Characteristic Response of a Photomultiplier Tube (PMT)

Introduction

Photomultipliers have been used to detect low-energy photons in the UV to visible range, high-energy photons (X-rays and gamma rays) and ionizing particles using scintillators. Today, photomultiplier tubes (PMT) remain unequalled in light detection in all but a few niche areas. The PMT's continuing superiority stems from three main features: large photosensing area, ultra-fast response and excellent timing performance, high gain and low noise.

Construction & operating principle

A typical photomultiplier tube consists of (i) a window (faceplate) to admit light, (ii) a photoemissive cathode (photocathode) followed by focusing electrodes, (iii) electron multipliers (dynodes) and (iv) an electron collector (anode) in a vacuum tube, as shown in Fig. 1. The semitransparent photocathode made of a thin layer of photoemissive material deposited on the inner surface of the window which emits electrons in response to absorbing photons. The photocathode can have either a head-on or a side-on configuration. The head-on type receives incident light through the end of the tube while for the side-on type light is received through the sides of the tube. The dynodes are covered with a layer of secondary emissive material. For each incident electron, each dynode emits several secondary electrons.

Light entering a PMT produces an output signal through the following process:

1. Light passes through the input glass window and excites the electrons in the photocathode to emit photoelectrons into the vacuum (external photoelectric effect).
2. These photoelectrons are then directed by the focusing electrodes accelerated towards the first dynode where they are multiplied by secondary electron emission.
3. These secondary electrons are accelerated onto the next dynode by an inter-dynode potential (typically of about 100 V) producing ever more secondary electrons. The electrode potentials are usually derived from a single high-voltage supply and a resistive or transistorized voltage divider. The secondary electron emission is repeated at each dynode.
4. A cluster of secondary electrons emitted from the last dynode are commonly multiplied up to 10^3 to 10^8 times depending on the number of dynodes and the inter-dynode potentials. Finally, the electron avalanche is collected at the anode as an output signal.

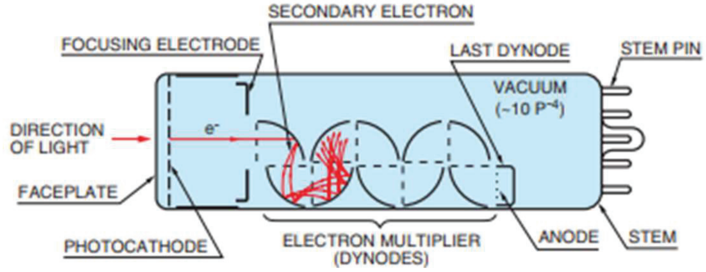

Figure 1: Construction of a typical PMT

Properties:

(I) **Current Gain:** Photoelectrons emitted from a photocathode are accelerated by an electric field so as to strike the first dynode and produce secondary electron emissions. These secondary electrons then impinge upon the next dynode to produce additional secondary electron emissions. Repeating this process over successive dynode stages, a high current amplification is achieved. A very small photoelectric current from the photocathode can be observed as a large output current from the anode of the photomultiplier tube.

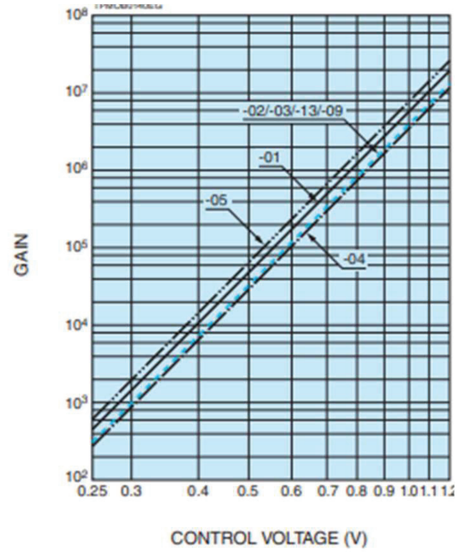

Figure 2: Typical gain response of a PMT

Current amplification is simply the ratio of the anode output current to the photoelectric current from the photocathode. Ideally, the current amplification of a photomultiplier tube having n dynode stage and an average secondary emission ratio δ per stage is δ^n. The secondary electron emission ratio δ is given by

$$\delta = A.E^{\alpha} \quad (1)$$

Here A is a constant, E is an interstage voltage and α is a coefficient determined by the material of the dynode and geometric structure. It usually has a value of 0.7 to 0.8. When a voltage V is applied between the cathode and the anode of a photomultiplier tube having n dynode stages, current amplification, μ, becomes

$$\mu = \delta^n = (A.E^{\alpha})^n = A.\left\{(\frac{V}{n+1})^{\alpha}\right\}^n = K'.V^{\alpha n} \quad (2)$$

Since photomultiplier tubes generally have 9 to 12 dynode stages, the value of αn should be typically in the range 6-10. A typical gain response of a PMT is shown in Fig.2.
Equivalently, one can measure the voltage gain, G, which is the ratio of the output voltage to input voltage at PMT for a particular applied voltage, i.e.

$$G= \left.\frac{Output\ voltage\ of\ PMT}{Input\ voltage\ to\ PMT}\right\}_{\text{at a constant supply voltage, V}} \quad (3)$$

Experimentally one can measure the voltage gains G_1 and G_2 at applied voltages V_1 and V_2 such that

$$\frac{G_2}{G_1} = K\left(\frac{V_2}{V_1}\right)^{\alpha n} \qquad (4)$$

An estimate of αn can be obtained by plotting a suitable graph and fitting it with the above equation.

(II) **Spectral response:** The photocathode of a photomultiplier tube converts energy of incident light into photoelectrons. The conversion efficiency (photocathode sensitivity) varies with the wavelength of the incident light. This relationship between photocathode sensitivity and wavelength is called the spectral response characteristic. Figure 3 shows the typical spectral response of a multialkali photomultiplier tube. The spectral response characteristics are determined on the long wavelength side by the photocathode material and on the short wavelength side by the window material at the input.

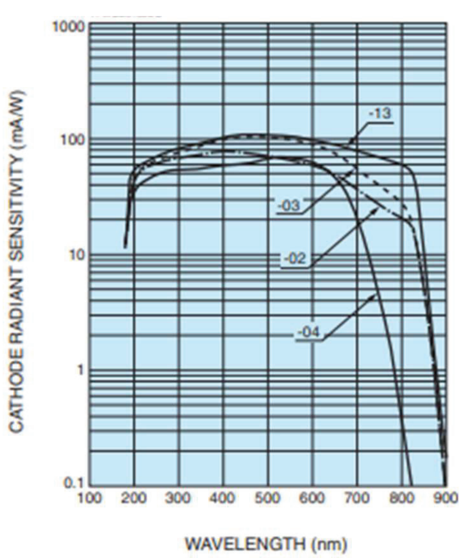

Figure 3: Spectral response of the PMT module

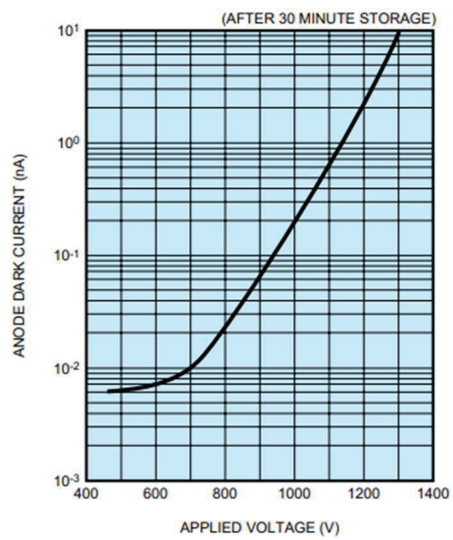

Figure 4: Dark current vs applied voltage

(III) **Dark current:** A small amount of current flows in a photomultiplier tube even when the tube is operated in a completely dark state. This output current, called the anode dark current, and the resulting noise are critical factors in determining the detectivity of a photomultiplier tube. As Fig. 4 shows, dark current is greatly dependent on the supply voltage. The major sources of dark current are (i) thermionic emission of electrons, (ii) ionization of residual gases, (iii) scintillation due to glass envelope, (iv) Ohmic leakage current and (v) field emission.

Experimental set up with PMT Module:

To make it more convenient to use PMTs, there are modules available which integrate PMT, voltage divider circuit and high voltage supply into a single compact module case. These are easy to handle since they can be operated by using a low supply (control) voltage.
The module used in this experiment is Hamamatsu H9305-03 PMT module (see Fig. 5) which contains a high voltage power supply circuit and a 13-mm (half inch) diameter side-on PMT in a compact aluminum housing. The PMT has a reflection mode multialkali (Na-K-Sb-Cs) photocathode, an adequate gain of more than 10^6. It uses UV glass as its window material and has a highly sensitive spectral response in UV to near IR range (185 – 900nm).
Figure 6 shows an external power supply of ±15V which provides the driving voltage as well as the control voltage for the PMT module. The control voltage can be varied from +0.25 to 1V using a potentiometer. The ratio of the control voltage to actual PMT voltage is 1: 10^3.

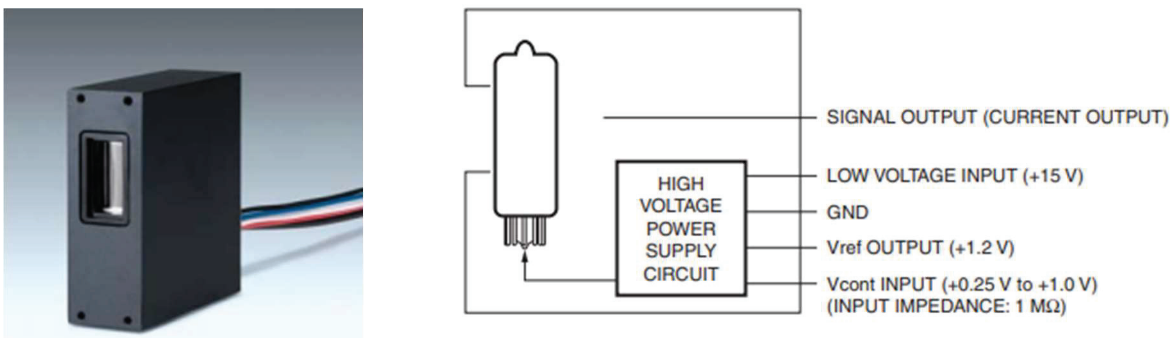

Figure 5: (a) PMT Module (H9305-03) **(b) Schematics of the PMT module**

Figure 6: Power supply for PMT Module

Apparatus:
(1) PMT Module (H9305-03), (2) Control voltage unit, (3) Digital Storage Oscilloscope (DSO), (4) Tungsten filament bulb, (5) DC power supply, (6) Optical Filters for different wavelengths (in the range 400 – 700 nm) with suitable holder, (7) Mounted photodiode, (8) Multimeters, (9) Breadboard and Connecting cables

Procedure:

Caution:
(1) The PMT module is an extremely photosensitive device. Avoid exposure to intense light in all circumstances. Keep the window covered when not in use.
(2) Do not operate the PMT at a control voltage above 1V.

(3) All the prescribed experimental parameters suggested in the procedure below are optimized for this experiment after testing multiple times. Deviations from the suggested values can be allowed only after discussion with the instructor.

(I) General assembling of the set up:

1. Observe the PMT module and control voltage unit carefully. Familiarize with the input and output terminals available. Check the power requirement of the control voltage unit.
2. Connect the control voltage unit to the AC mains and to the PMT module as marked on its rear side (see Fig.7).
3. Connect the PMT signal output (BNC cable) to an oscilloscope (DSO).
4. Switch on the control voltage and set it to a desired value by using the potentiometer on the it.
5. The PMT output signal can be read from the oscilloscope display. The DSO has an internal impedance of 1MΩ, which can be used for calculating current from the displayed voltage.

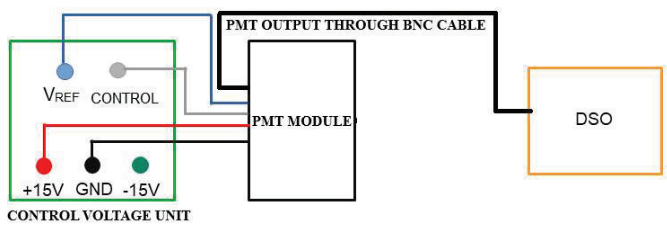

Figure 7: Schematics of Connections of PMT module to control voltage unit

(II) Gain:

1. Keep the PMT window covered and connect it to the control voltage unit as described above.
2. Now set up the source to which the PMT will be exposed and the corresponding signal output can be measured using oscilloscope.
3. A usual tungsten filament is used as a light source for the PMT. Set up a simple circuit using a breadboard and a DC power supply to make the bulb glow. Use multimeters to keep a record of the supply voltage and current flowing in the circuit. Use the supplied voltage in the range 1 – 1.5V which should be sufficient to carry out the experiment. You may place the circuit on a lab jack whose height can later be adjusted with the height of photodiode/PMT circuit.

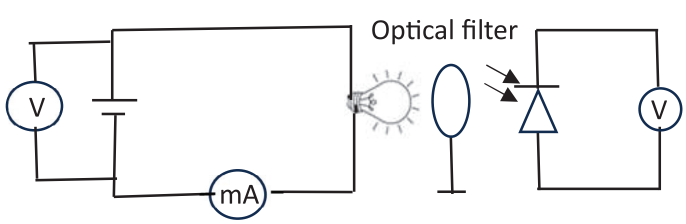

Figure 8: Schematics of the set up for measuring PMT input with a photodetector

4. On a second lab jack, now set up another circuit using the mounted photodiode and multimeter. Place this jack such that the photodiode is at a distance of 10cm (say) from the

bulb. Adjust the height of the lab jack as required. Mark the positions of the bulb and the photodiode carefully and do not disturb it throughout the measurement. Follow Fig. 8 to arrange the set up.

5. Mount one of the optical filters on the holder and place it close to the photodiode. Read the DC output voltage and current on the multimeter. Adjust the DC supply voltage (between 1 to 1.5V) to the bulb so that the photodetector voltage (current) is around 0.1-0.2V (0.1μA). The photovoltage measured by the multimeter will be the input voltage for the PMT.

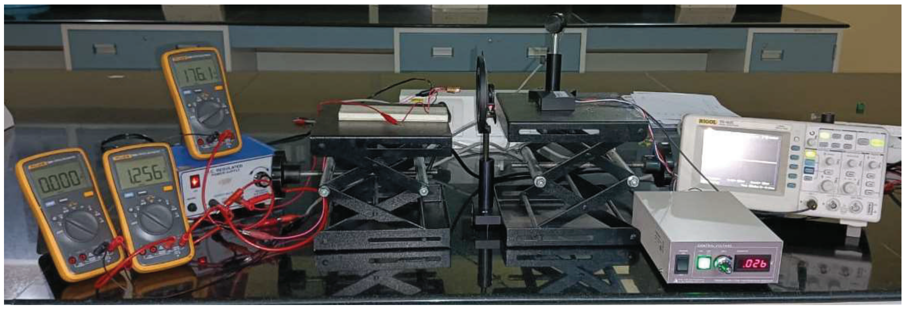

Figure 9: Actual experimental set up for gain and spectral response of PMT

6. After fixing the input voltage to PMT, carefully replace the photodiode with the PMT exactly at the same position without disturbing the source. Set up the circuit to measure the PMT output voltage on DSO as already explained in step (I). Vary the control voltage from 0.3V (vary till the DSO output saturates) in steps of 0.5 V and record the corresponding DSO output voltage. An actual set up with the complete assembly is shown in Fig.9.
7. Plot a graph as per Eq-4 and estimate αn.

(III) Spectral response:

1. Repeat the procedure as mentioned in (II) up to step 5. Do the step 5 for all available filters and note down the supply voltage and current to the bulb. Keep the optical power fixed around 0.01-0.02 μW to do all the measurements without much inconvenience.
2. After the measurement is over for all the filters, carefully replace the photodiode with the PMT exactly at the same position without disturbing the source.
3. Set up the circuit to measure the PMT output voltage on DSO as already explained in step (I). Set the control voltage anywhere between 0.3 to 0.5 V.
4. Introduce the optical filter close to the PMT module and read the DC output voltage on the DSO. Calculate the output current noting the impedance of the DSO. Estimate the radiant sensitivity which is the ratio of output current to input power (in units of A/W). Repeat this process for every optical filter and plot a graph to study the spectral response.
5. Calculate the optical power at the photodiode assuming 100% efficiency (?). The optical power should be fixed around 0.01-0.02 μW

(IV) Dark current:

1. Remove the tungsten bulb circuit.

2. Cover the PMT module completely so that no external light enters into it.
3. Connect the PMT output to a suitable multimeter to measure current/voltage.
4. Vary the control voltage from 0.3 to 1V and measure the dark current/voltage after 10 minutes of acquisition.

Observations:

Table-1: Gain

Table-2: Spectral response

Table-3: Dark current

Graphs:

Conclusions:

Precautions

References:

1. Radiation detection and measurement, G.F. Knoll
2. Handbook for PMTs by Hamamatsu
3. https://www.chem.uci.edu/~unicorn/243/handouts/pmt.pdf