Study of the Characteristic Response of a Photomultiplier Tube

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(Dated: April 30, 2025)

This study explores the fundamental characteristics of PMTs, focusing on their high amplification capability, spectral response, and intrinsic dark current. Using a Hamamatsu H9305 03 PMT module, we conduct an experimental analysis of gain dependence on control voltage, spectral sensitivity across the 400–700 nm range, and variations in dark current as a function of supply voltage. Our findings highlight the signal amplification properties of the PMT, its wavelength dependent detection efficiency, and the influence of dark current on measurement precision.

I. THEORY

Photomultiplier tubes (PMTs) are highly sensitive photon detectors widely employed in the detection of weak optical signals, spanning ultraviolet (UV) to visible wavelengths, as well as high-energy photons such as X-rays and gamma rays. When coupled with scintillators, PMTs are also instrumental in detecting ionizing radiation.

The main parts of the PM tube are (ref Fig. 1) –

1. A window (faceplate) that allows light to enter
2. A photoemissive cathode (photocathode) followed by focusing electrodes
3. Electron multipliers (dynodes)
4. An electron collector (anode) within a vacuum tube

The photocathode is a semitransparent thin layer of photoemissive material deposited on the inner surface of the window. When photons are absorbed, electrons are emitted. The photocathode can be configured in either a head-on or a side-on arrangement. In the head-on type, light enters through the end of the tube, while in the side-on type, it enters through the sides.

Dynodes are coated with a secondary emissive material. Each incident electron on a dynode releases multiple secondary electrons, leading to an amplification process.

The process of generation of an output signal in a PMT is detailed below.

- Incident light passes through the glass window and excites electrons in the photocathode, causing the emission of photoelectrons into the vacuum (external photoelectric effect)
- The emitted photoelectrons are directed by focusing electrodes and accelerated towards the first dynode, where secondary electron emission occurs.
- The secondary electrons are accelerated towards the next dynode by an inter-dynode potential, typically around 100 V, producing additional secondary electrons. The required electrode potentials are generally supplied by a high-voltage source and regulated through a resistive or transistorized voltage divider.
- This process of secondary electron emission is repeated at successive dynodes.
- The final cluster of secondary electrons, amplified up to a factor of 103 to 108 depending on the number of dynodes and inter-dynode potentials, is collected at the anode, generating an output signal.

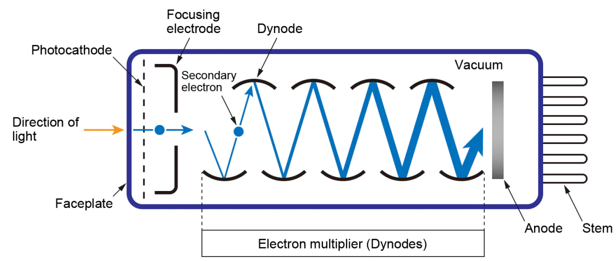

FIG. 1: Construction of a photomultiplier tube

A. PMT Characteristics

1. Current Gain

Electrons emitted from the photocathode are accelerated under the electric field and go to the first dynode and emit a secondary electron that hits the next dynode again emitting a secondary electron.Repeating this process over successive dynode stages achieves a high current amplification. So for a small value of current from photocathode gives rise to a large output current. The current amplification of a PMT is defined as the ratio of the anode output current to the photoelectric current from the photocathode. Ideally, for a photomultiplier tube with n dynode stages and an average secondary emission ratio δ per stage, the total current amplification is given by:

$$\mu = \delta^n \tag{1}$$

The secondary electron emission ratio δ is expressed as:

$$\delta = AE^{\alpha} \tag{2}$$

where A is a constant, E is the interstage voltage, and α is a coefficient determined by the dynode material and its geometric structure, typically ranging from 0.7 to 0.8. When a voltage V is applied between the cathode and anode of a PMT with n dynode stages, the current amplification μ becomes:

$$\begin{aligned}\mu &= \delta^n \\ &= (AE^\alpha)^n \\ &= A\left(\frac{V}{n+1}\right)^{\alpha n} \\ &= K'V^{\alpha n}\end{aligned} \tag{3}$$

Since PMTs typically have 9 to 12 dynode stages, the value of $n\alpha$ generally falls within the range of 6 to 10.

2. Voltage Gain

The voltage gain G of a PMT is defined as the ratio of the output voltage to the input voltage at a particular applied voltage V (at constant supply voltage V)

$$G = \frac{V_{out}}{V_{in}} \tag{4}$$

Experimentally, voltage gains G_1 and G_2 can be measured at applied voltages V_1 and V_2, respectively, satisfying the relation

$$\frac{G_1}{G_2} = K\left(\frac{V_1}{V_2}\right)^{n\alpha} \tag{5}$$

3. Dark Current

Even in the absence of incident light, a small current can still be observed in a photomultiplier tube. This residual current, known as the anode dark current, contributes to noise and affects the overall detectivity of the PMT.

The dark current strongly depends on the applied supply voltage. The primary sources of dark current include:

- Spontaneous emission of electrons due to thermal energy
- Ionization of residual gases within the vacuum tube
- Electron emission due to strong electric fields at sharp point
- Small leakage currents arising from imperfections in insulation
- Light emission caused by interactions with the glass envelope

These factors collectively contribute to the overall dark current, and their minimization is crucial for improving the sensitivity of the photomultiplier tube.

B. Spectral Response

The efficiency of a photomultiplier tube in converting incident photons into emitted electrons depends on the photocathode's sensitivity, which varies with wavelength. This dependency is referred to as the spectral response characteristic.

The spectral response is primarily influenced by two key factors.

The long-wavelength limit is determined by the composition of the photocathode material, which governs its ability to release electrons upon photon absorption.

The short-wavelength limit is dictated by the optical properties of the input window material, as certain materials absorb high-energy (short-wavelength) photons before they can reach the photocathode.

Understanding these spectral response characteristics is essential for selecting an appropriate PMT for specific applications, ensuring optimal sensitivity across the desired wavelength range.

II. EXPERIMENTAL SETUP

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 a suitable holder
7. Mounted photodiode
8. Multimeters
9. Breadboard and Connecting cables

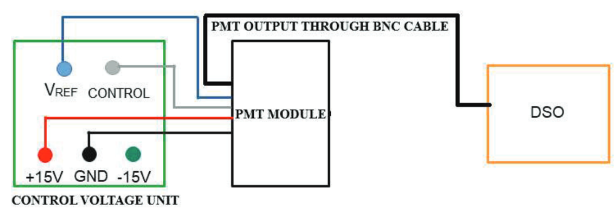

FIG. 2: Schematics of Connections of PMT module to control voltage unit

III. OBSERVATION AND CALCULATIONS

A. Gain Variations at a fixed wavelength

Here, Table I shows the output vs. supply voltage of the PMT. Using the relation between gain and two voltages, we can rewrite the equation to find the value of αn.

$$\log G = \alpha n \log V + \log K'$$

V_{Supply} (V)	$V_{O/P}$ (V)	Gain	log G	log V
0.30	0.96	3.20	0.5051	-0.5229
0.35	2.18	6.23	0.7944	-0.4559
0.40	7.21	18.03	1.2559	-0.3979
0.45	11.70	26.00	1.4150	-0.3468
0.50	17.10	34.20	1.5340	-0.3010
0.55	31.10	56.55	1.7524	-0.2596
0.60	41.90	69.83	1.8441	-0.2218
0.65	55.00	84.62	1.9274	-0.1871
0.70	69.10	98.71	1.9944	-0.1549

TABLE I: Current gain in output DSO

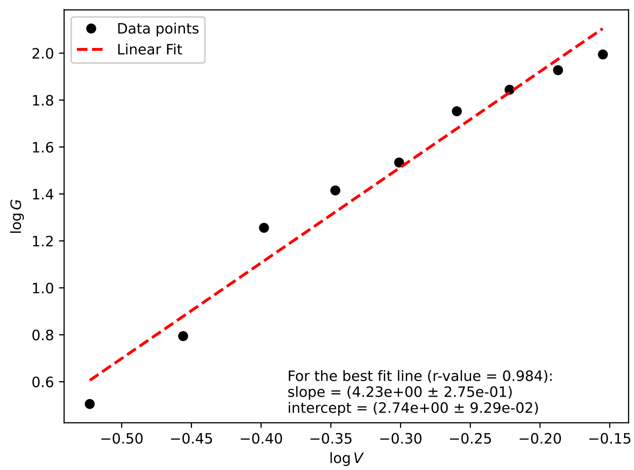

FIG. 3: Plot for gain Response for 600 nm

By applying least square fitting, we can approximate a linear fit for $\log G$ vs. $\log V$ (Fig. 3) and estimate the value of $\alpha n = 4.231$.

B. Spectral Response

Tables II and III show the wavelength dependednt characteristics of the LED and the PMT. Using these, the sensitivity of the PMT at different wavelengths were calculated and plotted (Fig. 4). We can see that the highest sensitivity is for blue light (460 nm) and there is a significant dip for yellow light (570 nm) after which it increases. Also note the high measurement uncertainty in the sensitivity values, which are primarily because of the high variation in the observed parameters and the high least counts of the instruments.

λ (nm)	V_{LED} (V)	I_{LED} (mA)	P_{LED} (W)	V_{PD} (V)	I_{PD} (mA)
460	1.090	138.4	0.151	192.3	0.1
500	0.889	125.6	0.112	186.9	0.1
540	0.696	115.1	0.080	179.5	0.1
570	0.669	113.3	0.076	176.1	0.1
635	0.598	115.2	0.069	184.4	0.1

TABLE II: Wavelength-dependent characteristics of LED and Photodetector

λ (nm)	V_{PMT} (mV)	I_{PMT} (A)	S_{PMT} (A/W)
460	800	0.800	5.303
500	520	0.520	4.657
540	280	0.280	3.495
570	180	0.180	2.375
635	320	0.320	4.645

TABLE III: Wavelength-dependent characteristics of PMT

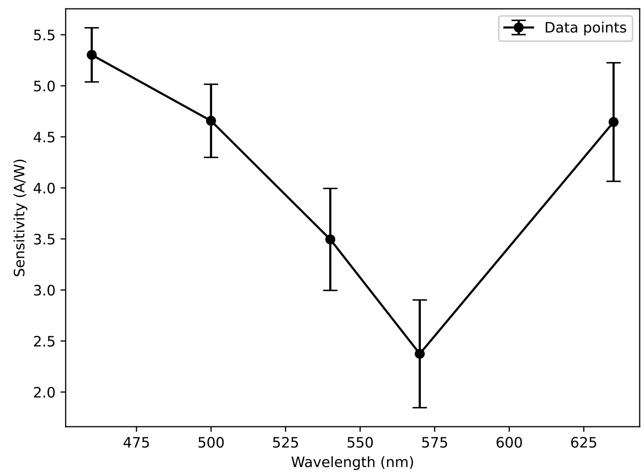

FIG. 4: Plot for anode sensitivity vs. wavelength

C. Dark Current

The anode dark current was measured at various control voltages while ensuring that the PMT was completely isolated from external light sources (Table IV and Fig. 5).

V_{PMT} (mV)	I_{PMT} (A)
0.5	0.0
0.6	0.2
0.7	0.8
0.8	1.4
0.9	6.2
1.0	14.1

TABLE IV: Dark current vs supply voltage in PMT

IV. ERROR ANALYSIS

Since αn is obtained from a linear fit, its uncertainty $\Delta(\alpha n)$ can be determined from the standard error propagation formula for the slope in linear regression.

$$\frac{\Delta(\alpha n)}{(\alpha n)} = \frac{\Delta\text{slope}}{\text{slope}}$$

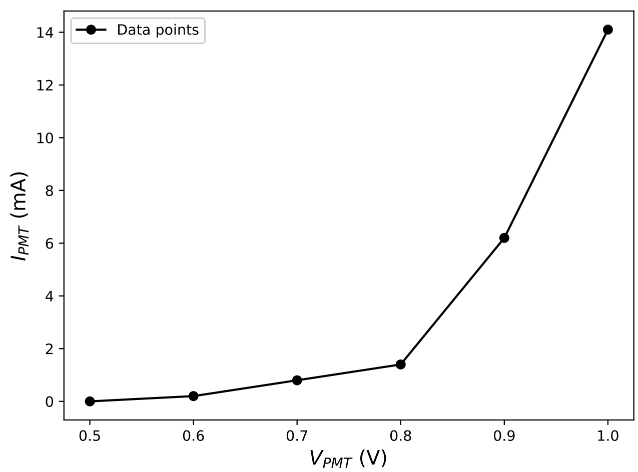

FIG. 5: Dark current vs supply voltage in PMT

which comes out to be the same as $\Delta\text{slope} = \Delta(\alpha n) = 0.275$.

V. DISCUSSION & CONCLUSION

From observing the gain response of the PMT for a particular filter, our analysis yielded a value of

$$\alpha n = 4.231 \pm 0.275$$

Since photomultiplier tubes generally have 9 to 12 dynode stages, the value of αn should be typically in the range 6-10. Our values are slightly lower which could be due to measurement errors. The relatively large uncertainty indicates the presence of significant sources of error. The primary contributor to this uncertainty is likely the instability of the light ource. Despite maintaining a constant supply voltage and current, we observed minor variations in light intensity. These fluctuations were amplified within the PMT module, leading to increased measurement variability. Employing a more stable power source could mitigate these variations and enhance the precision of our measurements.

When analyzing the full spectral response from ultraviolet to infrared, the visible range appears generally smooth, following an overall trend. However, upon closer examination of the visible spectrum, subtle fluctuations become apparent, such as the notable dip at 570 nm. Unlike an idealized smooth curve, the actual spectral response of a PMT is influenced by several physical factors, including photocathode efficiency and optical interference, which can cause unexpected deviations. Since absolute sensitivity values are derived from empirical measurements, there is no definitive theoretical model to predict the exact trend within the visible range. The dip at 570 nm may be attributed to specific material properties, but its exact cause remains unclear.

Another significant source of error in our sensitivity measurements is the resolution of the multimeter. The smallest detectable current increment is 0.1 nA, which impacts the accuracy of our data, particularly for low-intensity signals. Additionally, while the PMT module's dark current aligned with the expected theoretical trend, the noise level increased substantially as the control voltage was elevated. This underscores the necessity of implementing noise reduction techniques to improve measurement accuracy, especially at higher voltages.

In conclusion, our study highlights the challenges associated with achieving precise measurements in PMT-based systems due to various sources of error, including light source instability and multimeter resolution limitations. The observed fluctuations in the spectral response, particularly the dip at 570 nm, suggest that material properties and experimental conditions play a crucial ole in the performance of PMTs. To enhance the accuracy and reliability of future measurements, it is essential to employ more stable power sources, improve noise reduction techniques, and consider the impact of external factors such as temperature.

VI. PRECAUTIONS AND SOURCES OF ERROR

1. Ensure that the control voltage is never set above 1V, as this may lead to malfunction or damage to the PMT module.
2. Always use a stabilized power supply for the PMT. Avoid fluctuations or sudden voltage spikes, as they can affect the measurement ccuracy and potentially damage the PMT.
3. The PMT is a highly photosensitive device. Intense light can damage the photocathode and compromise the performance of the PMT. Always ensure that the PMT window is covered when not in use.
4. High ambient temperatures can affect the performance of the PMT and the associated electronics. Ensure that the PMT is perated in a cool, controlled environment.

[1] SPS, *Characteristic Response of a Photomultiplier Tube (PMT)*, NISER (2023).
[2] G. Knoll, *Radiation detection and measuremen.*