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TECHNICAL PAPERS

THE SECONDARY EMISSION MULTIPLIER—A NEW ELECTRONIC DEVICE*

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Summary—*This paper describes the construction, theory, and performance of various types of fixed field secondary emission multipliers. Detailed consideration is given of multiplier phototubes employing crossed electrostatic and magnetic fields and of electron multipliers using electrostatic focusing alone, to serve as coupling and amplifying units for cathode-ray tubes such as the "Iconoscope."*

It is shown that while the power required for the operation of the secondary emission multiplier is about the same as that for the conventional amplifier, it is superior to the latter from the standpoint of noise. In the case of the multiplier phototube the signal-to-noise ratio is essentially determined by the shot noise of the photoemission, and is therefore sixty to one hundred times greater than that for a thermionic amplifier and phototube under conditions of low light intensity.

Multiplier phototubes have been built with an amplification factor of several millions and serve to replace the conventional phototube and accompanying amplifier system.

Their low "noise" level, together with their excellent frequency response and extreme simplicity, make these electron multipliers a very satisfactory form of amplifier.

Introduction

FOR MORE than thirty years it has been known that when certain surfaces are bombarded with cathode rays they emit electrons. This effect, known as secondary emission, has, from an early date, been extensively studied by a large number of workers such as Lenard, Hull, Von Bayer, etc.

The study of this phenomenon revealed that the number of electrons emitted is proportional to the bombarding current, the factor of proportionality ranging from a mere fraction to ten times as many secondary as primary electrons. The value of this ratio depends upon the surface used and on the velocity of the bombarding electrons. Although these facts have been known for a long time, the effect was not put to any useful work, except in the case of the dynatron invented by A. W. Hull. In fact, secondary emission had chiefly been looked upon as a serious obstacle in the design of thermionic vacuum

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tubes, and much research was carried on with an aim towards suppressing and reducing it.

During the past fifteen years it became recognized that secondary emission could be used as a means of amplifying a small initial electron current and a number of workers began investigating this field. Patents on methods of carrying out this idea were filed as early as 1919 by Slepian[1] and later by such workers as Jarvis and Blair,[2] Iams,[3] Farnsworth and others.

The general method involved is to allow the initial electron stream to impinge upon a target which has been sensitized for secondary emission. The secondary electrons from this target are directed on to a second target, producing still further electrons, the multiplication being repeated as many times as is desired. Reference to Fig. 1 will make this process clear. In this figure, electrodes A, B, C, etc., represent a number of plane targets having a high secondary emission ratio. These electrodes are connected to successively higher positive potentials. The stream of electrons to be multiplied is directed against A. This target gives rise to secondaries which go to target B, in turn giving rise to secondary electrons which are directed against C. After this process has been repeated a sufficient number of times to give the desired over-all multiplication, the electrons from the final target are collected on collector O. If R be the number of secondary electrons per primary for each stage and n the total number of stages, then the initial current I_0 will be multiplied up to an output current

$$I = I_0 R^n. \tag{1}$$

Clearly, the over-all gain will be R^n times. It will be seen that the over-all gain becomes very large indeed as the number of stages is increased if the secondary emission ratio of the targets is large (e.g., between five and nine).

A second class of multipliers has been described by P. T. Farnsworth,[4] in which the electrons are made to go back and forth between a single pair of targets receiving their energy from a high-frequency electric field. Of these two classes of multipliers, only the type using successive targets, wherein the number of impacts can be rigorously controlled and the stability, consequently, is very great, will be discussed in this paper.

[1] Slepian, Patent No. 1,450,265, April 3, 1923 (1919).
[2] Jarvis and Blair, Patent No. 1,903,569, April 11, 1933 (1926).
[3] Iams and Salzberg, "The secondary emission phototube," PROC. I.R.E., vol. 23, pp. 55–64; January, (1935).
[4] P. T. Farnsworth, "Television by electron image scanning." *Jour. Frank. Inst.*, vol. 218, pp. 411–444; October, (1934); also see *Electronics*, vol. 7, pp. 242–243; August, (1934).

The problem of making a multiplier which gives high gain is not, however, so simple as it might seem at first sight. A simplified multiplier constructed in accordance with the diagram (Fig. 1) would be almost completely inoperative, for the reason that practically all the electrons leaving any target would not go to the following one, but would merely go down the length of the tube and be collected at the final collector with almost no multiplication. In order to construct a successful multiplier, not only must the targets have a high secondary emission ratio, but also means must be provided to focus the electrons on to each target, and to draw away secondary electrons from one target preparatory to focusing them on to the next succeeding target.

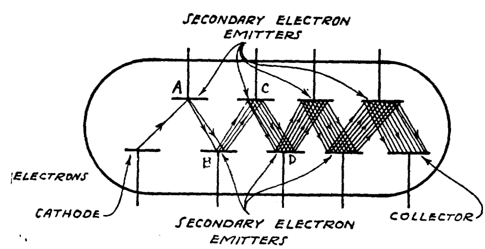

Fig. 1—Simplified secondary emission multiplier.

Before methods of electron focusing employed in specific multipliers are considered, there are certain general aspects of fixed field multipliers that should be discussed.

I. General Considerations

1. *Secondary Emission*

Since the successful operation of these multipliers depends upon a high secondary emission from the targets, it is of prime importance to discover the most suitable surfaces to use. In our search for good emitters, very little aid can be obtained from the theoretical physicist.

The most complete treatment of the theoretical aspect of secondary emission in the light of quantum mechanics was done by H. Fröhlich[5] in 1932. In this discussion he calculates the probability of the transfer of energy between an incoming primary electron and a conduction electron moving in the periodic potential field of the metal, where the exchange is such as to give the conduction electron sufficient momentum to escape from the metal. On this basis, he concludes that metals with a crystal structure having a large lattice spacing and with a low work function should be the best secondary emitters. However, this treatment applies only to simple metal surfaces.

[5] H. Fröhlich, *Ann. der Phys.*, Band 13, no. 2, pp. 229–248, (1932).

Experimentally, it has been found that the emission ratio from simple metal surfaces is invariably below that obtained from composite surfaces just as is the case with photoelectric emission. Since the theoretical knowledge of secondary emission does not extend to these composite surfaces, it is necessary to go ahead more or less empirically on the basis that, other things being equal, a surface of low work function is the most likely to be a good emitter. A large number of low work function surfaces were, therefore, studied having as a base metal, Ag, Be, Ta, Ni, Al, Zr, Ca, W, Cr, etc., and Na, K, Rb, and Cs as a surface layer. Of these, the most satisfactory to date have been oxidized Ag, Be, or Zr with a surface layer of cesium. These surfaces have a maximum secondary emission ratio of from eight to ten, occurring at a bombarding velocity of from 400 to 600 volts.

A curve showing the secondary emission ratio of Cs-CsO-Ag surface for various bombarding voltages is illustrated in Fig. 2. This is typical of the type of surfaces frequently used in the multipliers to be described later.

The method of preparation of this surface is very similar to that used in the preparation of the photoelectric cathode for a high vacuum cesium photocell. A matte silver sheet is oxidized to the second yellow by passing an electrical discharge through oxygen at low pressure. Then, after removing the oxygen from the vacuum system, cesium is admitted. The amount of cesium required is slightly less than that necessary to give maximum photosensitivity. The surface is then baked at 200 degrees centigrade for a few minutes to promote the reaction between the cesium and the silver oxide. This surface, when cooled, should be an excellent emitter.

2. *Multiplier Efficiency*

There are two ways of considering the efficiency of a multiplier. The first is the efficiency of secondary emission as a source of electrons, in terms of amperes per watt power supplied, while the second considers gain obtainable for a given over-all voltage as a function of the number of stages and voltage per stage. The second of these two considerations is more important from a practical standpoint, but both are worthy of some discussion.

Considering, first, the power efficiency, we have a target bombarded with a primary current I_0 at V_0 volts velocity. The power supplied by the primary beam is $V_0 I_0$ and, if the secondary emission ratio is R, the current I emitted is $I_0 R$. Therefore, the current per watt is

$$\frac{I}{W} = \frac{R}{V_0}\frac{I_0}{I_0} = \frac{R}{V_0}. \tag{2}$$

Hence the most efficient point of operation is that at which the secondary emission curve shows the greatest gain per volt.

From Fig. 2 the curve of the gain per volt plotted against bombarding voltage, as shown in Fig. 3, can readily be calculated. This curve shows that at its maximum around thirty volts the emission is sixty milliamperes per watt, dropping to forty-five milliamperes per watt

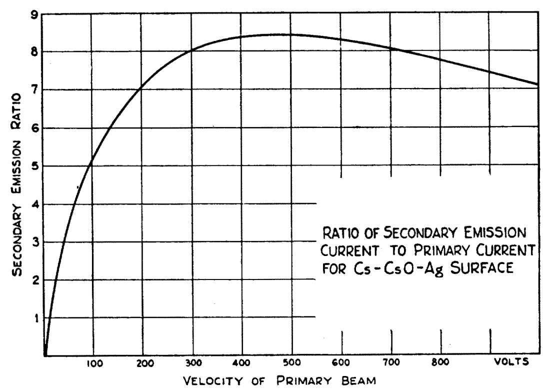

Fig. 2

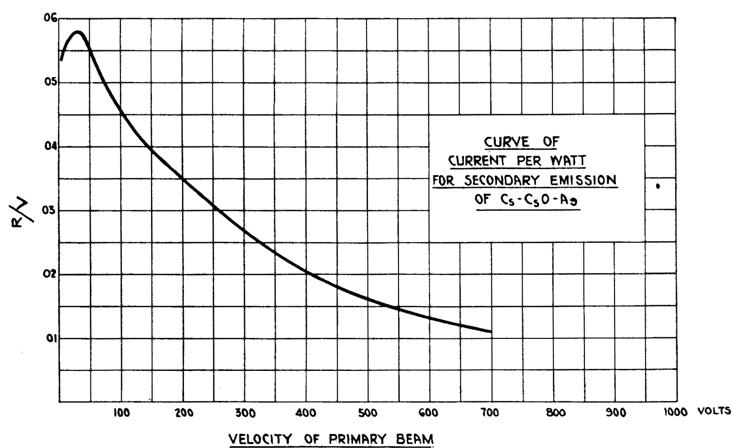

Fig. 3

at 100 volts, and seventeen milliamperes per watt at 500 volts. For comparison, it might be mentioned that a good thoriated tungsten thermionic cathode will deliver from fifty to seventy-five milliamperes per watt, while a very good oxide-coated cathode may run as high as one hundred milliamperes per watt. Thus, while secondary emission is not the most efficient way of obtaining an electron current, it compares rather favorably with other methods.

It is, of course, desirable to operate a multiplier under conditions such that maximum gain is had for a given over-all voltage. This condition may be determined as follows: Let R be the gain per stage, V_0 the voltage per stage, n the number of stages, and $V = nV_0$ the over-all voltage. The total gain is

$$G = R^n.$$

We can find the condition of maximum gain as n or V_0 is changed; i.e.,

$$\frac{dG}{dV_0} = R^{(V/V_0)-1}\left(\frac{V}{V_0}\frac{dR}{dV_0} - \frac{V}{V_0^2} R \log_e R\right) = 0. \qquad (3a)$$

In other words, the maximum occurs when

$$\frac{dR}{dV_0} = \frac{R}{V_0} \log_e R. \qquad (3b)$$

It is interesting to compare this with the slope of the emission curve when the power consumption is a minimum as obtained from (2)

$$\frac{dR}{dV_0} = \frac{R}{V_0}. \qquad (4)$$

For cesiated silver, these two points are fairly close together, so that a multiplier built to give close to the maximum gain also is fairly efficient from the standpoint of power consumption.

The question of maximum over-all gain will be made clearer by reference to Fig. 4. This family of curves shows the gain that can be obtained from multipliers with various numbers of stages plotted against voltage. These curves show that the most efficient multiplier is one operated with from forty to fifty volts per stage. Run in this way, very high gains may be obtained. For example, a ten-stage multiplier at 500 volts will have a gain of 30,000, while a fifteen-stage multiplier at 800 volts will multiply the initial current ten million times. It should be noted that the curves in Fig. 4 and the over-all voltages given do not include the voltage between the collector and the last target, as this will depend upon the use to which the tube is to be applied.

3. *"Noise" in Multiplier Output*

Regarding the question of "noise" in these multipliers, the first consideration will be that of the statistical fluctuation of the useful electron current through the tube. Assume that we have a source of electrons, for example a photoelectric cathode, and that the electrons from it impinge upon a secondary emitting target. The noise from the secondary electrons emitted will consist of two parts: first, the multiplied shot noise in the initial beam, and second, the fluctuation noise of the secondary emission from the target. For every target in the multiplier we shall have these two effects occurring simultaneously.

As yet, very little work has been done on the question of statistical fluctuation in secondary emission, either from a theoretical or an experimental standpoint, and there is some disagreement among the few

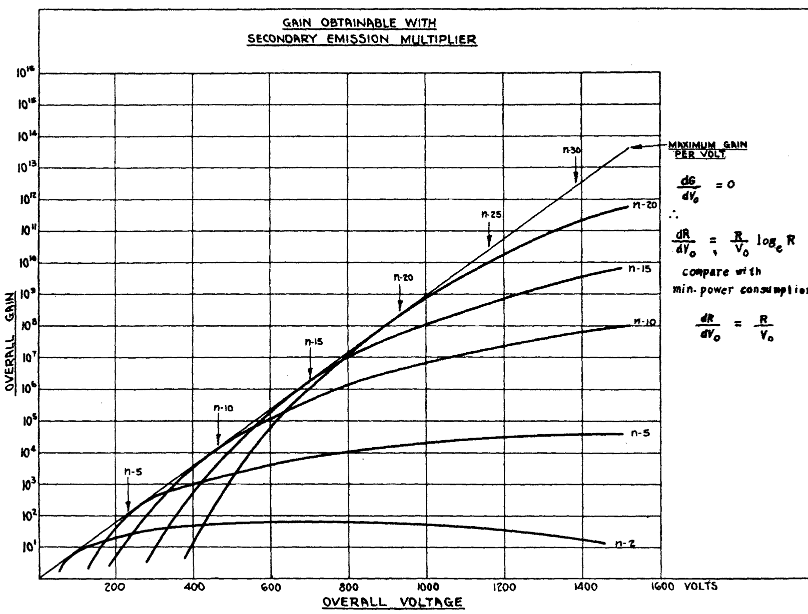

Fig. 4

experimental results available. However, these results indicate that the general magnitude of the effect is the same as the temperature limited shot noise from a thermionic cathode delivering a current equal to the secondary emission current.[6]

Let us, then, make the two following assumptions:

1. Shot noise from an emitter is multiplied by the subsequent stages in the same way in which an ordinary signal is multiplied.
2. Secondary emission from a target is subject to shot effect such that

$$i_n^2 = KI$$

[6] A. W. Hull and N. H. Williams, *Phys. Rev.*, vol. 25, p.147 (1925); Penning and Kruithof, *Physica*, vol. 2, pp. 793–804; August, (1935); L. J. Hayner, *Physics*, vol. 6, pp. 323–333; October, (1935).

where,

I is the output current,

$K = 2eF$,

e = the charge on an electron,

F = frequency band over which noise is measured.

On the basis of these two assumptions, the total noise output from a phototube multiplier having an over-all gain G and n stages of uniform gain per stage, would be

$$i_n^2 = \frac{G^{(n+1)/n} - 1}{G^{1/n} - 1} 2eFI = K'I. \tag{5}$$

The table given below indicates the agreement between the measured noise output of several types of multipliers, and the values calculated from (5).

TABLE I

No. of Stages	Gain	K'/K Observed	K'/K Calculated
3	60	77	80
3	28	40	41
3	6.8	12.1	12.3
2	29.5	36.2	36.0
1	6.0	7.2	7.0

This agreement is sufficiently close to indicate that (5) based on the two assumptions made above is accurate to the extent necessary for any practical noise calculation.

Rewriting (5) in terms of R and neglecting 1 in the numerator in comparison with G we have

$$i_n^2 = \frac{R^{n+1}}{R - 1} 2eFI$$

or in terms of the original photoelectric current

$$i_n^2 = \frac{R^{2n+1}}{R - 1} 2eFI_0. \tag{5a}$$

Let us compare the noise output with the signal output, where the light producing the original photocurrent is modulated so as to produce a signal $i_s = kI$, k being the modulation factor. Under these conditions, the signal-to-noise ratio S_M is given by

$$S_M^2 = \frac{i_s^2}{i_n^2} = k^2 \left(\frac{R^{2n}}{\dfrac{R^{2n+1}}{R - 1} 2eF} \right) I_{\text{cathode}}$$

$$= \frac{k^2}{2eF} \frac{R - 1}{R} I_{\text{cathode}}. \tag{6}$$

The signal-to-noise ratio S for the original photocurrent is obviously given by

$$S^2 = \frac{i_s^2}{i_n^2} = \frac{k^2}{2eF} I.$$

The signal-to-noise ratio from the multiplier, therefore, only differs from the fundamental limit imposed by the photoelectric emission, by the factor

$$\sqrt{\frac{R-1}{R}}. \tag{7}$$

It should be pointed out here that if, instead of assuming that the shot noise due to secondary emission was the same as that from a saturated thermionic emission, we had assumed

$$i_n^2 = p2eFI$$

where p is some factor which has a value near unity, (7) becomes

$$\frac{R-1}{R-(1-p)}. \tag{7a}$$

From these equations it is evident that if R is large, *the signal-to-noise ratio obtainable from these multipliers is practically that determined by the shot effect in the original photoelectric current.*

Let us consider the improvement obtainable over the conventional amplifier by the use of a phototube multiplier. In the case of the thermionic amplifier, the noise limit is determined by the thermal noise in the first coupling impedance. The noise voltage input to the first tube is

$$e_n^2 = 1.6 \times 10^{-20} Fr$$

$$r = \text{input resistance}$$

while the signal will be

$$e_s^2 = k^2 r^2 I^2$$

and the signal-to-noise ratio

$$S_A = \sqrt{\frac{e_s^2}{e_n^2}} = k\sqrt{\frac{r}{1.6 \times 10^{-20} F}} I.$$

This is to be compared with the corresponding ratio for the multiplier

$$S_M = k\sqrt{\frac{R-1}{R\,2eF}} I.$$

For example, let us calculate the value of photoelectric current in each case which will give a signal-to-noise ratio of five when $k = 1/2$. Using the following condition (typical of those met with in television practice):

$$F = 10^6 \text{ cycles}$$

$$r = 10^4 \text{ ohms}$$

$$R = 5 \text{ per stage}$$

we find the current must be

$$8 \times 10^{-9} \text{ amperes}$$

when a conventional amplifier is used; whereas the current need only be

$$4 \times 10^{-11} \text{ amperes}$$

in the case of the multiplier photocell. Thus, it is seen that only 1/200 of the light is required to produce this signal-to-noise ratio when a multiplier photocell is used.

It is interesting to consider the case where the secondary emission ratio is not the same for every stage. If the gains per stage be R_1, R_2, R_3, $R_4 \cdots R_n$, the total gain will be the product of these factors, while the noise output will be

$$i_n^2 = 1 + R_n(1 + R_{n-1}(1 + \cdots (1 + R_1)))2eF\,I_0$$

and the signal-to-noise ratio is therefore

$$S_M = \left\{1 + \frac{1}{R_1}\left(1 + \frac{1}{R_2} + \frac{1}{R_2 R_3} + \cdots\right)\right\}^{-1/2}\left(\frac{I}{2eF}\right)^{1/2}. \tag{8}$$

In this expression R_1 is the most important factor determining the signal-to-noise ratio. A multiplier which is to combine high signal-to-noise ratio with very efficient voltage operation should, therefore, be run with a high gain for the first one or two stages and the remaining stages set for greatest over-all gain per volt.

Where a multiplier is to be used in connection with an electron source other than a photoelectric cathode, as for example a television transmitting tube or "iconoscope," the noise output will be

$$i_n^2 = m^2 G^2 + \frac{G - 1}{G^{1/a} - 1}\, 2peFI \tag{9}$$

where m is the root-mean-square fluctuation on the cathode-ray beam to be multiplied. The second term is, of course, the noise generated in the multiplier and is in general much lower than the first term.

There are two other factors which limit the sensitivity of these multipliers. The first of these is thermionic emission from the secondary emission targets. Since all good secondary emitters have a low work function, they emit electrons in appreciable numbers even at room temperature. This difficulty may be overcome by running the tube at low temperature. However, this precaution need only be taken when the device is being used to detect an absolute minimum of current. Under any ordinary condition of operation, even where a gain of several millions is employed, the tube can be satisfactorily run at room temperature.

The final factor to be considered is noise due to positive ions. The magnitude of this effect will depend upon the configuration of the tube, the degree of exhaust, and the temperature of the walls of the tube. The last two factors mentioned, while troublesome, can be overcome if proper precautions are taken. Therefore, it may be said that the shot noise of electron emission sets the fundamental limit to the sensitivity of the secondary emission multiplier.

4. *Frequency Response*

The frequency response of the secondary emission multiplier is flat over a very wide range of frequencies. As far as the lower limit of frequency response is concerned, the multiplier performs equally well at very low frequencies (including direct current) as at an intermediate frequency. A number of factors influence the high-frequency response. Basically, the limits are due to the spread of the time of flight of electrons in the tube and to the time of secondary emission. This will set an upper limit at many hundreds of megacycles. In addition to this, the upper limit is determined by the nature of the voltage supply for the targets and the output circuit. The latter factors are controllable and can be made as high as desired. Between the upper limit and a direct-current signal, the frequency response is essentially uniform.

II. Magnetic Secondary Emission Multiplier

1. *Theory of Operation*

The magnetic multiplier is based upon the use of a crossed magnetic and electrostatic field to separate and focus the secondary electrons from one target to the next. This configuration of fields and electrodes was first suggested by Slepian in 1919, for use as a high current cathode.

The general arrangement of a multiplier based on this principle is shown in Fig. 5. It consists of two rows of electrodes, the bottom row being secondary emitters, while the upper row serves solely to maintain a transverse electrostatic field between the two sets of elements.

Each target in the bottom row is made positive with respect to the preceding one so that it will produce secondary electrons when struck by electrons originating from the latter. A magnetic field is established in the tube at right angles to its axis and to the field between the two rows of plates. Electrons leaving any of the lower plates are bent by

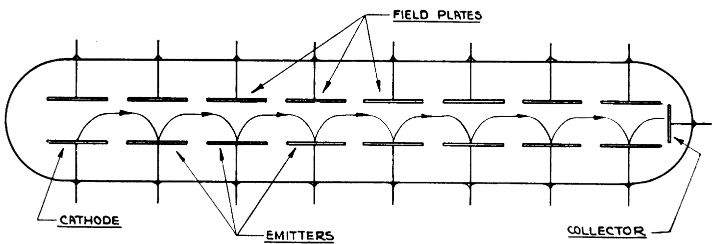

Fig. 5—Magnetic secondary emission multiplier.

the combined fields in such a way that they strike the next target, giving rise to secondary electrons which are in turn deflected on to another target, and so on through the tube.

This will be made clear by a consideration of the paths of the electrons under the influence of crossed fields. Let us assume, as a first approximation, that the potential difference between successive tar-

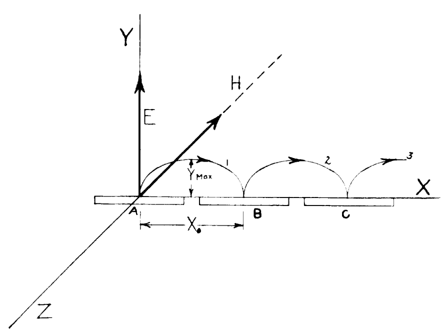

Fig. 6

gets is small compared with the potential between the targets and the top plates. Also, assume that the initial velocities are zero. The system as described can be represented by a rectangular co-ordinate system shown in Fig. 6, the targets lying along the axis of the tube, the electrostatic field E between the two rows of plates being in the y direction and the magnetic field H being in the negative z direction. The equations of motion of the electrons are therefore

$$\begin{aligned} m\ddot{x} &= eH\dot{y} \\ m\ddot{y} &= eE - eH\dot{x} \\ m\ddot{z} &= 0. \end{aligned} \tag{10}$$

A solution of these equations of motion leads to the following expression for the electron paths

$$\begin{aligned} x &= \frac{E}{H^2}\frac{m}{e}\left(\frac{eHt}{m} - \sin\frac{eHt}{m}\right) \\ y &= \frac{E}{H^2}\frac{m}{e}\left(1 - \cos\frac{eH}{m}t\right) \\ z &= 0. \end{aligned} \tag{11}$$

These are the equations of a cycloid. The paths of the electrons will, therefore, appear as shown in Fig. 6, leaving cathode A along path 1, then after striking target B cause electrons to leave along path 2 following a cycloidal trajectory to target C.

From these equations it can be seen that the distance between points of impact will be

$$X_0 = 2\pi\frac{E}{H^2}\frac{m}{e} \tag{12}$$

while the maximum vertical displacement will be

$$Y_0 = \frac{2E}{H^2}\frac{m}{e}. \tag{13}$$

Actually, the conditions we have used in making these calculations are not exactly those found to exist in the tube, for under the conditions assumed the electrons would reach each target with zero velocity. In the multiplier tube, the targets are made successively more positive, so that the electrons will strike them with sufficient velocity to produce secondary electrons. In order to maintain an equal field between each target and its top plate, it is necessary also to make the top plates successively positive with respect to each other. This introduces a component of electric fields in the x direction. Furthermore, the fields in the x and y directions are not constant, but become, under operating conditions, very complicated indeed. It is not possible to determine analytically the electron paths in the fields actually known to exist in these multipliers; therefore, for the present, we must base our calculations on the approximations given above.

So far, we have neglected the effect of initial velocities on the trajectories. If the initial velocities λ_0, μ_0, and ν_0 in the x, y, and z

directions are introduced as boundary conditions into the solution of (10), the equations of the paths become

$$x = \alpha\beta t + \frac{\mu_0}{\alpha} - \beta' \sin(\alpha t + \theta) \tag{14}$$

$$y = \beta - \frac{\lambda_0}{\alpha} - \beta' \cos(\alpha t + \theta) \tag{15}$$

$$z = \nu_0 t \tag{16}$$

where,

$$\alpha = \frac{e}{m} H$$

$$\beta = \frac{1}{\alpha}\frac{E}{H} = \frac{E}{H^2 e/m}$$

$$\beta' = \sqrt{\left(\beta - \frac{\lambda_0}{\alpha}\right)^2 + \left(\frac{\mu_0}{\alpha}\right)^2}$$

$$\theta = \tan^{-1}\frac{\mu_0/\alpha}{\beta - (\lambda_0/\alpha)}.$$

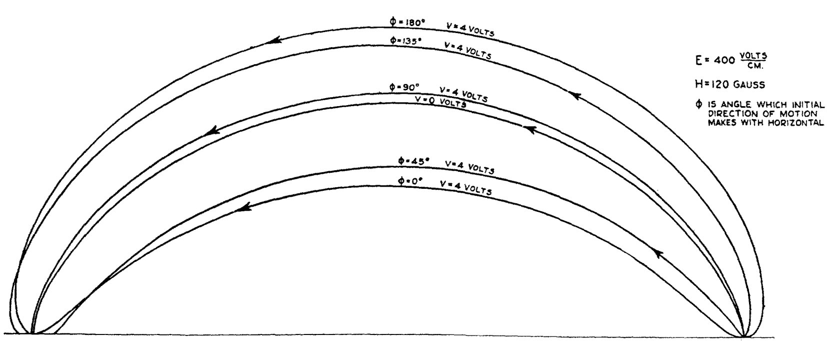

Fig. 7

These equations represent trochoidal paths, which degenerate into cycloids when the initial velocities become zero. Fig. 7 shows a family of these paths traced out by electrons having four volts initial velocity and emitted in various directions in the x, y plane.

It will be seen that the defocusing even at its maximum is only a very small fraction of the distance between points of impact. A general expression for the fractional defocusing (i.e., the distance ΔX that an electron with a given initial velocity strikes the target from the point where an electron with zero initial velocity impinges divided by the total path distance X_0 along the x axis) can be derived from (10) and (14). This equation takes the form

$$\frac{\Delta X}{X_0} = \frac{1}{\pi}\left(\frac{\mu_0}{\alpha\beta} - \theta\right) \tag{17}$$

and can be used to calculate the axial defocusing for any value of initial velocity.

From (16) it can be seen that there will be a transverse defocusing if the initial velocity in the z direction is not zero. This transverse spreading can be calculated by substituting the time of flight between two stages into the equation

$$z = \nu_0 t.$$

This leads to an equation for the displacement ΔZ from the center of the targets as follows

$$\frac{\Delta Z}{X_0} = \frac{H}{2E}\sqrt{2V_{0z}e/m} \tag{18}$$

where V_{0z} is the initial velocity of the electron in the z direction expressed in units of potential.

It should be noted that the transverse displacement is cumulative from stage to stage. However, due to the statistical nature of the effect, the spreading of all the electrons as they traverse the tube will be proportional to the square root of the number of stages, rather than to the number of stages.

It was shown that the ratio of maximum height that the electrons rise above the targets is

$$\frac{Y_{max}}{X_0} = \frac{1}{\pi}$$

in the case where the initial velocities are zero. The existence of initial velocities increase the maximum height slightly. Using (10) and (15), it can be shown that the equation for the maximum becomes

$$\frac{Y_{max}}{X_0} = \frac{\beta + \beta' - (\lambda_0/\alpha)}{2\pi}. \tag{19}$$

As yet, no accurate measurement has been made on the velocity distribution for secondary emission from cesiated surfaces; however, measurements have been made which show that 85 per cent of the electrons leaving a target have less than three volts initial velocity.

Using the value V_0 = three electron volts to calculate the defocusing in an actual multiplier operated under the following conditions

$$E = 400 \text{ volts per centimeter}$$
$$H = 120 \text{ gauss}$$
$$V_0 = 3 \text{ volts}$$

we find,

$$\frac{\Delta X}{X_0} = 0.02$$
$$\frac{\Delta Z}{X_0} = 0.3$$
$$X_0 = 0.97 \text{ centimeter.}$$

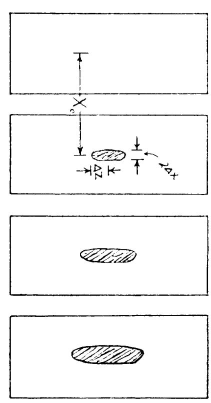

Fig. 8

This means that electrons leaving from a point on the cathode spread into an elliptical spot on the first target. This in turn is spread into a larger ellipse on the second target, the size of the spot increasing as the electrons progress down the tube. This is illustrated schematically in Fig. 8.

Eventually, the spot becomes so large that some of the electrons miss the target entirely, and there is a dropping off of the efficiency of the subsequent stages. The transverse spreading is such that there would be a serious loss after a comparatively few stages unless special precautions, that will be described later, are taken to prevent this type of defocusing.

Finally, the relative height above the targets to which the electrons rise will be

$$\frac{Y_{max}}{X_0} = 0.4.$$

Thus the top row of plates must be placed at a distance slightly greater than this above the targets, to avoid collecting any current. The actual spacing used is one half the distance between target centers.

2. *Design and Construction of Magnetic Multiplier*

A schematic diagram of the actual application of the principles, described above, to a multiplier phototube is shown in Fig. 9. Photoelectrons are focused upon a target $2a$. Secondary electrons from this electrode will be focused on target $3a$ giving rise to further electrons, and so on, for as many stages as are desired.

The plates are mounted in the tube in such a way that the upper and lower plates are as close together as is possible in order to make E_y large and thus increase the current that can be drawn away from a target before space-charge limitations occur. This minimum spacing, as was shown above, is half the distance between centers of successive targets. With this construction it is found that the current that can be drawn from the tube is limited only by the power that can be dissipated from the final stages in overcoming the heat generated by electron impacts.

In order to limit the sidewise spreading, the electrodes are mounted on vertical strips of mica. Charges which accumulate on these vertical walls so alter the field as to introduce an additional lens action which limits sidewise spreading. With this arrangement, the limit to the number of stages which may be used is set by the axial defocusing. However, this defocusing is so small as to permit the use of a great many stages. The upper limit to the number of stages has not been determined experimentally although multipliers employing as many as twelve stages without a decrease in gain per stage have been constructed.

When multipliers are operated at high gains into high impedance loads, some difficulty is encountered from oscillation. This can be eliminated by surrounding the collector electrode with a shield grid as shown in Fig. 9. The grid serves as an electrostatic shield and prevents changes of collector potential from reacting upon earlier stages. It also results in the alteration of the output characteristic from that of a triode to that of a conventional screen-grid tetrode.

For operation of the device, it is necessary that the upper electrodes be at a fixed positive potential with respect to the corresponding lower electrode, and that the voltage steps between adjacent electrodes be equal. In order to decrease the number of leads required, it has been found advantageous to connect upper electrodes to lower targets farther down in the tube. Satisfactory results have been attained when each upper electrode is connected to the next succeeding lower target.

Since the first few targets draw almost no current, their potential can be supplied very satisfactorily from a voltage divider or bleeder. In order to decrease further the number of leads in a multiplier employing many stages, it has been found practicable to incorporate the bleeder for the initial stages inside the tube. Resistors for this purpose must be able to withstand the evacuating, baking, and activating processes involved in the tube construction. In the case of the tube shown in Fig. 9, the first five stages are supplied from an internal divider. The remaining stages may be supplied from an external bleeder. However, for the sake of economy in power required for operation, it may be well to supply the output stage and the last few targets from

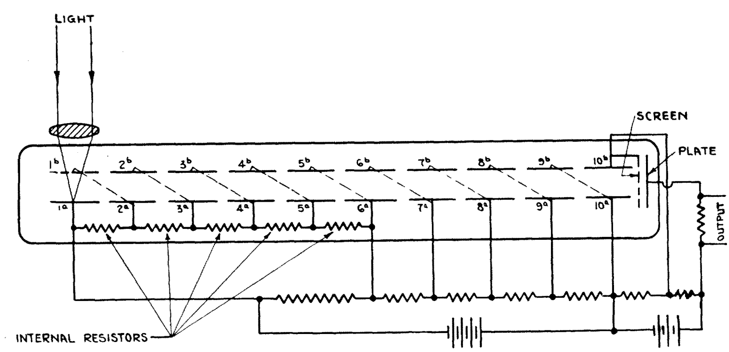

Fig. 9

a separate voltage supply, as the target currents may become quite high. In Fig. 9, the output is supplied from a separate source, the other stages being supplied from resistance voltage dividers.

It has been found possible to operate the device with alternating voltages on the electrodes. The operation will, of course, occur over only a portion of each cycle. The frequency of the applied alternating current must exceed the highest frequency which the multiplier is to transmit.

As a means of supplying the requisite magnetic field, permanent magnets have been found to be very satisfactory. These are superior to electromagnets from the standpoint of size and the fact that no external power is required.

In Fig. 10 is shown the effect of varying the magnetic field, while Fig. 11 is a similar curve for the effect of the over-all voltage. Both of these curves exhibit secondary maxima as well as the major peak. The secondary maxima are caused by more complex electron paths where one or more of the lower electrodes are missed by the electron stream.

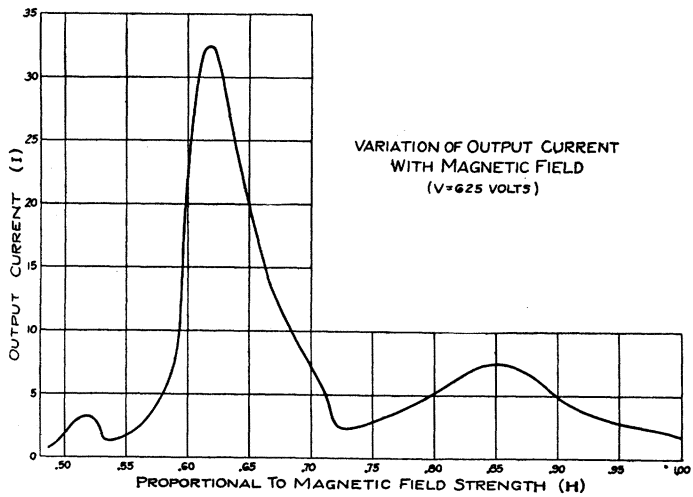

Fig. 10

The primary maximum is sufficiently broad so that ordinary fluctuations in line voltage do not result in appreciable variations in the

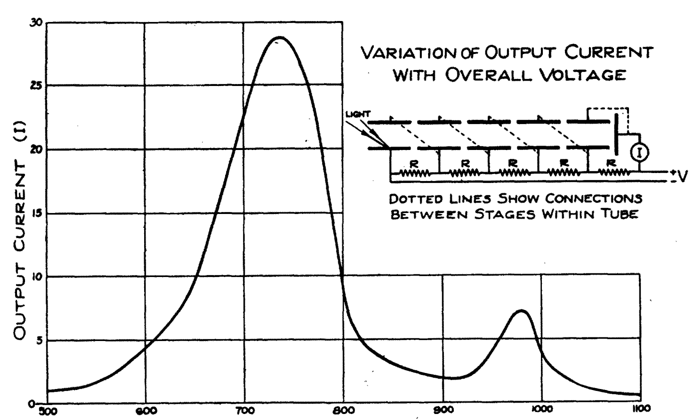

Fig. 11

output from the multiplier. If the current to any one stage is plotted as a function of the voltage to that stage alone or as a function of over-all voltage, characteristic curves are obtained similar to those of Fig. 11.

A photograph of the internal structure of a twelve-stage multiplier in which the voltage divider for the first five stages is incorporated in the tube, is shown in Fig. 12.

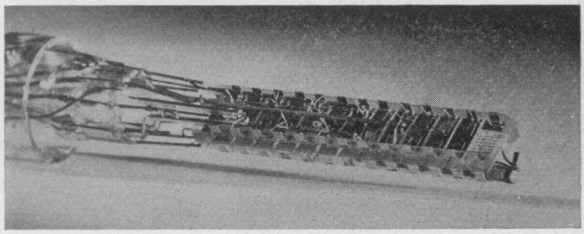

Fig. 12

III. Electrostatic Multiplier

Where the application of a secondary emission multiplier does not permit the use of a magnetic field, it is necessary to use a multiplier in which the electrons are focused by electrostatic fields alone.

The problems involved in designing the focusing system for such a multiplier are similar to many of those encountered in an electron microscope. It can be shown that in general a radially symmetric electrostatic field will have the properties of a lens over portions of the

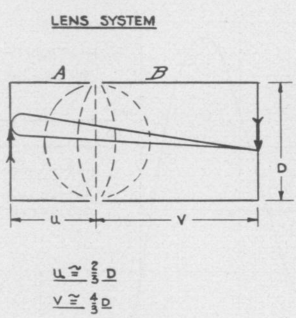

Fig. 13

field near the axis of symmetry. The radial distance from the axis over which this condition applies will depend upon the field configuration. The focusing system of the electrostatic multiplier is based on the field between two coaxial cylinders. Since it is desirable to have a minimum of separate voltages to operate the tube, one cylinder is made part of one target, while the other is connected to the next succeeding emitter. The configuration is made such that electrons from an area in the center of the first target will come to a focus at the center of the next target and that the magnification of the electron image formed will be unity.

This electron "optical" system will be made clearer by reference to Fig. 13. In this diagram the lens is formed between the cylinders A and B, A being at ground potential, while B is at the potential E. The electrons are emitted from the cathode in A with a very low velocity, are deflected by the "lens" formed between the two cylinders, and are focused on to the screen or electrode in B striking it with a velocity of E electron volts. The magnification of this system will depend upon the object and image distance from the lens, but instead of $m=v/u$, we have, from the varying index of refraction of the medium along the "optical" path (i.e., electron path), $m=v/2u$.

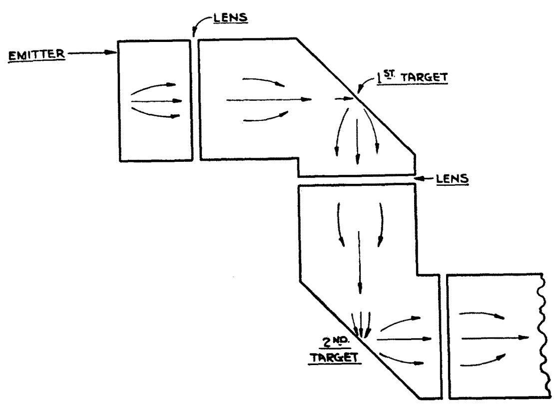

Fig. 14—L type multiplier.

The focal length is independent of the voltage between A, B, but is dependent on the diameter of the cylinders. It is found that in order to get good focus and unity magnification, the dimensions should be

$$u + v = 2D$$

with,

$$u = \frac{2D}{3} \quad \text{and} \quad v = \frac{4D}{3}.$$

The dimensions are only approximate, as the exact dimensions depend also upon the separation between cylinders. There will be some defocusing and lack of sharpness resulting from the initial velocities of the electrons (i.e., "chromatic" aberration) and also from aberrations in the lens system. This is not serious when the arrangement is used in a multiplier unless a very large number of stages is to be used.

The application of this optical system leads to the so-called L type multiplier whose construction is shown in Fig. 14. This multiplier is quite satisfactory from the standpoint of focus. However, the field at each target drawing away the secondary electrons is rather weak and the multiplier becomes space-charge limited at rather small current values. Further, the emitting spot on the initial cathode must be small if accurate focus is to be maintained.

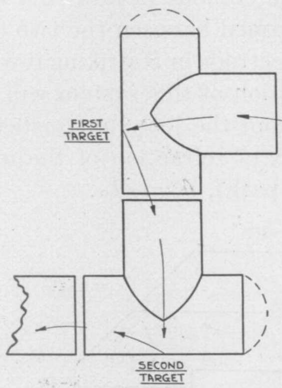

Fig. 15—T type multiplier.

A second type of multiplier has been designed which does not depend upon so sharp a focus and which has a higher collecting field at the targets. This is the T type multiplier which is shown in Fig. 15. This multiplier is built so that the cylindrical exits from the targets are as short as possible and yet long enough so that electrons entering

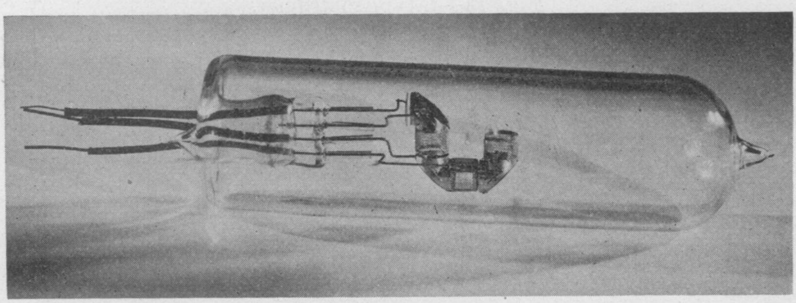

Fig. 16

through the stem of the T will not be deflected sufficiently by the field from the succeeding electrode to miss the target. The targets are formed by sensitizing the whole inside of the cylindrical crossarm of the T. Even with this arrangement, where currents of the order of a milliampere are to be used, it is necessary to operate the multiplier at a fairly high voltage per stage, that is, 200 to 400 volts, if space-charge effects are to be avoided. Figs. 16 and 17 show multiplier phototubes of the L and T type.

IV. Applications

The most obvious application of these multipliers is as a photoelectric amplifier. This use is very much simplified in view of the similarity between the photoelectric and secondary emissive surfaces. The most convenient type of multiplier to use for this purpose is the one combining electrostatic and magnetic fields. This is because of its excellent focusing characteristics and because of the high current output obtainable. A tube of this type having a gain of several millions or an output of ten or more amperes per lumen is but little larger than an ordinary receiving tube. A voltage of about 1500 volts is required

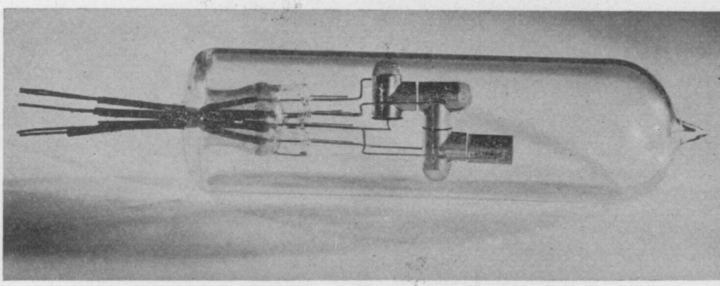

Fig. 17

for operation, and since the current consumed is small, may be supplied from a small socket power unit.

Since the tube serves to replace not only a phototube but also its accompanying amplifier, there is obviously a great gain in simplicity and a saving in bulk. In addition, these multipliers are very stable, are insensitive to external interference, and have an excellent frequency characteristic. An even more important factor is that the noise output is determined by the shot noise of photoelectric effect and therefore allows an increase of sixty to one hundred times in signal-to-noise ratio under ordinary operating conditions for extremely low values of light. These facts combine to make this type of multiplier a very excellent means of converting a light signal into an electrical signal. In order to compare the size of this tube with that of a conventional receiving tube Fig. 18 is included comparing a ten-stage multiplier with an RCA 59.

The applications of multiplier phototubes are extensive including in particular pickup from sound film, facsimile, automatic door control, alarm systems, automatic sorting machines, etc.

Although at present the most important application of the secondary emission multiplier is as a phototube it has a number of other applications which may become increasingly important. In general, these multipliers can be used in connection with any device where the signal to be amplified is generated in the form of an electron current. This use includes types of electron commutator tubes such as are used for high speed switching, secret sound systems, and frequency multi-

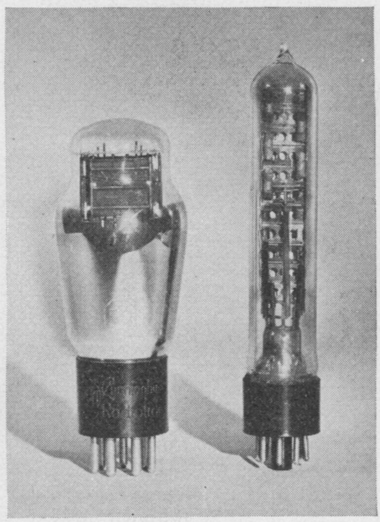

Fig. 18

pliers. One use in particular should be mentioned; that is, the application of the multiplier to the "iconoscope." For this purpose, an electrostatic multiplier is found to be the most satisfactory in that it avoids the use of a magnetic field which interacts detrimentally with the low velocity electrons in the tube. A multiplier used in this way serves not only as a very efficient means of coupling the tube to the television terminal equipment, but also replaces part or all of the picture amplifier.

As a voltage-controlled amplifier, the device does not lend itself so readily. This is because, in general, to couple the input of a voltage-controlled amplifier to its external circuit, it is necessary to use some form of coupling impedance and this, as in the case of a conventional thermionic amplifier, will limit the signal-to-noise ratio obtainable.

If the conventional type of thermionic cathode and control grid are used in connection with a multiplier, the problem of securing results superior to those obtainable with an ordinary vacuum tube presents considerable difficulties. There is the possibility of obtaining a higher per cent control per volt applied to the grid by deliberately throwing away a large fraction of the cathode current to gain this control, then using a multiplier to bring the average current back to a higher level. This is still in its initial experimental stages, and it is too early yet to say what the outcome will be. It should be noted also that this type of tube offers excellent opportunities to be used as a multiple-duty tube by using the control obtainable at various targets operated on different parts of their emission or focusing characteristics.

The secondary emission multiplier is too new an instrument to be able to foretell the full extent of its application; however, even now there is evidence that it may become a serious rival to the thermionic amplifier in many of the fields which that device has occupied alone for so long, and may also open up new fields in the realm of the electronics of small currents.

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