

Homework Set 3.5

Sensitive optoelectronic detectors: seeing single photons

Due by 12:00 noon (in class) on Tuesday, Nov. 7, 2006.

This is another hybrid lab/homework; please see Section 3.4 for what you need to turn in.

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1 Objectives

1. Understand the principles of operation of photomultiplier tubes (PMTs).
2. Build signal conditioning electronics to capture and detect the optical signal generated by a photomultiplier tube.
3. Observe single-photon events with the detector.
4. Understand some of the noise characteristics of the PMT-circuit system as affected by light level and gain.

2 Background

2.1 Photomultiplier Tube (PMT)

For low light-level detection and measurement, you can't beat the photomultiplier. This clever device allows a photon to eject an electron from a light-sensitive alkali metal photocathode. The photomultiplier then amplifies this feeble photocurrent by using a high voltage to accelerate the electron onto successive surfaces (dynodes), from which a cascade of additional electrons is easily generated (Figure 1).

This use of "electron multiplication" yields extremely low-noise amplification of the initial photocurrent signal. The final current is collected by the anode, usually run near ground potential.

A PMT is a linear device in the sense that the current output is proportional to the light power incident on the photocathode. The PMT we use in this lab is a Hamamatsu R7400P, which has a photocathode sensitivity of 60 mA/W (recall that a photon's energy depends on its wavelength – our LED's light is approx. 565nm). The gain of the dynode chain depends on the applied accelerating voltage. The overall anode sensitivity is the product of the photocathode sensitivity and dynode chain gain (Table 1 provides a summary, and the PMT data sheet has more detail).

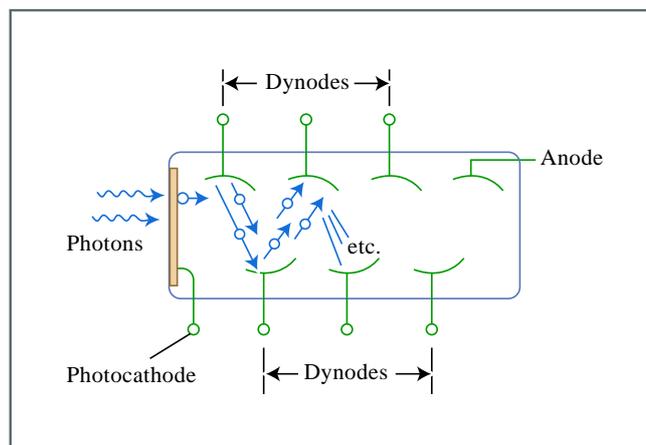


Figure by MIT OCW.

Figure 1: Principle of PMT operation: a high negative voltage applied to the photocathode accelerates electrons down the dynode chain.

PMT voltage (V)	dynode chain gain	total sensitivity (A/W)
-500	3×10^4	1.8×10^4
-800	10^6	6×10^4

Table 1: PMT gains at two operating voltages.

Due to its high sensitivity, a PMT can be used to observe individual photoelectron events. At low light levels, this is typically done by following the PMT with charge-integrating pulse amplifiers, discriminators and counters. In this lab, we will simply observe them visually on an oscilloscope.

At higher light levels, the individual photoelectron current becomes too high, so you measure the anode current as an analog quantity instead.

Note: A powered PMT should never be exposed to ordinary light levels. A PMT that has seen the light of day, even without power applied, may require 24 hours or more to "cool down" to normal dark-current levels. More on this later.

When compared to photodiodes, PMT's have the advantage of high quantum efficiency while operating at high speed. This makes the PMT particularly well-suited to biological imaging applications where small numbers of fluorescent molecules are observed on very short time scales. The main disadvantages of the PMT are its large size and need for a stable high-voltage source.

2.2 Noise Sources

2.2.1 Photon Shot Noise

An electric current is the movement of discrete electric charges, not a smooth fluid-like flow. Likewise, incoming light energy is quantized into the packets we know as photons. The “finite-ness” of the quantized photons and electronic charges results in statistical fluctuations of the resulting current. This is referred to as photon shot noise. If the charges act independently of each other, they follow Poisson statistics, and the current fluctuations are given by

$$I_{ES} = \sqrt{2qI_{dc}B}, \quad (1)$$

where q is the electron charge, and I_{dc} is the steady-state RMS current, and B is the measurement bandwidth in Hz. The assumption of independence of individual electron movement is true for electrons crossing a barrier such as electrons excited by single photons at the cathode of a PMT (An important exception is in metallic conductors, where there are long-range correlations between charge carriers).

2.2.2 Electron Shot Noise

In the absence of light, due to thermal excitation, electrons are occasionally generated at the cathode or one of the dynodes. These electrons will be accelerated through the circuitry and generate a current pulse similar to the effect of an incoming photon. However, because many of these don't propagate down the entire dynode chain, the current pulse from the “dark” electrons tends to be lower in amplitude. This current is typically in the neighborhood of 30 counts per second per square centimeter of cathode area.

The current generated in the photomultiplier tube in the absence of light is called the *dark current*. As a noise source, it is the fluctuation amplitude of the dark current and not its DC value that presents a problem. Similar to photon shot noise, the electrons generated spontaneously in the photomultiplier tube also follow Poisson statistics and the RMS noise is given by Equation 1 where I_{dc} is the steady-state RMS dark current.

2.2.3 Johnson Noise

Any resistor just sitting on the table generates a noise voltage across its terminals, which arises from the random thermal motion of electrons within it. This is known as Johnson noise, and has a flat power spectrum – having equal power density at all frequencies (you've also heard it described as “white noise”). The actual open-circuit noise voltage generated by a resistance R at absolute temperature T is given by

$$V_J = \sqrt{4k_BTRB}, \quad (2)$$

where k_B is Boltzmann's constant. Note that V_J is the RMS magnitude of the noise signal we measure; the actual signal fluctuates in time with a Gaussian probability distribution.

The significance of Johnson noise is that it sets a lower limit on the noise voltage in simple resistive circuits. The resistive part of a source impedance generates Johnson noise, as do the bias and load resistors of an amplifier.

3 Experimental Procedures

3.1 Hardware set-up

The apparatus for this lab consists of an enclosed tube containing an ordinary diffuse green LED pointed at a PMT as shown schematically in Figure 2.

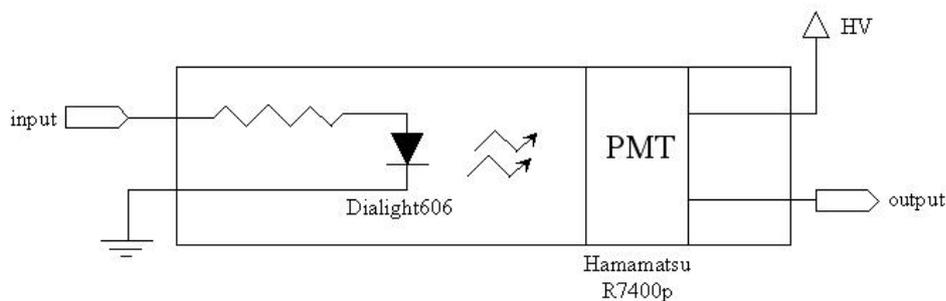


Figure 2: Experimental setup.

The PMT end of the tube has two connectors, labeled “HVin” and “Iout” which are the high-voltage input from the power supply and the output anode photocurrent, respectively. This photocurrent will be amplified using a by-now-familiar transimpedance amplifier, which you can build as shown in Figure 3. Use an LF411 op-amp, and ± 15 V supplies, as usual. Choose R_f and C_f values to give a DC gain of $V_{out}/i_{in} = 2 \times 10^6$ V/A and a time constant of $200 \mu\text{s}$.

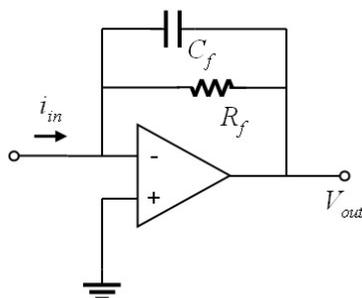


Figure 3: Transimpedance amplifier circuit.

Screenshot from LabVIEW software removed
due to copyright restrictions.

3.2 Software

The LED light source is driven from the computer DAQ system. (Why does this work for this experiment, but would not work for e.g. the blue LEDs in the DNA melting experiment and we needed a separate power supply?)

The output of the transimpedance amp is read by LabVIEW and observed on the screen shown in Figure 4. You should also connect this same signal to an oscilloscope for easier direct observation.

The LabVIEW panel is very simple. You can set the data sampling rate and number of data points to acquire, the data input and output channels (easiest to leave at the default value of 0), and the input limits. A word about these limits: they determine the digital that LabVIEW can see, and therefore the minimum signal level that you'll be able to read. Experiment with changing these to achieve better resolution at low signal levels.

Finally, the slider bar at the bottom, and the corresponding entry box to its left set the voltage being applied to the LED.

What you'll want to record are the "Signal Mean" and "Standard Deviation" values that LabView calculates from the signal waveform. These represent the photocurrent from the PMT and its noise, and this is what we'll study a bit more quantitatively.

3.3 Experiment Roadmap

1. With the PMT HVPS at -800 V, and no LED drive voltage applied, observe the output of your amp circuit on the oscilloscope. Predict the character and magnitude of the amplifier output signal for the following:
 - (a) A single photon hitting the PMT
 - (b) The PMT dark current
 - (c) Pure Johnson noise

Which of these can you see on your scope? Discuss with

2. Now observe the mean amplifier output signal and standard deviation as you increase the drive voltage on the LED. Remember that LEDs have a characteristic “turn-on” voltage, at which slight changes in voltage produce large increases in current, and light output. You’ll see this effect beginning at about 1.5 V.
3. Record the mean and standard deviation values for various input voltages (in particular around the “turn-on” transition of the LED).
4. Change the HVPS to -500V and repeat the observations in items 1. and 2. above.
5. Reduce the amplifier gain to 1.5×10^6 V/A while maintaining the same time constant and keeping the PMT supply voltage at -500V. Similarly to item 3. above, collect mean and standard deviation data.

3.4 Data Analysis and “Deliverables”

The key step here is to convert the signals you recorded (in volts), into units of “photons per time constant.” You can do this by tracing out the various signal-conversion steps that take place (photocathode, dynode chain, transimpedance amp) and noting the gain or amplification factor for each. Keeping track of the physical units via dimensional analysis is very useful here.

Once you have performed the conversion, the following two plots and associated explanation are all you’ll need to turn in:

1. Plot the noise level (in units of photons per time constant) versus the signal level (same units) on a log-log scale for both the -500 V and -800 V supply voltages.

*Compare the situations at -800 V and -500 V and **briefly** discuss in a few sentences:*

- (a) Explain the shape and slope of each curve, and what it tells you about the origin of the noise observed? Can you see the noise floor for the measurements? If so, what is the source of the noise? (Johnson noise? shot noise?)
 - (b) How does the noise characteristic change between -800 V and -500 V? What types of noise are observed in each case?
2. Finally, if you’ve been paying attention, you’ll notice that something is not quite right about the two noise plots relative to each other at -500 and -800 V (what is it?). This is because the PMTs have actually seen too much bright light, and are no longer able to reach their design-specified gain at -800 V. Using these plots (assuming the -500 V gain is correct), try to determine what the actual dynode gain is at -800 V.