be modulated thereon is impressed on either the control grid or the screen-grid; the biases thereon are fixed.

In either case, it is necessary to vary only the anode potential to accommodate different degrees of modulation, due to the fact that the angle of flow of the anode current is determined by the ratio of the bias on the screen-grid to that on the control grid, and is not affected by the plate potential unless it falls below that on the screen-grid.

My invention may be applied with similar facility to the control of pentodes. In the suppressor-grid type of pentode in common use, the angle of flow in the anode circuit is fixed by the ratio between the screen-grid bias and the control grid bias, as in screen-grid tubes, and is practically independent of the anode voltage, provided it is not so low as to permit space charge formation about the suppressor grid.

Since the pentode delivers large amounts of power, it is well adapted to grid-modulated class-C operation, with the carrier applied to the control grid and the signal to be modulated thereon impressed upon either the control grid or the screen-grid.

I do not wish to be limited to the specific embodiments described herein, as it is apparent that other types of tubes may be controlled in accordance with my method, and the embodiments of the controlling means are themselves susceptible of change, including means responsive to alternating as well as direct current, all within the scope of the appended claims.

I claim:

1. In an amplifier including an electron discharge tube having an envelope containing an anode, a cathode, and a control electrode, the method of operation which comprises applying to said tube anode and control electrode biasing potentials, having a predetermined ratio with respect to each other, creating a signal to be amplified having variations at audio frequencies, varying said anode and control electrode biasing potentials simultaneously in consonance with the envelope of said audio frequency variations and maintaining such ratio of anode and control electrode potentials during transition periods when said potentials are changing in response to said envelope.

2. In an amplifier including an electron discharge tube having an envelope containing an anode, a cathode and a control electrode, the method of operation which comprises developing anode and control electrode biasing potentials from a common source and applying same to said tube, applying to said control electrode a signal potential to be amplified having variations at audio frequencies, and varying said anode and control electrode biasing potentials simultaneously in consonance with the envelope of said audio frequency variations.

3. In an amplifier including an electron discharge tube having an envelope containing an anode, a cathode and a control electrode, the method of operation which comprises applying to said tube variable anode and control electrode biasing potentials, maintaining the ratio of said anode potential to said variable control electrode potential substantially equal to the amplification factor of said tube, applying to said control electrode constant additional biasing potential sufficient to maintain said tube at or near cut-off, applying a modulated signal potential to be amplified to said control electrode, and varying said anode and variable control electrode biasing potentials simultaneously in consonance with the envelope of the envelope of said modulated potential.

4. In an amplifier including an electron discharge tube having an envelope containing an anode, a cathode and a control electrode, the method of operation which comprises applying to said tube variable anode and control electrode biasing potentials, maintaining the ratio of said anode potential to said variable control electrode potential substantially equal to the amplification factor of said tube, applying to said control electrode constant additional biasing potential sufficient to maintain said tube at or near cut-off,

rectifying a portion of the signal current to be externally modulated upon a carrier, varying said anode and variable control electrode potentials in consonance with the envelope of said rectified current, and applying a carrier externally modulated by the unrectified portion of said signal current to said control electrode.

5. In a class-B amplifier including an electron discharge tube having an envelope containing an anode, a cathode and a control electrode, the method of operation which comprises applying to said tube variable anode and control electrode biasing potentials, maintaining the ratio of said anode potential to said variable control electrode potential substantially equal to the amplification factor of said tube, applying to said control electrode constant additional biasing potential sufficient to maintain said tube in operation at or near cut-off, rectifying a portion of the modulating signal current, varying said anode and variable control electrode potentials in consonance with the envelope of said rectified portion of the modulating current, delaying the unrectified portion of said current, and impressing a carrier modulated by said delayed current upon said control electrode.

6. An amplifier comprising an electron discharge tube having an envelope containing a cathode, an anode and a control electrode, means for obtaining anode and control electrode potentials from a common supply source, means comprising a low-pass rectifier-filter combination for passing a portion of the low-frequency pulsating direct current component derived from a signal current, means responsive to said portion of a signal passed by said rectifier-filter combination for utilizing said portion of said signal to control the output energy of said common anode and control electrode potential supply source, and means impressing upon said tube, energy varying in accordance with the variations of unrectified signal current.

7. An amplifier comprising an electron discharge tube having an envelope containing a cathode, an anode and a control electrode, means for obtaining anode and control electrode potentials from a common supply source, said means including a saturable reactor, controllable by direct current, a low-pass rectifier-filter for passing through said reactor a portion of a low-frequency pulsating direct current component, derived from a signal to be modulated upon a carrier, and means including a time delay circuit arranged to retard the modulation of such carrier with such signal.

8. An amplifier comprising an electron discharge tube having an envelope containing a cathode, an anode and a control electrode, a common anode and control electrode potential supply, including a saturable reactor, controllable by direct current, having a fixed ratio of said anode potential to said control electrode potential substantially equal to the amplification factor of said tube, a low-pass rectifier-filter unit for passing a portion of a low-frequency pulsating direct current derived from the modulating signal through said reactor, a fixed source of additional control electrode bias sufficient to maintain the said tube, when energized, in a desired class of operation, a time delay circuit arranged to impress the unrectified portion of said current upon a modulating circuit, and means for impressing a carrier modulated thereby upon said tube.

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