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[54] PHOTOMULTIPLIER TUBE CIRCUIT

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[51] **Int. Cl.** **H01j 39/12**

[58] **Field of Search** ..... 250/205, 207; 356/202, 205; 95/10 A; 313/105

[56] **References Cited**

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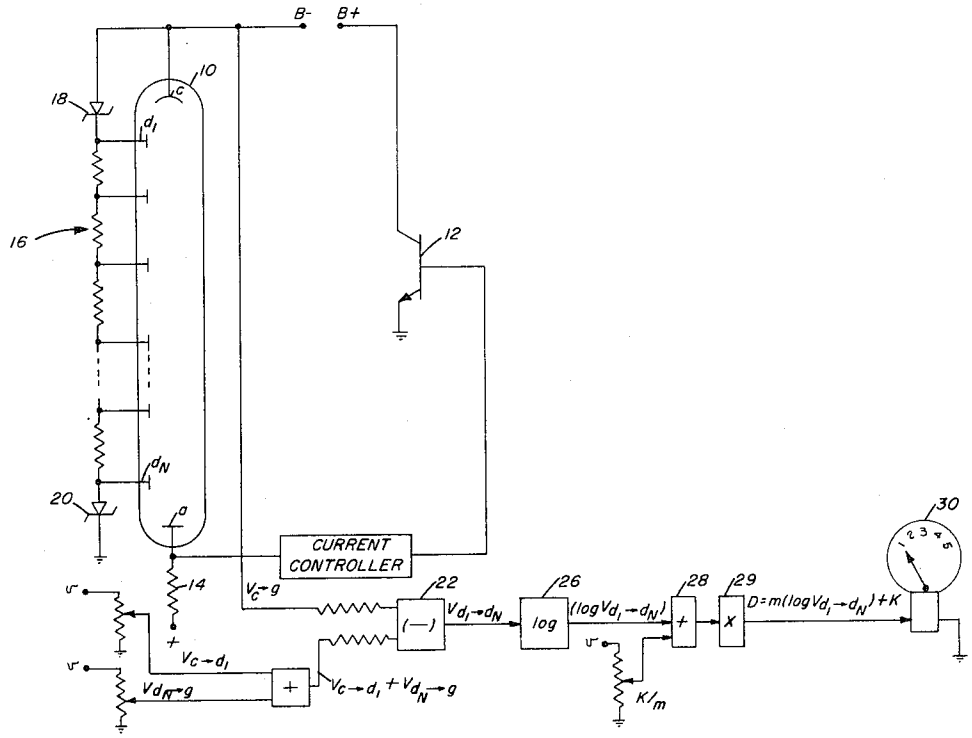
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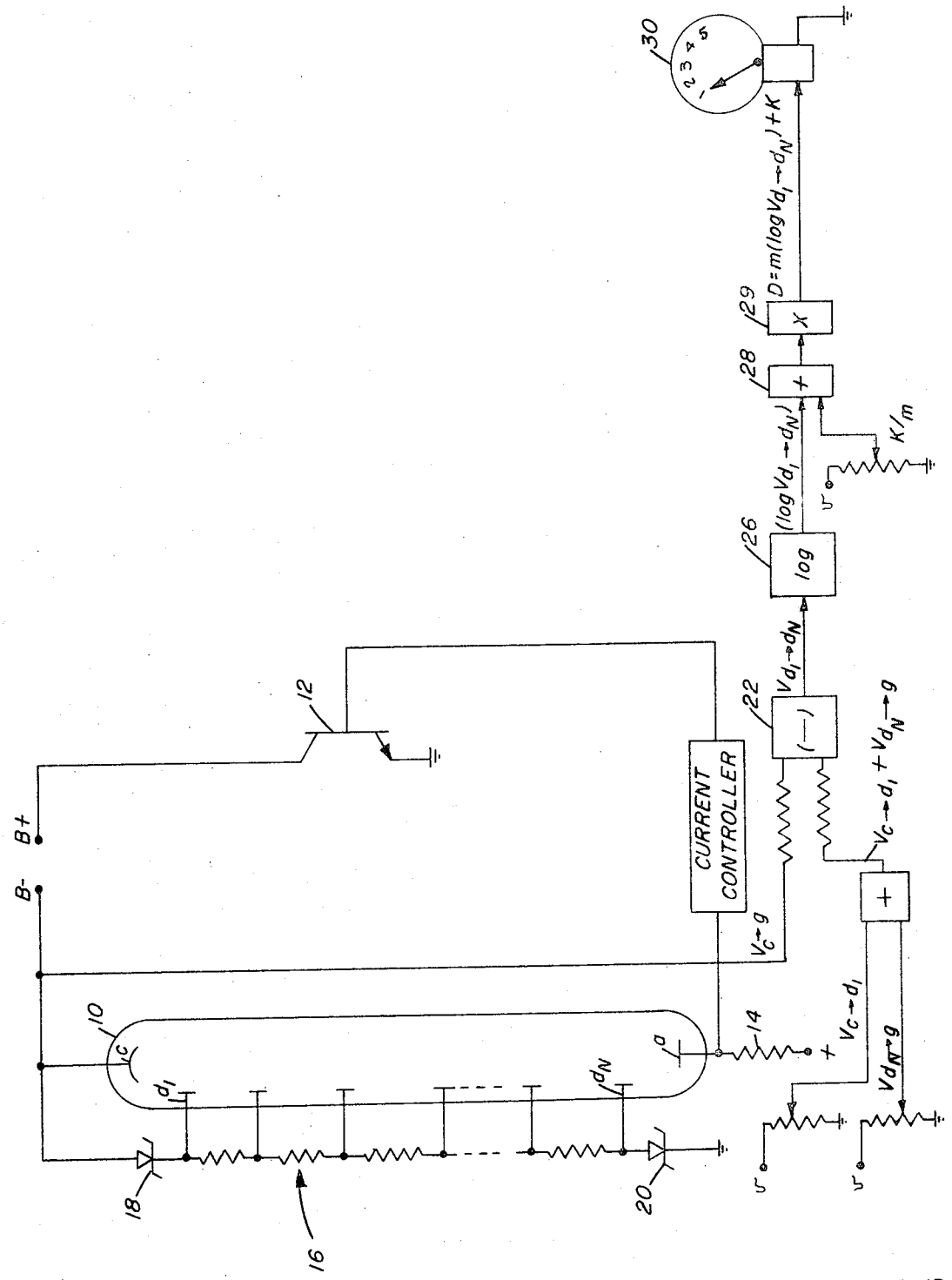
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[57] **ABSTRACT**

A voltage difference equal to the sum of the voltage differences appearing between the cathode and first dynode, and between the last dynode and ground of a photomultiplier tube is subtracted from the cathode-to-ground voltage difference of a photomultiplier tube. Optical density is calculated by producing the logarithm of the quotient signal so produced.

5 Claims, 1 Drawing Figure





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PHOTOMULTIPLIER TUBE CIRCUIT

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates in general to photomultiplier tube circuits. In particular, the invention provides means for making the useful output of a photomultiplier tube circuit a linear function of the logarithm of the input radiation to the photomultiplier tube.

2. Description Relative to the Prior Art

This invention is best appreciated cast in the environment of a densitometer, for it is in the field of densitometry that the invention has its closest known prior art, and in which field the problem solved by means of the invention has been most perplexing. Optical density is a property of concern in the photographic field, and it is defined as the negative logarithm of the light transmitted by a sample. Thus, if 100 percent of the source light passes through the sample, the sample has zero density; if 10 percent of the source light passes through the sample, the sample has an optical density of one; if 1 percent of the source light passes through the sample, the sample has an optical density of two, etc.

A photomultiplier tube connected into a constant anode current circuit in the manner taught by Gunderson, U.S. Pat. Nos. 2,413,706 and 2,454,871, has an exponential characteristic which is dependent on the type, number, and arrangement of its dynodes: The quantity of electrons made available by radiation received at the cathode of a photomultiplier tube is increased exponentially as a function of the voltages applied to (and number of) its dynodes.

Sweet, in U.S. Pat. No. 2,492,901, issued Dec. 27, 1949, provides a constant current photomultiplier tube densitometer circuit of the type indicated by Gunderson (see above), and indicates an incremental technique for linearizing the relationship of the output of a photomultiplier tube with optical density; Journal of Scientific Instruments, Volume 33, February, 1966, in an article entitled "A Wide Range, Recording, Logarithmic Photometer Circuti" by Hariharan and Bhalla, indicates a nonincremental technique for linearizing such relationship. Whereas the Sweet circuit arrangement is fairly simple in construction, it is functionally less than adequate because of its use of discrete corrections: i.e., quantizing an incrementally adjusted voltage is less than adequate if such voltage is to be digitally manipulated, a fact which has been reconciled by Neale, in U.S. Pat. No. 3,571,599. The Hariharan and Bhalla circuit, on the other hand, is functionally adequate, but is comparatively complex and expensive construction-wise.

Neale non-incrementally linearizes, in a very simple way, the output of a photomultiplier tube, by taking such output across a varistor. While the Neale technique is quite useful, it avoids the real essence of a problem implicit in the use of a photomultiplier tube and, attendantly, the Neale circuit is adequate for its intended purpose only over a limited range (depending, among other things, on the characteristics of the varistor employed by Neale) of tube inputs.

The problem referred to above resides in the fact that, though a photomultiplier tube is considered an exponential amplifier, exponential amplification, per se, stems essentially form the voltage which is applied across the tube dynodes, exclusive of the voltages which appear between the tube cathode and first dynode (d_1) and between the last dynode (d_n) and ground (g). The cathode-to-first-dynode voltage is strictly for the purpose of supplying electrons which may be exponentially increased; and the last-dynode-to-ground voltage is for the purpose of collecting those exponentially increased electrons . . . which is to say that the prior notion that the anode output current of a photomultiplier tube is both proportional to the flux ϕ received by the tube and to an exponential function of the total cathode-to-ground voltage is imprecise. Rather, the current produced by a photomultiplier tube is more properly indicated in terms of the following expression:

$$i = k\,\phi\,V^{m}_{d_1 \to d_N} \tag{1}$$

where m is an empirically determined characteristic of the tube in question that is constant for all tubes of this type.

SUMMARY OF THE INVENTION

The present invention proposes to translate a photomultiplier tube into a true exponential amplifier which, when cast in the environment of a densitometer, may have its exponential output algebraically manipulated into a resultant signal that is linearly related to the logarithm of light flux (density D) received by the photomultiplier tube over an extended range. The translation occurs as a result of the employment of (at least) saturation level voltages between the cathode and first dynode and between the last dynode and ground of a photomultiplier tube; and by subtracting, from the voltage which appears between the cathode and ground of the photomultiplier tube, a voltage corresponding to the sum of the two saturation level voltages employed. Thus,

$$V^{m}_{d_1 \to d_N} = [V_{c \to g} - (V_{c \to d_1} + V_{d_N \to g})]^{m} \tag{2}$$

A fixed voltage (herein called a saturation level voltage) between the cathode and firs dynode of the photomultiplier tube is applied which is sufficient to supply substantially all photomultiplier-produced cathode electrons to the first dynode. A saturation level voltage between the last dynode and ground is the voltage at which the anode is just able to collect substantially all of the electrons which have been emitted by the last dynode d_N.

Having connected a photomultiplier tube into a circuit which is a true exponential amplifier, the invention employs the photomultiplier tube circuit so modified in the environment of a densitometer based on the principle outlined by Gunderson, which principle is directed to the idea of keeping the photomultiplier tube current constant by appropriately varying the dynode volt-ages of the photomultiplier tube.

Density, as is known, is defined as the negative logarithm (base 10) of the optical transmittance of a sample. Thus,

$$D = \log \frac{1}{T} = \log \frac{1}{\frac{\phi}{\phi_o}} = \log \frac{\phi_o}{\phi} \tag{3}$$

where $\phi/\phi_o = T$ is the ratio of the light flux received from a sample under inspection to the light flux sup-

plied to that sample. Employing equation (1) as a basis for measuring the density D of a sample, we have:

$$i = k\,\phi/\phi_o\,V^m{}_{d_1 \to d_N} \tag{4}$$

or

$$(i/k)\,\phi_o/\phi = V^m{}_{d_1 \to d_N} \tag{5}$$

According to the invention, the logarithm of the voltage $V^m{}_{d_1 \to d_N}$ is produced, whereby:

$$\log i/k + \log \phi_o/\phi = m(\log V_{d_1 \to d_N}) \tag{6}$$

Since the tube current, in a Gunderson circuit, is a constant,

$$-\log(i/k) = K \tag{7}$$

causing

$$\log \phi_o/\phi = m(\log V_{d_1 \to d_N}) + K \tag{8}$$

In accordance with Equation (3) above,

$$D = m(\log V_{d_1 \to d_N}) + K \tag{9}$$

and which, by definition (i.e., $y = mx+b$), indicates a linear relationship between the density D of a sample and the logarithm of the voltage which appears across the dynodes of the photomultiplier tube receiving light from the sample.

An object of the invention is to provide photomultiplier tube apparatus for producing a signal that varies as an exponential function of the voltage appearing across the dynodes of the photomultiplier tube.

Another object of the invention is to provide a densitometer, according to the teaching of Gunderson, which provides a linear voltage-to-density relationship over an extended range.

The invention will be described with reference to the Figure, which is a schematic diagram of a circuit incorporating the invention:

A photomultiplier tube **10** is employed in a constant current circuit, substantially as indicated in the aforementioned U.S. Pat. No. 3,571,599. The photomultiplier tube **10** is serially connected to a variable impedance in the form of a transistor **12** (or a cascaded arrangement of transistors), and to a constant source of potential B−,B+. Any change which starts to occur in the photomultiplier tube current causes a signal to be developed across a resistor **14**; and such signal is applied to vary the current passed by the transistor **12.** The transistor **12** is serially connected with the dynode chains of resistances **16,** so that a variable voltage appears between the cathode C of the photomultiplier tube **10** and ground, thereby to keep constant the photomultiplier output anode current.

According to the invention, the dynode chain of resistances **16** constitutes a voltage divider network, and includes voltage regulator devices between the cathode C and first dynode d_1, and between last dynode d_N and ground. As shown, the voltage regulator devices are zener diodes, although other voltage regulator devices, such as batteries or gas-filled voltage regulators are applicable as well. The requirement of the zener diodes **18,20** is that the potentials $V_{c \to d_1}$, $V_{d_N \to g}$, developed thereacross, respectively, be at least at the above-discussed saturation levels for the photomultiplier tube cathode C and anode A.

The invention provides for the subtraction (**22**) of the sum (**24**) of the potentials $V_{c \to d_1}$, $V_{d_N \to g}$ from the total voltage developed across the dynode chain of resistances **16,** thereby to produce a signal that varies as an exponential function of the voltage appearing across the dynodes of the photomultiplier tube. Having identified and produced a signal which is independent of the cathode-to-first-dynode and last-dynode-to-ground voltages employed by the photomultiplier tube, the invention implements — in a densitometer — the teaching implicit in Equations (8) and (9) above:

A sample density which is employed to illuminate the cathode C of the photomultiplier tube causes a signal $V_{d_1 \to d_N}$, as indicated in Equation (5), to be developed. A logarithmic circuit **26** produces a signal ($\log V_{d_1 \to d_N}$ **9**); and such signal is combined (**28**) algebraically with a signal $K/_m$ and then multiplied (**29**) by m to produce the density signal D according to Equation (9) above. A meter **30** or the equivalent registers the density D as a linear function of the voltage applied to the meter . . . the signal $K/_m$ being for the purpose of zeroing the meter.

The invention has been described in detail with particular reference to preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention. For example, the meter zeroing K function can be provided by a facility for directly adjusting the meter **30.**

What is claimed is:

1. In a circuit having:

a. a photomultiplier tube,

b. voltage divider means for applying voltage differences between pairs of successive dynodes of the photomultiplier tube, and between the cathode and first dynode thereof, and between the ground and last dynode of the photomultiplier tube,

the improvement: wherein the voltage divider means includes voltage regulator means for providing at least saturation level voltages between the cathode and first dynode and between the last dynode of the photomultiplier tube and ground, and wherein said circuit includes:

1. means for producing a correction voltage substantially equal to the sum of the voltages across said cathode and first dynode and across said last dynode and ground, and

2. means for receiving the voltage across the said voltage divider means and said correction voltage for subtracting the correction voltage from said voltage across said voltage divider means, thereby to produce a voltage equal to the voltage appearing across the dynodes of the photomultiplier tube.

2. The apparatus of claim **1** wherein said voltage regulator means are zener diodes.

3. The circuit of claim **1** including:

a. means for adjusting the voltage applied across said voltage divider means to maintain constant the anode current of said photomultiplier tube irre-

spective of the flux received by said photomultiplier tube, and

b. means for converting the signal output of said means for subtracting voltages into a signal representing the logarithm of such signal, said logarithmic signal being linearly related to the logarithm of the flux received by said photomultiplier tube.

4. The circuit of claim **3** including means for converting said logarithmic signal into a visual display.

5. The circuit of claim **4** including means for adjusting the zero reference of said meter.

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