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[31] **42/65820**

[54] **PHOTOELECTRON MULTIPLIER**
5 Claims, 2 Drawing Figs.

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313/103, 315/5.25, 315/39.3
[51] **Int. Cl.** **H04b 9/00**
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313/103; 315/39.3; 315/5.25, (Inquired)

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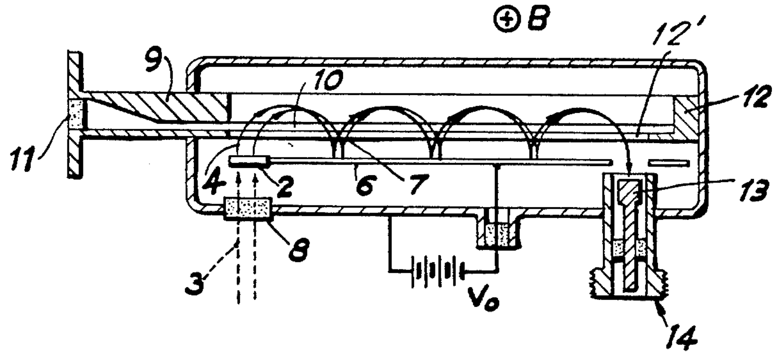
ABSTRACT: The invention provides a photodetector responsive to modulated laser light. A multiplier phototube is used having a photocathode and a dynode arranged on the same plane. An electric field is used to accelerate the electrons from the photocathode and a high frequency standing wave is provided adjacent to the dynode. The trajectories of the electrons are phase compressed and the electron stream is highly localized.



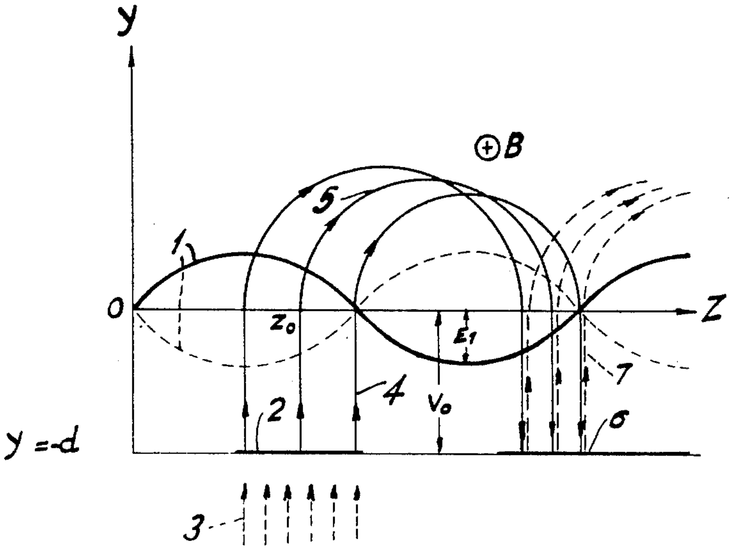


FIG. 1

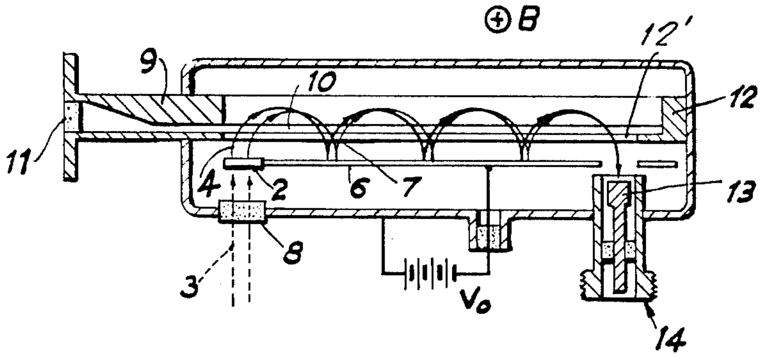


FIG. 2

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PHOTOELECTRON MULTIPLIER

This invention relates to a photomultiplier or a multiplier phototube for a light beam modulated by a high frequency or microwave signal and, more particularly, to a photomultiplier usable as means for demodulating a modulated laser light beam.

In the conventional photomultiplier used for demodulation of the modulated light beam, the electron transit time dispersion, which is caused by the random emission velocities of the electrons emerging from its photocathode and dynodes used for electron multiplication, limit the range of the frequency response of the multiplier.

Various methods have been proposed to obviate this difficulty. For example, a photomultiplier utilizing the motion of electrons in a crossed electric and magnetic fields is described in a paper disclosed in the IEEE Journal of Quantum Electronics, Apr. 1965, pp. 49—59. In the disclosed device, the influence of the random initial emission velocities is eliminated by the utilization of the fact that all the electrons simultaneously emitted from the same origin return to the plane of origin simultaneously, regardless of the emission velocity. The trajectories are trochoidal for electrons of finite emission velocity, while cycloidal for electrons with zero velocity.

As a practical matter, however, the arrangement of the dynodes disposed within a plane cannot cause sufficient electron emission to induce the emission at the next adjacent dynode stage. To give the electrons sufficient energy to cause the succeeding secondary electron emission, the dynodes should be disposed in a staircase configuration. In such a configuration, however, the complete elimination of the influence of the random emission velocity is impossible. Moreover, the residual effect accumulates as the number of dynodes increases. Also, since the radius of the circular trajectory of an electron varies in proportion to its initial emission velocity, the electrons, even if emitted from one point of a dynode stage, arrive at different points at the next stage, causing spatial dispersion. Furthermore, this dispersion also considerably accumulates as the number of the stages increases. Consequently, it is difficult with the disclosed device to design the electrode for finally collecting the electron beam having been subjected to secondary electron emission multiplication.

Another example is a dynamic crossed-field electron multiplier proposed in a paper disclosed in the Proceedings of the IEEE, Jan. 1963, pp. 153—162. The device utilizes the behavior of an electron moving in the mutually crossed microwave electric and static magnetic fields. This device suggests a solution to the above-mentioned problem of the electron transit time dispersion caused by the random emission velocity, and provides a means for causing electron bunching on the time axis. With this device, the energy for emitting the secondary electrons is transferred to each of the emitted electrons from the microwave electric field, the mutual phases of the electrons emitted from the preceding state are relatively compressed owing to the bunching action, causing more intensified collision of electrons against the next-stage dynode disposed on the same plane. Therefore, this device is operative at the microwave frequency with the driving electric field of the appropriate microwave frequency, because the electron transit time is precisely controlled. However, this device does not include any means for suppressing the spacial dispersion of electrons which accumulates as the number of the stages increases, as is the case with the above-mentioned photomultiplier of the static electric and magnetic fields type. Also, unavoidable inclusion of the photocathode and dynodes within the microwave cavity resonator adversely affects the characteristics of the device as a microwave circuit and makes its fabrication difficult. Occasionally, the oscillation is caused by the multitransit of the stray electrons.

The object of the present invention is, therefore, to provide an improved photomultiplier free from any defects of the above-mentioned conventional photomultipliers of the crossed electric and magnetic fields type.

The present invention is based on the above-mentioned principle of the photomultiplier of crossed electric (high frequency) and magnetic fields type, and provides an improvement in that the electric field is produced by the standing wave of microwave frequency. Owing to the existence of the microwave standing-wave field, the trajectories of the electrons are successfully phase compressed, with the result that the intensification of the successive secondary electron emissions are facilitated.

The above-mentioned and other features and objects of this invention and the manner of attaining them will become more apparent and the invention itself will be best understood by reference to the following description of an embodiment of the invention taken in conjunction with the accompanying drawing, wherein:

FIG. 1 is a diagram showing the relations between the trajectories of the electrons and the high frequency electric field intensity, used for explaining the principle of the invention; and

FIG. 2 shows a longitudinal sectional view of the structure of an embodiment of the invention.

Referring to FIGS. 1 and 2 simultaneously, a microwave having an angular frequency ω and an electric field component 1 in the y-axis direction propagates in both directions along the axis of $y=0$ or along the z-axis. Therefore, a standing-wave electric field represented by an expression:

$E=2E_1 \sin \omega t \cos \beta z$ (1) is formed along the z-axis as a whole, where E_1 and β stand for the peak value of the amplitude of the microwave electric field and its phase propagation constant, respectively. Static magnetic field B is applied in the direction perpendicular to the plane of the sheet of drawing or, in other words, in the x-axis direction. Under the situation, photoelectrons 4 are emitted, as a result of the introduction of the modulated laser light beam 3 through a transparent window 8, from a photocathode 2 disposed on the $y=-d$ plane parallel to the z-axis and with a velocity v_0 accelerated by a direct-current voltage V_0 applied across planes $y=0$ and $y=-d$. Since the electron beam is subjected to the velocity-modulation caused by the standing-wave electric field of equation (1) existent along the z-axis, the velocity v_1 of an electron crossing the point z_0 at time t_0 is represented by an equation:

$$v_1=v_0\left[1-\frac{(2p_oz_e)^{1/2}}{v_0}\beta g \cos \beta z_0 \sin \omega t_0\right] \qquad (2)$$

where p_c, z_c and βg stand for the microwave power on the z-axis, the circuit impedance and a constant determined by the time interval between the z-axis crossing, respectively. Thus, the electron crossing the z-axis moves along circular trajectory 5 within the y–z plane under the influence of the magnetic field B. The radius of the trajectory is given by:

$$R=\left(\frac{m}{e}\right)\frac{vd}{B} \qquad (3)$$

where m and e stand for the mass and electric charge of an electron, respectively. The lapse of time T until the return of the electron to another point on the z-axis is represented by an equation:

$$T=\pi\left(\frac{m}{e}\right)\frac{1}{B} \qquad (4)$$

This means that the lapse of time T does not depend on the emission point z on the dynode 6 or the emission velocity v_1. More particularly, all the electrons having simultaneously departed from the z-axis simultaneously return to the z-axis, regardless of the random emission velocities. In as much as the standing-wave electric field shown by equation (1) is existent, however, the radius of the circular trajectory becomes large in proportion to the increase in velocity, which is caused by the velocity modulation due to the standing wave electric field. As is obvious from the equation (3) and FIG. 1, it is possible, among the electrons being simultaneously emitted from the mutually different points on the z-axis (dynode 6) and again return to other points on the z-axis, that an electron emitted from a point behind another electron's simultaneous emission point (with respect to the z-axis) returns to the z-axis at a point ahead of said another electron's returning point, as a result of the spatial differences in accelerating field intensity.

Therefore, as shown in FIG. 1, the electrons can be bunched along the z-axis by subjecting the electrons repetitively to the acceleration phase of the standing-wave electric field.

More particularly, since the electrons returning to the z-axis have been twice subjected to velocity-modulation by the standing-wave electric field on the z-axis, the resultant increment ΔE of the kinetic energy of an electron is given by:

$$\Delta E = -2e(2p_c z_o)^{1/2}\beta g\Big[\cos\beta z_0 \sin\omega t_0 + \cos\beta\left(z_0+\frac{2mv_0}{eB}\right)\times\sin\left(\omega t_0+\frac{m}{eB}\right)\Big] \quad (5)$$

Therefore, the transfer of energy from the electric field to an electron takes place twice, increasing the electron's kinetic energy as a whole. Thus, the electrons which have acquired the additional kinetic energy collide against the dynode **6** spaced below the z-axis at $y=-d$. The dynode emits the secondary electrons **7**, the number of which is multiplied according to the secondary emission ratio determined by the material of dynode **6**. The emitted secondary electrons are accelerated by the direct-current voltage V_0 in the $+y$-direction to reach the z-axis again. On this occasion, it is possible to bring the electron trajectory into coincidence with the acceleration phase of the high-frequency electric field, by suitably choosing the electron transit time between $y=-d$ and $y=0$. The above-mentioned process is repeated to the end of the cycloidal or trochoidal trajectory.

As will be understood from the foregoing, the magnetic field B, direct-current voltage V_0 and space $\underline{d}$ between the photocathode or dynode **6** and the z-axis should satisfy the following conditions for optimum operation:

(1)
$$B=\frac{\pi f}{\left(\frac{e}{m}\right)N}$$

The reason: The transit time T of the electron on the semicircular trajectory must be equal to the period of oscillation

$$T=\frac{2\pi N}{\omega}$$

, N being an integer of the high-frequency electric field.

(2)
$$V_0=\frac{1}{2}\left(\frac{e}{m}\right)\left(\frac{\lambda g B}{4}\right)^2$$

The reason: The radius of the trajectory

$$R_0=\frac{v_0}{\left(\frac{e}{m}\right)B}$$

must be equal to one-fourth of the guide wavelength λg.

(3)
$$d=\frac{N'}{4f}\left(2\frac{e}{m}V_0\right)^{1/2}$$

The reason: the transit time τo of the electron covering the distance $\underline{d}$, which is equal to

$$\frac{4d}{\left[2\left(\frac{e}{m}\right)V_0\right]^{1/2}}$$

provided that the influence of the magnetic field is neglected, must be equal to the oscillation period τ of the high-frequency electric field.

Now, an embodiment of the present invention is explained with particular reference to FIG. 2.

In FIG. 2, a transmitted laser beam **3** is introduced to a photocathode **2** through a transparent window **8** attached to the envelope of the device. Photoelectrons **4** emitted from the photocathode **2** pass through a gap **10** of a ridge waveguide **9** after being accelerated by direct-current voltage V_0 applied between the dynode **6** and the lower wall of the waveguide **9**. On the other hand, a microwave having the transverse electric field is supplied to the wavequide through window **11** disposed at the end of waveguide **9** for forming a part of the vacuum envelope. The wavelength and phase of the microwave are selected so that a standing wave may be formed under the influence of reflection caused by plate **12** disposed at the end. The electrons pass through an elongated central opening **12′** formed in plate **12** into gap **10**, and are subjected to velocity modulation during their traveling in the gap **10** from photocathode **6** to waveguide **9** and then caused to return to the gap **10** following a circular trajectories owing to the influence of the magnetic field B. The velocity-modulated electrons finally collide against the dynode **6** to emit the secondary electrons **7**. As these secondary electrons repeatedly move in a manner identical to that of the first-stage photoelectrons, the number of the electrons increases in a well-known manner. After repeating the same process, the electrons are collected by a collector **13**. Thus, the photoelectric-converted and multiplied or amplified electric signal is derived from an output terminal **14** connected to the electrode **13**.

As has been explained above, a photomultiplier having a simple construction is provided according to the invention, which substantially obviates the adverse effects of the random emission velocity of the electrons. More particularly, the present invention has made it possible to bunch the electrons which are emitted at random in their emission points and velocities. Thus, the present invention has provided a photodetector of high sensitivity responsive to a wide band modulating signal extending to the microwave frequency region.

While the foregoing description sets forth the principles of the invention in connection with specific apparatus, it is to be understood that this description is made only by way of example and not as a limitation of the scope of the invention as set forth in the objects thereof.

I claim:

1. A multiplier phototube comprising:

an envelope, a photocathode for emitting electrons, an anode for collecting said electrons, at least one dynode to provide secondary emission, said photocathode, dynode and anode being contained within said envelope and defining a drift space through which said electrons may move along chained-semicircular trajectories, said dynode being disposed within substantially the same plane as said photocathode, a waveguide section disposed substantially parallel to said dynode and having one of its ends shorted for providing a high frequency standing electric wave within said drift space along said dynode to accelerate said electrons, said waveguide section having a gap for allowing said standing electric wave to interact with said electrons, said gap being smaller than the distance of the furthest end of each of said seimicircular trajectories from said dynode as measured in the direction perpendicular to the axis of said waveguide section, and means for applying a static magnetic field within said drift space to deflect the accelerated electrons, whereby said standing wave means further causes said accelerated deflected electrons to bunch.

2. The phototube of claim 1, in which said waveguide section comprises, a ridge waveguide for forming said gap.

3. The phototube of claim 1 including, DC-biasing means coupled to said dynode.

4. The phototube of claim 3 in which said DC-biasing means provides a voltage V_0, and the electrons follow a semicircular trajectory, the magnetic field B, direct-current voltage V_0, and space 1 between the photocathode and z-axis approximately satisfying the following conditions:

$$B=\frac{\pi f}{\left(\frac{e}{m}\right)N} \quad (1)$$

$$V_o=\frac{1}{2}\left(\frac{e}{m}\right)\left(\frac{\lambda qB}{4}\right)^2 \qquad (2)$$

the radius of the trajectory

$$R_o=\frac{v_o}{\left(\frac{e}{m}\right)B}$$

being equal to one-fourth of the guide wavelength λg;

$$d=\frac{N'}{4f}\left(2\frac{e}{m}V_o\right)^{1/2} \qquad (3)$$

the transit time τo of the electron covering the distance 1 equal to

$$\frac{4d}{\left[2\left(\frac{e}{m}\right)V_o\right]^{1/2}}$$

being equal to the oscillation period τ of the high frequency electric field.

5. A system for demodulating a modulated laser light beam comprising; means providing a modulated laser light beam; photomultiplier means for demodulating said laser light including; an envelope, a photocathode for emitting electrons;

means directing the light beam to said photocathode; and anode for collecting said electrons; at least one dynode to provide secondary emission; said photocathode, dynode and anode being contained within said envelope and defining a drift space through which said electrons may move along chained-semicircular trajectories; said dynode being disposed within substantially the same plane as said photocathode; a waveguide section disposed substantially parallel to said dynode and having one of its ends shorted for providing a high frequency standing electric wave within said drift space along said dynode to accelerate said electrons; said waveguide section having a gap for allowing said standing electric wave to interact with said electrons, said gap being smaller than the distance of the furthest end of each of said trajectories from said semicircular dynode as measured in the direction perpendicular to the axis of said waveguide section, and means for applying a static magnetic field within said drift space to deflect the accelerated electrons; whereby said standing wave means further causes said accelerated deflected electrons to bunch.