PHOTOMULTIPLIER TUBE CIRCUIT WITH SUBSTANTIALLY LINEAR OUTPUT

Filed Nov. 14, 1963 2 Sheets-Sheet 1

Fig. 1 PRIOR ART

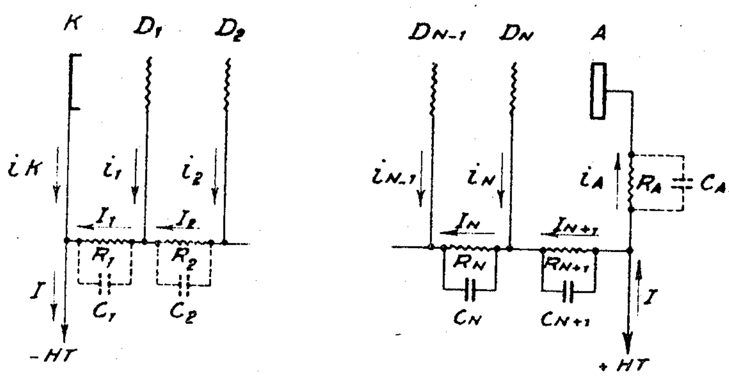


Fig. 2

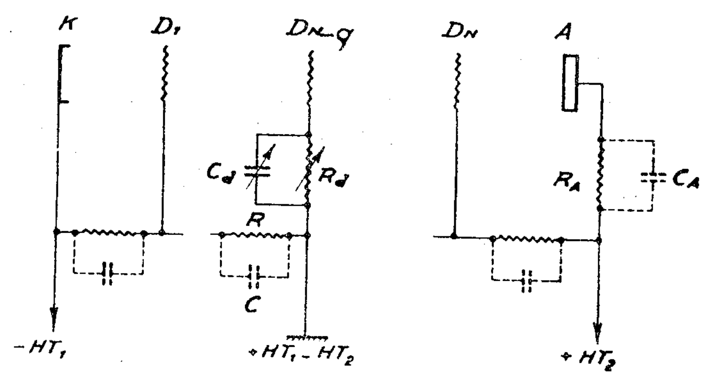
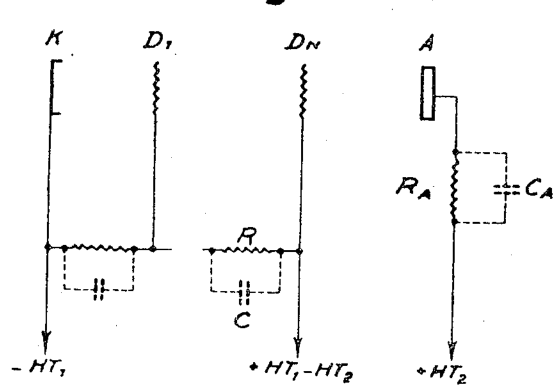


Fig. 5



Inventor
Paul Joseph Moatti
By Littlepage & Quaintance
His Attys.

PHOTOMULTIPLIER TUBE CIRCUIT WITH SUBSTANTIALLY LINEAR OUTPUT

Filed Nov. 14, 1963 2 Sheets-Sheet 2

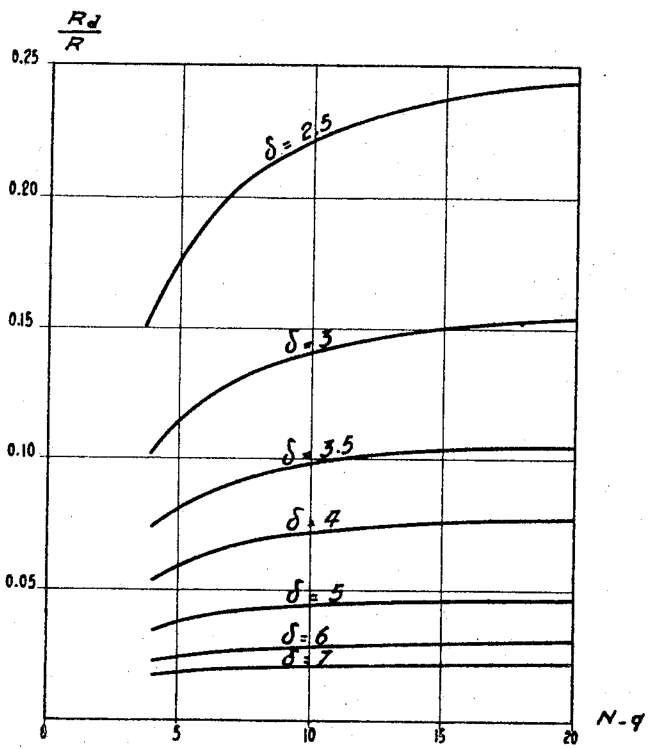
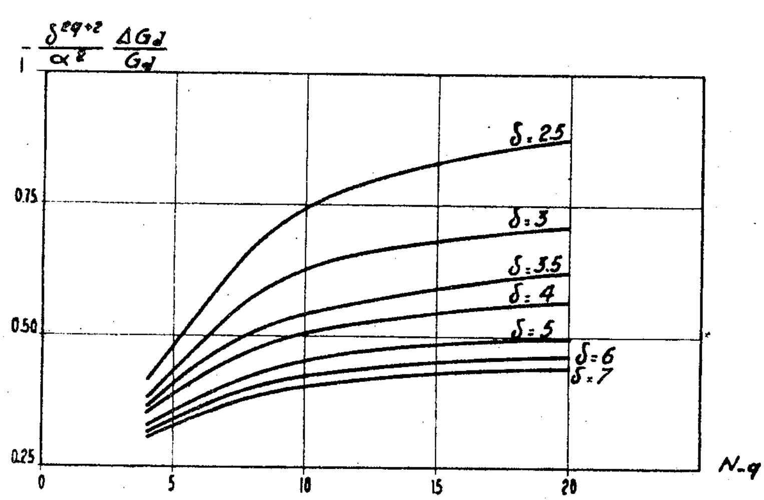


Fig. 3

Fig. 4



Inventor
Paul Joseph Moatti
By Littlepage & Quaintance
His Attys.

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3,320,425

PHOTOMULTIPLIER TUBE CIRCUIT WITH SUBSTANTIALLY LINEAR OUTPUT

Paul Joseph Moatti, Vernouillet, France, assignor to Etablissement Public: Centre de la Recherche Scientifique, Paris, France, a corporation of France

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Claims priority, application France, Nov. 15, 1962, 915,433
10 Claims. (Cl. 250—207)

The present invention relates to a photomultiplier tube circuit enabling a photomultiplier tube to supply a substantially linear output current, both as a function of the amplitude and the frequency of the input signal in D.C. and in A.C. operation.

Photomultiplier tubes, also known as electronmultiplier phototubes, have been widely used in recent years, more particularly in nuclear physics. As is now well known in the art, such apparatus comprise an anode and a cathode between which are arranged a plurality of secondary emissive electrodes called dynodes, as will be more specifically detailed hereinafter, and are conventionally energized by means of a single high-voltage stabilized power source and a potentiometer bridge consisting of resistors having equal or unequal resistance values, the terminals of said bridge being respectively connected to the terminals of said source, and to the cathode and the anode, while the dynodes are respectively connected to the connecting points of the successive resistors of said bridge. For the sake of clarity of the specification, the currents carried by the electrodes are hereinafter referred to as i_A for the anode, i_K for the cathode, and $i_1, i_2 \ldots i_{N-1}, i_N$ for the respective dynodes, and the load currents carried by the resistors in the bridge are hereinafter referred to as $I_1, I_2, \ldots I_{N-1}, I_N$, respectively. See FIGURE 1.

Such a conventional photomultiplier tube circuit has however the serious drawback of not providing a linear amplification of the anodic pulse amplitude, as shown for the first time by J. F. Raffle, E. J. Robbins ("Proc. Phys. Soc." 1952, B65, No. 5, 320–4). Up to the present time, the cause of this objectionable non-linearity phenomenon was ascribed to small space charges produced by the pulses in the vicinity of the dynodes, or to the effects of the dynode currents which give rise to dynode potential variations.

A pulse amplification, if achieved non-linearly by a conventional photomultiplier tube, results, in particular, in a distortion of the pulse height and in a broadening of the radiation lines, when the intensity of the incident radiations increases. Thus, when the input signal is formed of pulses of radioactive origin the gain distortion is a function of the radiation energy and of the activity of the source, even if the high-voltage source is perfectly stabilized.

To obviate these drawbacks, it has already been proposed to fix the potential of the last dynodes in order to reduce the effects of the dynode currents, or to provide, to the same end, an individual regulation of the inter-dynode voltages by means of junction diodes or neon tubes, but in all such cases the resulting circuit arrangements are complicated, while the gain obtained therein is not perfectly constant, and such circuits are not adapted for high anodic currents or for very short signals.

It has now first of all been clearly shown that, the problem of the amplification linearity was actually connected with the respective effects of the dynode currents and of the space charge. The first of the said effects occurs whatever the amplitude and the frequency components of the cathode current. The space charge phenomenon takes place only for comparatively high anode currents and does not appear during the usual amplitude measurements. The general operation of a photomultiplier tube is thus essentially affected by the dynode currents.

In the case of a D.C. power supply, it has been established by calculating theoretically the above mentioned load currents, $I, I_1, \ldots I_N, I_{N+1}$, on a conventional photomultiplier circuit that said currents were different from the rest current I_o, on account of the superposition of the dynode currents.

The bridge therefore does not operate any more as a simple potentiometer. It follows that the gains of the stages are in operation different from the gains at rest, resulting in an amplitude distortion of the anode current, i.e., of the overall gain of the photomultiplier tube. It has also been shown experimentally that in the conventional circuit arrangement, the photomultiplier tube does not constitute a linear current amplifier, even for weak currents, due to the sole effect of the dynode currents. The overall distortion as a function of the amplitude of the anode current may reach 40% of the total gain when the anodic current intensity i_A is close to the rest current I_o.

The near perfect stabilization of the high-voltage D.C. source is thus inadequate to assure the gain linearity of the photomultiplier tube in operation, and the dynode current effects must therefore necessarily be attended to. It has moreover been found that the first stage of the photomultiplier circuit displayed substantial overvoltages resulting in a return bombardment from the ions and, consequently, in an increase of the background noise of the photomultiplier tube and even in possible breakdowns. Finally, it is in the anodic stage that the highest voltage drop takes place in operation, the said stage also indirectly contributing to the increase of the photomultiplier gain.

When the photomultiplier tube amplifies A.C. currents, it is usual to insert, particularly in the last stages, by-pass capacitors of equal or unequal capacity values adapted to partly integrate the potential variations due to the dynode currents. The total supply current of a given stage n is the sum of the current I_{N+1} and of the dynode currents which follow it. The insertion in the last stages of such by-pass capacitors does not improve at all the average distortion of the overall gain for the D.C. component, since said component passes only through the supply resistors $R_1 \ldots R_{N+1}$, causing a constant modification of the stage gains. The A.C. components, although limited by the capacitors, also pass through said resistors, thus producing gain variations which are the more rapid as the time constant RC is smaller.

When a circuit arrangement is used comprising a single high-voltage source, it is therefore desirable to reduce the amplitude of the resistive components by selecting RC circuits such that the time constants thereof are identical and the largest possible. The average distortion will however still subsist, at the same time as the slowest gain variations.

Thus, for the random frequency and amplitude pulses, the gain variations change as a function of the amplitude and of the count rate and result in an absence of linearity (shift and broadening of radiation lines), even if the high-voltage source is perfectly stabilized.

Considering therefore that in spite of the known improvements, the conventional photomultiplier tube circuits including a single high-voltage source present a serious absence of linearity of the output current, the main object of the present invention is to provide a circuit adapted to achieve a substantial linearity of the cathode current amplification independently from the cathode current or pulse amplitude, from the counting rate thereof and from the frequencies composing the cathode signal.

This and other objects will be apparent from the following specification.

According to the invention, the circuit of a photomultiplier tube, the various successive stages of which include an anode electrode, a cathode electrode and N dynodes fed through a resistor bridge network, comprises two stabilized high-voltage sources, and, connected in series, the first of said sources feeding the cathode and a first group of N–q dynodes as counted from the cathode, q being an integer smaller than N, and the second source feeding the last dynode of the said first group, the groups of the remaining q dynodes and the anode, the output being at the dynode common to both high voltages and including a RC-circuit comprising a resistor and a capacitor, both of which are adjustable.

The photomultiplier tube circuit should also include, as above-mentioned, by-pass capacitors connected in parallel across the feed resistors in the bridge. At the dynode output and for the A.C. amplification, the time constants of the RC circuits of the general supply circuit and at the output of the common dynode should be identical.

It has been found that for suitably selected values of the load resistance and of the capacitance of the resistor and capacitor, respectively, at the output of the dynode common to both sources, the potential of the high-voltage sources is constant under load. For convenience and safety, it is preferable but not indispensible to ground the base common to both said high voltage sources.

The RC circuit of the common dynode (N–q rank) functions both as a regulating circuit and as a load circuit. The resistance value of the load resistor at the output of the common dynode provides the D.C. regulation, while the associated capacitor intervenes in the case of A.C. or pulse operation. The value of the said load resistance may be determined, as will be seen below, by means:

Of the feeding resistance for the output regulator stage;

Of the order of the dynode selected for the output (i.e., of number q);

Of the average stage gain at rest of the photomultiplier tube, such gain being designated by δ.

The capacitance value of the capacitor cooperating with said resistance is determined by the time-constant equation, after calculating the load resistance and once the capacitance C of each stage of the supply bridge has been measured.

According to an alternative embodiment of the invention, more particularly desirable for rapid spectometric measurements, the cathode and all the dynodes of the photomultiplier tube are fed by the first high-voltage source, while the second high-voltage source feeds only the last dynode before the anode and the anode itself at which the output is taken.

The invention will be best understood from the following description and appended drawings, wherein:

FIGURE 1 illustrates a conventional photomultiplier circuit;

FIGURE 2 is a diagrammatic circuit arrangement of a photomultiplier tube according to the present invention, incorporating two high-voltage sources and the output being at the dynode common to both sources.

FIGURE 3 is a graph showing the variation of the load resistance R_d on the dynode output in the circuit illustrated in FIGURE 2.

FIGURE 4 is a graph showing the output distortion $\Delta G_d/G_d$ as a function of the ratio α of the amplitude of the anodic current to the rest current I_o and of the number q of independently fed dynodes.

FIGURE 5 illustrates an alternative embodiment of the circuit according to the invention.

Referring to FIGURE 1, a conventional photomultiplier tube circuit comprises a photomultiplier tube having an anode A, N dynodes D_1, D_2 . . . D_N and a cathode K, cathode K, anode A and the dynodes are energized by voltage produced by a high-voltage source HT, which

is uniformly or non-uniformly distributed between the various stages of the tube through resistors R_1, R_2 . . . R_{N+1} forming a bridge.

By-pass capacitors C_{N+1}, C_N . . . C_2, C_1 may be connected in parallel with resistors R_{N+1}, R_N . . . R_2, R_1 respectively to form R-C circuits, as shown in solid lines in the last circuit stages and in dotted lines in the first stages, and a capacitor C_A cooperates similarly with a resistance R_A connected on the feeding line of anode A. All the mentioned above capacitors are such that their capacitance values are not smaller than those of the residual capacitances in the circuit arrangement. The anode current is indicated by i_A and the currents carried by the dynodes D_N, D_{N-1} . . . D_2, D_1 by i_{N-1}, i_2, i_1, respectively, the cathode current being designated by i_k. Finally, the load currents carried by resistances R_{N+1} . . . R_1 are indicated, respectively, by I_{N+1} . . . I_1 and the load current produced by the high-voltage source HT, by I.

The photomultiplier circuit illustrated in FIGURE 2 also comprises a photomultiplier having an anode A, a cathode K and N dynodes designated by D_1 . . . D_N, respectively, a feeding resistor bridge network comprising resistors R_1, R_2 . . . R_{N+1} which may have equal or different resistance values, as well as capacitors C_1, C_2 . . . C_{N+1} shunted across said resistors, whilst the anode may also comprise a R_AC_A-circuit. According to the invention, a first source (not shown) of stabilized high voltage HT_1 feeds cathode K and the $N-q$ first dynodes as counted from the cathode, q being an integer lower than N, and one terminal thereof is therefore connected to cathode K while the other is connected to the connection point of the feeding lead of dynode D_{N-q} with the said resistor bridge, said connection point possibly may be grounded, and a second source (also not shown) of stabilized high voltage HT_2 feeds dynode D_{N-q}, the remaining q dynodes and anode A, one of the terminals thereof being therefore connected to said connecting point while the other is connected to anode A, the said two sources being in series. The outlet is taken on the dynode D_{N-q} common to both said sources and includes an R-C circuit comprising an adjustable resistor R_d and an adjustable capacitor C_d.

It has been established that the necessary condition for achieving a substantially linear regulation of the output of the tube in the case of a D.C. feed is given by relation (1) hereafter between the values of resistance R_d, the supply resistance R of stage ($N-q$), the number q (or the number $N-q$, which the order of the selected dynode common to both feeding sources) and δ, which is the average stage gain at rest, of the photomultiplier tube:

$$\frac{R_d}{R}=\frac{1}{\delta(\delta-1)}\left[1-\frac{\delta}{\delta-1}\frac{1}{N-q}\right] \quad (1)$$

It should be stressed that the value R of the feeding resistance of stage $N-q$ is not necessarily equal equal to the resistance values of the other resistors forming the bridge.

In FIGURE 3, there is shown the network of curves showing in ordinates the values of ratio Rd/R plotted against the values of $n-q$ in abscissae, according to various values of δ. Use may be made of the nomogram in FIGURE 3 to determine with a good approximation the value of resistance R_d. In the case of detection of scintillations from a radioactive source, requiring a very sharp adjustment, the intensity of the radioactive source may be varied, for instance by removing the same at a distance. In order for the adjustment to be satisfactory, it is necessary that the amplitudes of the photoelectric peaks do not vary during the movement of the source.

The regulation may be readily extended to the case of an A.C. or variable signal by defining the equality of the time constants of the various stages by means of relation (2) hereafter:

$$R_1C_1=R_2C_2= \ldots =R_{N-q}C_{N-q}=R_dC_d \quad (2)$$

Therefore, the value of capacitor C_d may be obtained, after measurement of the capacitances of the successive stages of the supply bridge by means of above relation (2). In the case of scintillations from radioactive sources, the fine adjustment of C_d may be effected by varying the pulse amplitude in a broad range by means of radioactive sources having widely different radiating energies. For the adjustment to be satisfactory, it is necessary that the photoelectric peak amplitudes be proportional to the energies transmitted by said sources.

Under these conditions, the instantaneous current regulation achieved by the circuit according to the invention holds true for each frequency component and may be effected for the nonperiodic current and for pulse operation, this feature being a highly desirable fundamental property of the photomultiplier circuit according to the invention.

The control thus achieved of the output current is worthy by its simplicity and by its near perfect linearity, in the case of both D.C. and A.C. input signal, independently of amplitude and frequency. With the photomultiplier circuit as illustrated in FIGURE 2, it is possible to effect time measurements (nonlinear) at the anode and energy measurements (linear) at the dynode output.

The graph of FIGURE 4 may be used to calculate the regulation provided by the photomultiplier as shown in FIGURE 2, in said graph, the number $N-q$ has been plotted on the abscissae (order of the dynode selected for the output) and on the ordinates the following expression:

$$\delta(2q+2)/\alpha^2.\Delta G_d/G_d$$

wherein q is number of the dynodes fed by the second source,

$\Delta G_d/G_d$ is the distortion
δ is the average gain at rest
α is the approximate ratio of the amplitude of the anodic current to that of the rest current I_o, i.e., more exactly:

$\alpha=G.i_k/I_o$

with

i_k: cathode current intensity
G: gain of the photomultiplier at rest.

By means of the nomogram in FIGURE 4, it is possible to determine the value of q after having selected $\Delta G_d/G_d$ and α, for a predetermined value of the total number N of the dynodes and of the stage gain δ.

The practical utilization limit of the circuit illustrated in FIGURE 2 is provided by the value of $\alpha=1$, which may thus be taken as a basis for calculating the regulation, the accuracy achieved being highly sufficient in the range of low energies (0 to 20 m.e.v. approximately).

However, the time constant R_dC_d may not have any desired value, since it is limited by the known condition:

$$R_dC_d.\omega_{max.}=1 \quad (3)$$

Wherein $\omega_{max.}$ is the maximum angular frequency of the output signal. If the previous equality (2) is met, the time constants are equal and relation (3) becomes:

$$RC.\omega_{max.}=1 \quad (3')$$

To have a linear response in frequency, the RC time constant must be matched to the maximum frequency of the input signal. The rapidity of response of the photomultiplier is thus essentially connected to its method of supply.

Under usual circumstances, the value of RC is of the order of one microsecond. The circuit illustrated in FIGURE 2 is therefore limited to the use in convention spectrometry. This circuit is extremely simple, con-

sidering that a single capacitance C_d has been inserted therein.

If it is desired to increase the response speed of the photomultiplier, and reduce consequently the time constant of the system, the resistances R may be reduced, thus increasing the rest current I_o and consequently the amplitude of the output current. With the usual stage gains ($\delta=4$) and with $R_d/R\approx0.1$, it is possible to reach RC values of the order of 10^{-8}, suitable for organic scintillators. In this case high voltage pulses should be used. The drawback lies in that the amplitude of the dynode output current is very much lower than that of the anodic current. In fast operating electronics, it is necessary to have a high current, without amplification subsequent to the photomultiplier, which therefore commands the provision of the anode output.

FIGURE 5 of the drawings shows an alternative embodiment of the circuit according to the invention, incorporating such an anodic output. In this case, q is zero, there is no dynodic circuit $R_d—C_d$, which would introduce a strong distortion in the dynode and in the anode, voltage HT_1 from the first source feeds cathode K and all the dynodes $D_1 \ldots D_N$, whereas voltage HT_2 from the second source feeds only dynode D_N and the anode.

Such a circuit provides, in D.C. operation, a satisfactory linearity with a conventional photomultiplier. This holds also true in A.C. operation if the time constants of the bridge network are all equal, a high common time constant being desirably selected (for instance about 100 microseconds). For fast measurements, the higher amplitude components are those of higher frequency: they are therefore limited by the capacitances of the bridge (for instance 1000 pf.). However, modern photomultipliers may provide an anodic current which is substantially higher than the bridge current I_o. For a very high scaling ratio, for instance, it then becomes necessary to increase I_o. Therefore, high-voltage pulses will advantageously be used, which, in this case, are current pulses, the supply voltages being conventional. In this latter case, the time constants of the bridge should obviously be all equal, but in order to maintain the steep leading edge of the supply pulses, very short time constants should be selected (for instance 10^{-9} seconds). By means of the photomultiplier circuit illustrated in FIGURE 5, high-linearity spectrometric measurements may be carried out in the nanosecond range.

A photomultiplier tube has been tested, connected in a dynode-output circuit according to the invention, having the following particulars:

Type 53 AVP Photomultiplier manufactured by "Radiotechnique," Paris, France
$R=100$ kilo-ohms
$C=30$ pf.
$R_d=7.5$ kilo-ohms
$C_d=400$ pf.
$\delta=4$

The scaling ratio of the γ rays emitted by a sample of cobalt-60 was caused to vary from 250 to 11,000 Hz., and a good agreement of the corresponding energy spectra was obtained.

The invention therefore provides a solution to the problem of linearity of the photomultiplier tubes, both in amplitude and in frequency, over the whole passband of the presently known apparatus, even the speediest.

It is to be understood that the invention is in no way limited to the circuit arrangements specifically described hereinabove by way of example, since various modifications and variations pertaining to the electronics field, may be brought thereto without departing from the spirit and scope of the following claims.

What I claim is:

1. A photomultiplier tube circuit comprising a photomultiplier tube having an anode, a cathode, and a number

N of dynodes arranged in succession between said cathode and said anode, first and second stabilized high-voltage sources each having two terminals, one terminal of said first source being connected to one terminal of said second source for series grouping of said sources, said reciprocally connected terminals of said sources being further connected through a parallel resistor and capacitor which comprise a regulation and output circuit to the dynode of order $(N-q)$ as counted from said cathode, q being an integer smaller than N which may be zero, the other terminal of said first source being connected to said cathode and the other terminal of said second source being connected to said anode, and a resistor bridge comprising one resistor connected between said cathode and the dynode adjacent to said cathode, a plurality of further resistors, each two successive dynodes being connected by one of the resistors in said plurality of further resistors, and one resistor connected between said anode and the dynode adjacent to said anode when q is different from zero.

2. A circuit as claimed in claim **1**, wherein the said first and second high-voltage sources each have a constant potential under load currents varying from zero to maximum.

3. A circuit as claimed in claim **1**, wherein said reciprocally connected terminals of said high potential sources are grounded.

4. A photomultiplier tube circuit comprising a photomultiplier tube having an anode, a cathode, and a number N of dynodes arranged in succession between said cathode and said anode, a first and a second stabilized high-voltage source each having two terminals, one terminal of said first source being connected to one terminal of said second source for series grouping of said sources, said reciprocally connected terminals of said sources being further connected to the dynode of order $(N-q)$ as counted from said cathode, q being an integer smaller than N which may be zero, the other terminal of said first source being connected to said cathode and the other terminal of said second source being connected to said anode, a chain of $(N+1)$ fixed resistances forming a bridge network of said cathode, each of said N dynodes and said anode, respectively, an anode resistance connected between said anode and said bridge to form a non-linear anode circuit, and an output and regulation circuit connected to said dynode of order $(N-q)$, said output and regulation circuit including an adjustable resistance in series between said dynode of order $(N-q)$ and said bridge.

5. A photomultiplier tube circuit comprising a photomultiplier tube having an anode, a cathode, and a number N of dynodes arranged in succession between said cathode and said anode, a first and a second stabilized high-voltage source each having two terminals, one terminal of said first source being connected to one terminal of said second source for series grouping of said sources, said reciprocally connected terminals of said sources being further connected to the dynode of order $(N-q)$ as counted from said cathode, q being an integer smaller than N which may be zero, the other terminal of said first source being connected to said cathode and the other terminal of said second source being connected to said anode, a chain of $(N+1)$ fixed resistances forming a bridge network with said cathode, each of said N dynodes and said anode, respectively, each resistor in said chain having a capacitor connected in parallel therewith, each pair of said resistors and capacitors thereby forming an R-C circuit, an anode resistance connected between said anode and said bridge and a capacitance shunted across said anode resistance to form an anode R-C circuit, and an output and regulator circuit connected to said dynode of order $(N-q)$, said output circuit including an adjustable resistance in series between said dynode of order $(N-q)$ and said bridge, and an adjustable capacitance in parallel with said adjustable resistance to form a dynode R-C output and regulator circuit.

6. A photomultiplier circuit as claimed in claim **5**, in which said R-C circuits in said chain of resistors, said anode R-C circuit and said dynode R-C circuit all have the same time constant.

7. A photomultiplier tube circuit comprising a photomultiplier tube having an anode, a cathode, and a number N of dynodes arranged in succession between said cathode and said anode, a first and a second stabilized high-voltage source each having two terminals, one terminal of said first source being connected to one terminal of said second source for series grouping of said sources, said reciprocally connected terminals of said sources being further connected to the dynode adjacent to said anode, the other terminal of said first source being connected to said cathode and the other terminal of said second source being connected to said anode, and a resistor bridge comprising one resistor connected between said cathode and the dynode adjacent to said cathode, a plurality of further resistors, each two successive dynodes being connected by one of the resistors in said plurality of further resistors, and an output circuit connected to said anode and including a resistor.

8. A photomultiplier tube circuit comprising a photomultiplier tube having an anode, a cathode, and a number N of dynodes arranged in succession between said cathode and said anode, a first and a second stabilized high-voltage source each having two terminals, one terminal of said first source being connected to one terminal of said second source for series grouping of said sources, said reciprocally connected terminals of said sources being further connected to the dynode adjacent to said anode, the other terminal of said first source being connected to said cathode and the other terminal of said second source being connected to said anode, and a resistor bridge comprising one resistor connected between said cathode and the dynode adjacent to said cathode, a plurality of further resistors, each two successive dynodes being connected by one of the resistors in said plurality of further resistors; each resistor in said bridge having a capacitor connected in parallel therewith, each pair of said resistors and capacitors thereby forming an R-C circuit, and an output circuit connected to said anode and including a resistor and a capacitor connected in parallel therewith to form an anode R-C circuit.

9. A photomultiplier circuit as claimed in claim **8**, in which the said R-C circuits in said bridge all have the same time constant and said anode R-C circuit has a time-constant different from said time constant of said R-C circuits in said bridge.

10. The photomultiplier circuit as claimed in claim **5**, wherein said first and second stabilized high voltage sources comprise pulsating current sources.

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RALPH G. NILSON, *Primary Examiner.*

M. A. LEAVITT, *Assistant Examiner.*

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,320,425 May 16, 1967

Paul Joseph Moatti

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

In the heading to the printed specification, lines 4 and 5, "Etablissement Public: Centre de la Recherche Scientifique" should read -- Etablissement Public: Centre National de la Recherche Scientifique --. Column 3, line 47, "spectometric" should read -- spectrometric --. Column 4, line 14, "i_{N-1}, i_2, i_1," should read -- i_N, i_{N-1}... i_2, i_1, --; line 49, after "which" insert -- is --; line 58, cancel "equal", second occurrence; line 62, "Rd/R" should read -- R_d/R --; line 63, "n-q" should read -- N-q --. Column 5, line 36, the equation should appear as shown below

$$\frac{\delta(2q+2)}{\alpha^2} \cdot \frac{\Delta G_d}{G_d}$$

line 57, "m.e.v." should read -- M E V --. Column 6, lines 34, 54 and 56, "pf.", each occurrence, should read -- picofarad --. Column 7, line 42, "of", first occurrence, should read -- with --. Column 8, line 54, the claim reference numeral "5" should read -- 8 --.

Signed and sealed this 9th day of September 1969.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents