Single Photon Detection with a reverse-biased LED in Avalanche mode

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ABSTRACT

The main objective of this experiment is to show that a simple LED can be used as a single photon detector. An inexpensive experiment using a reverse-biased LED as an avalanche photodiode is described. The SPAD device (single photon avalanche detector) is a photodiodelike device that can react to a single photon producing a measurable current pulse. It is shown that a normal red LED can work, although with lower efficiency, like a SPAD device. The experiment allows to explore the statistics of random events, basic discriminator circuits, and the behavior of avalanche photodiodes. The experiment is done by using three different types of light sources(open source or stray photon source, diode laser and He-Ne gas laser).The statistical behaviour of photon detection is studied. The time interval between two successive detections is normally an exponential distribution while a Gaussian distribution is observed to suitably describe the number of detections in a given interval of time. Generally a linear trend is observed for the variation of mean photon number as a function of counting time. The distribution of the analog pulse widths from oscilloscope traces are observed. It is noticed that the pulse width increases with increase in quenching resistance. The inefficient working of the detector is discussed in great detail in this report and the effects of After-pulsing(Correlated signals) and Dead time of the detector on the photon counting statistics are observed and discussed in this report.

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Chapter 1

Objective and Introduction

1.1 Objective

- To build a cost effective (inexpensive LEDs) single photon detector with simple construction.
- To build a sensible enough detector that can sense single photon with wider spectral range of operation.
- To build a detector with low power consumption as well as greater photon detection efficiency.
- To model the statistical behaviour of photon detection. Or, to use a photon detector to illustrate properties of random counting experiments.

1.2 Introduction

Photons are defined as individual packets of energy, which fundamentally compose light. Single-photon detectors (SPDs), which are sufficiently sensitive to detect single photon clicks, are increasingly used in more fields of importance, such as quantum key distribution (QKD), positron emission to- mography, optical time domain reflectometry and biomedical researches. Among them, the dramatic growth of the applications of optical quantum information has become the major driver for the development of single photon detection. As the requisite optical components in quantum information processing, SPDs with high detection efficiency, high signal-to-noise ratio, short dead time, low timing jitter and ability to resolve photon numbers are in great need. Thus far, many concepts and techniques have been proposed to develop SPDs[1]. For instance, photomultiplier tubes, single-photon avalanche photodiodes (SPADs), frequency up-conversion, superconducting nanowire SPDs, and SPDs based on quantum dots and semi-conductor defects, despite of different design features, differ in terms of spectral response, detection efficiency and photon-number resolving capability, providing optimal choices for various specific applications.In this experiment, we focus on single photon detection based on avalanche breakdown.(SPAD)

LEDs are intended to be used as their name suggests, as light emitting devices. However, the semiconductor physics that governs their behaviour also allows them to be used as light detectors. LEDs can be used as photodiodes (essentially tiny solar cells) to detect light near their own wavelength. Even non-light emitting glass-encapsulated diodes generate photocurrents when exposed to light.

Detecting single photons of light is another matter entirely. Single-photon detectors such as the avalanche photodiode (APD), Photomultiplier (PMT), Silicon Photomultiplier (SiPM) and bolometer are often expensive, require dangerous high voltages, and are easily damaged. Fortunately, a few intrepid physicists have found a handful of inexpensive LEDs that undergo the avalanche breakdown required of single-photon detectors. These LEDs are not designed for this purpose, so they make rather poor detectors, but they are excellent for the didactic exercises that follow.

1.3 What is SPAD?

The SPAD (single photon avalanche detector) is a photodiode-like device that works in an operating area that is usually avoided : the breakdown region (Geiger Mode). A conventional photodiode is usually realized with a reverse-biased p-n junction (a

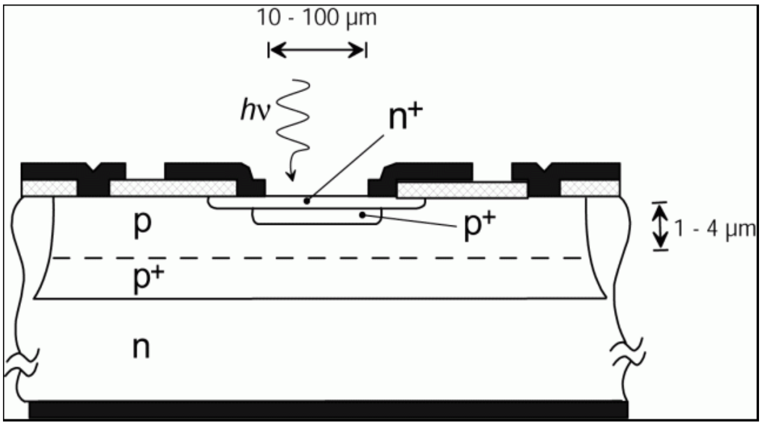


Figure 1.1: The cross section of a typical SPAD[1]

diode) where the photons can interact with silicon and generate electron-hole pairs, mainly because of the photoelectric effect in the visible wavelength range. These pairs are then separated by the strong electric field existing in the depletion area and thus they can reach the electrodes giving rise to a current. In normal photodiodes many photons are needed to have an observable current signal so these devices are not suitable for measuring very low intensity light[1].

Increasing further the bias voltage, beyond the breakdown voltage, the avalanche process becomes self-sustained with even higher gains (around 10^6) and the photodiode becomes a digital device that respond even just to a single photon with a macroscopic current pulse of value independent of the number of initial photons, this device is now called SPAD[2]. A photon generated carrier triggers an avalanche current due to impact ionization. Obviously the avalanche current must be somehow limited otherwise the device could be damaged, moreover during the avalanche current the device cannot react to other photon so it is "blind", hence the need to switch off rapidly the current pulse. The above image (Fig. 1.1) shows the cross section of a typical SPAD with the upper "window" to let the photons enter the active area which is the depletion area between the n+ and p+ layers.

Chapter 2

Theoretical Background

2.1 How Does a Photon get detected? (by SPAD)

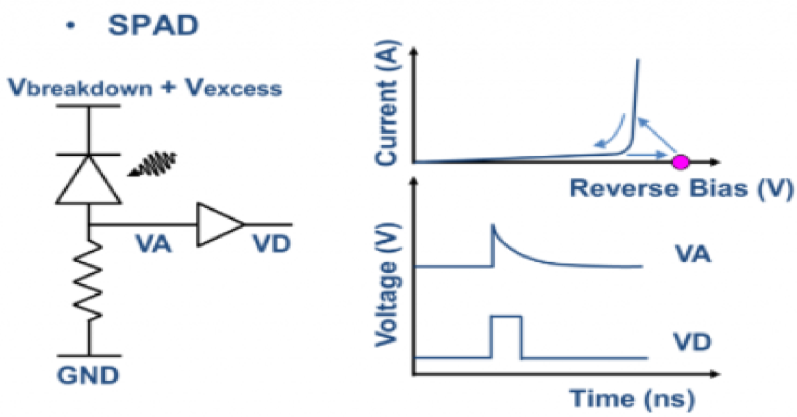


Figure 2.1: In the diagram above a SPAD basic scheme is shown[1]

2.1.1 Geiger-mode Avalanche Photodiodes

A p-n junction is formed within a semiconductor material, and the junction is reverse-biased. At low bias voltages, no current will flow through the junction, because charge carriers do not have enough energy to overcome the potential energy barrier created at the depletion region of the junction. At sufficiently high reverse bias voltages, if a photon is absorbed in the junction and creates an electron-hole pair, the large electric field in the junction will cause the pair to separate before they have a chance to recombine. As the excited electron accelerates in the electric field, it gains kinetic energy. If the electron interacts with an atom within the junction, that kinetic energy can be converted into the creation of another electon-hole pair[3]. Now there are two

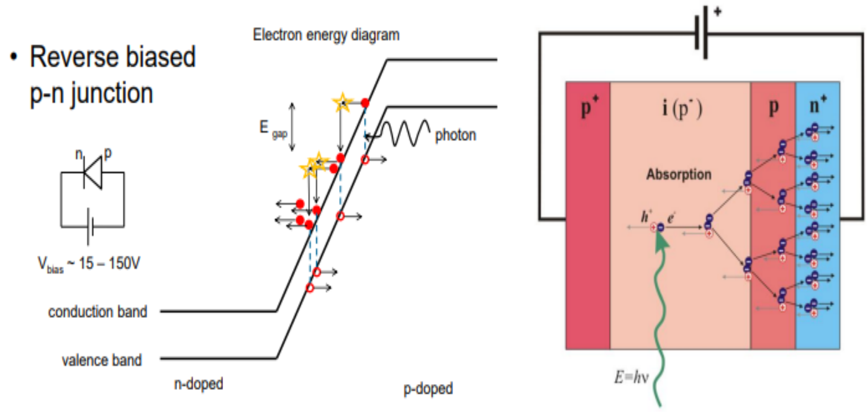


Figure 2.2: Electron energy diagram in a reverse biased p-n junction. An absorbed photon creates an electron (solid circle) and a hole (empty circle). The large reverse bias voltage produces an electric field in the junction that accelerates the electrons toward the n-doped side. When an electron collides with an atom, its kinetic energy can be used to excite an additional electron into the conduction band. Inset: diagram of a reverse biased p-n junction[5].

electrons that are accelerated by the field, and the avalanche process continues, so that a single photon can produce a small but measurable pulse of current. Fig. 2.2 illustrates this process. This mode of operation is called the Geiger mode, in reference to the great similarity with the behavior of Geiger-Muller tubes.

In the diagram above (Fig. 2.1) a SPAD basic scheme is shown. In series with the SPAD detector there is a resistor. When the current increases after an avalanche multiplication process, the voltage drop on the resistor increases and consequently the bias voltage on the SPAD drops below V_{bd} causing the avalanche current to turn off. The voltage on the resistor shows a pulse which can produce a squared pulse which is the indication that a photon has triggered the process. The SPAD in practice works as a detector of single photons and the measurement of the intensity of light that hits the device is made through the frequency of the pulses produced (count rate)[1]. Hence the need to shorten the duration of the single pulse as much as possible in order to allow higher counting frequencies.

2.Dark Counts

Photon interactions are not the only way to cause an avalanche. Thermal energy can excite electrons to the conduction band as well, and commercial avalanche photodiodes are often cooled below room temperature to reduce the number of 'dark counts' avalanches that are not initiated by photons. This dark count rate is dependent upon the construction of the photodiode and the bias voltage as well[3]. The avalanche does not continue indefinitely unless the bias voltage is too large or the quenching resistor in series with the photodiode is too small.

3.Dead Time

The avalanche does not continue indefinitely unless the bias voltage is too large or the quenching resistor in series with the photodiode is too small. The time for the pulse to be quenched determines the 'dead time' of the detector - the time during which it is impossible to detect the arrival of another photon.

4.Afterpulsing

Afterpulsing is the phenomenon by which one avalanche begets a second (or more) avalanche. These avalanches are indistinguishable from an avalanche caused by another photon, and leads to an over count of the number of photons. The SPAD device shows the phenomenon of Afterpulsing. During an avalanche, charges may be trapped inside deep levels and then released afterward. This causes additional correlated avalanches that are described by the probability of After-pulsing occurrence[1]. While the avalanche is occurring, current is flowing through the junction and, via Joule heating, causing the temperature of the junction to increase. This increased temperature enhances the probability that after the avalanche stops, another one will begin due to thermal excitation. This is one of the main causes of afterpulsing.[7].

2.1.2 LED Diode used as SPAD device

SPAD devices are quite expensive and often require rather high operating voltages (100-200V), however there is a low-cost alternative suitable for use for educational purposes to carry out some experiments : it is the LED! LEDs in fact have a structure similar to SPAD and, suitably polarized, they can also function as a single photon detector.
Here a gallium phosphide-arsenide (GaAsP) LED with red light emission is used as SPAD. This is a rather common type of LED. However, not all LEDs work the same, it was necessary to do some tests before finding a suitable model[5]. A simple

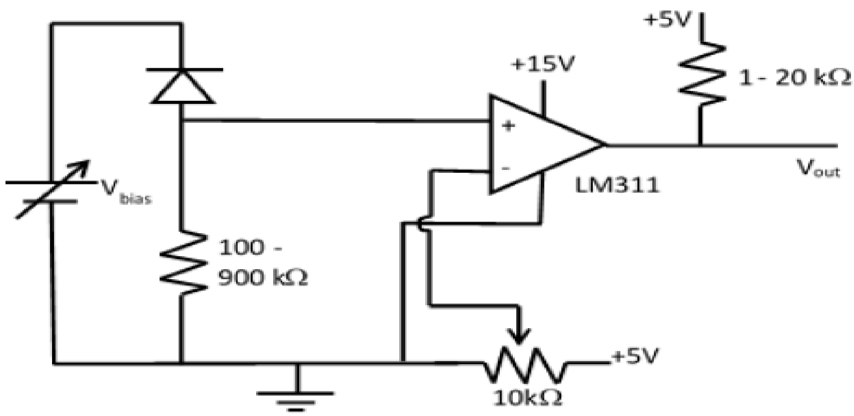


Figure 2.3: Circuit diagram for reverse-biasing an LED and using an op-amp comparator (LM311) to produce a 5 V output pulse. Vbias is typically around 24 V for the AND114R LEDs [1].

passively-quenched, reverse-biased LED circuit is shown in Fig. 4. When no current is flowing, no voltage drop occurs across the quenching resistor in series with the LED, but when an avalanche occurs the voltage on the non-grounded side will increase, typically in the range of 100's of mV. To detect these voltage pulses with a computer it is convenient to add a discriminator to the output. Here, an inexpensive LM311 op-amp comparator is used for this purpose. The output will remain at ground until a voltage pulse at the non-inverting input (+) of the op-amp rises above the voltage at the inverting input (-). The 'pull-up' resistor on the output sets the amplitude of the output pulses to 5 V[1]. The voltage at the inverting input is controlled by the potentiometer between the inverting input and the 5 V supply.

This basic discriminator circuit is highly useful in getting students to understand the triggering on an oscilloscope. By monitoring the voltage at the two inputs and the output of the op-amp, students can visually see that 5 V output pulses only occur when the original pulses cross the voltage threshold set by the potentiometer[2]. This forces students to confront the idea that they are discarding some events based on the discriminator level.

Finally, the TTL-level pulses produced can be detected by any number of devices. We can use oscilloscopes, LabView DAQs, Vernier LabQuests, and TeachSpin's Pulse Counter/Interval Timer. With these devices, tests of the statistical properties of the arrival of photons at the detector are possible[3].

2.1.3 Process and types of Quenching

Passive Quenching

The simplest configuration to use a SPAD is that which uses a resistance in series with the device in order to turn off the discharge current. This configuration is known as passive quenching. In practice, two resistors are used, one for bias and one for quenching, as shown in the diagram below.

When the current following the triggering of the avalanche begins, the resistances limit the discharge current and, as the current increases, decrease the voltage on the SPAD to levels below the V_{bd} value, with the effect of turning off the discharge. The quenching resistance value is between $10K\Omega$ and $100K\Omega$, values lower than $10K\Omega$ do not allow to turn off the discharge, while values higher than $100K\Omega$ lengthen the switch-off times[5]. In fact, it should be considered that the shutdown of the discharge follows an exponential curve guided by the time constant RC, where R is the quenching resistance and C is the capacity of the SPAD junction (in our case of the LED). In the layout below a typical impulse is obtained with our LED, with a 39KΩ quenching resistance, from the impulse shape it is possible to estimate a junction capacity of about 150 pF.

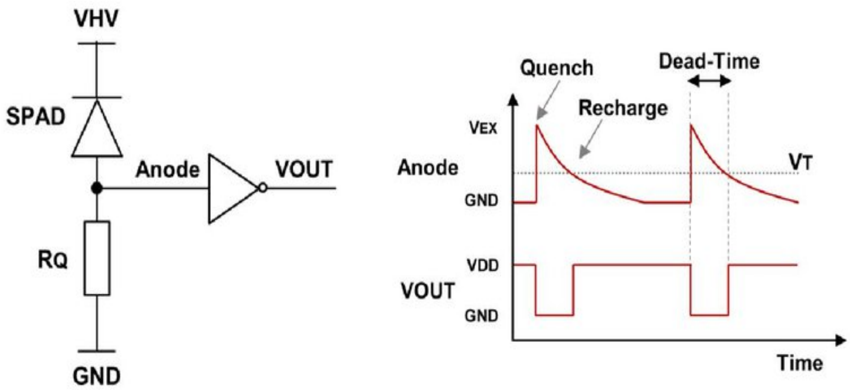


Figure 2.4: SPAD Passive Quenching circuit diagram[4].

Active Quenching

For passive quenching it is not possible to reduce the duration of the pulse beyond a certain value. Reducing the quenching resistor has the effect of reducing the pulse duration, but beyond a certain value it no longer has the effect of turning off the discharge because the voltage drop on the resistor becomes too small.

The alternative is to adopt a different technique, known as active quenching.

In active quenching an element is used to quickly detect the discharge, in practice an operational amplifier used as a comparator. the signal produced by the amplifier is used to drive the gate of a CMOS which, when in conduction, resets the polarization voltage of the SPAD and thus turns off the discharge. The configuration adopted is shown in the following diagram[6]. With the active quenching technique it is possible to significantly reduce the duration of the pulses in order to increase the counting rate. The traces shown below show the impulses on the load resistor, in yellow, and the impulses produced by the comparator, in blue. Active Quenching improves control over duration of dead-time and detection uniformity[6].

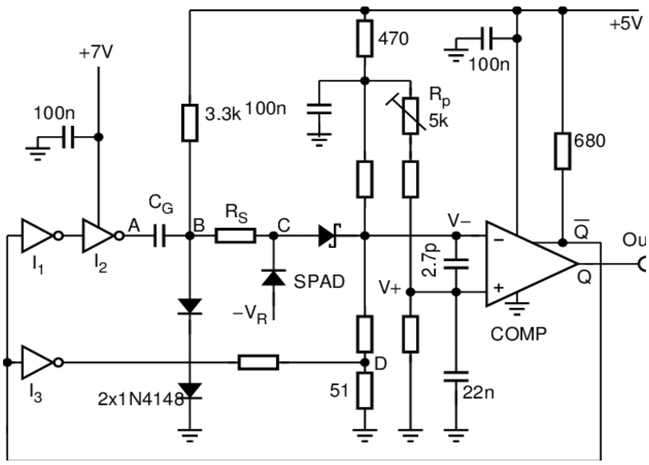


Figure 2.5: SPAD active Quenching circuit diagram[4].

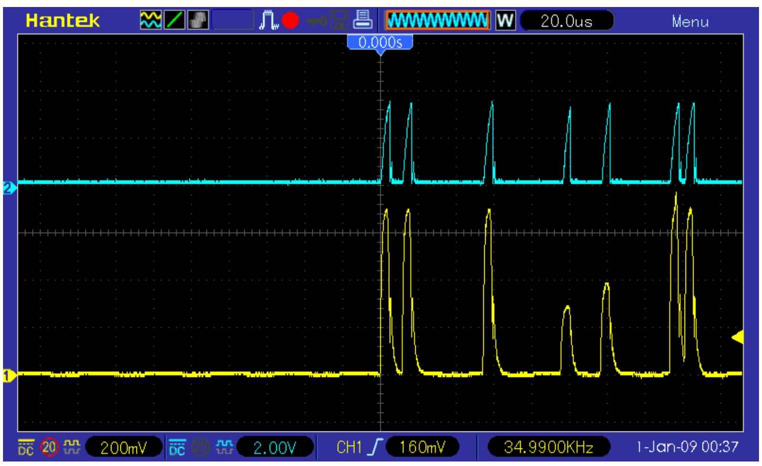


Figure 2.6: Comparison between output of active and passive quenching[4].

2.1.4 Competition and Advantage of SPADs

Compared to Photomultiplier Tubes

SPADs have (compare to PM Tube)-

- Higher sensitivity over wider spectral range.
- Better time resolution.
- No need to be cooled for near infra-red spectrum.
- Less bulk.
- More stability - As PM tube is more sensitive to mechanical vibration and Electromagnetic noise, it need proper internal structure. So it becomes more costly than SPADs.

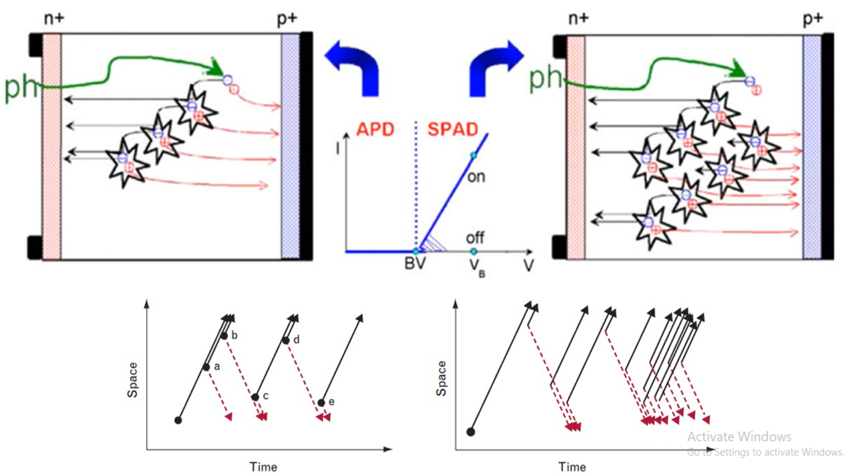


Figure 2.7: Comparison between APDs and SPADs[4].

Compared to Avalanche Photodiodes

For APDs

- Biased below breakdown voltage.
- It works in Linear mode.
- Not divergent, current is proportional to light received.
- It has low detection efficiency.
- It has high active areas.
- It has high active areas.
- Reset when the light source turns off.

For SPADs

- Biased above breakdown voltage.
- It works in Geiger mode.
- Divergent current grows exponentially
- Higher detection efficiency.
- It has Smaller active areas.
- Less thermally generated dark counts.
- It resets through quenching.

2.2 Single Photon Counting Statistics

Under the proper conditions, the arrival of photons at a detector should occur at random, uncorrelated times. This means that photon detection should exhibit the same statistical behavior as radioactive decay[5]. A Poisson distribution is expected to describe the number of events counted in a given interval of time:

$$p(x, \mu) = \frac{\mu^x e^{-\mu}}{x!} \tag{2.1}$$

where p is the probability of measuring x events in a specified interval if μ is the average number of events found during that interval. An exponential distribution is expected to describe the time intervals between subsequent photon arrivals:

$$p(t)dt = re^{-rt}dt \tag{2.2}$$

where p(t)dt is the probability that one random event is followed by another event during a window of time dt and at a time t after the previous event, with r being the average rate of events.

It is common to use radioactive decay measurements to examine both of those distributions. In fact, the measurement of the distribution of time between events is an excellent way to quickly determine the dead time of a detection system, because the dead time leads to predictable deviations from the expected p(t) at short time intervals.

The arrival of photons at a detector is random, which means that its behaviour should be the same as that of radioactive decay. This implies that for a low mean, the distribution is poisson whereas for a high mean value, it should transition to gaussian. The gaussian probability distribution looks something like this:

$$p(x, s, \mu, \sigma) = se^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{2.3}$$

where s, μ and σ are fitting parameters with μ as mean of the distribution. On the other hand, for smaller value of mu, the distribution is poisson given by: equation(2.1). In order to depict the transition from poisson to gaussian, take $x = \mu(1+\epsilon)$

where ϵ is very small. Using Sterling's formula to approximate the value of $x!$ as $\sqrt{2\pi x}e^{-x}x^x$ as $x \to \infty$The condition of a large mean is thus, necessary and plugging these values in Eq. (2.1), we get the new expression as

$$p(x) = \frac{\mu^{\mu(1+\epsilon)}e^{-\mu}}{\sqrt{2\pi\mu(1+\epsilon)}e^{-\mu(1+\epsilon)}(\mu(1+\epsilon))^{\mu(1+\epsilon)}} \tag{2.4}$$
$$= \frac{e^{\mu\epsilon}(1+\epsilon)^{-\mu(1+\epsilon)-\frac{1}{2}}}{\sqrt{2\mu\pi}}$$
$$= \frac{e^{\frac{-(x-\mu)^2}{2\mu}}}{\sqrt{2\pi\mu}}$$

2.2.1 Dead Time

Dead time τ, as the name suggests, is the time after the absorption of photon during which the detector becomes dead, i.e., it is unable to detect any other photons during this time. In order to reduce afterpulsing, one can also deliberately lengthen the dead time which can be done by controlling the value of the quenching resistor and the bias voltage.Dead time is a common characteristic of detectors that record discrete events.

If the observed counts are taken to be N and the actual be N_0 with the dead time τ and time period T, the relation between N_0 and N is given by the equation

$$N = \frac{N_0}{1 - \frac{\tau}{T}} \tag{2.5}$$

However, instead of directly using this equation, we use an equation which connects the dead time directly to the distribution of dead time. This equation is given by

$$p(t) = Ne^{-N(t-\tau)} = Ne^{-Nt+\alpha} \tag{2.6}$$

where$\alpha = N\tau$. We calculate the dead through fitting our distribution, thus obtaining the actual counts and value of α.

Chapter 3

Experimental

3.1 Apparatus

- AND114R LED, LM311 Comparator
- Multiple Power Supply , Oscilloscope
- Cables and Connectors , Arduino UNO board
- 100-900 $K\Omega$ resistors , 1-20 $K\Omega$ resistors
- Breadboard , 10 $K\Omega$ potentiometer
- different types of light source (Stray photon, Diode and He-Ne Laser)

3.1.1 Arduino UNO

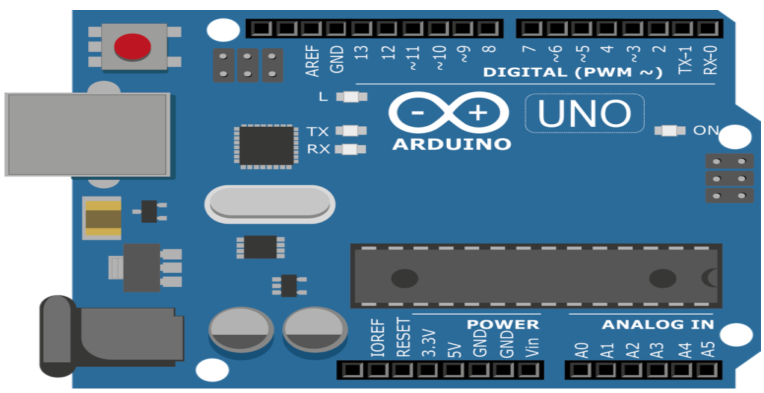


Figure 3.1: Arduino UNO Board[4].

Arduino/Genuino Uno is a microcontroller board based on the ATmega328P (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller; simply we can connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. "Uno" means one in Italian and was chosen to mark the release of Arduino Software (IDE) 1.0. The Uno board and version 1.0 of Arduino Software (IDE) were the reference versions of Arduino, now evolved to newer releases. The Uno board is the first in a series of USB Arduino boards, and the reference model for the Arduino platform; for an extensive list of current, past or outdated boards see the Arduino index of boards.In this experiment, we have used the Arduino UNO board for the purpose of counting pulses and time between them.

```
int pin = 2;
unsigned long period;
unsigned long timeRes = 100;
int numPulses = 0;
unsigned long timeStart = millis();

void setup() {
  Serial.begin(9600);
  pinMode(pin, INPUT);
}

void loop() {
  if (millis() - timeStart >= timeRes) {
    Serial.println(numPulses);
    numPulses = 0;
    timeStart = timeStart + timeRes;
  }
  period = pulseIn(pin, HIGH);
  if (period > 0) {
    numPulses++;
  }
}
```

Figure 3.2: The above C code was used for Arduino to count the number of pulses.

```
int pin = 2;
unsigned long duration;

void setup() {
  Serial.begin(9600);
  pinMode(pin, INPUT);
}

void loop() {
  duration = pulseIn(pin, LOW);
  Serial.println(duration);
}
```

Figure 3.3: For counting the time difference between two pulses, the above C code was used in Arduino.

3.2 Experimental Set Up

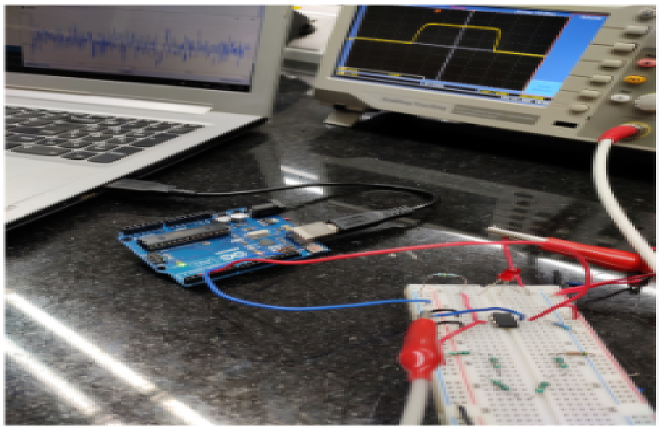


Figure 3.4: Experimental Set Up for Open Source or Stray Photon Source

Figure 3.5: Experimental Set Up for He-Ne Laser

The purpose of this experiment is to measure P (t) for several coherent and thermal light sources. Three different types of photon sources are used for this experiment, those are- (i) Open source or stay photon source for a open lit room, (ii) Diode Laser source, (iii) He-Ne Laser Source. These three sources have different mechanism for photon generation. So their corresponding photon counting statistics are expected to be different. For a coherent source (lasers) follows Poissonian photon distribution statistics. But, The electromagnetic radiation emitted by a thermal light is considered like a black-body radiation. It is governed by the laws of statistical mechanics concerning an enclosed cavity at a temperature T. Thermal light follows either Super-Poissonian or Gaussian photon distibution. The coherence length of red He-Ne laser is more than green gas laser, so it is expected that red He-Ne laser will show better poissonian distribution.

3.2.1 Experimental Procedure

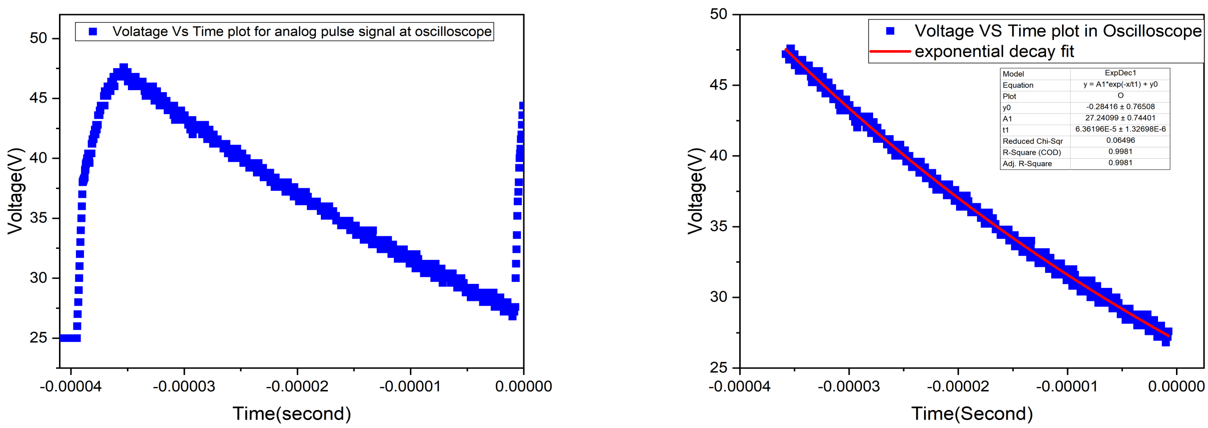
In this experiment, a Gallium Phosphide [7] LED (Purdy Electronics Corp., AND114R) is used as a very inexpensive photodiode. In part because it was manufactured to produce rather than detect light, the LED has a very low quantum efficiency. It is found that this and the AND113 LEDs to work as Geiger mode photodiodes at $V_{bias} < 30V$.A simple passively-quenched, reverse-biased LED circuit is shown on the left side of Fig. 3.4 and 3.5. When no current is flowing, no voltage drop occurs across the quenching resistor in series with the LED, but when an avalanche occurs the voltage on the non-grounded side will increase, typically in the range of 100's of mV.To detect these voltage pulses with a computer it is convenient to add a discriminator to the output. Here, an inexpensive LM311 op-amp comparator is used for this purpose. The output will remain at ground until a voltage pulse at the non-inverting input (+) of the op-amp rises above the voltage at the inverting input (-).The 'pull-up' resistor on the output sets the amplitude of the output pulses to 5 V.The voltage at the inverting input is controlled by the potentiometer between the inverting input and the 5 V supply.By monitoring the voltage at the two inputs and the output of the op-amp, we can visually see that 5 V output pulses only occur when the original pulses cross the voltage threshold set by the potentiometer. Finally, the TTL-level pulses produced can be detected by any number of devices. We have used oscilloscopes, Arduino uno board and software to test the statistical properties of the arrival of photons at the detector.

Chapter 4

Observation and Result

4.1 Open source or Stray Photon Source

4.1.1 Input and Output signal



(a)..(b)

Figure 4.1: (a)Input Signal at Oscilloscope, (b)Fitted curve of the Input signal

Above is the figure that shows the Input signal at Oscilloscope. This signal is mainly concerned with the circuit before placing the discriminator. This figure shows a exponential trend which clearly gives us the idea that the first part of the circuit is nothing but a R-C circuit. From fitting this curve we can know the value of time constant of the circuit which characterizes the Dead time of our detector. Thus, Dead time here is a controlled parameter up-till certain limit and can be minimized by choosing the smallest possible Quenching Resistance. The Fitting function chosen is given as $Y = y0 + Ae^{(-t/R)}$ So here here time constant$(\tau = RC)$=63.61 μS. which give the value of Capacitance for LED, C = 0.1115nF as we have used $570k\Omega$ quenching resistor in series with the LED. Figure 4.2 shows the output pulse at Oscilloscope after connecting the discriminator part to the circuit. This pulse act as a Digital signal unlike the input signal which is an Analog signal and hence act as a better signal for counting the number of pulses. Here in Fig. 4.3 input pulse at the oscilloscope is shown for two different resistor and it is shown that the detection time increases with increasing resistance so the pulse become wider.

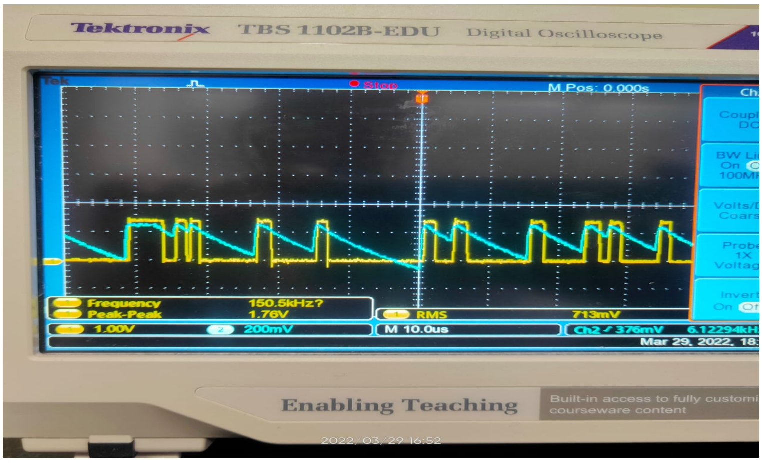
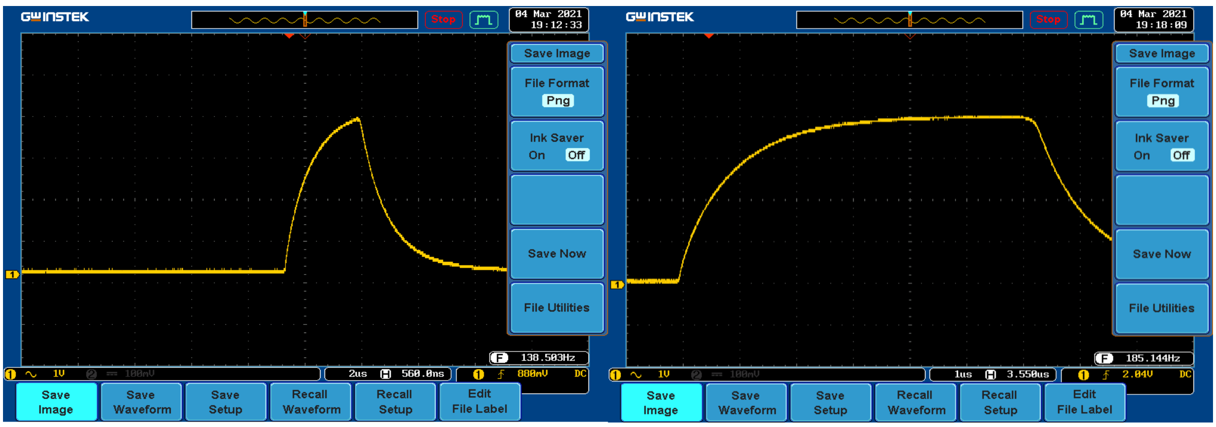


Figure 4.2: Analog and digital output together at oscilloscope

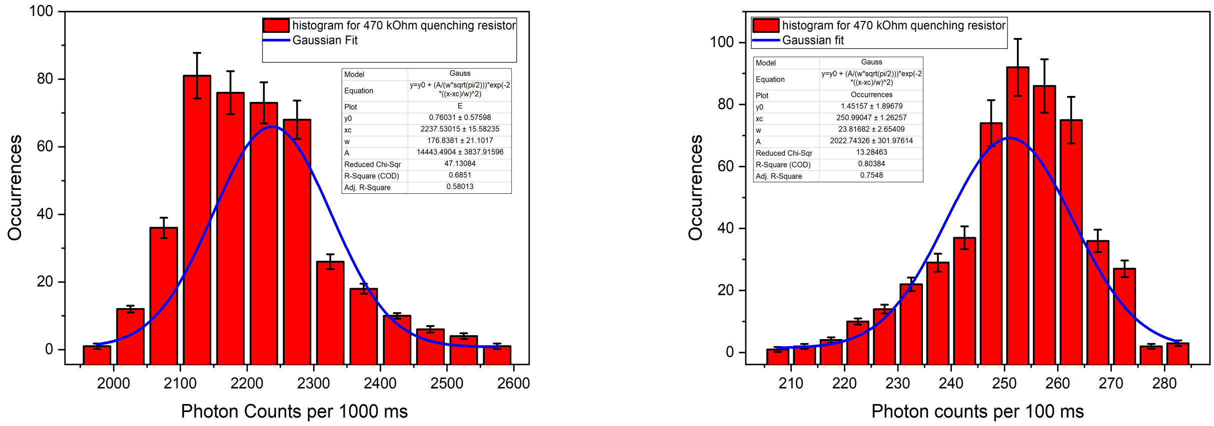


(a)...(b)

Figure 4.3: analog input pulse at oscilloscope for (a) 470 $k\Omega$ quenching resistance (b) 830 $k\Omega$ quenching resistance

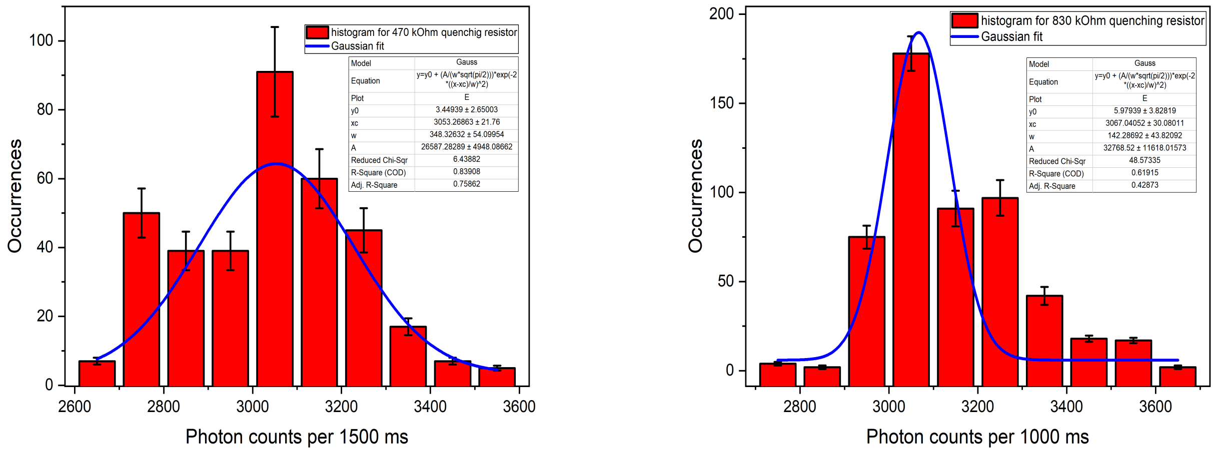
4.1.2 Counting Statistics

Figure 4.4,4.5,4.6,4.7,4.8 illustrates typical distributions of the number of counts per interval compared to Gaussian distributions with the same mean and standard deviation as the data. The data (using ambient room light as the source) is reasonably well described by a Gaussian distribution for all three intervals(100 ms, 1000ms, 1500 ms) and three different quenching resistor($470k\Omega$,$530k\Omega$,$830k\Omega$). The noticeable discrepancy is due mostly to afterpulsing, which causes the distribution's variance to not be equal to its mean as expected for Poisson distributions. As expected, the Gaussian agrees very well when the average increases and the distribution becomes symmetric. The error bars represent the square root of the values.



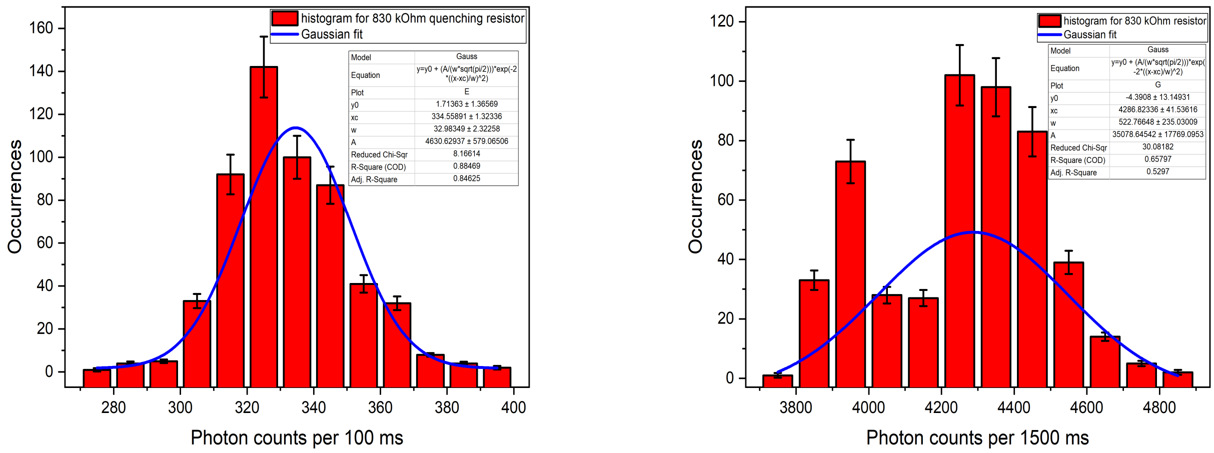
(a)...(b)

Figure 4.4: Pulse distribution for open source with 470 $k\Omega$ quenching resistors per (a) 1000 ms (b) 100 ms time interval



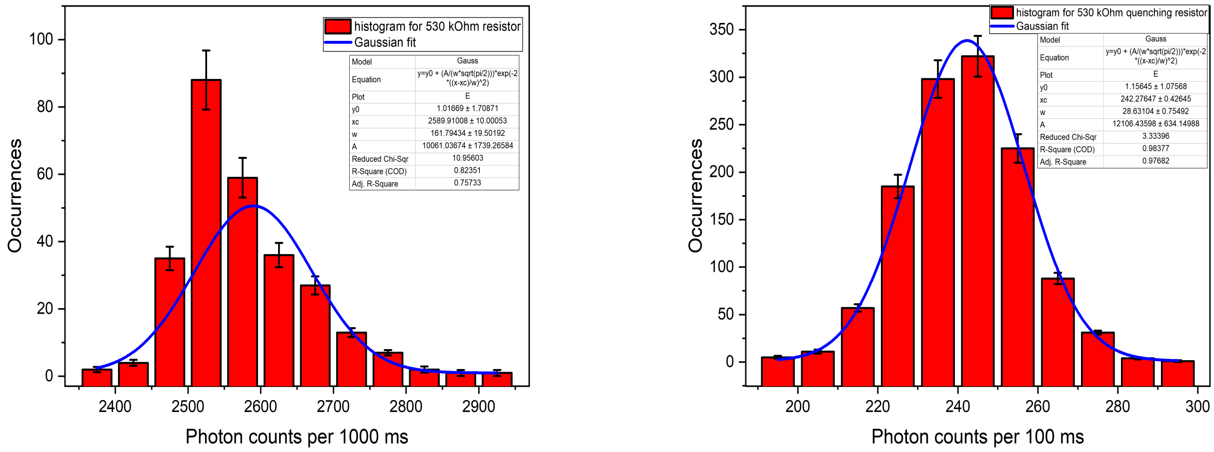
(a)..(b)

Figure 4.5: Pulse distribution for open source (a) with 470 $k\Omega$ quenching resistors per 1500 ms (b)with 830 $k\Omega$ quenching resistors per 1000 ms time interval



(a)..(b)

Figure 4.6: Pulse distribution for open source with 830 $k\Omega$ quenching resistors per (a) 1000 ms (b) 1500 ms time interval



(a)...(b)

Figure 4.7: Pulse distribution for open source with 530 $k\Omega$ quenching resistors per (a) 1000 ms (b) 100 ms time interval

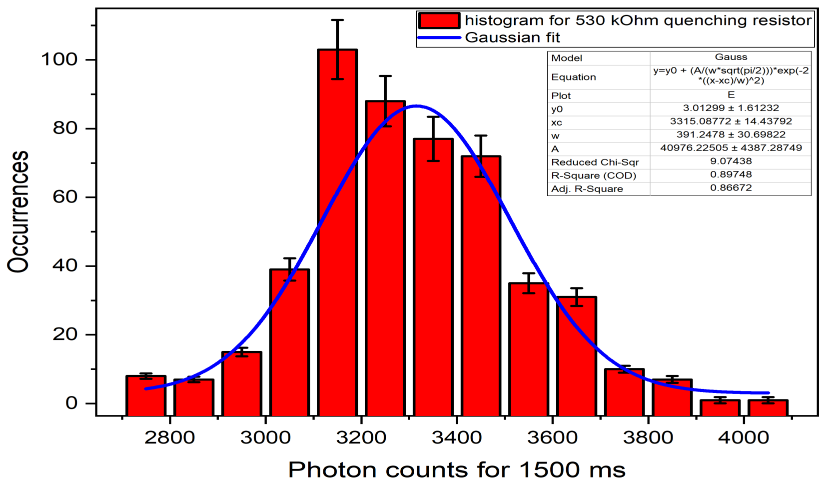


Figure 4.8: Pulse distribution for open source with 530 $k\Omega$quenching resistors per 1500 ms time interval

4.1.3 Dead time for open source

Figure 4.9 shows plot for the data of the time between pulses with $470k\Omega$ quenching resistor.Histogram of the time between events (pulses) showing the expected exponential behavior after a large peak due to afterpulsing. Those correlated pulses are produced at very short intervals after a 'real' pulse. The dead time of this detection system can be controlled by the choice of the quenching resistor in series with the LED. From Figure 2.6, we get the the dead time as $\tau = \frac{\alpha}{N} = \frac{14.1}{\frac{1}{39.41}} = 555.681\mu S$

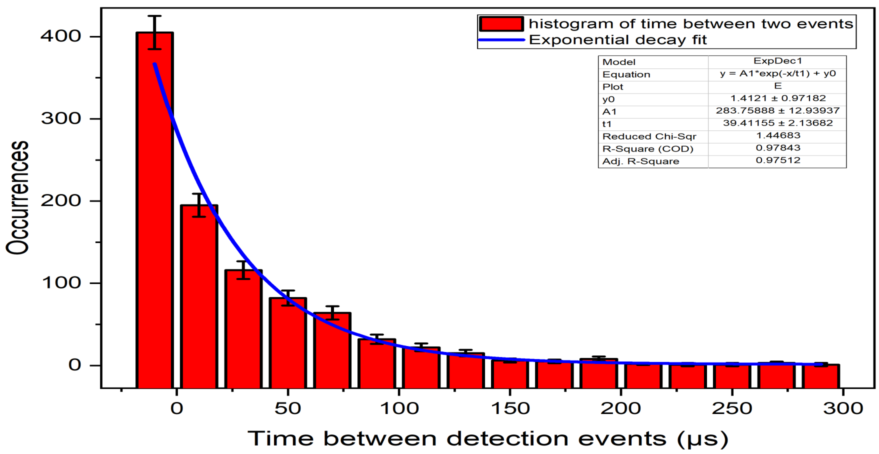


Figure 4.9: Time between pulses for quenching resistor $470k\Omega$

4.2 Diode Laser Source

A green diode laser is used at dark room as a photon source. The photon distributions for three different quenching resistor($470k\Omega$,$570k\Omega$,$830k\Omega$) at two different time interval(100 ms, 250 ms) are shown in Fig. 4.11,4.12,4.13. As diode laser is a coherent source it is expected to get Poisson distribution but most of the plots converging with Gaussian distribution because for all time interval more than or near 100 photons are detected. So most of the cases have large mean value and it transition to Gaussian.

But we have taken a data for 10ms to get less photon count and it's converging to Poisson distribution Fig. 4.10. The correlation matrix for this Poisson distribution is also shown below. The off-diagonal terms are positive and near to 1 and all diagonal terms are 1 so this suggests the plot is converging to Poisson distribution.

$$\begin{bmatrix} 1 & 0.083 & 0.60 \\ 0.083 & 1 & 0.188 \\ 0.60 & 0.188 & 1 \end{bmatrix}$$

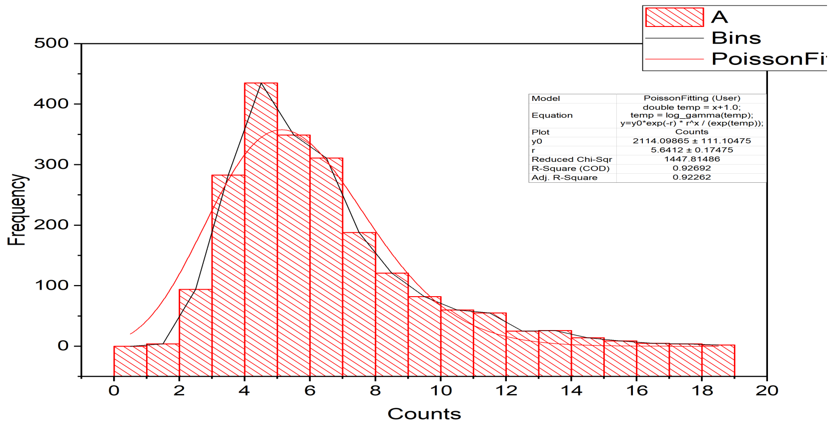
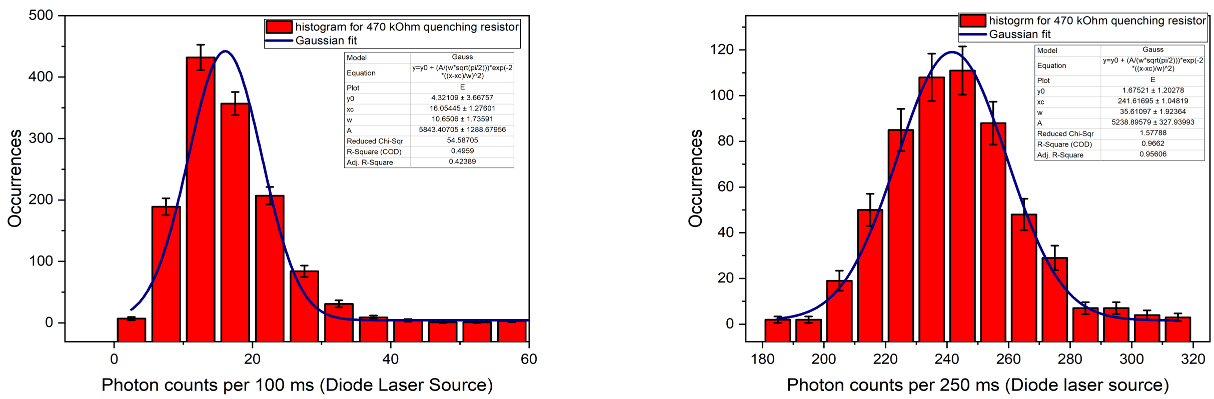
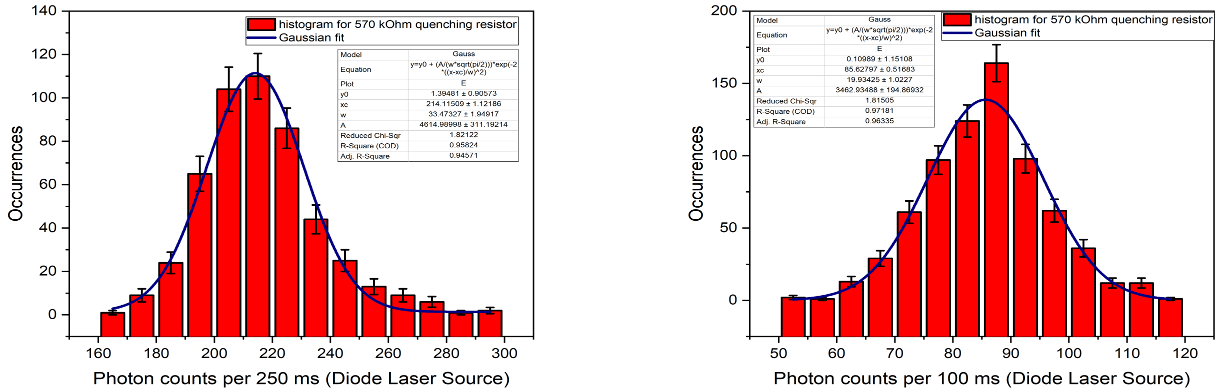


Figure 4.10: Pulse distribution for Diode Laser source with 830 $k\Omega$ quenching resistors per 10 ms time interval



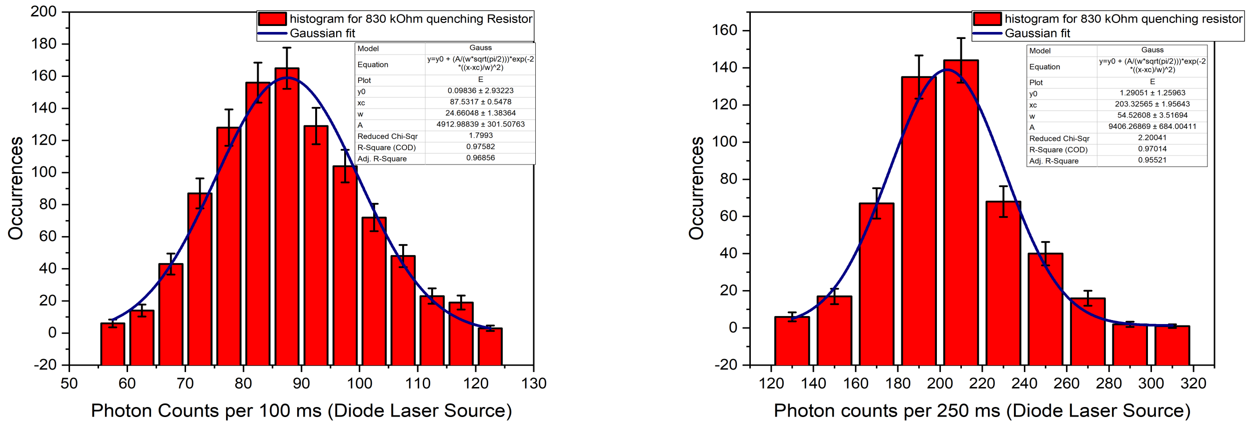
(a)..(b)

Figure 4.11: Pulse distribution for Diode Laser source with 470 $k\Omega$ quenching resistors per (a) 100 ms (b) 250 ms time interval



(a)..(b)

Figure 4.12: Pulse distribution for open source with 570 $k\Omega$ quenching resistors per (a) 250 ms (b) 100 ms time interval



(a)..(b)

Figure 4.13: Pulse distribution for open source with 830 $k\Omega$ quenching resistors per (a) 100 ms (b) 250 ms time interval

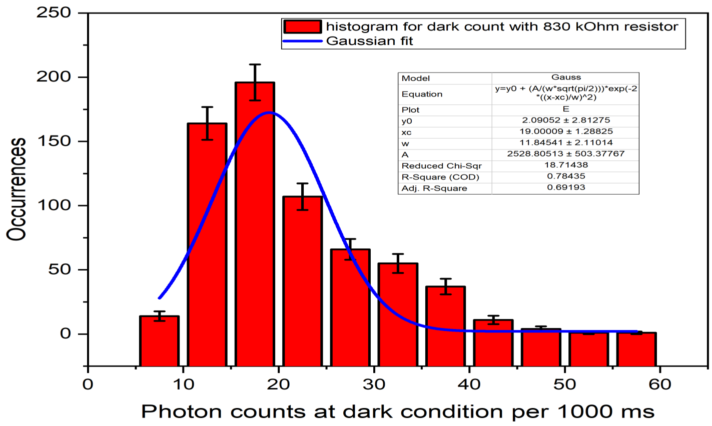


Figure 4.14: Pulse distribution for dark count with 830 $k\Omega$ quenching resistors per 1000 ms time interval

4.3 He-Ne Laser Source

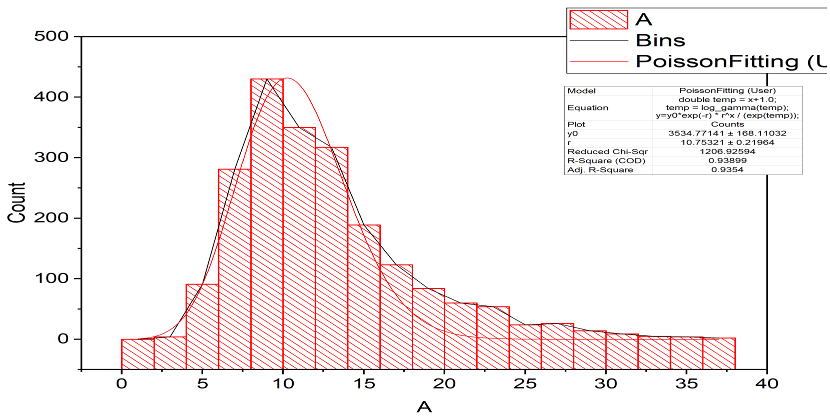
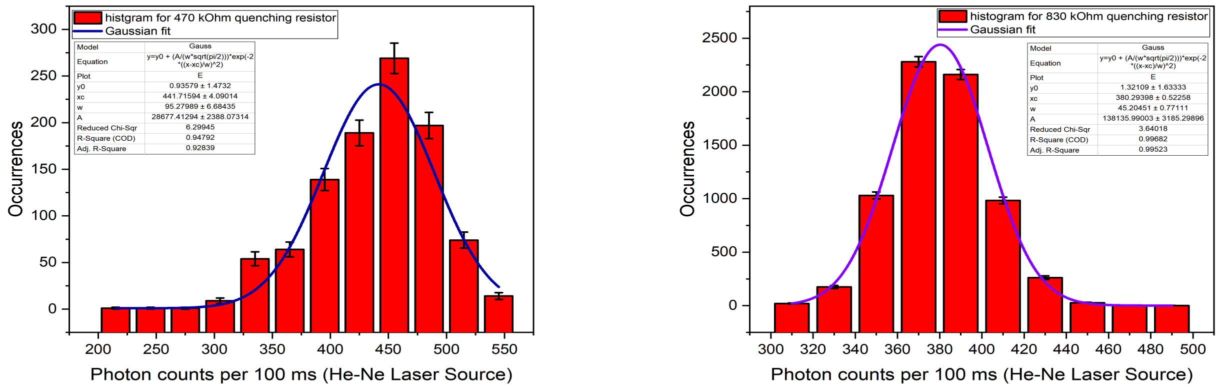


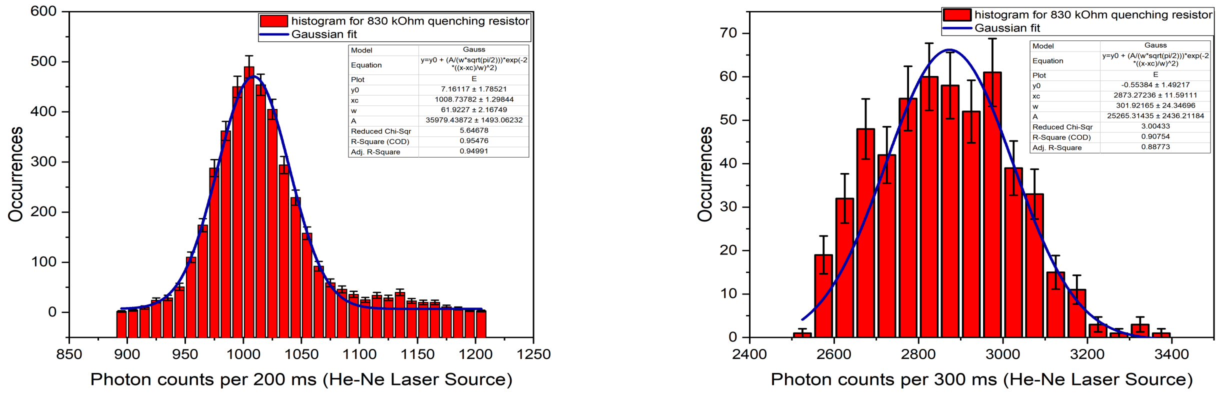
Figure 4.15: Pulse distribution for He-Ne Laser source with 830 $k\Omega$ quenching resistors per 20 ms time interval

A He-Ne laser is used at dark room as a photon source. The photon distributions for two different quenching resistor($470k\Omega$, $830k\Omega$) at different intervals are shown in Fig. 4.16,4.17.



(a)..(b)

Figure 4.16: Pulse distribution for He-Ne Laser source per 100 ms time interval with (a) 470 $k\Omega$ quenching resistor (b) 830 $k\Omega$ quenching resistor



(a)..(b)

Figure 4.17: Pulse distribution for Diode Laser source with 830 $k\Omega$ quenching resistors per (a) 200 ms (b) 300 ms time interval

As He-Ne laser is a coherent source it is expected to get Poisson distribution but most of the plots converging with Gaussian distribution because for all time interval more than or near 100 photons are detected. So most of the cases have large mean value and it transition to Gaussian. But we have taken a data for 20ms to get less photon count and it's converging to Poisson distribution Fig. 4.15. The correlation matrix for this Poisson distribution is also shown below. The off-diagonal terms are positive and near to 1 and all diagonal terms are 1 so this suggests the plot is converging to Poisson distribution. $\begin{bmatrix} 1 & 0.045 & 0.49 \\ 0.045 & 1 & 0.082 \\ 0.49 & 0.082 & 1 \end{bmatrix}$

4.4 Measurement Error and Sources of Error

4.4.1 Sources of Error

- While taking the counts with both the laser source, we have to make sure that the LED is not taking any sort of photons from other sources.
- The experiment should be done in a cool place to ensure that there is no after-pulsing due to thermal energy.
- After constructing the circuits, we have to choose a time interval and measure the number of counts per interval over many intervals. Then we should correct the data for the background signal (dark counts at same situation).
- Due to the low efficiency of the detector, it is not able distinguish between low number of photons falling at the Detector. The reason of the plots not following a Poisson distribution for coherent sources can be attributed to the Afterpulsing effects and the background noise present in the form of Dark counts as well as the large mean value of photon count for most of the cases.

4.4.2 Procedure to measure error:

The following procedure is followed to measure error for photon distribution histogram plots. All the relevant values along with their errors is given in the inset of each plot till appropriate decimal place.

- For the entire valid data set, we have calculated the mean, variance σ^2, standard deviation σ, and the standard deviation of the mean, $\sigma_x = \frac{\sigma}{\sqrt{N}}$.
- We have Calculated the average absolute deviation $d' =< |x - \bar{x}| >$, for the whole valid set of readings. If the distribution is Gaussian, we should find that $d' = \sqrt{\frac{2}{\pi}\sigma}$. We have calculated d' for our data set and seen if it agrees with this expected relationship.
- We have made a histogram of the data, with error bars. Then we have checked it seem like a Gaussian distribution or not.
- Then we have reported our mean value and its uncertainty with the correct number of significant digits.

4.5 Limitation and Trade off of SPAD

- **After-pulsing** - During an avalanche, charges may be trapped inside deep levels and then released afterward. This causes additional correlated avalanches that are described by the probability of After-pulsing occurrence.
- **Dark Count** - Thermal energy can also excite electrons to the conduction band , and commercial avalanche photodiodes are often cooled below room temperature to educe the number of 'dark counts' – avalanches that are not initiated by photons. This dark count rate is dependent upon the construction of the photodiode and the bias voltage as well.

- Requires strict control of contamination- Impurities and crystal defects cause significant after-pulsing.
- Breakdown voltage is strongly dependent on junction temperature.
- Trade off between efficiency and Jitter. If we made thick depletion region then absorption efficiency of photon will increase (good) but it will increase the timing jitter. (bad)
- Lower operating temperature leads to lower dark count(good) , but increases the probability of after pulsing (bad).

4.6 Applications and Advantages

4.6.1 Applications

- LIDAR (3D ranging and sensing).
- Photon correlation and ultrasensitive spectroscopy.
- Fluorescence lifetime measurements.
- Medical imaging.
- Any applications where light needs to be focused on a small region.

4.6.2 Advantages

- Simple in construction.
- Small dimensions.
- Low power consumption.
- Sensitive enough to sense single photon

- Increase photon detection efficiency.
- Wider spectral range of operation.

4.7 Conclusion

- We first explored the use of a LED as a SPAD in a passive circuit. This passive design introduced a variety of key considerations for detectors: max count rate, dark counts, afterpulsing, bias voltage. We found that a LED canbe used effectively as a SPAD, but was limited to sub megahertz count rates.
- This experimental system provides another inexpensive means by which we can investigate the statistics of ran- dom events, learn the operation of avalanche photodiodes, and learn the basics of discriminator circuits.
- The pulse width of the signal increases as a function of quenching resistance.
- The time interval between successive events follows an exponential distribution. The counting statistics for open source are seen to obey a Gaussian distribution which is also as predicted from theory. For coherent laser sources at small time interval like 10 ms, 20 ms poisson distribution is observed.
- The mean photon number varies linearly with the count- ing time. This is to be expected as for a constant flux, the number of photons detected should increase as the detection time is increased.
- The dark count distribution for a certain quenching resistor and at a fixed time interval is observed and plotted. As expected it is also converging to Gaussian distribution.

- From the oscilloscope input analog pulse data, Voltage Vs time is plotted from there the time constant,RC and the capacitance of the LED is found out.

- The time difference between pulses for open photon source is plotted for 830 $k\Omega$ quenching resistor with 24.5 V reverse bias voltage and it is fitted to an exponential decay function. From this plot we have calculated the dead of the detector at that bias voltage and quenching resistance.

- It should be noted that the parameter space for experimentation and analysis is quite large. In this work, we focused on improving the maximum count rate for practical applications. However, further study may include a better characterization of the quantum efficiency of LEDs, active cooling to reduce dark counts or fine-tuning of the electronic components to reduce non-linearities. Also, an actively quenched circuit can help in reducing the Dead time by significant amount. Hence, this may be a better option in order to recover a good statistics at low photon number.

References

4.7.1 Website

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4.7.2 Journals

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[7] P. Koczyk, P. Wiewior, and C. Radzewicz, Am. J.Phys. 64, 240 (1996)