Nov. 26, 1940. P. T. FARNSWORTH 2,223,001

HIGH EFFICIENCY AMPLIFIER

Filed April 24, 1939 3 Sheets-Sheet 1

Fig. 1.

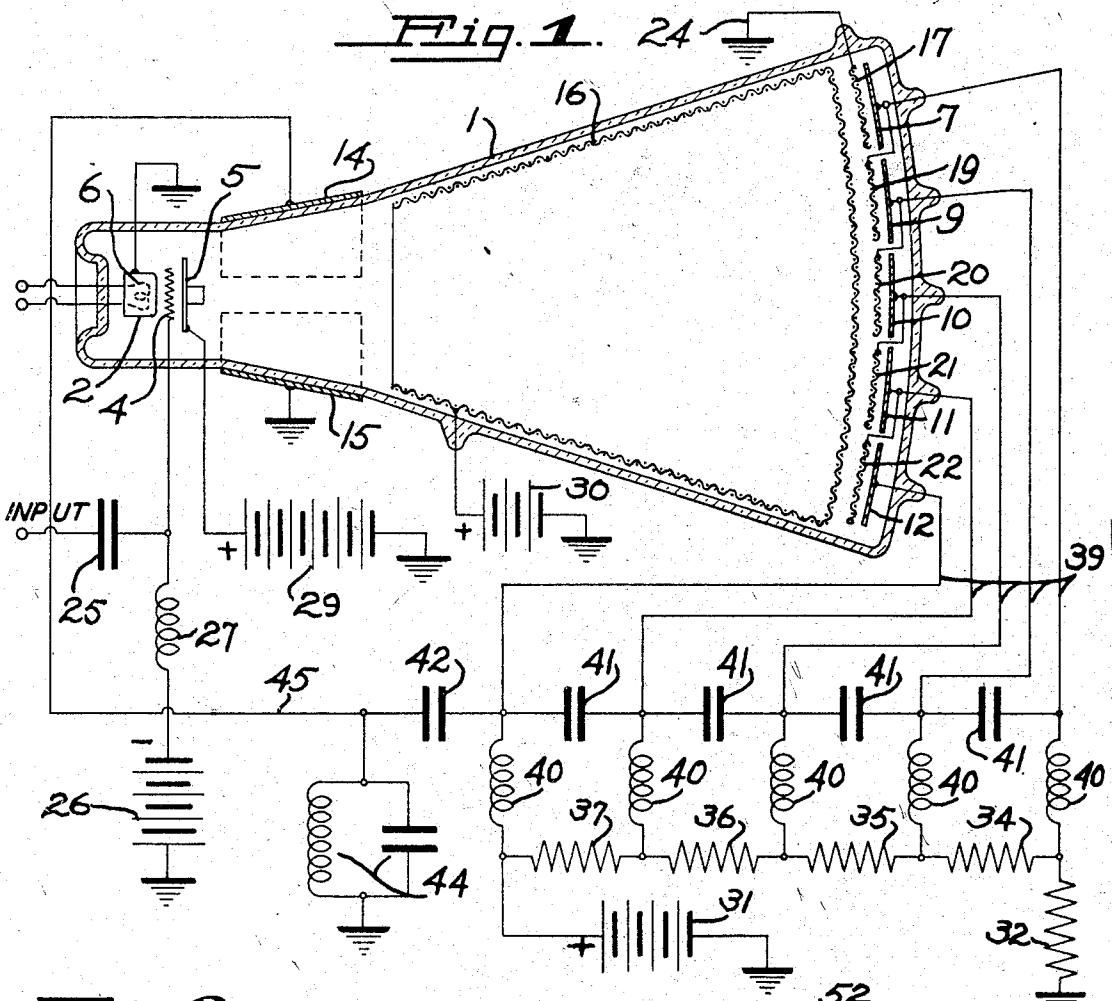
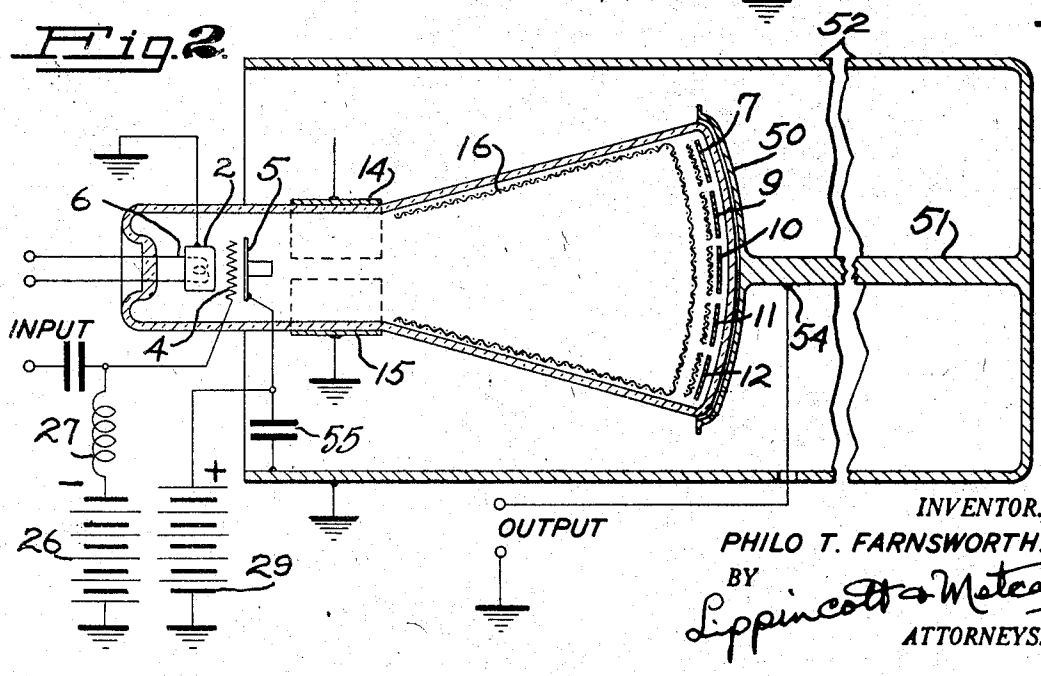


Fig. 2.



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Fig. 3.

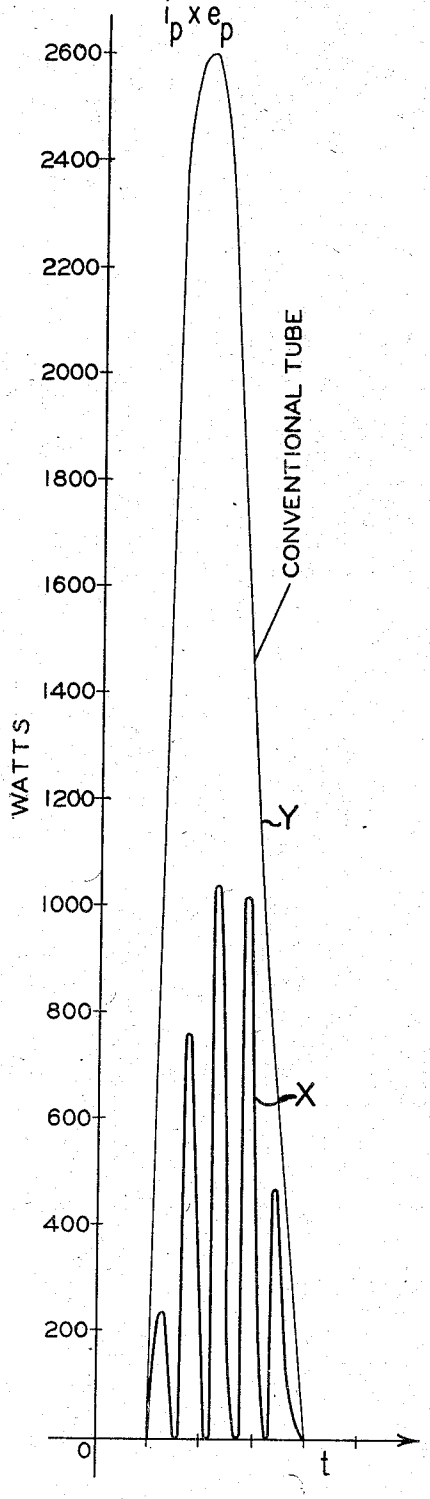


Fig. 4.

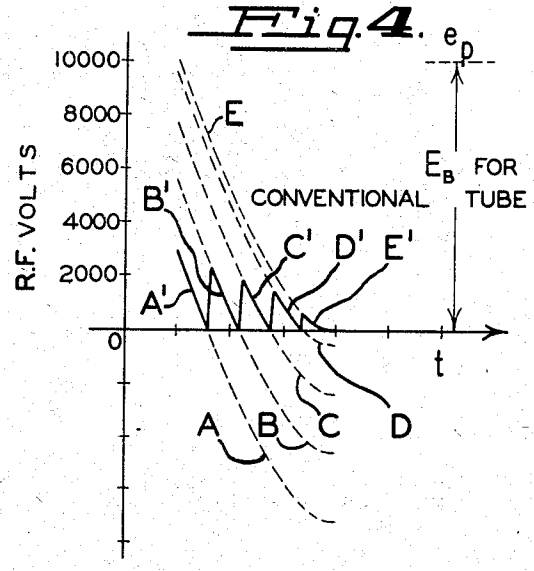


Fig. 5.

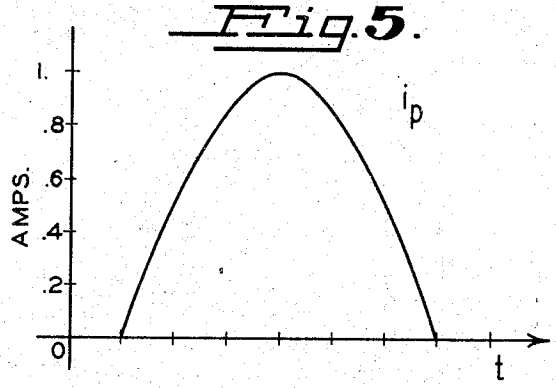
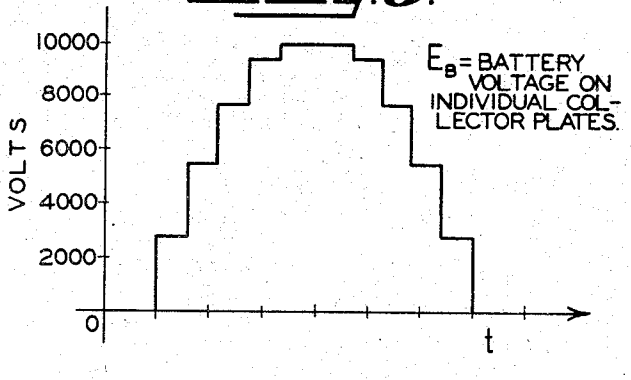


Fig. 6.



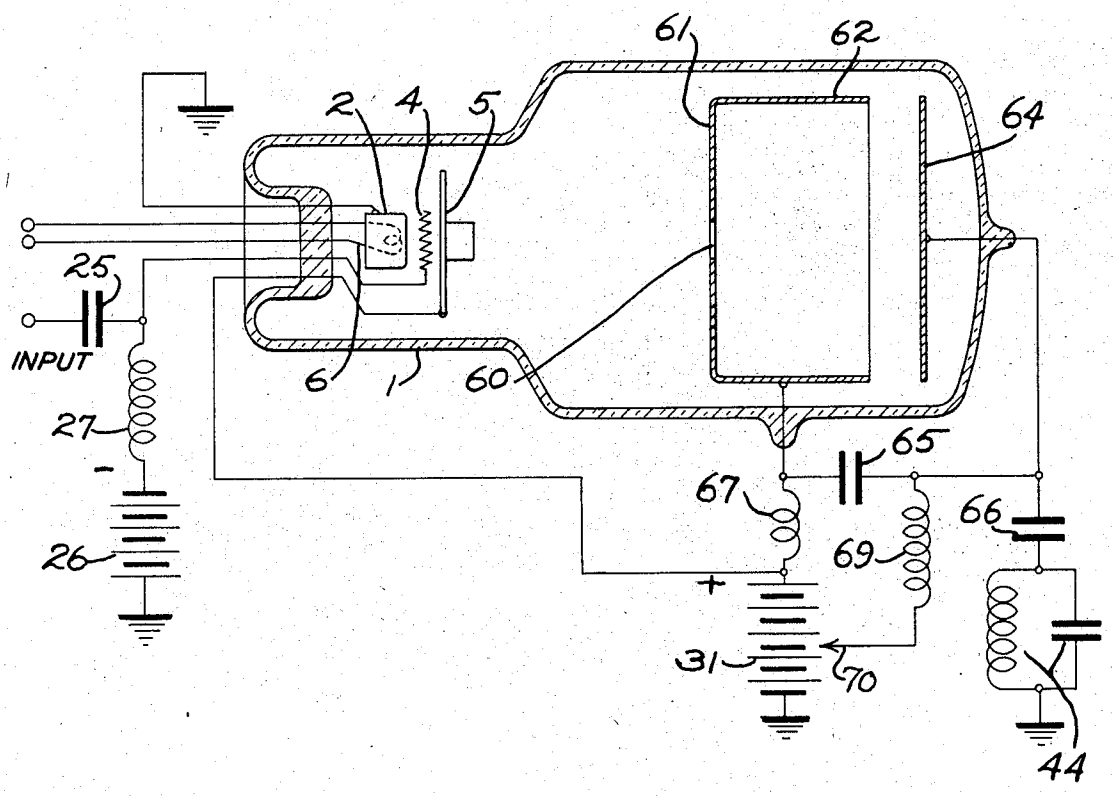
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Fig. 7.



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Examiner

Patented Nov. 26, 1940

2,223,001

UNITED STATES PATENT OFFICE

2,223,001

HIGH EFFICIENCY AMPLIFIER

Philo T. Farnsworth, Philadelphia, Pa., assignor to Farnsworth Television & Radio Corporation, New York, N. Y., a corporation of Delaware

Application April 24, 1939, Serial No. 269,589

16 Claims. (Cl. 179—171)

My invention relates to electron discharge tubes, and more particularly to an electron discharge tube utilizing an electron beam, in such a manner as to create a radio-frequency amplifier which may be operated in class B at high efficiency.

Among the objects of my invention are: To provide a high efficiency radio-frequency amplifier; to provide a radio-frequency amplifier which may be operated with high efficiency as a class B amplifier; to provide a radio-frequency amplifier having low plate losses; to provide a high efficiency class B amplifier utilizing an electron beam; to provide a means for and method of reducing plate losses in a class B amplifier; to provide a means for and method of reducing plate losses in a radio-frequency amplifier; to provide a means for and method of coordinating plate voltage with instantaneous radio-frequency voltage in a radio-frequency amplifier; to provied a means for and method coordinating plate voltage and instantaneous radio-frequency voltage in a radio-frequency amplifier to produce low plate losses; and to provide a simple, highly efficient radio-frequency amplifier.

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.

Referring to the drawings:

Fig. 1 is a diagrammatic sectional view of one form of my invention, together with one circuit for operation thereof.

Fig. 2 is a sectional view of one form of my invention as applied to a transmission line output circuit.

Fig. 3 is a graph showing plate losses in conventional tubes as compared to the tube of my invention.

Fig. 4 is a graph of a group of curves showing effective plate voltages operating in one illustrative energization of the tube of my invention.

Figs. 5 and 6 show the relationship in the tube of my invention of total plate current to individual plate battery voltages.

Fig. 7 is a diagrammatic sectional view of another form of my invention utilizing only two plates.

Conventional triodes and multi-grid tubes are usually operated as class C amplifiers when utilized for the amplification of radio-frequency voltages because of high plate losses and consequently low efficiency, when operated other than class C. Inasmuch as the instantaneous plate loss is equal to $i_p \times e_p$, where i_p is the instantaneous plate current and e_p is the instantaneous plate voltage, current in class C amplifiers is allowed to flow only in that part of the cycle during which the plate voltage is at a minimum in order to keep the product of $i_p \times e_p$ smaller. The plate voltage necessary for the operation of a conventional tube such as a triode, for example, is predetermined by the maximum radio-frequency voltage amplitude. However, in parts of the radio-frequency cycle the plate voltage is unnecessarily high for the instantaneous radio-frequency voltage. Also, if the peak value of the modulated radio-frequency voltage be smaller than the maximum value the plate voltage is also unnecessarily high. Thus, in both cases the plate losses are appreciably increased without a simultaneous increase in output. These losses naturally decrease the efficiency of the tube.

Theoretically, maximum efficiency would be obtained if the battery voltage applied to the plate were to be variable and of such instantaneous value as would be required by the instantaneous radio-frequency voltage. If this could be accomplished an efficiency of 100% could be approached, even in class B operation, and efficiency would no longer be a function of the percentage of modulation.

The main object of the present invention is to provide a tube and a method of operating such a tube which causes the output efficiency to be greatly increased, and which makes the operation of the tube approach the above-recited conditions necessary for high efficiency.

Broadly as to means, my invention comprises a tube containing an electron gun of any conventional type producing an electron beam. Means are provided to move the beam over a predetermined path, and in this path are positioned a plurality of plates which serve to collect electrons in the beam. These plates are preferably interconnected by capacitances, thus constituting one unit as far as radio-frequency potentials are concerned. The plates are, however, isolated as to unidirectional potentials and are held at unidirectional potentials increasing serially in steps along the extent of the beam path. The electron beam is normally adjusted in such a manner that it impacts the plate which is be-

ing held at the lowest unidirectional potential at the beginning of the half cycle of current flow.

Broadly as to operation, the tube may be operated as a class B amplifier, and the input radio-frequency signals may be applied to the grid of the electron gun. The radio-frequency voltage amplitude may be equal to the highest unidirectional plate voltage and may be considerably greater than the unidirectional voltage of the first plate upon which the electron beam impacts at the beginning of the half cycle.

The effective plate voltage shall be taken as the sum of the applied unidirectional voltage and the instantaneous radio-frequency voltage across a work circuit in the radio-frequency connection common to all plates. At the beginning of the cycle the plate current increases and the radio-frequency voltage increases in negative polarity. Thus, as the radio-frequency cycle progresses the effective plate voltage will decrease, and finally will reach the minimum value necessary for collection of electrons and would, if allowed to do so, drop below this value. This would prevent further collection of electrons and thereby cause a cessation of plate current flow. This latter condition, however, is prevented because substantially at the instant when the effective plate voltage would reach the minimum required value for collection the electron beam is deflected to the next plate which carries a higher unidirectional potential, and the effective plate voltage will be again sufficient to cause current flow. As the radio-frequency voltage goes still more negative, the unidirectional potential of the second plate will also become insufficient to prevent the effective plate voltage from falling below the required minimum value, and again at this predetermined value of effective plate voltage the electron beam is deflected to the third plate which carries a still higher unidirectional anode voltage, thus again compensating for the increase in negative radio-frequency voltage.

This procedure is sequentially carried on until the electron beam is deflected to the final plate which carries a unidirectional potential equal to or slightly greater than the radio-frequency voltage amplitude. As the cycle progresses, the negative radio-frequency voltage will decrease and the effective plate voltage increase. However, as soon as the effective plate voltage exceeds a predetermined value and reaches a value greatly in excess of the required minimum value, the electron beam is deflected back to the next to the last plate which carries a lower unidirectional potential, thus reducing the effective plate voltage. This procedure is carried on until the electron beam reaches the plate of lowest unidirectional potential, whereupon the half cycle is completed and the plate current is cut off. The same procedure is then repeated upon re-establishment of the plate current.

It should be understood that the effective plate voltage can be allowed to sink to cathode potential so that the arriving electrons have velocities as low as zero, because in the tube of my invention the plate current is no longer a function of the effective plate voltage as long as this voltage is not negative. A deflection of the electron beam occurs, broadly as described above, at a predetermined value of radio-frequency voltage. Any convenient deflecting means may be utilized to which a voltage proportional to the radio-frequency voltage is applied, thus rendering the angle of deflection a function of the instantaneous radio-frequency voltage.

Referring directly to the drawings for a more detailed description of my invention, and more particularly to that modification shown in Fig. 1, an envelope 1 of the usual conical shape, is provided at the small end thereof with an electron gun comprising an electron-emissive cathode 2, a control grid 4, and an accelerating anode 5. The cathode 2 may be heated by the usual type of heating coil 6.

At the opposite and larger end of the tube are positioned a series of five plates, numbered from top to bottom, 7, 9, 10, 11 and 12. It should be distinctly understood, however, that the use of five plates is illustrative only, as different numbers of plates can be used, following the teachings given herein.

Adjacent the gun, deflection electrode 14 and 15 may be utilized, positioned either inside or outside of the tube, as desired, and so located as to, when energized, deflect the beam across the series of plates. Between the deflection means and the plate assembly I position a Faraday cage 16. As will be described later, I find it convenient, in certain cases, to provide each plate with a suppressor grid, and consequently plate 7 is provided with suppressor grid 17, plate 9 is provided with suppressor grid 19, plate 10 is provided with suppressor grid 20, plate 11 is provided with suppressor grid 21, and plate 12 is provided with suppressor grid 22. The suppressor grid of each stage is connected to the plate of the stage just above in the drawing, with the exception of anode 7 whose suppressor grid 17 is grounded through a ground connection 24.

Returning again to the gun end of the tube, cathode 2 is grounded. Modulated radio-frequency voltage is applied to grid 4 through an input condenser 25, and the grid is biased to cut-off by means of bias battery 26 through choke coil 27. Gun anode 5 is maintained at a steady unidirectional potential by gun anode battery 29. Faraday cage 16 is held at a slight positive potential by cage battery 30. A plate voltage source 31 is shunted by serially connected voltage dividing resistors 32, 34, 35, 36 and 37, and connections 39 are taken therefrom through choke coils 40 in order to serially energize the plates, with plate 7 at the lowest positive potential, plate 9 at the next higher positive potential, plate 10 at the next higher positive potential, plate 11 at the next higher positive potential, and plate 12 at the highest positive potential. Resistors 34 to 37 inclusive are each bridged above choke coils 40 by radio-frequency condensers 41, thus forming the anodes into one unit for radio-frequency potentials, and the radio-frequency anode unit is then connected through direct-current blocking condenser 42 to output or work circuit 44. A further connection 45 is taken from work circuit 44 to one deflecting electrode 14, the other electrode 15 being grounded. The function of Faraday cage 16 may be seen to be for the purpose of preventing the field due to the differing anode potentials from deviating the electron beam from its desired path, as predetermined by deflecting plates 14 and 15.

In considering the operation of the tube and circuit as described above, I will first assume that all plates are made of perfectly non-secondary electron emitting material, and that the suppressor grids, as described, are not used.

At the beginning of the half cycle of current flow in the beam, as determined by the potential of grid 4, the electron beam is focused upon anode 7 which may be held, for example, at a certain

unidirectional potential of, for example, 2800 volts. In the following description of operation of my invention I have selected certain relative voltages which have been found to operate one example of my tube satisfactorily, but it must be understood, however, that I do not wish to be limited to the voltages recited herein in any way, as they are illustrative only of one type of circuit and one type of tube. Other voltages, together with modifications of the tube structure, will be apparent to those skilled in the art.

As the negative radio-frequency voltage increases the effective plate voltage on plate 7 will decrease. The radio-frequency voltage proper, or a voltage proportional to it, is applied to deflecting electrode 14, the opposite electrode 15 being grounded. Thus, the electron beam will be deflected toward plate 9, and at a predetermined value of the radio-frequency voltage the beam will be deflected to such an extent that it passes off from plate 7 and from then on impacts plate 9 to which a battery voltage of, for example, 5500 volts is applied.

Referring now to the group of curves shown in Fig. 4, curve A represents the e_p curve for 2800 volts on anode 7, and a radio-frequency amplitude of 10,000 volts. As long as the electron beam impacts plate 7 the dark portion A' of curve A represents the curve of operation. As can be seen, the effective plate voltage e_p decreases until it has reached a predetermined value, in this case cathode potential, and the electron beam is then deflected onto plate 9 to which a battery voltage of 5500 volts is applied, as represented by curve B. From then on the black portion B' represents the curve of operation, illustrating e_p for a voltage of 5500 volts and a radio-frequency amplitude of 10,000 volts. As the cycle progresses, e_p again decreases to cathode potential and the electron beam is then deflected upon plate 10 carrying 7700 volts, as shown in curve C. The e_p values are then shown by the black portion C' of curve C. This procedure is repeated as the beam passes onto plate 11, represented by curve D with an operating portion D', and finally the beam passes onto last plate 12 represented by curve E with the operating portion E'. The last plate may may be held at a voltage of 10,000 volts.

After the negative peak of the radio-frequency voltage is passed, the effective plate voltage tends to become greater as the cycle progresses. However, as the radio-frequency voltage becomes less negative the deflecting power on the electron beam becomes less, and at a predetermined value on curve E the electron beam will be deflected back to plate 11 again and the e_p value will follow curve D, and so on until curve A is reached, and the e_p values follow this curve until current flow starts again in the succeeding cycle.

Thus, it may be seen by the darkened portions A', B', C', D' and E' in Fig. 4 that it is possible to obtain an effective plate voltage which does not greatly exceed the minimum required value for substantially the entire part of the half cycle during which current flows.

Fig. 5 shows an assumed form of plate current (i_p) flow during the half cycle as the tube is operated in class B, and Fig. 6 is shown immediately below Fig. 5 to show the manner in which the anode unidirectional voltages are varied to spread over the current half cycle of Fig. 5. The darker curve X of Fig. 3 shows the instantaneous plate loss over one-half of the operating portion of the radio-frequency cycle for a tube made in accordance with the invention herein described and claimed, and this curve was obtained by multiplying the corresponding ordinates of Fig. 5 with those of Fig. 4. Curve Y in Fig. 3 shows the instantaneous plate loss which would obtain for a conventional tube or for the tube of my invention if the electron beam was not deflected but instead a single plate supplied with a unidirectional plate voltage of 10,000 volts. A comparison of curves X and Y shows that the plate loss in the tube of my invention may be reduced to approximately one-third or one-fourth of the loss in a tube operated in the conventional manner. It may be seen also by an analysis of curves in Figs. 4, 5 and 6 that the velocities of the impacting electrons are substantially the same within predetermined limits over the entire period of current flow in the tube. Consequently, the time of flight of the electrons does not enter into the operation of the tube.

The efficiency of the tube is, within very small limits, independent of the percentage of modulation, but as can be readily seen from a comparison of Figs. 5 and 6, is only dependent upon the number of plates in the tube.

Referring back now to the use of the suppressor grids 17, 19, 20, 21 and 22, these may be found desirable because of the difficulty in obtaining for the plates a material which is absolutely non-secondary electron emitting in practice. The positioning and connecting of the suppressor grids has been described above, and the use of these suppressor grids changes the mode of operation to some extent in that the suppressor grid of the stage in action cannot be allowed to drop to a potential lower than cathode potential because a blocking effect would otherwise occur. Thus, when suppressor grids are used it is necessary to shift the beam from one stage to the following when the effective plate voltage of the preceding stage approaches cathode voltage. However, the actual efficiency is not greatly reduced when using suppressor grids.

Thus, it will be seen that I have provided a tube and circuit, and method of operation, which provides class B operation at a high efficiency independently of the percentage of modulation. This leads to a number of advantages, namely, more power may be handled in one tube, or for the same power output the tube electrodes may be made considerably smaller, thereby decreasing the internal capacitances and making possible the amplification of higher frequencies.

In Fig. 2 I have shown a tube capable of high-frequency use, wherein the plates 7, 9, 10, 11 and 12 are capacitively coupled through a metal cap 50, fitting the plate end of the tube, to the central conductor 51 of a transmission line whose outer shield 52 is held at ground potential. The outer shield 52 of the transmission line is connected to anode 5 of the gun through a blocking condenser 55, thereby holding both at radio-frequency ground potential. In this illustration I have omitted, for purposes of clarity, the connections to the anodes, the latter being taken out of the side of the tube, rather than the end as in Fig. 1; otherwise the two tubes may be identical. The output may be taken from a point 54 on inner conductor 51 of the transmission line a quarter wavelength from cap 50.

In Fig. 7 I have shown a simplified structure embodying my invention wherein only two separate plates are utilized. In this modification the electron gun is mounted in one end of the envelope, as in the other modifications, and the beam issuing from gun anode 5 under nor-

mal circumstances passes through an aperture 60 in a cup-shaped plate 61, the side walls 62 of the cup being extended away from the gun. Spaced slightly beyond the open end of the cup just inside the end of the envelope is a planar plate 64. Plates 61 and 64 are connected by radio-frequency condenser 65 so that they form one unit for radio-frequency potentials. The tuned output circuit 44 is connected at one end to the two plates through a direct-current blocking condenser 66. Plate source 31 is connected at one end so that the full positive potential thereof is placed directly on plate 61 through radio-frequency choke coil 67, and plate 64 is energized with approximately one-half of the voltage of source 31 through radio-frequency choke coil 69 by plate battery tap 70. In this modification the input radio-frequency voltage is supplied to the grid of the gun as in the other modifications, and the tube is operated in Class B by being biased to cut-off by bias battery 26.

At the beginning of the half cycle during which current flows in the beam, the electron beam will pass directly through aperture 60 and will impact the plate 64 to which half the battery voltage is supplied. As the current cycle in the beam progresses, the potential of plate 64 becomes lower and lower until it falls below cathode potential, whereupon electrons will be no longer collected by plate 64 but by cup plate 61, and toward the end of the half cycle during which the potential on plate 61 becomes lower, the electron collection will pass back again to plate 64. Thus, the operation of this simplified modification is the same as in the more complicated structure described first above, except for the fact that the beam is shifted only twice during the half cycle of beam current flow. While, of course, the efficiency gain will not be as great as in the prior modifications described, the simplification of the circuits is highly advantageous because it will be seen that no special means is required for deflecting the electron beam, and deflection occurs automatically.

It should also be pointed out herein that the plate 61 does not necessarily need to be cup-shaped but may be in the form of a cylinder. The main reason for making the device cup-shaped is to prevent the possibility of electrons drifting back toward the gun assembly and thereby escaping collection.

Thus, I have been able to increase the efficiency of a radio-frequency amplifier by shifting the electron beam during the collection cycle to plates having unidirectional potentials related to the instantaneous radio-frequency potential, to avoid excess unidirectional voltages at differing portions of the cycle.

I claim:

1. An amplifier comprising an envelope containing means for producing an electron beam, means for cyclically varying the intensity of said beam, means for moving said beam over a predetermined path in accordance with the varying intensity of said beam, and a plurality of plates along said path, said plates being energized to unidirectional potentials increasing in accordance with the intensity of said beam and the position of said beam.

2. Apparatus in accordance with claim 1, wherein all of said plates are capacitively coupled to a work circuit.

3. An amplifier comprising an envelope containing means for producing an electron beam, means for cyclically varying the intensity of said beam, means for moving said beam over a predetermined path in accordance with the varying intensity of said beam, a plurality of plates along said path, said plates being capacitively coupled to a work circuit, and means for energizing said plates serially to increasing unidirectional potentials in accordance with the intensity of said beam and the position of said beam.

4. An amplifier comprising an envelope containing means for producing an electron beam, means for cyclically varying the intensity of said beam, a plurality of plates positioned to be impacted by said beam, means for energizing said plates at serially increasing unidirectional potentials, means for deflecting said beam serially over said plates, means for capacitively coupling all of said plates to a work circuit, and means for moving said beam from one plate to the next in order when the instantaneous radio-frequency voltage neutralizes the unidirectional potential on the impacted plate.

5. An amplifier comprising an envelope containing means for producing an electron beam, means for cyclically varying the intensity of said beam, a plurality of plates positioned to be impacted by said beam, means for energizing said plates at serially increasing unidirectional potentials, means for deflecting said beam serially over said plates, means for capacitively coupling all of said plates to a work circuit, and means for moving said beam from one plate to the next in order before the instantaneous radio-frequency voltage prevents collection of additional electrons by the plate impacted.

6. Apparatus in accordance with claim 4, wherein the means for moving said beam is energized in synchronism with the variation of radio-frequency voltage in the work circuit.

7. Apparatus in accordance with claim 4, wherein the means for moving said beam is energized by energy taken from said work circuit.

8. Apparatus in accordance with claim 4, wherein the means for moving said beam is energized by energy taken from said work circuit and in a direction to move said beam from the plate having lowest unidirectional potential at the beginning of the radio-frequency cycle to the plate having highest unidirectional potential and back to the plate having lowest unidirectional potential, at the end of the radio-frequency cycle.

9. Apparatus in accordance with claim 4, wherein the work circuit is a transmission line having its inner conductor capacitively coupled to all of said plates.

10. Apparatus in accordance with claim 4, wherein the work circuit is a transmission line having its inner conductor capacitively coupled to all of said plates, and wherein the output is taken from said inner conductor at a point one-quarter of the radio-frequency wavelength from the capacitive coupling means.

11. Apparatus in accordance with claim 4, wherein two only plates are utilized, one of said plates being nearer said beam-producing means than the other, said nearer plate being apertured to allow passage of beam electrons to the other plate, and wherein the nearer plate is held at the highest unidirectional potential.

12. Apparatus in accordance with claim 4, wherein two only plates are utilized, one of said plates being nearer said beam-producing means than the other, said nearer plate being aper-

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tured to allow passage of beam electrons to the other plate, and wherein the nearer plate is held at the highest unidirectional potential, the other plate being held at substantially one-half said highest potential, said plates also acting as the recited deflection means due to change of potential thereon by electron collection.

13. The method of amplifying radio-frequency signals which comprises generating a defined beam of electrons, modulating said beam with the radio-frequency signals to be amplified, moving said beam through a predetermined path in space, collecting electrons in different areas along said path at unidirectional collection voltages varying in accordance with the variation of the instantaneous radio-frequency voltage produced by said collection in an external circuit, and utilizing energy from said external circuit to move said beam.

14. The method of amplifying radio-frequency signals which comprises generating a defined beam of electrons, modulating said beam with the radio-frequency signals to be amplified, moving said beam across and back over a predetermined path corresponding in time to one-half radio-frequency cycle, collecting electrons in different areas along said path at unidirectional collection voltages varying in accordance with the variation of the instantaneous radio-frequency voltage produced by said collection in an external circuit, and utilizing energy from said external circuit to move said beam.

15. The method of amplifying radio-frequency signals which comprises generating a defined beam of electrons, modulating said beam with the radio-frequency signals to be amplified, moving said beam through a predetermined path in space in synchronism with the modulations of said beam, collecting electrons in different areas along said path at unidirectional collection voltages varying in accordance with the variation of the instantaneous radio-frequency voltage produced by said collection in an external circuit, and utilizing energy from said external circuit to move said beam.

16. The method of amplifying radio-frequency signals which comprises generating a defined beam of electrons, modulating said beam with the radio-frequency signals to be amplified, moving said beam through a predetermined path in space in synchronism with the modulations of said beam, intercepting the beam electrons in different areas along said path by a positive collection potential differing in each area over the path of said beam in accordance with the instantaneous radio-frequency potential developed by collection, and utilizing energy from said external circuit to move said beam.

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