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Photo-Cell Multiplier Tubes

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Structural and performance data on a $Cs-Cs_2O-Ag$ type of photoelectric cell whose current output is amplified by an integral 6- or 11-stage electron multiplier are given.

A PHOTO-CELL multiplier tube is essentially a combination of a vacuum type photoelectric cell and an electronic multiplier. It thus shows the advantages of both kinds of equipment, namely, linear response, wide frequency range, and high signal-to-noise ratio.

The performance of an electronic multiplier is based on the principle of secondary emission: electrons impinging on a surface release secondaries, and conditions can be arranged so that each arriving electron generates 2 to 5 secondaries. If this process is repeated a number of times, a very high multiplication ratio results. Thus, while the thermionic amplifier is fundamentally a device amplifying voltages, the multiplier amplifies electron currents. In the photo-multiplier the original electron current is supplied by a photo-cathode. The output current of the tube then varies linearly with the amount of light on the cathode.

In what follows, we shall describe the properties of the tubes as made by the Farnsworth Television & Radio Corporation, in which the multiplier stages have the shape of small boxes, and only d.c. electrostatic fields are used to direct the flow of electrons. Except for their size, the tubes are similar in structure to the multiplier as used in the image dissector.[1] Both the photocathode and the secondary emitting surfaces are caesium coated. The peak photoelectric sensitivity lies in the near infra-red, which makes

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[1] C. C. Larson and B. C. Gardner, Electronics, October, 1939.

the tube especially adapted to work with incandescent light sources.

Figure 1 is a photograph of a 6-stage multiplier with an octal-type base, and a cathode window 1″ in diameter. Fig. 2 shows schematically the structure of this tube and also the structure of an 11-stage multiplier with a special base and a cathode window $1\frac{1}{2}''$ in diameter.

PERFORMANCE

The principle of operation as explained above, leads to the following formula:

$$i_0 = i_c k^n = LS_c k^n = LS,$$

i_0 (amperes) being the output current, i_c the current leaving the cathode, L (lumens) the light input, k the multiplication factor per stage, n the number of stages, S_c the cathode sensitivity and S the over-all sensitivity, both in amperes/lumen.

Some typical data on the sensitivity that may be expected from the Farnsworth multipliers will be given. They refer to "Type A" tubes, which are more sensitive. Recently another, Type B, has been developed which has a lower sensitivity, or as it might also be expressed, which needs a higher voltage for a required amount of sensitivity. But for a given sensitivity this type has a much lower dark current and, therefore, lower noise, and it is sometimes more important to reduce the dark current than to get the highest sensitivity. Generally speaking, this will be the case whenever the tube has to be used with very low light levels.

The cathode sensitivity S_c is 10 to 20 microamperes/lumen. The multiplication factor depends on the voltage per stage V_{st}. In the range in which the multipliers usually are operated the multiplication factor varies roughly as the root of the voltage: $k = a(V_{st})^{\frac{1}{2}}$; $a = 0.33$ may be taken not as an average, but rather as a safe value above which our Type A tubes usually remain. This means, at 80 volts per stage, a total multiplication of $k^n = 660$ for a 6-stage and 150,000 for an 11-stage tube. For Type B, the numerical factor 0.33 might be replaced by 0.30 approximately.

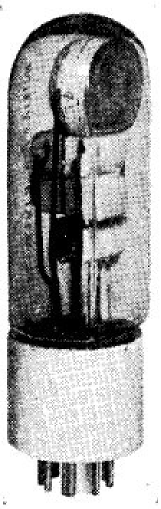

FIG. 1. Photograph of a 6-stage multiplier.

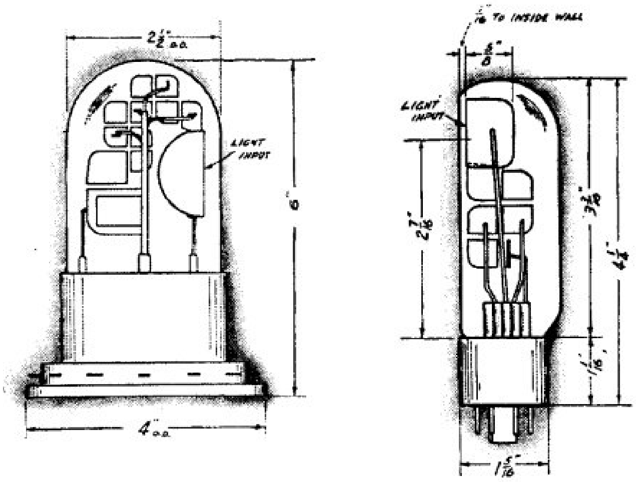

FIG. 2. Schematic diagrams: 11-stage multiplier on the left and 6-stage on the right.

Figure 3 shows, for an 11-stage tube and for 77 volts per stage, the variation of output current with light input, showing the good linearity of the tube.

There exists a minimum and a maximum light level between which the tube may be safely and successfully operated. The lower limit is, as in every amplifying system, given by the inherent noise of the equipment and will be discussed below. The upper limit is caused by the fact that the last stages will stand only a power of about 0.01 watt in a 6-stage tube, and 0.1 watt in an 11-stage tube. Thus, for a 6-stage tube operated at 100 volts per stage, with a sensitivity of, for example, 30μa/lm, the maximum permissible output current would be 100 microamperes, which corresponds to 3.3 millilumens light input. If, with a given tube, higher light levels have to be handled, the voltage and, therefore, the sensitivity will have to be reduced, and the remaining amplification provided for by a subsequent amplifier, or another number of stages has to be chosen.

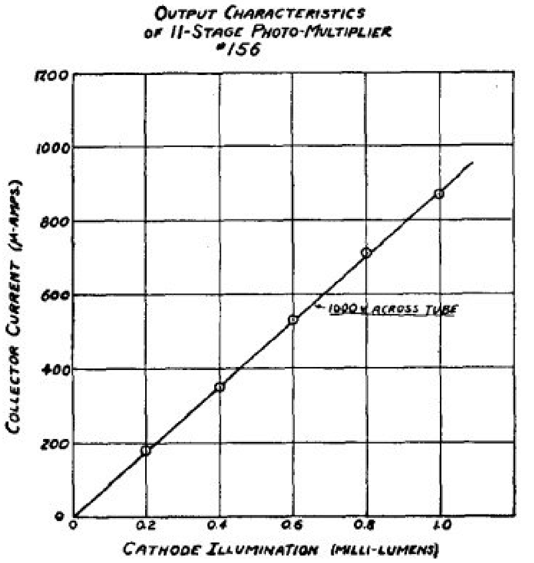

FIG. 3. Output current *vs.* light input for a typical 11-stage tube.

No special investigation has as yet been made on the frequency response of the cells; but as they are entirely satisfactory in the television range, they can be relied upon at least in the range from 0 to 5 megacycles. The theoretical limit is much higher. Unlike a thermionic amplifier, the multiplier has no lower frequency limit.

NOISE

Even if the tube is kept entirely in the dark, there is a dark current which is chiefly due to thermionic emission from the cathode surface at room temperatures.[2] The shot effect variations of this current are the main source of tube noise. The multiplier stages add some more noise, as the release of secondaries is a random process, but this increases the original noise by less than 50 percent, usually by about 30 percent.[3] With light on, there is an increased shot effect due to the photo-current, but, of course, the signal-to-noise ratio goes up as the light increases.

The noise is proportional to the square root of the frequency range of the total set-up including the terminal equipment. The following figures are based on a 10-kc band width. As measured in actual tubes of Type A (the Type B tubes show an appreciably lower noise), this ratio is about 60 db at 1 millilumen light input, which means a ratio of 1000 : 1. The dark noise is best expressed as an equivalent light fluctuation; it is of the order of 2×10^{-7} lumen. (Recent experiments with tubes cooled with dry ice or liquid air indicate that this limit can be lowered by several orders of magnitude. These observations will be the subject of a subsequent report.)

In order to remain well above the dark noise, we may take the minimum permissible light input as 10^{-6} lumen, at 10 kc band width. In the example previously given we would, therefore, have a total dynamic range, i.e., a ratio of maximum to minimum light levels, of 3300 : 1, or 70 db.

The noise level which so far has been attained is at least as low as that shown by the best thermionic amplifiers. But while these are laboratory instruments in which the results can be obtained only by careful shielding, battery operation and with specially selected tubes and resistors, the multipliers can be operated with much simpler equipment.

EXTERNAL CIRCUIT

Figure 4 shows the circuit for a 6-stage tube; its extension to any number of stages is obvious. It is seen that a 6-stage tube has 8 electrodes, namely, the photo-cathode, six multiplying stages, and a collector. The voltage per stage V_{st} may be anywhere between 30 and 140 volts. It is advisable to apply the voltage $2V_{st}$ between the cathode and the first stage in order to make sure that all electrons leaving the cathode are pulled into the multiplier. The total voltage needed for a n-stage multiplier will then be $(n+2)V_{st}$.

In special cases which will be discussed presently, it is necessary to increase also the voltage between the collector and the last stage above V_{st}. The voltage divider resistances in Fig. 4 should be chosen as high as possible in order to reduce the power consumed in the divider. On the other hand, the voltage drop caused by the currents in the last stages must be kept low enough not to upset the voltage ratios, as this would cause a nonlinear response. A convenient rule is to keep the divider current at about 10 times the output current. This means resistances of 20,000–100,000 ohms per stage for a 6-stage and 10 times smaller resistors for an 11-stage tube.

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[2] For a detailed discussion of these effects, see J. Rajchman, Arch. des Sciences Physiques et Naturelles **20**, 5, Sept.-Dec. (1938).

[3] See, e.g., W. Shockley and J. R. Pierce, Proc. I. R. E. **26**, 321 (1938).

R in Fig. 4 is the output resistor. In most cases this will be the grid resistor of a subsequent amplifier stage, for the multiplier itself is only capable of handling a very small power, although the voltage developed on *R* may be quite large.

Thus, take a tube with a maximum output of 100 μa. The value of *R* depends on the frequency band which has to be handled. As the electrostatic capacity of the collector is of the same order of magnitude as in ordinary vacuum tubes, an output resistor of 100,000 ohms is satisfactory for 10 kc. The 100 μa will cause a voltage drop of 10 volts in *R*, which is enough to drive, e.g., a 6G6 tube. If only 1 kc is needed, the resistor could be raised to 1 megohm. The useful output voltage would then be 100 volts. But, in order to make the tube work, the collector has always to be sufficiently positive above the last stage to collect all the electrons. Thus, in this case, the voltage difference between the last stage and the + pole of the voltage supply must be raised to about 150 volts, so that the collector, even for the strongest signals, remains 50 volts above the last stage.

For a multiplier, this method of designing the output current is preferable to the one used with thermionic amplifiers, where an "internal resistance" is ascribed to the tube.

PRECAUTIONS

As can be shown from the formula given above, a 2 percent ripple in the supply voltage will cause a fluctuation of n percent in the output current of a n-stage tube. Careful filtering of the voltage supply is therefore necessary.

As the dark noise is of thermionic origin, it will depend on the temperature of the cell. It is, therefore, important to mount the voltage divider equipment of Fig. 4 so as not to heat the tube.

If the light input is taken from an a.c. operated incandescent lamp, a 120-cycle spurious signal will appear. Therefore, the lamp must be excited by d.c. if the signal contains frequency components in the neighborhood of 120 cycles.

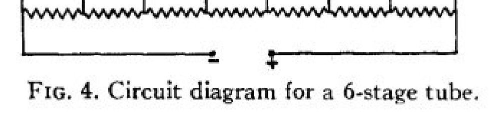

FIG. 4. Circuit diagram for a 6-stage tube.

Immediately after putting a tube into operation, there usually occurs a drift in sensitivity. The tubes should, therefore, be allowed a time of about 20 minutes (with voltage and light on) before being used. Similar phenomena have been observed by W. Kluge and his collaborators.[4]

APPLICATIONS

Although there are some trick circuits by which a multiplier can be turned into a nonlinear device, we will consider here only cases in which a linear response is wanted. We may, then, depending on the kind of output apparatus used, distinguish between:

(a) A.c. applications, in which we are interested in the signal variations within a certain frequency range. A typical example is the amplification of signals from sound film tracks. The advantages of the multiplier as against the thermionic amplifier lie in its greater frequency range (both in the direction of low and high frequencies) and in its lower noise level. If very low light inputs have to be considered, Type B tubes must be chosen; for a light level above 10^{-6} lumen the Type A tubes are more economical, as they require less total voltage.

(b) D.c. applications, in which the multiplier operates a meter or a relay. Although the above description of tube performance has mainly been based on the assumption of a.c. applications, the general principles are the same. In this case, however, the noise proper is unimportant but the dark current is objectionable and sets a lower limit to the permissible light level. Type B tubes are, therefore, indicated for these cases.

The d.c. applications can sometimes easily be changed into the a.c. type if the light signal is interrupted periodically. We then have to work only inside a definite and usually a very narrow frequency band, and it will be found that the minimum detectable light level is lowered by several orders of magnitude in this way.

Generally speaking, these tubes will prove useful whenever low light levels are involved or a large frequency range is wanted. They have, for instance, been successfully used for a period of over one year in spectroscopic work and in color-matching machines.

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[4] W. Kluge *et al.*, Zeits. f. tech. Physik **18**, 219 (1937).