This invention relates to a dynode control circuit for a multiplier phototube and, more particularly, to a regulator circuit for automatically adjusting the amplification of a multiplier phototube in response to contemporary values of the output current thereof to maintain the average current output of the phototube substantially constant.

Multiplier phototubes are often used for detecting low intensity light, and are especially suited for use in environments where it is desired to detect modulation of low intensity light. As respects the detection of light having low intensity, such phototubes offer advantages over other photoelectric devices in that the minute current generated by light impinging upon the photocathode of the tube is amplified by the action of a series of dynodes or secondary emission stages contained within the tube itself, thereby obviating the necessity of amplification stages that might otherwise be required. Generally stated, the amplification factor of multiplier phototubes may be in the range of five orders of magnitude.

In operation of a multiplier phototube, light incident upon the photocathode thereof causes the release of electrons which are then attracted to the first of a series of secondary emission electrodes (that is, dynodes)—which first dynode is maintained at a positive potential relative to the photocathode by an amount usually in the order of 100 to 200 volts. Upon arriving at the first dynode, the electrons striking the same dissipate some of their energy at the dynode surface, thereby causing the release of secondary electrons that are ejected from the dynode surface at a relatively low velocity. Depending upon the potential of the first dynode, as many as eight to ten secondary electrons may be emitted for each primary electron striking the dynode surface.

Typically, electrons liberated from the surface of the first dynode are accelerated toward a second dynode, the surface of which is maintained at a positive potential with respect to the first dynode usually by from 50 to 150 volts. Upon arrival of the electrons at the second dynode and their striking the surface thereof, a plurality of electrons are released for each electron striking the dynode surface, and all of the thusly released electrons are accelerated toward a third dynode which is maintained at a positive potential relative to the second dynode. This action of electrons being attracted toward a dynode, striking the surface thereof, and causing the secondary emission of a much greater number of electrons is repeated at each dynode contained within the multiplier phototube; and in current practice, tubes of this type generally have between six and twelve dynodes.

The number of secondary electrons emitted per primary electron at each dynode stage is essentially a function of the kinetic energy of the primary electron, and such kinetic energy is directly proportional to the potential difference between the emitting electrode (usually dynode) from which the primary electron was emitted and the dynode at which it arrives. Over the useful operating range of voltage differences between successive dynodes, the number of electrons emitted is very nearly a linear function of the potential difference between adjacent dynodes. Therefore, in a multiplier phototube containing ten dynodes, the amplification of the tube as a whole will vary substantially as the tenth power of the voltage applied across the dynode string. As a result, the final anode current of the phototube is strongly dependent upon the value of the voltage applied thereacross.

Evidently then, accuracy in the amplification of multiplier phototubes requires that the applied voltage be maintained relatively constant, and usually a voltage variation of more than 1% to 2% at the very most is exceedingly undesirable. A further complication connected with the use of multiplier phototubes is that the dynodes thereof vary widely in their electron-multiplying efficiency from unit to unit; and as a result of this variation together with the sensitivity of phototubes to fluctuations in the supply voltage, each installation of a tube requires careful tailoring and adjustment within rather narrow limits. Further, however, there is a slow change in dynode efficiency throughout the useful life of multiplier phototubes which cannot be predicted with accuracy and which disturbs the amplification characteristics thereof, and also temperature changes are found to alter the dynode efficiency. Generally stated, the amplification of multiplier phototubes is significantly affected both by changes in the internal characteristics thereof and by changes in environmental conditions; and because of this, accurate determination and maintenance of the tube amplification is difficult to attain.

In view of the foregoing, an object of the present invention is to provide an arrangement that is automatically operative to compensate for changes in the numerous variables (such as changes in supply voltage, in temperature conditions, and in dynode efficiency) which would otherwise alter the over-all amplification of a multiplier phototube so as to maintain such amplification substantially constant.

Another object is in the provision of a regulator circuit in association with a multiplier phototube for automatically adjusting the amplification thereof to maintain the average current output of the tube substantially constant—such automatic adjustment being effective not only to compensate for changes in the aforementioned variables, but also to compensate for changes in the average intensity of the light incident upon the photocathode of the tube.

Still another object is that of providing a regulator circuit of the character described in which the average current output of a multiplier phototube is maintained at a substantially constant value by automatically adjusting the potential difference between at least two and usually between several successive or adjacent dynodes in response to contemporary values of the output current of the tube.

Yet another object is that of providing an arrangement as described, in which the regulator circuit is substantially insensitive to rapid fluctuations in the anode current of the multiplier tube so that modulation of the light incident on the photocathode thereof, and which causes such rapid fluctuations, can be detected. Additional objects and advantages of the invention will become apparent as the specification develops.

Embodiments of the invention are illustrated in the accompanying drawings, in which:

FIGURE 1 is a schematic diagram of a multiplier phototube and regulator circuit thereof; and

FIGURE 2 is a schematic diagram of a modified multiplier phototube and regulator circuit.

In accordance with the present invention, a string of cascaded transistors are coupled to the dynodes of an electron multiplier tube for the purpose of regulating the
voltage applied to the dynodes. The emitter-collector transistor junctions are coupled to associated dynodes while the dynodals are coupled to a resistive voltage divider. This configuration has the effect of reducing the likelihood of regenerative oscillation since the low impedance side of the transistor string is coupled to the dynodes. With prior art circuits, slight changes in the quantity of electrons flowing into the dynodes cause slight shifts in dynode potential which in turn cause resulting changes in dynode current, and so on, to produce regenerative oscillation.

The multiplier phototube depicted in FIGURE 1 is designated in its entirety with the numeral 10, and comprises a photocathode 11, an anode 12 and a plurality of secondary emission electrodes or dynodes—there being ten in number respectively designated with the numerals 14 through 23, inclusive. The cathode 11 is connected through a conductor 24 and serially arranged resistances 25 and 26 to the negative terminal of a power supply which may, for example, provide a potential at the terminal indicated in the order of -2.0 kilovolts. One side of a capacitance 27 is connected in common to the series resistances 25 and 26, and the other side thereof is grounded. The resistances 25 and 26 limit the current flow from the power supply 16 and the capacitance 27 define a filter network operative to smooth the output of the power supply and eliminate high frequency noise picked up externally by the leads or conductors.

A plurality of resistances are connected in series between the conductor 24 and ground, there being eleven in the particular circuit shown, respectively designated with the numerals 28 through 38, inclusive. A voltage reference device 39 in the form of a Zener diode is connected in series between the resistance 38 and ground, and is operative to maintain the voltage drop thereacross at a substantially constant irrespective of the value of the current flow therethrough. Also connected between the conductor 24 and ground (through the reference diode 39) are a plurality of transistors, there being eleven in number, respectively designated with the numerals 40 through 50, inclusive.

Each of the transistors 40 through 50 has an emitter, base and collector, and they are cascade-connected collector-to-emitter such that the emitter of the final transistor 50 in the chain shown is connected to the common point between the resistance 38 and diode 39, and the collector of the first transistor 40 connected to the conductor 24. Further, the diode 15 is connected in common to the emitter of the transistor 40 and collector of the transistor 41; the diode 16 is connected in common to the emitter of the transistor 41 and collector of the transistor 42; the diode 17 is connected in common to the emitter of the transistor 42 and collector of the transistor 43; and so on through each of the dynodes 17 through 23, inclusive, the last of which is connected in common to the emitter of the transistor 40 and collector of the transistor 50.

The base of the transistor 40 is connected to the junction of the resistances 28 and 29; the base of the transistor 41 is connected to the junction of the resistances 29 and 30; the base of the transistor 42 is connected to the junction of the resistances 30 and 31; and so on through the transistors 43 through 49, inclusive, the base of the last of which is connected to the junction of the resistances 37 and 38 and the base of the transistor 50, however, is connected through a conductor 51, resistor 52 and a conductor 53 to the anode 12 of the multiplier phototube 10, which is grounded through a resistance 54. The base of the transistor 50 is also connected to ground through a capacitance 55.

In certain instances, the cathode 11 of the multiplier phototube may be grounded through a capacitance 56 which is operative to suppress parasitic oscillations of the circuit network, but the requirement for such capacitance depends upon the details of the circuit layout and conductor inductions and capacitances. A test point, indicated by the terminal Tm, is shown connected to the conductor 24 but is readily omitted, and its inclusion in the circuit is a convenience in metering the potential drop across the transistor network under varying conditions of light incident on the photocathode 11.

In the function of the circuit, ground constitutes the positive side of the power supply, and the anode 12 of the multiplier phototube is connected thereto through the resistance 54. The opposite side of the power supply provides a relatively high negative voltage which is connected to the resistance 26. The number of electrons emitted by the cathode 11 depends primarily upon the amount of light incident thereon, and the electrons emitted therefrom are collected on the surface of the first dynode 14. The much larger number of electrons then emitted by the dynode 14 (as described heretofore) are collected on the surface of the second dynode 15, the greatly increased number of electrons emitted therefrom are collected on the next dynode 16, and so on, with the electrons emitted by the final dynode 23 being collected on the anode 12—which collected electrons constitute the current output of the multiplier phototube.

The current out of the multiplier phototube 10 is in general quite small and is usually in the order of a few microamperes. Consequently, substantially all of the current flowing from the power supply and through the resistances 25 and 26 follows a path to ground through the resistances 25 through 38 and the reference diode 39 rather than through the photocathode 11 and dynodes of the phototube.

The transistors 40 through 50, inclusive, are PNP transistors capable of withstanding collector-to-emitter potentials in the order of 100 volts, since a voltage reference of such importance is generally required between the respective dynodes of the phototube 10 under operating conditions where maximum amplification is desired. The transistors 40 through 50 are cascade-connected emitter-to-collector so that the current flow through the transistor string is a series flow and, therefore, is essentially identical in each of the transistors, and is substantially equal to the current flowing into the base of the transistor 50 multiplied by the current amplification or beta thereof.

The transistor 50 is reverse-biased in certain operating conditions of the circuit (elaborated further hereinafter) because of the negative superiority (relative to the emitter) of the substantially constant potential applied to the emitter as a consequence of the voltage drop across the reference diode 39 and, then, essentially no current flows through the transistor string. Therefore, the current flow is to ground through the serially connected resistances 28 through 38 and reference diode 39; and the collector-to-base potential difference of the transistor 40 is equal to the voltage drop across the resistance 28, the potential difference between the bases of the transistors 40 and 41 is equal to the voltage drop across the resistance 29, and so on, with the potential difference between the bases of the transistors 48 and 49 being equal to the voltage drop across the resistance 37.

The emitters of the various transistors 40 through 49 will respectively assume potentials that are close to the base potentials thereof because of emitter follower action, and therefore, the resistance between the cathode 11 by an amount substantially equal to the voltage drop across the resistance 28, the dynode 15 will be positive relative to the dynode 14 by an amount substantially equal to the voltage drop across the resistance 29, and so on through the dynode 23. The potential difference between the dynode 23 and anode 12 is essentially equal to the voltage drops across the resistance 38 and reference diode 39—the anode 12 being substantially at ground potential discounting any voltage drop across the resistance 54.
Quite evidently then, the potentials applied to the dynodes 14 through 23 can be changed by altering the magnitude of the current flowing through the resistances 28 through 37; and more particularly, the respective potentials applied to these dynodes can be decreased by diverting some or most of the current flowing through the resistances 28 through 38 to the transistor string so that such current flows therethrough to ground rather than through the resistances.

The aforementioned statement of reverse-bias of the transistor 50 is maintained so long as the voltage drop across the reference diode 39 exceeds the voltage drop across the resistance 54. Until the current flow through the resistance 54 is of such value that the voltage drop there across is in excess of that across the diode, the potential applied to the base of the transistor 50 is more positive than that applied to the emitter thereof, and a condition of reverse-bias is defined.

If the anode current of the multiplier phototube increases to a predetermined value, the voltage drop across the resistance 54 increases because the primary path of such current flow is therethrough to ground; and if the voltage drop across this resistance is sufficiently great, the potential applied to the base of the transistor 50 becomes more negative relative to the emitter potential until finally the transistor becomes forward-biased.

When this transistor commences to conduct current, the path of the current flow is through the transistor string so that some of the current formerly flowing through the resistances 28 through 38 is diverted therethrough, and 35 flows through the transistor string and reference diode 39. Consequently, each of the voltage drops across the resistances 28 through 38 decreases, and the potentials applied to the dynodes 14 through 23 and the potential differences therebetween consequently decrease. Therefore, the amplification of the phototube 10 is decreased accordingly.

Evidently then, such regulatory adjustment of the potentials respectively applied to the dynodes 14 through 23 occurs only upon the transistor 50 becoming forward-biased, and this condition of bias depends upon the magnitude of the current flow through the resistance 54. Therefore, by proper adjustment of the reference diode 39 and the value of the resistance 54, relative to a predetermined current flow therethrough, the regulator circuit may be made inoperative to change the dynode potentials for average current outputs of the phototube 10 which are below predetermined value.

When the average current output exceeds such predetermined value, the resulting forward bias on the transistor 50 causes some of the anode current to be diverted from the resistance 54 into the base of the transistor 50 and is amplified thereby and appears as a collector current through the string of transistors 40 through 50. As a consequence, a portion of the supply current is diverted from the resistances 28 through 38 and flows through the transistor string, thereby reducing the potentials applied to the dynodes 14 through 23 as heretofore described. The end result of this corrective action is that the multiplication factor of the dynodes 14 through 23 is accordingly decreased, and over-all amplification of the phototube is reduced to the extent necessary to maintain the average anode current at a value substantially equal to the aforesaid predetermined value.

The capacitance 55 which is connected between ground and the base of the transistor 50 is operative to make the regulator circuit non-responsive to rapid changes in the voltage developed across the resistance 54; and as a result, rapid fluctuations in the intensity of the light incident upon the photocathode 11 and the associated rapid fluctuations in the anode or output current of the phototube are not equalized by the regulator circuit, and such output current causes a fluctuating voltage to appear across the resistance 54 which constitutes the output signal of the phototube. Such fluctuating output signal is delivered to the output terminal \( T_o \). The resistance 52 is effective to prevent by-passing of signal voltages by the capacitance 55.

The modified circuit illustrated in FIGURE 2 is particularly useful in association with multiplier phototubes characterized by the requirement for relatively high potential differences between two or more successive dynodes in the first several dynodes in order to optimize the amplification function of the tube. The modified circuit also illustrates a reduction in the range of regulation over the amplification factor of a multiplier phototube. Generally, however, the circuit of FIGURE 2 is similar and in many respects identical in function with the circuit of FIGURE 1.

The multiplier phototube depicted in FIGURE 2 is designated in its entirety with the numeral 100, and comprises a photocathode 111, an anode 112, a control electrode 113, and a plurality of secondary emission electrodes or dynodes—there being ten in number respectively designated with the numerals 114 through 123, inclusive. The cathode 111 is connected through a conductor 124 and serially arranged resistances 125 and 126 to the negative terminal of a power supply which may, as in the circuit of FIGURE 1, provide a potential at the terminal indicated in the order of -2.0 kilovolts. One side of a capacitance 127 is connected in common to the series resistances 125 and 126, and the other side thereof grounded. The resistances 125 and 126 limit the current flow from the power supply to a safe value; and the resistance 126 and capacitance 127 define a filter network operative to smooth the output of the power supply and eliminate high frequency noise picked up by the leads or conductors.

A plurality of voltage reference devices are connected in series between the conductor 124 and the various dynodes 114 through 118; and in the particular illustration, there are six such voltage reference devices respectively denoted with the numerals 128 through 133, inclusive. Thus, the first dynode 114 is connected to the common point between the reference devices 129 and 130, the second dynode 115 is connected to the common point between the reference devices 130 and 131, and so on to the reference device 133 which is connected to the fifth dynode 118. The reference devices 128 through 133 are operative to maintain the voltage drops thereacross substantially constant irrespective of the value of the current flowing therethrough (within limits), and may be Zener diodes although glow tubes or other gaseous discharge devices, or similar voltage reference devices, may be employed.

The control or focus electrode 113 is connected to the variable tap of a potentiometer 134, one side of which connects to the conductor 124 and the other side to the common point between the reference diodes 128 and 129. Quite evidently, the voltage applied to the control electrode 113 may be selectively varied through a maximum range defined by the voltage drop across the reference diode 128. In certain instances, it may be desired to provide a greater range of voltage adjustment for the control electrode, in which case the potentiometer 134 may be connected across both of the reference devices 128 and 129. Particularly in this latter instance, it may be advantageous to use a single reference diode instead of the two diodes 128 and 129.

In certain instances, the dynode 118 may be grounded through a capacitance 135 which is operative to terminate parasitic oscillations of the circuit network, as in the prior embodiment. A test point, indicated by the terminal \( T_e \), is shown connected to the dynode 118 as a convenience in metering the potential drop across the transistor network now to be described, under varying conditions of light incidence on the photocathode 111.

A plurality of resistances are connected between the dynode 118 and ground, there being six in the particular circuit shown respectively designated with the
3,321,629

numerals 136 through 141, inclusive. A voltage reference device 142 is connected in series between the resistance 141 and ground, and is operative to maintain the voltage drop thereon substantially constant irrespective of the value of the current flow therethrough. The reference device 142 may be a Zener diode or its equivalent. Also connected between the dynode 118 and ground (through the reference diode 142) are a plurality of transistors, there being six in number respectively designated with the numerals 143 through 148, inclusive.

Each of the transistors 143 through 148 has an emitter, base and collector, and they are cascade-connected collector-to-emitter such that the emitter of the final transistor 148 in the chain thereof is connected to the common point between the resistance 141 and reference diode 142, and the collector of the first transistor 143 is connected to the dynode 118. Further, the dynode 119 is connected in common to the emitter of the transistor 143 and collector of the transistor 144; the dynode 120 is connected in common to the emitter of the transistor 144 and collector of the transistor 145; the dynode 121 is connected in common to the emitter of the transistor 145 and collector of the transistor 146; the dynode 122 is connected in common to the emitter of the transistor 146 and collector of the transistor 147; and the final dynode 123 is connected in common to the emitter of the transistor 147 and collector of the transistor 148.

The base of the transistor 143 is connected to the junction of the resistances 136 and 137; the base of the transistor 144 is connected to the junction of the resistances 137 and 138; and so on, with the base of the transistor 147 being connected to the junction of the resistances 140 and 141. The base of the transistor 148, however, is connected through a conductor 149, inductances 150 and 151, resistance 152 and conductor 153 to the anode 112 of the multiplier phototube 100, which is grounded through a resistor 154. The base of the transistor 148 is also connected to ground through a capacitor 155, and a capacitor 156 which is connected in parallel with the inductance 150. The inductances 150 and 151 and capacitor 156 constitute in part an equalizing network which compensates for high frequency losses elsewhere in the system and, depending upon design, one or all may be omitted.

A portion of the output current of the anode 112 of the multiplier phototube 100, and particularly the fluctuations of modulation thereof, may be amplified as by means of the amplifier network shown, which includes a transistor 157 the base of which is connected to the anode 112 of the phototube 100 through the conductor 153. The collector of the transistor 157 is connected to a low voltage d.c. power supply, which may be in the order of —30 volts d.c. through a filter network comprising a resistor 158 and capacitor 159. The emitter of the transistor 157 is grounded through a resistance 160, and by emitter follower action an output signal is fed to the terminal 16 through a coupling capacitance 161 which is connected to the emitter above the resistance 160.

The function of the circuit shown in FIGURE 2 is generally similar to that of the circuit illustrated in FIGURE 1, with ground constituting the positive side of the power supply and the anode 112 of the multiplier phototube being connected thereto through the resistance 154. The opposite side of the power supply provides a relatively high negative voltage which is connected to the resistance 126. The number of electrons emitted by the cathode 111 depends primarily upon the amount of light incident thereon; and the electrons emitted therefrom are collected on the surface of the first dynode 114, the much larger number of electrons then emitted by the dynode 114 are collected on the surface of the second dynode 115, and so on, with the electrons emitted by the final dynode 123 being collected on the anode 112—which collected electrons constitute the current output of the multiplier phototube. The electrode 113 is a focusing electrode, and the potential applied thereto is adjusted by means of the potentiometer 134 to provide optimum collection by the first cathode 114 of the electrons emitted by the photocathode 111.

Substantially all of the current flowing from the power supply and through the resistances 125 and 126 follows a path to ground through the reference diode 128 through 133, the resistances 136 through 141, and the reference diode 142, and rather than through the photocathode 111 and dynodes 114 through 118 of the phototube. Therefore, the voltages respectively applied to the dynodes 114 through 118 will be determined by the voltage drops across the various reference diodes 128 through 133.

More particularly, the voltage applied to the first dynode 114 will be positive relative to the voltage applied to the cathode 111 by an amount equal to the sum of the voltage drops across the reference diodes 128 and 129; the voltage applied to the second dynode 115 will be positive relative to the voltage applied to the dynode 114 by an amount equal to the voltage drop across the reference diode 130, and so on, with the voltage applied to the dynode 118 being positive with respect to the voltage applied to the dynode 117 by an amount equal to the voltage drop across the reference diode 133. As stated herebefore, the voltage drops across the various reference diodes is substantially independent of the current that flowing therethrough with the result that the voltages applied to the dynodes 114 through 118 remain substantially constant.

The transistors 143 through 148, inclusive, are PNP transistors capable of withstanding collector-emitter potentials in the order of 100 volts since a voltage difference of such magnitude is generally required between the respective dynodes of the phototube 100 under operating conditions where maximum amplifications is desired. The transistors 143 through 148 are cascade-connected emitter-to-collector so that the current flow through the transistor string is a series flow, and therefore is essentially identical in each of the transistors, and is substantially equal to the current flowing into the base of the transistor 148 multiplied by the beta thereof.

As in the circuit of FIGURE 1, the transistor 148 is reverse-biased in certain operating conditions of the circuit because of the negative superiority (relative to the base) of the substantially constant potential applied to the emitter as a consequence of the voltage drop across the reference diode 142 and, then, essentially no current flows through the transistor string. Therefore, the current flow through the reference diode 128 through 133 is to ground through the serially connected resistances 136 through 141 and the reference diode 142; and the collector-to-base potential difference of the transistor 143 is equal to the voltage drop across the resistance 136, the potential difference between the bases of the transistors 143 and 144 is equal to the voltage drop across the resistance 137, and so on.

The emitters of the various transistors 143 through 147 will respectively assume potentials that are close to the base potentials thereof because of emitter follower action, and therefore the dynode 119 will be positive relative to the dynode 118 by an amount substantially equal to the voltage drop across the resistance 136, and so on. The potential difference between the dynode 123 and anode transistor is determined by the voltage drop across the resistance 141 and reference diode 142—the anode 112 being substantially at ground potential, thus e.g. any voltage drop across the resistance 154 is of such value that the potential applied to the base of
the transistor \( T_1 \) is more positive than that applied to the emitter thereof, and a condition of reverse-bias is defined. If the anode current of the multiplier phototube increases to some predetermined value, the voltage drop across the resistance \( R_{154} \) increases because the principal path of such current flow is therethrough to ground; and if the voltage drop across this resistance is sufficiently great, the potential applied to the base of the transistor \( T_1 \) becomes more negative relative to the emitter potential until finally the transistor becomes forward-biased. When this transistor commences to conduct current, some of the current formerly flowing through the resistances \( R_{136} \) through \( R_{141} \) is diverted therefrom and flows to ground through the transistor string and reference diode \( R_{142} \); the voltage drops across the resistances \( R_{136} \) through \( R_{141} \) decrease; and the amplification of the phototube \( R_{100} \) is decreased accordingly, as heretofore explained.

The capacitance \( C_{155} \) is operative to make the regenerative circuit non-responsive to rapid changes in the voltage developed across the resistance \( R_{154} \); and as a result, rapid fluctuations in the intensity of the light incident upon the photocathode \( R_{111} \) and the associated rapid fluctuations in the anode or output current of the phototube are not equalized by the regenerative circuit action, and such output current causes a fluctuating voltage to appear across the resistance \( R_{154} \) which constitutes the output signal of the phototube. Such fluctuating output signal is amplified by the transistor \( T_{157} \) and is delivered to the output terminal \( T_2 \) through the capacitance \( C_{161} \). The resistance \( R_{152} \) is effective to prevent by-passing of signal voltages by the capacitance \( C_{155} \).

It is believed that a summary of circuit function in terms of typical voltage and current values will be of benefit, and in this connection, the following exemplary circuit components may be considered, reference being explicitly made to the circuit illustrated in FIGURE 2 because of the greater variety of components incorporated therein:

- **Multiplier phototube**: 100–6364
- **Resistance**: 125–300K ohms
- **Resistance**: 126–470K ohms
- **Capacitance**: 127–0.1 microfarad
- **Reference diodes**: 128–133–IN985
- **Potentiometer**: 134–500K ohms
- **Capacitance**: 135–100 microfarads
- **Resistances**: 136–141–100K ohms
- **Reference diode**: 142–IN738
- **Transistors**: 143–148–PNP 2N398
- **Inductance**: 150–10 microhenries
- **Inductance**: 151–3 microhenries
- **Resistance**: 152–3.3K ohms
- **Resistance**: 154–100K ohms
- **Capacitance**: 155–0.1 microfarad
- **Capacitance**: 156–0.01 microfarad
- **Transistor**: 157–2N1189
- **Resistance**: 158–5.6K ohms
- **Capacitance**: 159–4.7 microfarads
- **Resistance**: 160–2.2K ohms
- **Capacitance**: 161–1.0 microfarad
- **High voltage power supply**: 20KV volts with respect to ground
- **Low voltage power supply**: 30 volts with respect to ground

In view of the applied voltages and component values indicated, the potential applied to the photocathode \( R_{111} \) will be substantially equal to \(-2.0KV\) volts less the sum of the voltage drops across the resistances \( R_{125} \) and \( R_{126} \); and assuming a typical current flow of the order of \( 1000 \) microamperes, the phototube will be in the general order of 1200 volts. The potential appearing on the diode \( R_{114} \) will be positive with respect to the photocathode \( R_{111} \) by an amount substantially equal to the sum of the voltage drops across the reference diodes \( R_{128} \) and \( R_{129} \), and a typical value therefor is about 200 volts made up of approximately 150 volts appearing across the diode \( R_{128} \) and 50 to 75 volts across the diode \( R_{129} \). The potentiometer \( R_{134} \) may be adjusted to provide a potential at the focusing electrode \( R_{113} \) of from zero to about 150 volts positive with respect to the photocathode \( R_{111} \). The voltage drops appearing across each of the diodes \( R_{130} \) through \( R_{133} \), inclusive, are substantially constant, and a typical value of \( 50 \) volts which would be 50 to 75 volts. Thus, the total voltage drop across the string of reference diodes \( R_{128} \) through \( R_{133} \), inclusive, may approximate 525 volts so that the diode \( R_{118} \) is then positive with respect to the photocathode \( R_{111} \) by an amount of 525 volts.

With the diode string in a non-conducting state, the current flow through the reference diodes \( R_{128}–R_{133} \) is to ground through the series resistances \( R_{136}–R_{141} \) and the reference diode \( R_{142} \). Since the value of each of the resistances \( R_{136} \) through \( R_{141} \) is 100K ohms, the current flow of approximately one milliamper is produce a voltage drop across each such resistance of about 100 volts; and because of the emitter follower action of the transistors as herefore described, the diode \( R_{119} \) will be positive with respect to the diode \( R_{118} \) by approximately 100 volts, the diode \( R_{120} \) will be positive by about 100 volts with respect to the diode \( R_{119} \), and so on, with the final diode \( R_{123} \) being positive with respect to the diode \( R_{122} \) by approximately 100 volts. Similarly, the anode \( R_{112} \) will be positive with respect to the diode \( R_{123} \) by the sum of the 100-volt drop across the resistance \( R_{141} \) and the 10-volt drop across the diode \( R_{142} \)—the anode therefore being at approximately ground potential for small anode currents.

Assume, as a starting condition, that no light energy is incident upon the photocathode \( R_{111} \) and therefore there are substantially no diode currents and substantially no anode current: under such conditions, the base of the transistor \( R_{148} \) will be maintained substantially at ground potential because of its connection thereto through the resistance \( R_{154} \). The emitter of the transistor \( R_{148} \) will be maintained at approximately 10 volts negative with respect to ground because of the flow of the supply current of approximately one milliamperere through the reference diode \( R_{142} \). Therefore, the transistor \( R_{148} \) is reverse-biased and there will be substantially no collector current except for any leakage current which might be perhaps 20 microamperes. Since the transistors \( R_{143} \) through \( R_{148} \) are cascade-connected, there will be substantially zero collector current in each of the transistors except for leakage currents. Therefore, essentially all of the supply current flow will be through the series resistances \( R_{125} \) and \( R_{126} \), the diode string \( R_{128} \) through \( R_{133} \) and the resistance string \( R_{136} \) through \( R_{141} \) and diode \( R_{142} \) to ground.

Light incident upon the photocathode \( R_{111} \) will cause the emission of electrons therewith which will be multiplied by the diodes \( R_{114} \) through \( R_{123} \) as heretofore described, and appear as an anode current flowing to ground through the resistance \( R_{154} \). As the average value of the anode current (such current will fluctuate in accordance with fluctuations in the intensity of the light incident upon the photocathode) increases from substantially zero to some higher value, the transistor \( R_{148} \) will remain reverse-biased until the voltage drop across the resistance \( R_{154} \) becomes greater than 10 volts. Therefore, for anode currents of less than approximately 100 microamperes, the regulator circuit remains inoperative because the transistor \( R_{148} \) is maintained in a condition of reverse-bias.

For anode currents greater than such value of 100 microamperes, a voltage drop across the resistance \( R_{154} \) in excess of 10 volts will occur, thereby causing the potential on the base of the transistor \( R_{148} \) to become more negative than the voltage on the emitter thereof, whereupon the transistor will be forward-biased. Consequently, some current will be diverted from the resistance \( R_{154} \) and will flow into the base of the transistor \( R_{148} \).
through the resistance 152 and inductances 151 and 150. Such base current will be amplified by the transistor 148 and will appear as a collector current through the string of transistors 143 through 148.

This collector current through the string of transistors diverts a portion of the supply current that would otherwise flow through the resistances 136 through 141, with the result that the voltage drop across each such resistance is accordingly decreased. Consequently, the respective potential differences between the successive dynodes 118 through 123 are decreased, the current multiplication of each of these dynodes is accordingly decreased, and the number of electrons arriving at the anode 112 is accordingly reduced. Evidently then, the action of the regulator circuit under such conditions maintains the current flow through the resistance 154 at slightly more than 100 microamperes, which value is sufficient to develop a voltage drop across the resistance in excess of the 10 volts developed across the reference diode 143, wherefore the transistor 148 is forward-biased.

Any increase in the average anode current of the multiplier phototube beyond such value of approximately 100 microamperes flows into the base of the transistor 148 and is amplified thereby and appears as a collector current through the string of transistors 143 through 148. As the intensity level of the light incident on the cathode 111 continues to increase, the average value of the anode current increases accordingly and more supply current is diverted from the string of resistances 136 through 141. The potential across such string of resistances may fall from an initial value of approximately 600 volts, as herebefore described, to as low as 50 to 75 volts. Correspondingly then, the potential difference between the respective successive dynodes 118 through 123 and between the final dynode 123 and anode 112 may fall from the aforementioned initial value of 100 volts down to about 10 volts.

At a potential difference of about 100 volts between successive dynodes, each dynode can be expected to have a multiplication factor of approximately 5. Therefore, for the five dynodes 119 through 123 concerned with the regulatory function in the FIGURE 2 embodiment, the combined amplification is approximately 5, or slightly in excess of 5, at a potential difference of about 100 volts between successive dynodes, each dynode can be expected to have a multiplication factor of approximately 5. Again with respect to the five dynodes 119 through 123, the combined amplification is approximately 5, or slightly in excess of 5, at a potential difference between the illustrated circuit of FIGURE 2 to a range of multiplication or current amplification of about 3,000 to 0.03 or 100 to 1, although such amplification range may be limited somewhat as, for example, by the current to the dynode 116 becoming excessive.

As a result of the described regulator action, the flow of electron through the resistance 154 is maintained at approximately 100 microamperes provided that there is sufficient illumination of the photocathode 111 to produce a final average anode current of at least this value. Therefore, variations in the average anode current are substantially eliminated and the output signal of the multiplier phototube is essentially an accurate measurement of the modulation percentage of the light incident upon the photocathode 111. For example, a sudden cessation of the incident light which represents a 100% downward modulation causes an immediate reduction in the anode current of the multiplier phototube. Since the anode current is in all conditions about 100 microamperes on the average, such 100% downward modulation represents a step output of 100 microamperes or 100% modulation or fluctuation of the incident light. Likewise, a 50% downward modulation or fluctuation in the intensity of the incident light produces a 50 microampere signal from the anode 112 of the multiplier phototube. Similarly, in a corresponding but reverse manner, a sudden increase in the intensity of the light incident on the photocathode 111 will result in an associated increase in the anode current of the multiplier phototube—such increase being a measure of the modulation percentage of the light incident on the photocathode.

The regulator circuit is made non-responsive to any rapid changes in the voltage developed across the resistance 154 because of the inclusion of the inductance 155 which is connected between ground and the base of the transistor 148. As a result, rapid variations in the anode current about the average value enforced thereon by the regulator circuit (which variations correspond to rapid fluctuations in the intensity of the light incident on the photocathode 111) are not equaled by the amplifier. The fluctuating signal output from the multiplier phototube (which fluctuation output represents the percentage modulation of the light incident on the photocathode 111) is delivered to the base of the transistor 157, is amplified thereby, and an amplified output signal is coupled to the output terminal T1 by the capacity 161.

The specific circuit illustrated in FIGURE 2 is provided with six regulator transistors 143 through 148 and associated resistances 136 through 141 serving to control the potentials on the five dynodes 119 through 123, and such control thereon provides the aforementioned amplification range of approximately 10 to 1. However, larger or smaller modulation ranges of the incident light may be accommodated by either increasing or decreasing the number of regulator transistors and resistances in association therewith. For example, to increase the range of regulation and thereby accommodate a larger modulation range of the incident light, a transistor and resistance could be used to replace the reference diode 133.

In this same manner, the range could be further increased (in the circuit of FIGURE 1, the range has been maximized) by adding a total of four transistors to respectively replace the reference diodes 133, 132, 131 and 130, whereupon the potentials of all of the dynodes 115 through 123 would be regulatively controlled. It is usually not advisable to vary the potential between the photocathode 111 and the first dynode 114 in a phototube having a control electrode because the variation of voltage therebetween accomplishes a potential at approximately 10 to 1, and also a high multiplication factor is generally required at the first dynode in order to minimize shot noise generated by the first and subsequent dynodes. Similarly, the circuit can be altered to accommodate smaller modulation ranges of the incident light by the use of regular transistors, for example, the transistor 143 and resistance 136 supplying base current thereto could be replaced by a reference diode, as could the transistors 144, 145 and 146.

The resistance defined by the resistances 25 and 26 in the circuit illustrated in FIGURE 1, and by the resistances 125 and 126 in the circuit of FIGURE 2, cooperates with the transistor string and resistance string associated therewith in accomplishing the regulation function in that the total voltage difference between ground and the high voltage terminal appears across all of these elements (and the reference diodes 39 in the circuit of FIGURE 1, and reference diodes 128 through 133 and 142 in the circuit of FIGURE 2); and therefore, when the voltage drop across the transistor-resistance strings (that is, between the test point T and ground) decreases, it correspondingly increases across such resistance; and conversely, as the anode current of each transistor-resistance strings increases, it correspondingly decreases across such resistance.

In each embodiment of the invention, the effective power supply impedance as evidenced at each dynode is relatively low because of the aforementioned emitter follower action of the transistors in the circuit of FIGURE 1 and 143 through 147 in the circuit of FIGURE 2. This result is advantageous in that it substantially avoids undesirable fluctuations in the dynode.
potentials which would be caused by fluctuations in the dynode currents. The circuit of FIGURE 1 in particular is adaptable for maintaining the instantaneous current output of the multiplier phototube substantially constant. This result may be attained by removing the capacitance 55 and taking the output of the circuit at the terminal \( T_p \).

In each of the circuits, the anode resistance to ground (54 or 154) serves as a sampling device and the voltage developed thereacross is continuously compared with the voltage across the reference diode (39 or 142). So long as the anode current of the phototube is sufficiently low that the sample thereof appearing as a voltage across the resistance is less than the voltage drop across the diode, the regulator circuit is inactive. However, when the sampled current produces a voltage drop across the resistance which exceeds the voltage drop across the reference diode, a feedback loop is closed and a control signal is fed from the control means (which includes the resistance, reference diode and associated transistor) to the voltage-determining means (which includes the dynode resistances and associated transistors) to effect a corrective change in the dynode potentials so as to maintain the anode current substantially at a predetermined value.

While in the foregoing specification embodiments of the invention have been set forth in considerable detail for purposes of making an adequate disclosure thereof, it will be apparent to those skilled in the art that numerous changes may be made in such details without departing from the spirit and principles of the invention.

1. In a circuit providing two points adapted to have different potentials applied thereto by appropriate connection thereof to a power supply, the combination of: a multiplier phototube having a cathode connected with one of said points, an anode connected with the other of said points, and a group of dynodes for amplifying the cathode current in proportion to the values of the potentials respectively applied to said dynodes; and a regulator circuit for automatically adjusting the current amplification of said phototube to maintain the average anode current thereof substantially constant comprising voltage-determining means connected with a plurality of said dynodes for respectively applying voltages thereto of progressively higher values in an increasing order in the direction from the first such dynode adjacent said cathode to the final dynode adjacent said anode and including a plurality of serially connected resistances coupled with said points and providing a current path therebetween and being respectively coupled with said plurality of dynodes for applying voltages thereto proportional to the magnitude of the current flow through said resistances, current control means connected with said anode and with said resistances and being operative to regulatively adjust the magnitude of the current flow through said resistances in response to deviations in the anode current from a predetermined average value and thereby alter the voltages respectively applied to said plurality dynodes to correctively change the current amplification of said multiplier phototube to maintain the average anode current thereof substantially constant at such predetermined value, signal isolation means for making said regulator circuit nonresponsive to relatively rapid fluctuations in the anode current of said multiplier phototube so that the regulator circuit is operative to maintain the average anode current substantially constant, said current control means further including a plurality of transistors each having an emitter, base and collector and being cascade-connected emitter-to-collector and coupled with said points, the emitter-collector junctions of certain successive transistors being respectively connected to said plurality of dynodes and the bases of the certain successive transistors being respectively connected to the successive junctions of the relatively correspondingly resistances, whereby the potentials applied to said plurality of dynodes are essentially equal respectively to the voltage drops across the associated resistances as a consequence of the emitter follower action of said transistors.

2. The circuit of claim 1 in which means are provided for reverse-biasing one of said transistors when the anode current is no greater than the aforesaid predetermined average value to substantially prevent the flow of current through said certain transistors, means also being provided for forward-biasing said one transistor when said anode current exceeds such predetermined average value whereby said certain transistors become conductive to divert some of the current otherwise flowing through said resistances.

References Cited by the Examiner

UNITED STATES PATENTS

2,605,430 7/1952 Marcy ----------------- 230–207
2,922,945 1/1960 Norris et al. -------- 333–22
2,964,653 12/1960 Cagle et al. ------- 307–88.5

OTHER REFERENCES


RALPH G. NILSON, Primary Examiner.

M. ABRAMSON, Assistant Examiner.