technical reprint

R/P093

why photomultipliers need amplifiers

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1 introduction

Photomultipliers are still the preferred light detectors for many applications, principally because they offer a unique combination of large detection area (up to 1500 cm^2) together with an internal amplifier of exceptional performance (known as an electron multiplier). Electron multipliers have the following outstanding attributes:

- high gain - up to 10^9
- wide bandwidth – up to 1 GHz
- exceptionally low noise
- near zero offset
- low and constant output capacitance

Given such performance, why should there be any need for additional amplification?

In practice the photomultiplier is one of several elements in a detection system, an example of which is shown in **figure 1**. The required overall sensitivity is achieved by selecting a combination of pmt gain and electronics gain. The key to successful instrumentation design is to apportion gain between pmt and electronics in the optimal way. The obvious and first requirement is to operate the electronics and the pmt within their ranges of satisfactory performance. The system designer must take advantage of those functions that a pmt can best perform and those that are best done in the electronics.

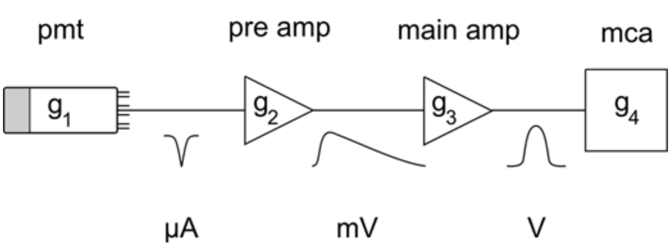

figure 1 The overall sensitivity of a measuring system is proportional to the product of the gain of each element. This is illustrated for a scintillation counter where measurements are displayed on a multichannel analyser (mca). The skilled experimenter will always choose the optimal combination of $g_1.g_2.g_3.g_4$ to achieve the required sensitivity.

Amplifiers perform operations other than amplification, such as:

- impedance matching
- filtering and pulse shaping
- bandwidth limiting

It is the above considerations, together with the limited range of satisfactory pmt performance, that have created the need for electronic amplifiers

2 photomultiplier performance limitations

Photomultipliers suffer from multiplier gain loss under continuous operation, but in an unpredictable way. The major consideration is the total charge taken from the multiplier and external amplification is advisable where continuous anode current of >1 µA is to be drawn. Utilising an amplifier with gain of

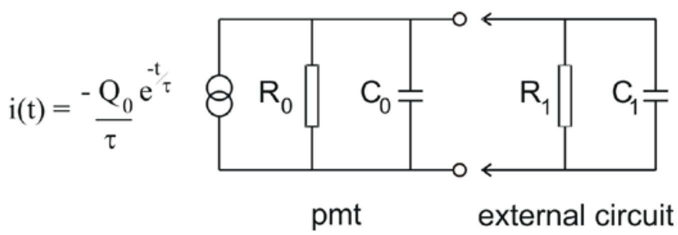

figure 2 The equivalent circuit for a pmt is a current generator in parallel with R>>$10^9\Omega$ and C_o~5pF. Most applications can be analysed in terms of an equivalent R and C combination. Without loss of generality we can take $R_1=R_oR/(R_o+R)$ and $C = C_1 + C_0$. In this example the current generator has been chosen to mimic a scintillator with decay time constant τ.

100, for example, permits a corresponding decrease in pmt gain, and consequently an anode current of only 10 nA.

The second consideration concerns peak signal current performance. Photomultipliers with linear focussed dynodes are capable of delivering peak currents of up to ~100 mA, or equivalently a peak signal of 5 volts into 50 Ω. Other dynode types do not offer the same peak current capability and additional amplification may be required.

The third consideration relates to the pmt equivalent circuit. Gain in a pmt is generated by electron multiplication and therefore the equivalent circuit is one of an ideal current generator, as shown in **figure 2**. A current generator has many advantages as a signal source but it also has some disadvantages as we shall see.

3 amplifiers for photon counting

All photomultiplier applications can be classified into just three categories: photon counting, pulsed signals and analogue detection. In photon counting the photomultiplier output signals are initiated by single photoelectrons and the basis of the technique is to count all signals that exceed a fixed voltage threshold. The first requirement is to convert the current signal into a voltage one and the second is to amplify the signal to a level compatible with commercially available discriminators - about 50 mV.

For the moment let us consider a simple resistor, R, connected to the anode to perform the current to voltage conversion we desire, see **figure 4a**. This resistor sees a stray capacitance, C, of at least 10 pF, contributed by the pmt, the socket and voltage divider board with time constant τ_1 = RC. If an unterminated coaxial cable or oscilloscope probe is added then there could easily be an addition 20 pF. We can approximate the single electron signal at the anode by:

$$i(t) = (-eg/\tau)\ \exp(-t/\tau) \qquad \ldots(1)$$

where e is the electronic charge, g is the gain of the multiplier, τ is the decay time of the pmt pulse. An exponential decay is a sufficiently accurate, representation of the anode output for analysis purposes. The output voltage $v_o(t)$ for such a stimulus is given by (2)

$$v_o(t) = -egR/(\tau_1-\tau).\{\exp(-t/\tau_1) - \exp(-t/\tau)\}$$

provided $\tau_1 \neq \tau$ ...(2)

It might appear from (2) that we can increase the amplitude of v_o simply by increasing R. However increasing R also increases τ_1 and for $\tau_1 >> \tau$, we see from (2) that v_o (peak) amplitude then varies inversely with C, so we want to keep C small. If, as is often the case, the requirement is to cover a wide dynamic counting range then we must choose $\tau_1 \sim \tau$ otherwise the imposed time constant will broaden the output pulse, leading to overlap and deadtime effects. A plot of equation **(2)**, given in **figure 3**, illustrates these points very nicely and indicates a maximum amplitude of only 1.2 mV when R = 50 Ω. If as stated previously we are looking for a 50 mV signal, then the required pmt gain is about 3 x 10^7.

Photomultipliers are capable of operating at this gain but at a rate of 10 MHz the mean anode current will be

$$I_a = 1.6 \times 10^{-19} \times 3 \times 10^7 \times 10 \times 10^6 = 48\ \mu A$$

Although the maximum recommended mean node current is 100μA, the pmt will lose gain over time at this level. So it is advisable to seek additional gain from an electronic amplifier.

An ideal amplifier for this purpose is a transimpedance one, shown in **figure 4(b),** which converts the input current into an output voltage. This is just what is required, and the output from the amplifier with feedback resistor R is also described by **(2)**.

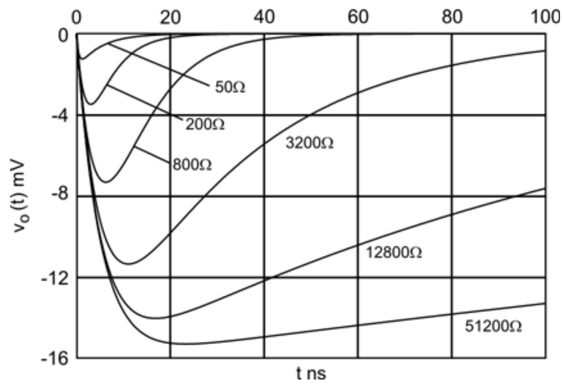

figure 3 Evaluation of equation (2) for C = 10pF t = 5ns and g = 10^6 for various values of R. The amplitude and the shape of the pulses can be easily confirmed with a fast oscilloscope

This amplifier configuration isolates the voltage-generating resistor from the capacitance associated with the pmt. In a well-laid out circuit board, the stray capacitance seen by R will now be ~ 0.1 pF and provided the op-amp is sufficiently fast and stable, R values up to about 10 kΩ may be used. Such a resistor value will provide a peak signal at g = 10^6 of about 320 mV. The amplifier is best mounted close to the anode as possible to minimise input stray capacitance – always undesirable in fast electronics.

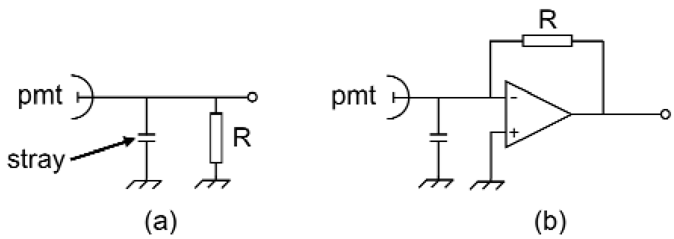

figure 4 a) Current to voltage conversion of the anode signal of a pmt. **b)** The transimpedance amplifier with its virtual earth input is ideally suited to a current generator, such as a pmt. The best amplifiers are still those made with discrete components although fast and stable op-amps are now more readily available. In practice R may be as high as 10 kΩ in (b) for fast applications

Another very important consideration is that the transimpedance amplifier has a low output impedance, typically << 50 Ω, making it suitable for driving subsequent circuitry without loading R. Clearly this isolation cannot be achieved if R is directly connected to the anode, and in this case there is no drive capability.

An alternative is to use a so-called voltage amplifier, available in a NIM unit or ideally as a board that may be connected directly to the pmt base. These typically have 50Ω input impedance and provide from 10 to 100 gain . They can be realised by using two or three fast transistors configured in the current feedback mode.

4 amplifiers for multiphotoelectron, pulsed applications

The majority of multiphotoelectron applications are in the field of scintillation spectroscopy. However, the considerations discussed here can be adapted to cover other pulsed applications. One way to detect energetic charged particles is to measure the light emitted when they interact with an organic scintillator. The decay time constant of the light is typically 1 – 2 ns and comparable with the time resolution of the fastest pmts. We have in reality already covered this application in 3 except that now the pulses are n times bigger (n is the number of photoelectrons in each pulse).

High density, inorganic, scintillators are used for the detection of γ rays. NaI(Tl) is the most widely used and it produces about 30 photons per keV of γ-ray energy deposited. A γ-ray of 1 MeV will thus produce about 6000 photoelectrons from a bialkali cathode with an exponential decay time of 240 ns. The required information from a series of measurements may be any of the following: the rate of events; the size and time of occurrence of each pulse. Measuring the rate is relatively straightforward but determining the number of photoelectrons in each pulse is more complicated. For energies above a few keV it is obvious that not all the individual photo electrons within the same event will be sufficiently separated to be counted – there will be a degree of overlap in time leading to an underestimate of the energy of the event. Clearly the ability to see individual photoelectrons decreases with increasing energy.

The way to measure the energy in such an event is to integrate the signal to convert the sum of the photo electrons to a single pulse, the area of which is directly related to the number of photon in the event. If the output from the pmt is connected to a capacitor then each charge pulse will be integrated, regardless of whether it overlaps or not, and the capacitor will charge to a voltage proportional to the total number of photoelectrons generated. The transimpedance amplifier previously mentioned is ideal for this purpose but in this case a capacitor is used in the feedback loop to perform the integration. The capacitor must discharge between events and with NaI(Tl) it is usual to choose the parallel resistor such that CR ~ 1 μs (4 time constants). This ensures that the majority of the light output is included in the energy determination of the event while permitting count rates of up to ~ 20 kHz.

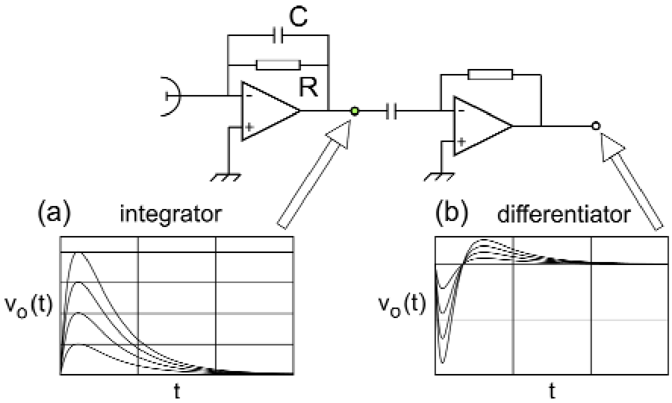

figure 5 a) Capacitor C integrates the output from the pmt producing an output v(max) of ~Q/C. The reader can verify that a 1 MeV γ producing 6000 photoelectrons will generate a 1 volt output for C = 100 pF with pmt gain = 10^5.
b) the "differentiating" amplifier produces bipolar pulses which cross the time axis at a common point. A zero-crossing discriminator detects the time of occurence of this point.

Best timing is achieved when based on the arrival of the first photoelectron of the event but such low level detection is not always practical. It is customary to follow the integrating amplifier by a so-called differentiating one. Readers may be confused by this terminology because integration followed by differentiation constitutes a null operation – so why do it? The processes involved in fact bare only similarities to differentiation and integration but the terminology is now well entrenched. An amplifier with a capacitor at its input passes no dc and so the unipolar pulses of **figure 5(a)** are converted to bipolar ones. We see that the time of zero crossing is independent of pulse amplitude. This is highly desirable in critical timing applications.

5 analogue applications

Film scanning is an example of an analogue application. A positive film is attached to a fast rotating drum and the reflected light from a sharply focussed, intense light source is picked off by a photomultiplier. The light source and the pmt traverse the drum to scan the entire information content of the picture for subsequent digitisation by an ADC. The key parameter in this process is the bandwidth, BW, which must be optimised taking account of the speed of the drum and the required pixel size. In practice, bandwidths of up to 5 MHz may be required in the high resolution machines. Once again, the best way to realise the required bandwidth is to use a transimpedance amplifier, such as that shown in figure 5(a) choosing 1/4RC = BW.

An intense light source ensures high resolution and minimum scan time and a photomultiplier with only six dynodes is required, providing comparatively low gain in the region of 10^3 - 10^4. As previously mentioned it is important in these applications to maintain a mean anode current below 1 µA to ensure stable gain. Of course excursions up to 100 µA are permitted for short time periods only.

6 conclusions

All modes of pmt operation and the associated amplifier types required have been covered high-lighting:

- the pmt is a current generator which produces a charge pulse. For encoding it requires conversion to a voltage one.
- the output may contain unwanted fine structure and amplifiers can be used to achieve pulse smoothing and shaping.
- amplifiers can eliminate pmt fatigue by providing a portion of overall system gain.

A more detailed and advanced article RP/094 on this subject is available on request from Electron Tubes Ltd and via our website www.electrontubes.com

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