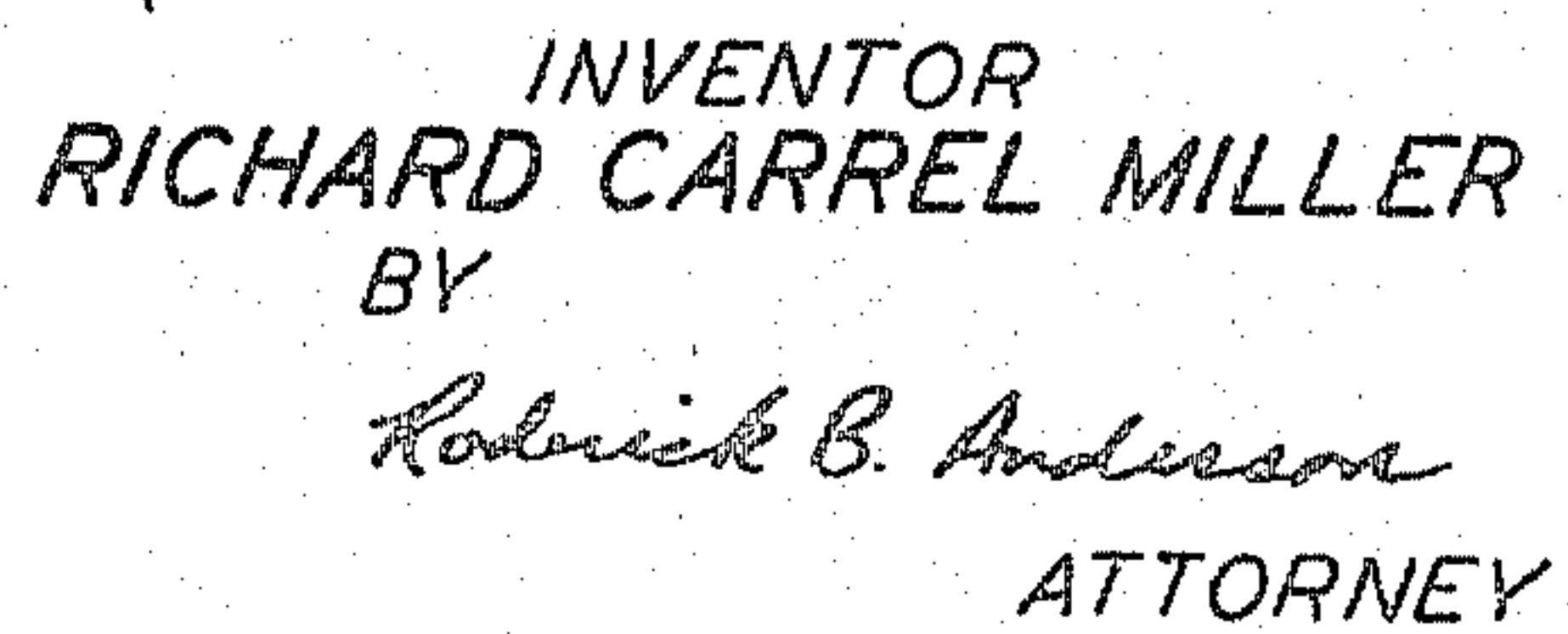


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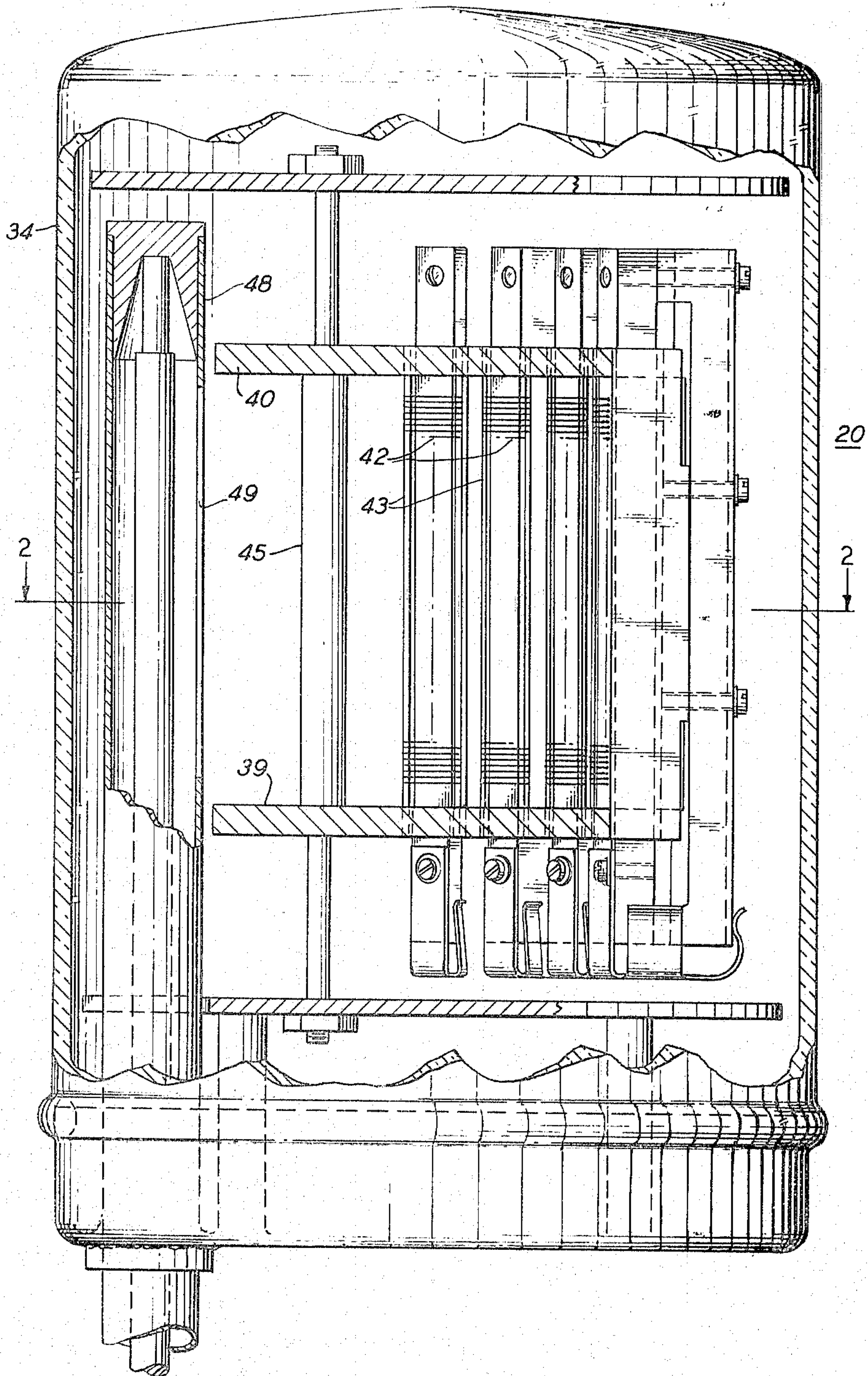
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R. C. MILLER
PHOTOMULTIPLIER RESPONSIVE TO HIGH
FREQUENCY MODULATED LIGHT WAVES

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FIG. 3



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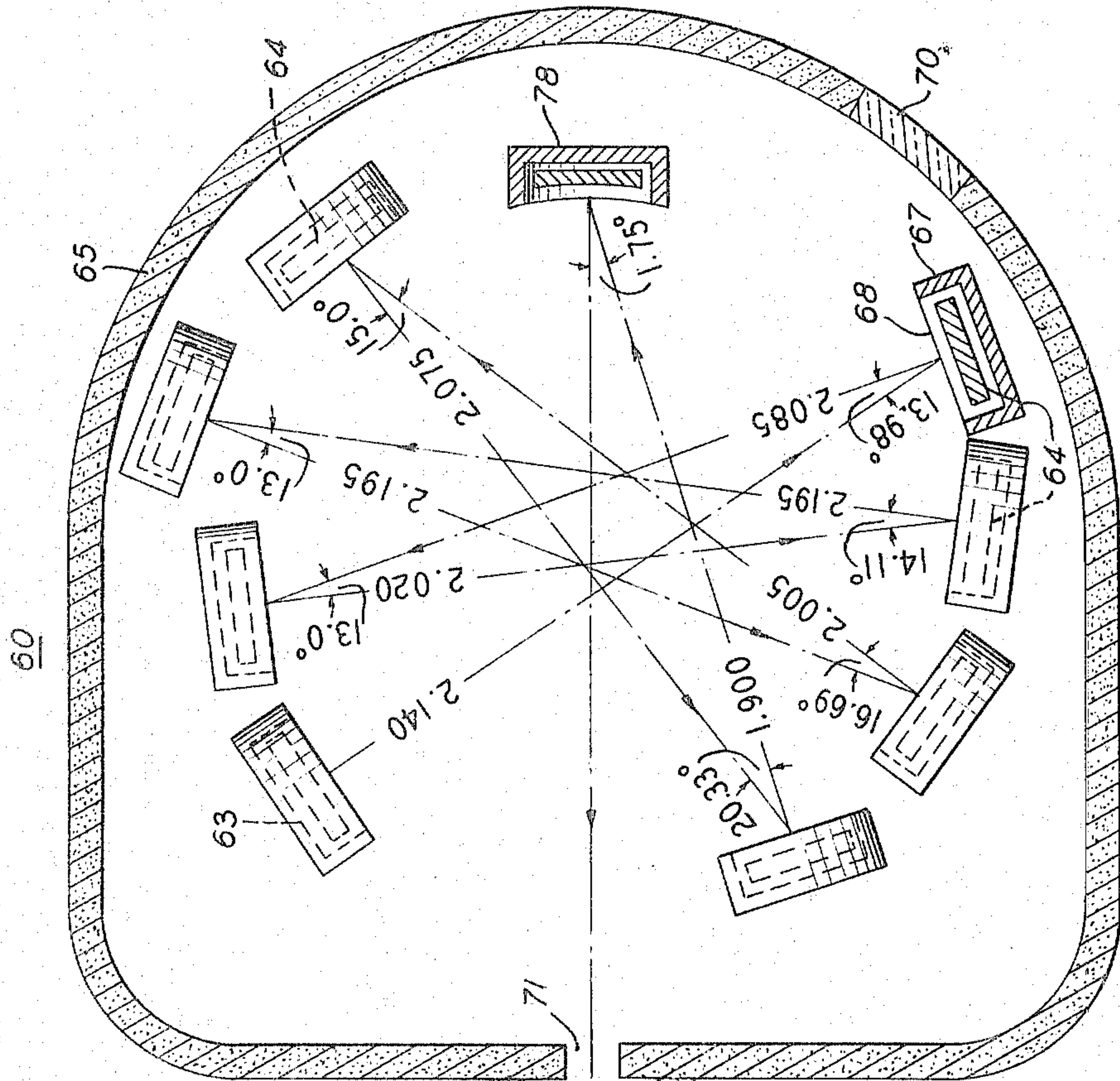
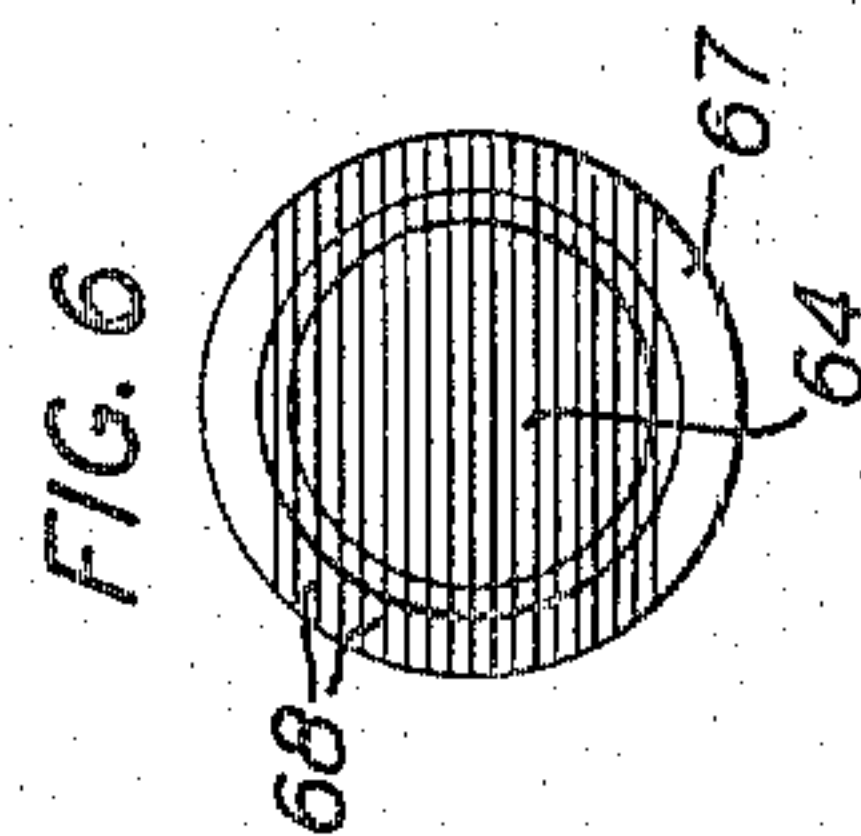
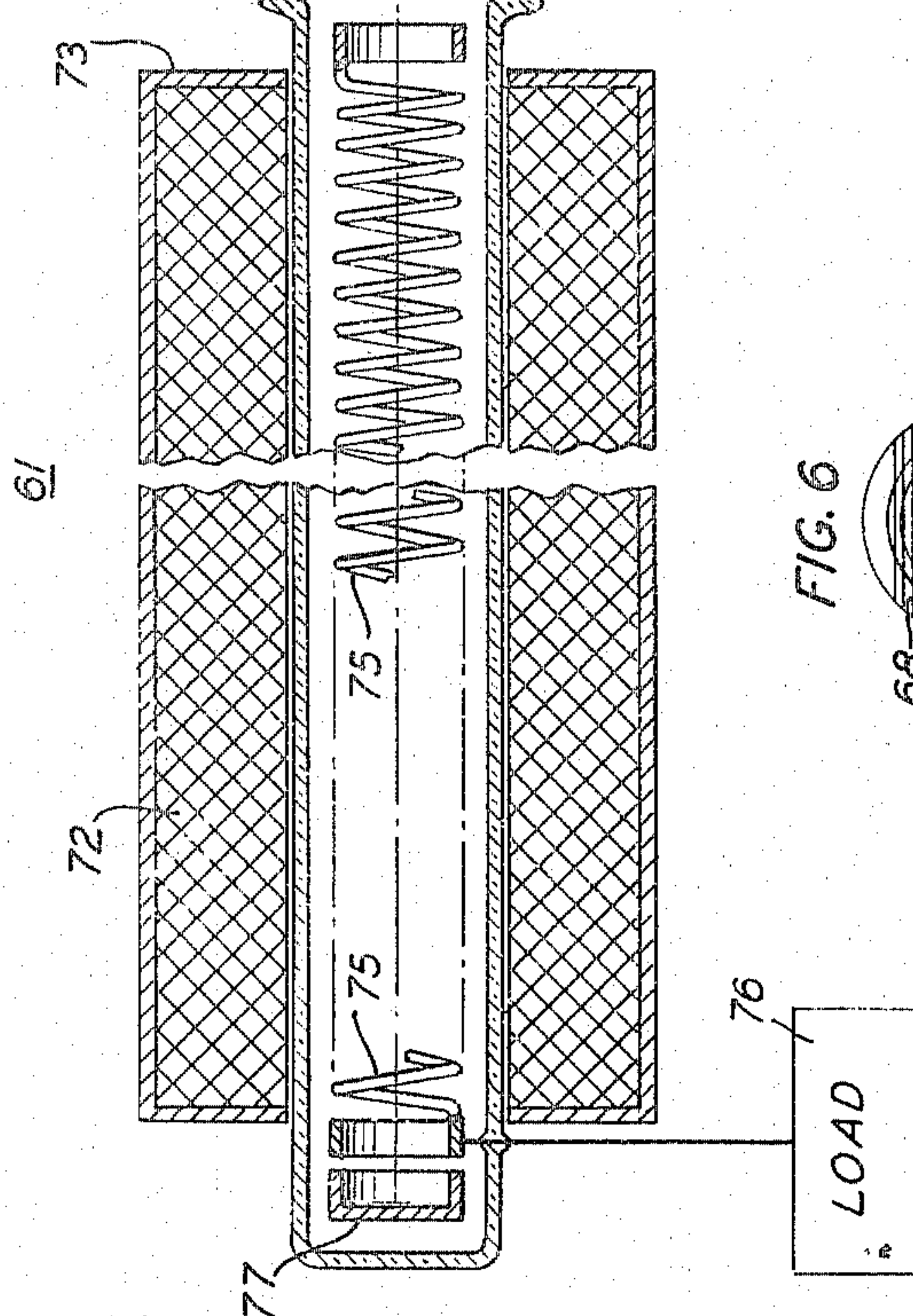


FIG. 5



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3,302,029
PHOTOMULTIPLIER RESPONSIVE TO HIGH FREQUENCY MODULATED LIGHT WAVES

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15 Claims. (Cl. 250-207)

This invention relates to photomultipliers, and more particularly, to photomultipliers for amplifying high frequency modulated light waves.

The optical maser, a device for generating and amplifying coherent light waves, has stimulated considerable activity in the communications field because, at least in theory, coherent light can be modulated over exceedingly large frequency bandwidths. Much of this activity has been directed at the improvement of the photomultiplier tube, a device capable of detecting and amplifying light wave modulations. The photomultiplier first converts light energy to electrical current by means of a photocathode which emits electrons in response to the impingement of light waves. The emitted electrons are directed at a series of electrodes, called dynodes, which are coated with a material having a high ratio of secondary emission. The original modulation energy is amplified by virtue of a progressively higher quantity of secondary electrons that is emitted by each successive dynode. The electron stream is then collected and its modulation energy is transmitted to an appropriate load.

In order to take advantage of the large bandwidth capabilities of light wave transmission, the photomultiplier must be responsive to extremely high modulation frequencies. One of the frequency limiting characteristics of virtually all photomultipliers is the transit time dispersion of the electron stream as it travels from the photocathode to the collector. Transit time dispersion refers to differences in the time taken by electrons at different locations in the electron stream to travel between dynodes. Such time differences normally increase as the number of dynodes in the device is increased. If the total transit time dispersion, or electron transit time differences over the entire path, is comparable to the period of a given modulation frequency, then modulation energy at that frequency will be distorted and attenuated by the photomultiplier.

Attempts have been made to reduce transit time dispersion by strongly focusing the electron stream. In some conventional electrostatically focused photomultipliers such focusing produces an electron stream of small cross-section and high electron density which tends to deteriorate those dynodes near the collector, where electron stream current density is highest. The electron trajectories can also be controlled by using crossed electric and magnetic focusing fields which cause the electrons to follow trochoidal or circular-like trajectories between adjacent dynodes. This type of photomultiplier generally presents additional complexities and is impractical if the photomultiplier electron stream is to be injected into a traveling wave tube amplifier, as will be explained later.

It is an object of this invention to reduce the effects of transit time dispersion in a photomultiplier.

It is another object of this invention to reduce the effects of transit time dispersion in an electrostatically focused photomultiplier.

The dynodes of the conventional electrostatic photomultiplier are arranged to define a zig-zag electron stream path between the photocathode and the collector. It can be observed that one extreme boundary of this zig-zag path is inherently longer than the opposite extreme boundary. This discrepancy in electron path length is largely

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responsible for the undesirable transit time dispersion. It is, however, impossible to make the electron path lengths between each pair of dynodes equal because each dynode must be tilted at an angle with respect to the preceding dynode in order to project secondary electrons toward a succeeding dynode.

I have found that it is possible to eliminate the effects of transit time dispersion created by one or more pairs of dynodes by intentionally creating a compensating transit time dispersion in a different pair or pairs of dynodes. This is done by defining a field-free region around which all of the electrodes of the photomultiplier, including the photocathode, the dynodes, and the collector, are located. An accelerating grid closely adjacent the emitting surfaces of the photocathode and dynodes project the electrons through the field-free region to the succeeding electrode. As will be explained fully hereafter, transit time dispersion is eliminated by arranging the voltages and the angular positions of the electrodes to substantially satisfy the relation

$$\sum_{n=1}^N \frac{\Delta_n}{v_n} = 0 \quad (1)$$

where Δ_n is the path length difference of electrons on opposite extreme boundaries of the stream incident on the grid of a dynode n under consideration, v_n is the speed of the electrons incident on that same grid, and N is the total number of electrodes. When this relationship is met, the modulation energy on opposite boundaries of the electron stream arrives at the collector with the same phase relationship that it had when it left the photocathode. Hence, the attenuating and distorting effects of transit time dispersion are substantially reduced.

Equation 1 implies that the last pair of electrodes in the photomultiplier can be arranged to compensate for all of the cumulative transit time dispersion of all of the preceding electrodes. Although this type of arrangement would be a distinct improvement over photomultipliers, of the prior art. I have found that it is preferable to prevent an accumulation of transit time dispersion within the electron stream because substantial spurious phase displacements within the stream can cause some disruption and interference even though compensation is made for it subsequently. Hence, it is desirable that the transit time dispersion between one pair of dynodes should compensate for the dispersion between the preceding pair. One requirement for accomplishing this is that all of the dynodes emit secondary electrons at a clockwise angle with respect to incoming electrons or that they all emit secondaries at a counter-clockwise angle. As will become clear later, this implies that the dynodes define a sort of star-shaped electron stream path, rather than a zig-zag path. Another requirement is that the angle of incidence of electrons incident on the grid adjacent to any electrode under consideration conform to the relationship

$$\tan \theta_n = \frac{v_n}{v_{n-1}} \sin \theta_{n-1} \quad (2)$$

where v_n is the speed of electrons incident on the grid of a given electrode, θ_n is the angle of incidence of electrons incident on that same grid, v_{n-1} is the speed of electrons on the grid next preceding the grid of the given electrode, and θ_{n-1} is the angle of incidence of electrons on the grid of the electrode next preceding the given electrode.

These and other objects and features of the invention will be more fully understood from a consideration of the following detailed description, taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a schematic illustration showing the principles of operation of a typical prior art photomultiplier tube;

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FIG. 2 is a schematic sectional view of one embodiment of the invention;

FIG. 3 is an elevation view of the embodiment of FIG. 2;

FIG. 4 is a schematic view of photomultiplier electrodes which illustrate the principles of operation of the device of FIG. 2;

FIG. 5 is a schematic sectional view of another embodiment of the invention; and

FIG. 6 is a view of a dynode assembly of the embodiment of FIG. 5.

Referring now to FIG. 1 there is shown a schematic representation of an electrostatic photomultiplier 10 of the prior art for detecting and amplifying light waves from a source 11. Enclosed within a substantial vacuum by an envelope 12 are a photocathode 13, a plurality of dynodes 14, and an electron collector 15. Photocathode 13 is coated with a photoemissive material that emits electrons when light strikes it. Dynodes 14 are coated with a material having a high ratio of secondary emissions; that is, a material that emits secondary electrons in response to the impingement of primary electrons, with the number of secondary electrons exceeding the number of primary electrons. Adjacent the emitting surfaces of each electrode is a grid 16 which is normally at a higher positive voltage than any of the electrodes, and thereby serves to direct and accelerate the electrons.

In operation, information in the form of light modulations from a source 11 strikes photocathode 13 causing a modulated electron stream to be emitted. The electrons form a stream defined by boundaries 17 and 18 and are directed at the first dynode of the dynode series. Each successive dynode is biased at a higher potential than the preceding dynode, this incremental voltage being indicated on FIG. 1 as ΔV . Secondary electrons are emitted from the first dynode of the series in response to electrons from the photocathode and are directed toward the second dynode. This process is repeated by each dynode with the electron current being increased by each successive impingement because of the large number of secondary electrons that are thereby generated. Hence the original light wave modulations are converted to electrical energy which is greatly amplified by the time the electrons reach the collector 15. The electron stream is directed along a substantially coherent zig-zag path by virtue of the appropriate tilt of the dynodes, the progressively higher dynode voltages, and because the secondary electrons are projected substantially at right angles to the emitting surfaces.

It is to be noted that the length of boundary 18 is considerably longer than the length of boundary 17 between the photocathode and the first dynode and between each subsequent pair of dynodes (boundary 18 is shown with dashed lines to facilitate this comparison). It is therefore easily seen that it takes electron stream modulation energy longer to travel from the photocathode to the collector along boundary 18 than along boundary 17. This transit time discrepancy, or transit dispersion, will seriously attenuate and distort the modulation energy if it is comparable to the period of the modulation frequency.

FIG. 2 shows a photomultiplier 20 in accordance with the invention which comprises a photocathode 21, an array of dynodes 22 through 29, some of which are shown in phantom, and an electron stream collector 30. The general purpose and mode of operation of photomultiplier 20 is the same as that of photomultiplier 10 of FIG. 1. Photocathode 21 has a surface 32 coated with photoemissive material while dynode 22, which is identical with dynodes 23 through 29, has a surface 33 of a material having a high ratio of secondary emission. All of the electrodes are maintained within a substantial vacuum by an envelope 34. Modulated light is directed at the photocathode 21 through a transparent window 36 in envelope 34. Emitted electrons from the photocathode are

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accelerated to high speeds by a grid 42 closely adjacent the emitting surface and are directed at dynode 22 which, in turn, emits secondary electrons which are accelerated by an associated grid toward dynode 23. The dynodes and grids 42 are arranged to direct the emitted electrons along an electron stream path 37, the arrows of which show the direction of travel of the emitted electrons. As in FIG. 1, the original modulation energy is amplified by the progressively higher quantity of secondary electrons that are emitted by the successive dynodes.

With reference to FIGS. 2 and 3, the photocathode, dynodes, and the collector are located around the periphery of a field-free region defined by the grids 42 and two parallel conductive plates 39 and 40, all of which are at the same electrical potential. Each of the dynodes and the photocathode is contained within an assembly which comprises the grid 42 and a grid housing 43. Each grid and grid housing completely surrounds its corresponding dynode, and each are electrically connected to plates 39 and 40 to maintain the volume between plates 39 and 40 at a constant electrical potential. The electron stream path 37, between successive dynode grids, therefore lies completely within the electrically field-free region. The photocathode and dynode assemblies are supported by plates 39 and 40 which in turn are supported by supporting posts 45 and 46. The grids 42 should be parallel to the emitting surfaces of their corresponding dynodes and as close thereto as possible without generating a spurious electrical discharge.

The electron collector 30 constitutes part of the inner conductor of a coaxial cable 48; the electrons reach the inner conductor by way of a slot 49 in the outer conductor. As is explained in the application of N. C. Wittwer, Jr., Serial No. 214,302, filed August 2, 1962, now Patent No. 3,215,844, the modulated electron stream excites an electromagnetic wave in the cable which is representative of the electron stream modulations. This electromagnetic wave is then transmitted by the cable to an appropriate load. The coaxial cable electron collector is sensitive to higher frequency electron stream modulations than are conventional collectors because its load impedance is distributed along its length rather than constituting a lumped impedance.

The field-free region defined by plates 39 and 40 is maintained at a higher positive potential than that of any of the dynodes in order that grid 42 may accelerate the emitted electrons and project them toward the next succeeding dynode. As in the device of FIG. 1, each dynode is at a higher positive potential than the preceding dynode. For example, plates 39 and 40 may advantageously be maintained at ground potential with the photocathode at -3800 volts. Each of the dynodes may be maintained at potentials more positive by 300 volts than the preceding dynode. Hence, dynode 22 has a potential of -3500 volts, dynode 23 has a potential of -3200 volts, dynode 24 has a potential of -2900 volts, with each successive dynode and the collector 30 having positive incremental voltages of 300 volts each with respect to the preceding dynode. The relative voltages on the electrodes are indicated by the reference letter a through j which correspond to the relative voltages a through j on direct current voltage source 50.

The locations of the electrodes are shown in FIG. 2 by angles expressed in degrees and minutes and by lengths expressed in inches. The purpose of the particular orientation of the photocathode, dynodes, and collector is to reduce or eliminate the transit time dispersion effects which are inherent in the device of FIG. 1. To appreciate how this is accomplished, consider next FIG. 4 which is a schematic illustration of three dynodes designated as n , $n-1$, and $n-2$, respectively. The electron stream projected from dynode $n-2$ to dynode $n-1$ and from dynode $n-1$ to dynode n has opposite extreme boundaries 52 and 53. For purposes of simplicity, the distance by which path length 53 exceeds path length 52 will be

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denoted by a positive number. Hence, the path length difference of boundaries 53 and 52 between dynode n and dynode $n-1$ is equal to Δ_n , and the difference between dynode $n-1$ and dynode $n-2$ is equal to $-\Delta_{n-1}$. The widths of the dynodes are defined as w_n , w_{n-1} , and w_{n-2} . The path length differences are therefore defined as

$$\Delta_n = w_n \sin \theta_n \quad (3)$$

$$\Delta_{n-1} = -w_{n-1} \sin \theta_{n-1} \quad (4)$$

where θ_n and θ_{n-1} are the angles of incidences of electrons on the grids of dynodes n and $n-1$, respectively. As used herein, the term "angle of incidence on a grid" will refer to incoming electrons from the next preceding dynode, rather than electrons from the dynode with which the grid is associated. The widths of dynodes $n-1$ and $n-2$ are defined as

$$w_{n-1} = w_n \cos \theta \quad (5)$$

$$w_{n-2} = w_{n-1} \cos \theta_{n-1} \quad (6)$$

At first glance, it may appear that transit time dispersion could be eliminated by making the total of the path length differences along the entire device equal to zero. This is not true because of the different speeds at which the electrons travel between different electrodes. The speed of the electrons is proportional to the square root of the voltage on the dynode from which they are emitted. Since the dynodes are at different voltages and the grids are all at the same voltage, the electron stream travels at different speeds between different pairs of dynodes. The velocity of electrons between dynode $n-1$ and dynode n can be shown to be

$$v_0 = 5.93 \times 10^7 \sqrt{V_g - V_{n-1}} \text{ cm./sec.} \quad (7)$$

where v_0 is the electron velocity, V_g is the grid voltage, and V_{n-1} is the voltage on dynode $n-1$. Since total transit time is equal to distance divided by velocity, transit time dispersion along the entire electron beam path of the device can be eliminated if the following condition is met:

$$\sum_1^N (\Delta_n / v_n) = 0 \quad (8)$$

where N is the number of electrodes of the entire device including the photocathode, dynodes, and collector, Δ_n is the path length differences of electrons on opposite extreme boundaries of the stream incident on the grid under consideration, and v_n is the speed of electrons incident on that same grid. When this relationship is met, the net electron transit time of all segments of the electron stream path are equal. Hence, the modulation energy at opposite boundaries of the electron stream arrives at the collector with the same phase relationship it had when it left the photocathode. It can be shown that this condition is met in the device of FIG. 2 with the angular positions of the dynodes being as shown and with the voltages on the dynodes and grids as indicated above.

Even when full compensation for transmit time dispersion is made in accordance with the requirement of Equation 8, some attenuation and distortion of the modulation energy can occur if relatively large transit time differences are permitted to accumulate within the photomultiplier electron stream before the compensation is effected. Transit time differences between individual pairs of dynodes are inevitable because of the angles at which the dynodes must be tilted to change the direction of the electron stream. If, however, each pair of dynodes provides transit time compensation for the preceding or succeeding pair, substantial transit time differences will not be permitted to accumulate, and such attenuation and distortion can be substantially eliminated. For purposes of simplicity this type of transit time compensation will be referred to as "cancellation in pairs."

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Cancellation in pairs requires that the path length difference of opposite electron stream boundaries be alternately positive and negative. In FIG. 4, for example, Δ_{n-1} is negative while Δ_n is positive. This requirement is fulfilled by arranging the dynodes such that they all project secondary electrons at a clockwise angle with respect to the incident incoming electrons, or that they all project secondary electrons at a counterclockwise angle. In the device of FIG. 2, for example, all of the dynodes project secondary electrons at a clockwise angle with respect to the incident electrons thereon. For precise cancellation in pairs, the transit time differences resulting from path length differences between a pair of dynodes should be equal and opposite to a corresponding transit time difference between the preceding pair of dynodes, or, in the notation of FIG. 4

$$\frac{\Delta_n}{v_n} = \frac{\Delta_{n-1}}{v_{n-1}} \quad (9)$$

Combining Equation 9 with Equations 3 and 4 gives

$$\frac{w_n \sin \theta_n}{v_n} = \frac{w_{n-1} \sin \theta_{n-1}}{v_{n-1}} \quad (10)$$

Combining Equation 10 with Equation 5 gives

$$\frac{w_n \sin \theta_n}{v_n} = \frac{w_n \cos \theta_n \sin \theta_{n-1}}{v_{n-1}} \quad (11)$$

Multiplying Equation 11 by v_n and dividing by $\cos \theta_n$ gives

$$\tan \theta_n = (v_n / v_{n-1}) \sin \theta_{n-1} \quad (12)$$

Equation 12 may be interpreted as follows: the transit time dispersion of electrons incident on the grid of the dynode n will cancel out the transit time dispersion of electrons incident on the grid of the next preceding dynode $n-1$ if the tangent of the angle of incidence of incoming electrons on the grid of dynode n is equal to the ratio of the speeds of electrons incident on the grid of dynode n to the speed of electrons incident on the grid of dynode $n-1$, multiplied by the sine of the angle of incidence of electrons on the grid of dynode $n-1$. When an array of electrodes is used, each alternate grid should present an angle of incidence θ_n which fulfills Equation 12 with respect to the angle of incidence θ_{n-1} on the grid of the next preceding electrode. The electrode locations and voltages of the device of FIG. 2 not only meet the requirement of Equation 8, but they also meet the requirements of Equation 12 to give cancellation in pairs.

A final criterion for constructing a photomultiplier in accordance with my invention is that the angle of incidence θ of the electron stream on each grid should be sufficiently small with respect to the voltages of the grid and dynode which it is approaching to preclude the possibility of substantial electron reflection back into the field-free region. In other words, the electrons should not approach the grid at so steep an angle that they cannot penetrate it and impinge on the dynode. It can be shown that this condition is met if the angle of incidence θ_n on the grid of any dynode n fulfills the relationship

$$\sin \theta_n < \sqrt{V_n / V_g} \quad (13)$$

where V_n is the voltage on dynode n and V_g is the voltage on the grid of dynode n .

One advantage of a photomultiplier of the type shown in FIG. 2 is that a substantially dispersionless electron stream is formed by flat dynodes which project electrons along straight parallel paths. Conventional electrostatic photomultipliers frequently employ elaborately curved dynodes in an effort to reduce transmit time dispersion. These structures are difficult to fabricate and introduce complicated design problems. Moreover, dynodes of this type typically concentrate the electrons in a narrow stream which tends to deteriorate those dynodes near the collector that are subjected to the highest levels of elec-

tron current density. The dynodes of my invention have flat surfaces over which electron impingement is essentially uniformly distributed and they can be made very long as shown in FIG. 3, which distributes further the electron impingement to prolong tube lifetime even when high current electron streams are generated.

Because of the power limitations inherent in conventional electrostatic photomultipliers, crossed electric and magnetic focusing fields are frequently used for controlling the electron trajectories while avoiding undesirably high electron densities. This type of photomultiplier introduces additional complexities and, as will become clear later, cannot be readily adapted to inject its electron stream into a traveling wave tube. FIG. 5 illustrates, on the other hand, how a device of the type shown on FIG. 2 can be adapted for injecting its electron stream into a traveling wave tube.

The device of FIG. 5 comprises a photomultiplier 60 for forming and projecting a modulated electron stream into a traveling wave tube 61. Photomultiplier 60 is of the same general type as that shown on FIG. 2 and comprises a photocathode 63 and an array of dynodes 64 which are maintained within a substantial vacuum by an envelope 65. Each of the dynodes is surrounded by a grid housing 67 and a grid 68, the construction of which is further illustrated in FIG. 6. The relative potentials of the electrodes may be the same as those of FIG. 2, that is, the photocathode is at -3800 volts, the first dynode at -3500 volts and the remaining dynodes of increasing positive incremental voltages of 300 volts.

The modulated light is directed at the photocathode through a window 70 in the envelope 65. After photomultiplier amplification, the last dynode of the array directs the electron stream through an aperture 71 in the envelope 65 and onto the central axis of the traveling wave tube 61. The traveling wave tube comprises an electromagnet 72 which produces a longitudinal magnetic field along the central axis for focusing the electron stream. An appropriate magnetic shielding member 73 minimizes or eliminates the extension of magnetic fringing fields into the photomultiplier. Surrounding the central axis of the tube is a conductive helix 75 which is constructed to propagate electromagnetic waves at an axial phase velocity which approximates the direct-current velocity of the electron stream. The helix is of a proper length and is biased at an appropriate potential to amplify the modulation energy of the electron stream according to known traveling wave tube principles and to extract the modulation energy for transmission to an appropriate load 76. Other known slow-wave structures could alternatively be used in place of the helix. The electron stream is collected by a conventional traveling wave tube electron collector 77.

The grid and dynode electrodes of the dynode assembly 78, the last dynode assembly of the array, are curved slightly for focusing the electron stream onto the central axis of the traveling wave tube. The center of the radius of curvature may be taken at the intersection of the traveling wave tube central axis with aperture 71. In a crossed-field photomultiplier a much more elaborate modification would be necessary because the magnetic focusing field of the photomultiplier is transverse to the electron stream, while the traveling wave tube magnetic field produced by electromagnet 72 is parallel with the electron stream. This would unavoidably result in a magnetic field discontinuity between the multiplier and the traveling wave tube which (in the absence of elaborate transition structure) would disrupt the modulation waves on the electron stream.

Another practical requirement of photomultiplier 60 is that the electron stream should have a circular cross section for giving proper traveling wave tube interaction. For this reason the dynodes are cylindrical as shown on FIG. 6. The design of the photomultiplier such that it would produce an electron stream having a density which could be conveniently focused and constrained within the

helix 75 and otherwise be compatible with the traveling wave tube is a matter within the ordinary skill of a worker in the art.

The photomultiplier 60 has also been presented to give another practical illustration of a photomultiplier which meets the requirements of Equations 8 and 12. With the electrode locations shown in FIG. 5 and with the electrode voltages as set forth above, photomultiplier 60 achieves effective transit time compensation in accordance with Equation 8 and cancellation in pairs in accordance with Equation 12.

Numerous other combinations of electrode locations and electrode voltages can alternatively be used to eliminate electron stream dispersion in an electrostatic photomultiplier in accordance with the invention. Structure other than the parallel plates 39 and 40 could be used for defining the field-free region. The coaxial cable collector 30 of FIGS. 2 and 3 is particularly advantageous in conjunction with my invention because it has a frequency response which is consistent with the high frequency amplification capabilities of the photomultiplier; however, a strip transmission line could be substituted for the coaxial cable or a conventional collector could be used. The collector electrode could be tilted at an angle with respect to the last dynode (although no advantage is presently seen in doing this) in which case compensation for the transit time dispersion between the last dynode and the collector could be made by considering the collector as being one of the dynodes of the array when Equations 8 or 12 are applied. One could also curve the emitting surface of dynode 29 and its corresponding grid of FIG. 2 to focus the electron stream onto the collector in the manner of dynode assembly 78 of FIG. 5. Moreover, the invention could be used in any of various electron multipliers in which means other than a photocathode is used for generating the electron stream. Numerous other modifications may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A photomultiplier comprising:

an array of electrodes including a photocathode coated with a photoemissive material, and a plurality of dynodes, each coated with a material having a high ratio of secondary emission;

said photocathode being arranged to emit, in response to the impingement of light thereon, a stream of electrons toward a first dynode;

all but a last one of the dynodes being arranged to emit, in response to the impingement of electrons thereon, secondary electrons toward a successive dynode of the array;

the last dynode being arranged to emit, in response to electron impingement thereon, secondary electrons toward an electron collector;

a plurality of electron permeable grids, each being closely adjacent one of the electrodes of the array; said grids having an electric potential different from that of the electrodes, whereby electrons incident thereon from the next preceding electrode have a velocity which is related to the grid potential and the potential of the next preceding electrode;

the various electrodes and their adjacent grids being tilted at angles with respect to the next preceding electrode, whereby electrons traveling therebetween describe paths of different lengths;

the angles of the respective electrodes and the potentials on the respective electrodes and grids being arranged such that the summation, along the entire array, of the maximum path length differences of electrons emitted from a given electrode divided by the speed of these same emitted electrons as they reach the grid of the successive electrode is substantially equal to zero.

2. The photomultiplier of claim 1 wherein:

all of the dynodes are tilted at a clockwise angle with respect to incoming electrons or all dynodes are tilted at a counter-clockwise angle with respect to incoming electrons.

3. The photomultiplier of claim 2 wherein:

the tangent of the angle of incidence of the electron stream on each alternate grid is substantially equal to the sine of the angle of incidence of the stream on the next preceding grid multiplied by the ratio of the speed of the electrons incident on the alternate grid to the speed of the electrons incident on the next preceding grid.

4. A photomultiplier comprising:

an array of electrodes;

one of said electrodes being a photocathode for emitting an electron stream having a finite width in response to the impingement of light thereon;

other electrodes of said array being dynodes, each having a surface with a high ratio of secondary emission;

another electrode being an electron collector;

said photocathode being arranged to direct the electron stream toward one of the dynodes;

each of the dynodes being arranged to direct secondarily emitted electrons toward a succeeding electrode of the array, whereby the array of electrodes defines a tortuous electron stream path within the photomultiplier;

and an electron-permeable grid closely adjacent to each electrode;

the angular position of the electrodes and the electrical bias on the electrodes being arranged to substantially satisfy the relation

$$\sum_{n=1}^N \frac{\Delta_n}{v_n} = 0$$

where Δ_n is the path length difference of electrons on opposite sides of the stream which are incident on the grid under consideration, v_n is the speed of electrons incident on the grid under consideration, and N is the number of electrodes.

5. The photomultiplier of claim 4 wherein:

all of the dynodes emit secondary electrons at a counter-clockwise angle with respect to the incoming electrons.

6. The photomultiplier of claim 4 wherein:

all of the dynodes emit secondary electrons at a clockwise angle with respect to the incoming electrons.

7. The photomultiplier of claim 6 wherein:

alternate grids are tilted at an angle θ with respect to incoming electrons which is substantially defined by the relationship

$$\tan \theta_n = \frac{v_n}{v_{n-1}} \theta_{n-1}$$

where v_n is the speed of electrons incident on the grid under consideration, v_{n-1} is the speed of electrons incident on the grid next preceding the grid under consideration, and θ_{n-1} is the angle at which the grid next preceding the grid under consideration is tilted with respect to incoming electrons thereon.

8. In combination:

a source of light having a finite width and being modulated at a predetermined frequency;

a photocathode located in the path of the modulated light for emitting a modulated electron stream of finite width in response thereto;

means comprising an array of dynodes, each having a surface with a high ratio of secondary emission, for multiplying the photocathode electron emission;

said dynodes defining with the photocathode an electron stream path;

an electron-permeable grid closely adjacent to the emitting surface of each dynode;

the angular position of the dynodes substantially satisfying the relation

$$\sum_{n=1}^N \frac{\Delta_n}{v_n} = 0$$

where Δ_n is the path length difference of electrons under consideration on opposite sides of the stream between any pair of dynodes or between the photocathode and the dynode toward which electrons emitted from the photocathode are directed, v_n is the velocity of the electrons under consideration incident on the grid toward which they are projected, and N is the total number of electron emissive electrodes including the dynodes and the photocathode;

a collector for collecting the electron stream;

and means located between the dynode array and the electrode collector for extracting modulation energy from the electron stream.

9. A photomultiplier comprising:

means defining an electrically field-free region;

an array of electrodes arranged around the periphery of the field-free region;

one of the electrodes being photoemissive and the remainder of the electrodes being secondarily emissive dynodes;

said photoemissive electrode being arranged to emit, in response to the impingement of light thereon, a stream of electrons through the field-free region toward a first dynode;

all but a last one of the dynodes being arranged to emit, in response to electron impingement thereon, secondary electrons through the field-free region toward a successive dynode of the array, whereby a tortuous electron stream path is established;

the last dynode being arranged to emit, in response to electron impingement thereon, secondary electrons toward an electron collector;

a plurality of electron-permeable grids each being at the same electric potential as the field-free region and each being closely adjacent to and parallel with the emitting surfaces of one of the electrodes;

the various electrodes and adjacent grids being inclined at an angle with respect to the next preceding electrode whereby opposite electron stream boundaries between successive electrodes have different lengths;

the electrical potentials on the electrodes and grids and the angles of electrode and grid inclination being arranged such that the net electron transit times along the two opposite electron stream boundaries of the entire path established by the array are substantially equal.

10. An electron multiplier comprising:

means electrically biased at a predetermined direct-current potential for defining a field-free region;

means for injecting a modulated electron stream into the field-free region;

means comprising a series of electrode elements arranged around the periphery of the field-free region for amplifying the power of the electron stream;

said series comprising a series of secondarily emissive dynodes and a series of corresponding electron-permeable grids;

each of the grids being biased at the predetermined potential and being closely adjacent to and parallel with the emitting surface of a corresponding dynode;

each of the dynodes comprising means for projecting secondary electrons through the field-free region toward a succeeding dynode in the series;

the relative angular positions of the electrode elements and the electrical potentials thereon substantially satisfying the relationship

$$\sum_{n=1}^N \frac{\Delta_n}{v_n} = 0$$

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where Δ_n is the maximum path length difference of electrons incident on any given grid of the series, N is the number of electrode elements, and v_n is the speed of the electrons incident on the given grid.

11. The electronmultiplier of claim 10 wherein the angle of incidence θ_n of the electron stream on the grid of any dynode n fulfills the relationship

$$\sin \theta < \sqrt{V_n/V_g}$$

where V_n is the voltage on dynode n and V_g is the voltage on the grid of dynode n .

12. The electron multiplier of claim 11 wherein the said angle of incidence θ_n also fulfills the relationship

$$\tan \theta_n = (v_n/v_{n-1}) \sin \theta_{n-1}$$

where v_n is the speed of the electrons incident on the grid of dynode n , v_{n-1} is the speed of the electrons incident on the grid of the dynode preceding dynode n , and θ_{n-1} is the angle of incidence on the electron stream on the grid preceding the grid of dynode n .

13. The electron multiplier of claim 11 further comprising:

an electron collector;

means located between the last dynode and the collector for removing modulation energy from the electron stream;

said last-mentioned means comprising a slow-wave structure in close proximity to the electron stream which is capable of propagating electromagnetic waves at approximately the same phase velocity as the velocity of the electron stream.

14. The electron multiplier of claim 11 wherein:

said series of dynodes consists of at least 8 dynodes;

the predetermined potential is equal to zero volts;

the potential on the first dynode of the series is equal to -3500 volts;

the angle of incidence of the electron stream on the first dynode is substantially equal to 11 degrees 12 minutes;

the second dynode is at a potential of -3200 volts and is tilted at a clockwise angle of 10 degrees 30 minutes with respect to the first dynode;

the third dynode is at a potential of -2900 volts and is tilted at a clockwise angle of 11 degrees 18 minutes with respect to the second dynode;

the fourth dynode is biased at -2600 volts and is tilted at a clockwise angle of 10 degrees 30 minutes with respect to the third dynode;

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the fifth dynode is at a potential of -2300 volts and is tilted at an angle of 11 degrees 28 minutes with respect to the fourth dynode;

the sixth dynode is biased at a potential of -2000 volts and is tilted at a clockwise angle of 10 degrees 30 minutes with respect to the fifth dynode;

the seventh dynode is biased at a potential of -1700 volts and is tilted at a clockwise angle of 11 degrees 12 minutes with respect to the sixth dynode;

the eighth dynode is biased at -1400 volts and is tilted at a clockwise angle of 10 degrees 30 minutes with respect to the seventh dynode.

15. The electron multiplier of claim 11 wherein:

the predetermined potential is equal to zero volts;

the series of dynodes consists of at least 8 dynodes;

the voltage on the first dynode of the series is equal to -3500 volts;

the angle of incidence of the electron stream on the first dynode is equal to 13.98 degrees;

the second dynode has a voltage of -3200 volts and is inclined at an angle of 13.0 degrees with respect to the first dynode;

the third dynode is at a voltage of -2900 volts and is inclined at an angle of 14.11 degrees with respect to the second dynode;

the fourth dynode is biased at -2600 volts and is inclined at an angle of 13.0 degrees with respect to the third dynode;

the fifth dynode is biased at -2300 volts and is inclined at an angle of 16.69 degrees with respect to the fourth dynode;

the sixth dynode is biased at -2000 volts and is inclined at an angle of 15.0 degrees with respect to the fifth dynode;

the seventh dynode is biased at -1700 volts and is inclined at an angle of 20.33 degrees with respect to the sixth dynode;

and the eighth dynode is biased at -1400 volts and is inclined at an angle of 1.75 degrees with respect to the seventh dynode.

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