Lab 2: Single Photon Interference and Quantum Eraser Experiments

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This lab is comprised of two experiments which demonstrate quantum phenomena: Young's double slit experiment and a quantum eraser experiment with a Mach-Zehnder interferometer. In both experiments, a He-Ne laser beam is sent through neutral density filters to obtain single photons per meter level that can then be imaged with an electron-multiplying CCD camera (EMCCD). In the double slit experiment, we explore how different settings like exposure time, accumulation settings, the temperature of the EMCCD camera, and the number of optical density filters of the setup affect the quality of the interference pattern, and the contrast between the peaks and troughs from the interference. We see that higher exposure and accumulation settings correspond to better images, and more filters and higher temperature of the EM-CCD correspond to worse image quality as expected. In the Mach-Zehnder experiment, a linear polarizer placed after the interferometer is a quantum eraser that can be used to erase the "which path information". The results showed that the maximum visibility of fringes occurs at a polarizer angle of 45° (or its odd multiples), but when the polarizer was rotated to 0° or 90° so that the path of the photon can be determined. The results agree with the general pattern as we see minimums and maximums of visibility in these angles but the visibility is not as low as 0 for $0°, 90°$, etc or as high as 1 for $45°, 135°$, etc. However, the data does not quite fit the theoretical curve of $|\sin 2\theta|$ for visibility vs the polarizer angle.The possible reasons for this discrepancy, limitations of the system, the possible improvements are discussed in the result and conclusion sections.

CONTENTS

I. THEORY AND BACKGROUND

Light, as we know it, can behave like particles or like waves under different physical conditions. This is what is called the wave-particle duality of light. A review of physics will show that physicists argued for centuries over whether light was a particle or a wave. Isaac Newton's Theory of Light was a popular theory, but had to compete with Huygens and Fresnel's wave theory of light. Young's double slit experiment in showed that light must be a wave because it created a double slit interference pattern of a wave shown in figure 1. However, the wave model could not explain the ultraviolet catastrophe or the photo electric effect. The photoelectric effect was explained using the particle nature of light by Einstein. It was then hypothesized by De-Broglie that light and matter acts as both wave and particles, also referred to as the wave-particle duality. In this lab, this is what we explore through different experiments.

A. Double Slit Experiment

It is a classic experiment used to demonstrate the wave nature of the particle; in the basic version of this experiment, a coherent light source illuminates two parallel slits, and the light passing through the slits is observed on a screen behind the plate. The wave nature of light causes the light waves passing through the two slits to interfere. This produces bright and dark bands on the screen. The basic setup used for double slit experiment and the interference pattern observed is show in fig 1:

B. Mach Zehnder Interferometer

Another version of such particle duality demonstrations can be done using Mach Zehnder Interferometer, where the light is split using a polarizing beam spliter (PBS) instead. The setup of the Mach Zehnder Interferometer is shown below in fig 3.

In a Mach-Zehnder interferometer, the PBS splits laser beam into two paths: one horizontally polarized and the other vertically polarized. These are then recombined in a non-polarizing beam spliter

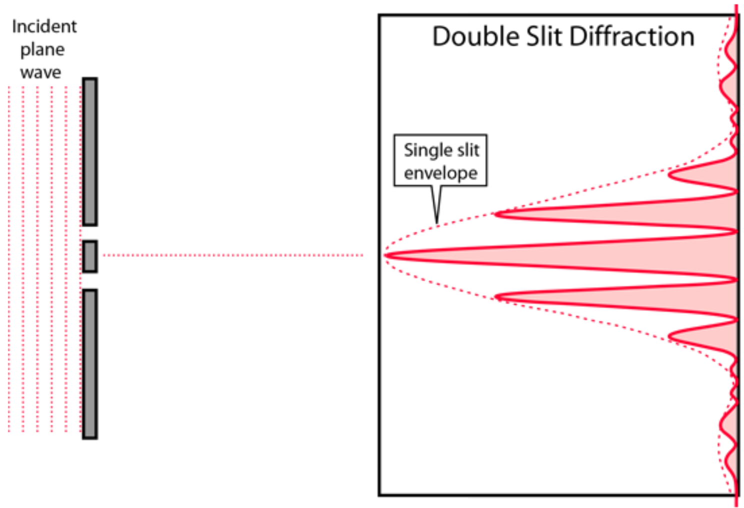

FIG. 1: A figure demonstrating the interference pattern in double slit experiment [1]

and passed through a linear polarizer. This linear polarizer acts as a quantum eraser, as it dictates if the “which path information” of the photons is accessible. For instance, when the polarizer is at 45 degrees the observer doesn't have ”which path” information, as both the polarizations are equally transmitted- thus we see clear interference fringes. However, for an orientation of 0 or 90 degrees we have perfect information about the path taken by the photons. Due to the which-path information, the interference is not seen. Photons instead act as particles, and there wave nature is lost. Thus setting the angle of the polarizer allows us to the control the state of the system, giving it the name of **quantum eraser**.

C. Visibility

Visibility quantifies the contrast of the fringes. It is given as:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

here I stands for the intensity of the incident wave.

When two beams combine and interfere, the visibility is also given as:

$$V = 2\frac{\sqrt{I_1 I_2}}{I_1 I_2} \tag{2}$$

Combing this with the knowledge that we have vertical and horizontal polarization in the waves, we get:

$$I_1 = I_0 \cos^2(\theta) \ , \ I_2 = I_0 \sin^2(\theta) \tag{3}$$

$$V = 2\frac{I_0\sqrt{\cos^2(\theta) \cdot \sin^2(\theta)}}{I_0\left(\cos^2(\theta) + \sin^2(\theta)\right)} \tag{4}$$

$$V = 2\sqrt{\cos^2(\theta) \cdot \sin^2(\theta)} \tag{5}$$

$$V = \sqrt{\sin^2(2\theta)} \tag{6}$$
$$V = |\sin(2\theta)| \tag{7}$$

Thus, according to Eq (7), we expect the maximum at the odd multiples of 45° and minimum at the even multiples.

D. Laser Attenuation

The observation of a single photon is at the core of this lab; we are not using single photon emitters and thus we need to attenuate laser to single photon levels.

For N_s = Number of photons per second, E = Energy per photon, P=Power, we have that:

$$N_s \cdot E = P \tag{8}$$
$$N_s = \frac{P}{E} = \frac{P}{hf} = \frac{P}{h \cdot (c/\lambda)} \tag{9}$$
$$N_s = \frac{P \cdot \lambda)}{h \cdot c} \tag{10}$$
$$N_s = \frac{P \cdot \lambda}{hc} \tag{11}$$

Now, the number of photons per meter is given by N_m below:

$$N_m = \frac{N_s}{c} = \frac{P \cdot \lambda}{hc}\frac{1}{c} \tag{12}$$
$$N_m = \frac{N_s}{c} = \frac{P \cdot \lambda}{hc^2} \tag{13}$$

ND filters are typically defined by their Optical Density (OD) which describes the amount of energy blocked by the filter. The number of optical filters to attenuate the laser is selected appropriately in the experiment so we are down to 1 photon per meter, the desired level. In our experiment the $N_m \approx 10^4$, so we used 4 OD filters to get to single photon per meter levels.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Experiment 1: Single Photon Interference in Young's Double Slit Interferometer

The aim of this lab was to explore the interference pattern and how the settings like temperature, exposure time, and accumulation number affect the quality of the data recorded. The lab was also designed on teaching how to use EM-CCD of Andor Technologies (Oxford Instruments). Using eq (13), for our setup 4 OD, meaning a laser attenuation by a factor of 10^{-4}, was selected to get to 1 photon per meter level.

The experimental setup of the experiment comprised of Electron Multiplying Charge-coupled device -camera (EMCCD) iXon DV-887, He-Ne laser (632.8 nm), Young's-double slit, Mach-Zehnder interferometer, linear polarizers, neutral density filters, iris apertures. FieldMaster with a detector to measure laser power, Solis software by Andor Technology.

As it can be seen from the schematic in fig 2, a He-Ne laser is used, using a lens (Lens A) it is focused through a spatial filter. Then we use Lens B that makes the beam wider so we can make sure that the laser passes through the ND filters. Finally the interference is watched through the EMCCD sensor at the end of the setup.

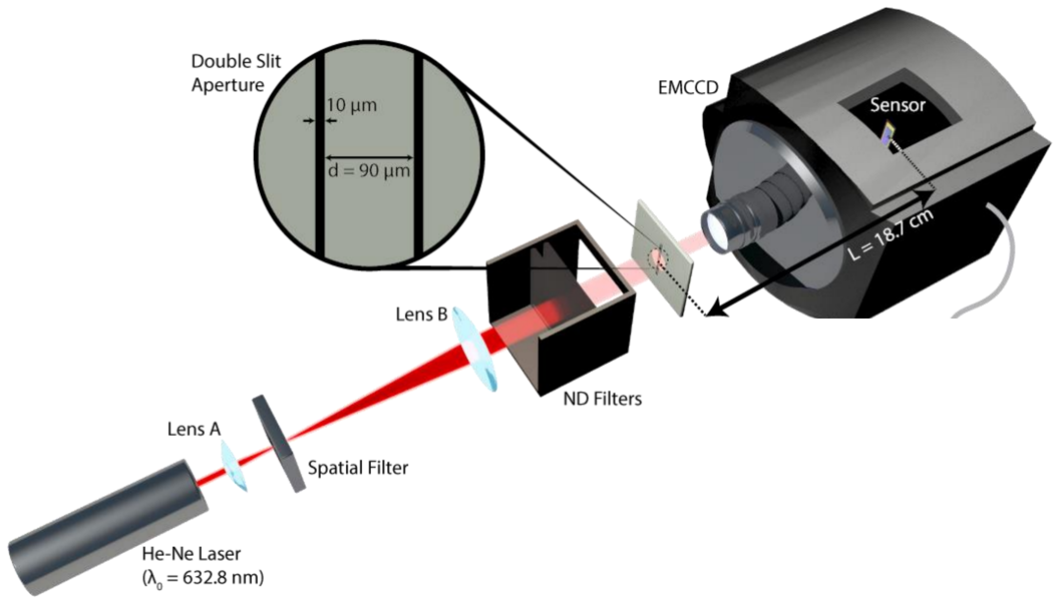

FIG. 2: Schematic of the double slit setup used in experiment 1 [2]

The laser and the setup was already aligned for use. Before starting the light were turned off. Then using the Field Master detector, we checked the power of the laser used in the experimental setup. This was done to make sure that the laser was properly aligned. We found the power to be $1.12\,\mu W$ which was in line with what was expected, indicating the setup was properly aligned. Then we start the cooler of the sensor to cool it town to -65 degrees C.

We start with 4 OD filters, then using the software (Solis), exposure times, we change the settings of capture type (single or accumulation), for the latter we varied the number of accumulation points. We record the pictures of the interference pattern for each of these configurations. Then we repeat the same process for 5 and 6 OD filters. For one of the 6 OD data points, we increase the temperature for the same other settings to see the effect of increasing the sensor temperature on the quality of the image.

B. Experiment 2: Mach-Zehnder interferometer

The purpose of the Mach-Zehnder interferometer in this experiment was to allow us to observe single photon interference and see how the availability of *"which-path"* information affects the visibility.As we can see from the diagram shown below in figure 3, by setting polarizers A and B respectively, we have a system where we can use the final polarizer, polarizer B, to select which path we receive at the detector. Polarizer B functions as the quantum eraser by allowing us to gain or erase "which-path" information. In the case of angles 90° and 0°, we have all the information to determine which path the photon took. An angle of 90° selects the upper arm, while an angle of 0° selects the lower arm. An angle of 45° means that we don't have this information; thus we expect to see maximum visibility in this case.

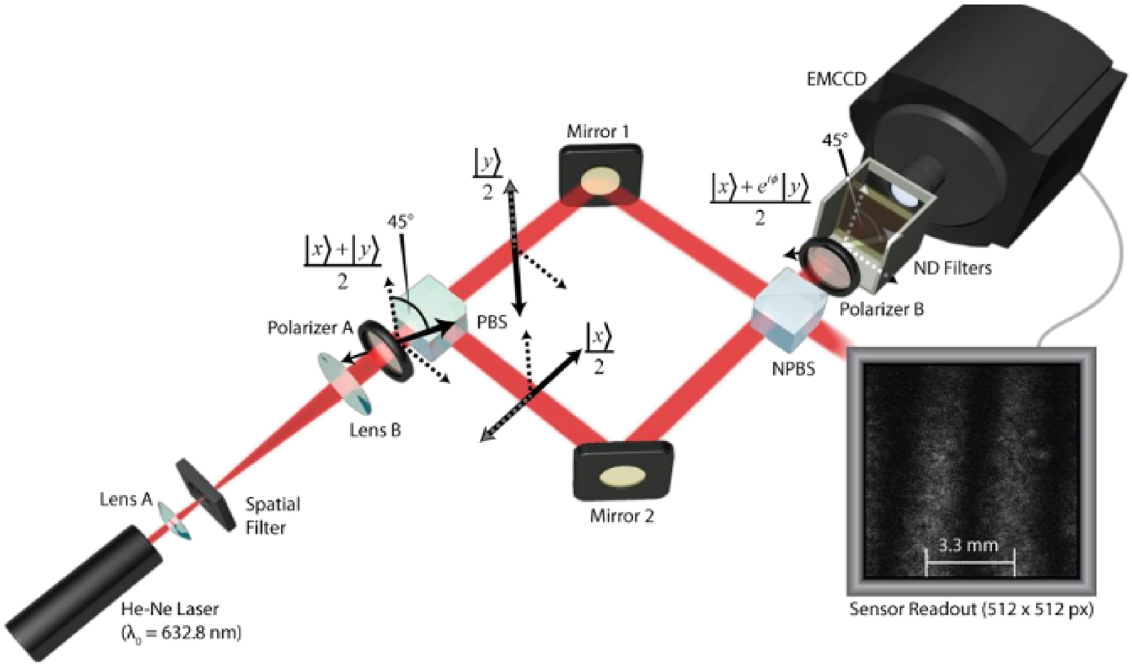

FIG. 3: Schematic of the setup used in experiment 2 [2]

The Mach-Zehnder interferometer was already set up. Before starting, the background illumination was set to a minimum. We then attenuated it to get to single photon levels using ODs. With 4 ODs we were in the single photon regime. The setup was similar to the Young's double slit experiment up to the spatial filter. In the interferometer, the beam passed through a polarizer than a polarizing beam splitter. The light was split among two paths, where they were reflected into a non-polarizing beam splitter, by 2 mirrors, into a second polarizer through ND filters onto the camera sensor.

First we set the polarizer angle to be at 45°; then we found the optimal capture settings by varying different accumulation and single settings and observing the quality of fringes observed ont the Solis Software. Then to begin the main part of the experiment, we set up the polarizer B angle at 0° for the setting with accumulation 50 and exposure of 500 ms. We start with with four OD1 ND filters. We recorded the pictures of the interference pattern for each of these configurations. Then we repeat the same process for polarizer B angles angles in increments of 10 ($10°, 20°, \ldots, 350°$). In addition we also recorded the data for polarization angle 45° for the purposes of comparison. We also recorded some points for 6 OD setup at 45° polarization to see the effect of attenuation on the fringe contrast.

C. Experiment 3: Aligning the Mach-Zehnder interferometer

We used the same setup as we used in Experiment 2, however we began with the mirrors removed. We then inserted the mirrors into the system, then rotated them until they were aligned properly. The two mirrors corresponding to each arm was aligned separated. Then we checked that both beams were aligned near the output of the NPBS. A piece of paper was used to see if the two spots were aligned. The beam was aligned at a distance 'far' from the output as well as the near spot. A good distance was about a meter from the output. Once the beam was aligned far and close to the output, ie. we saw an overlap, the interferometer was considered aligned.

III. RESULTS AND ANALYSIS

A. Experiment 1: Experiment 1: Single Photon Interference in Young's Double Slit Interferometer

1. Four Optical Density (OD) Filters

As noted above, 4 OD corresponds to 1 photon per meter levels. We collected data by varying different factors to see what the optimal settings are needed for imaging the interference pattern properly. Note that cooled means the temperature of the Em-CCD was cooled down to -65 °C

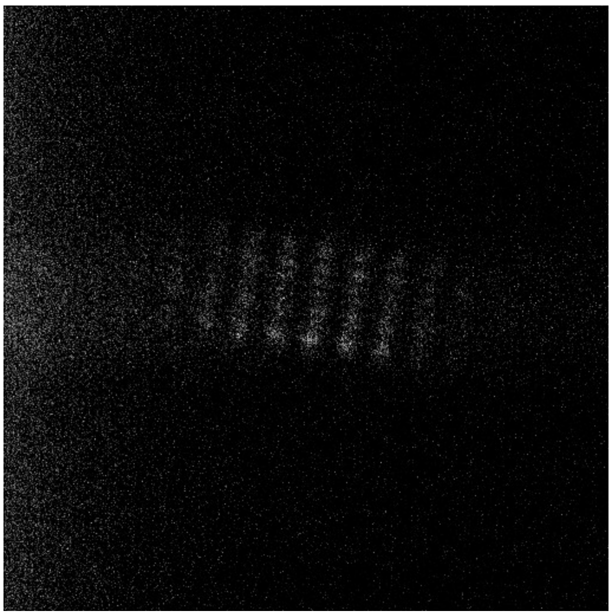

FIG. 4: 4 OD filter, single accumulation, 1ms exposure, cooled

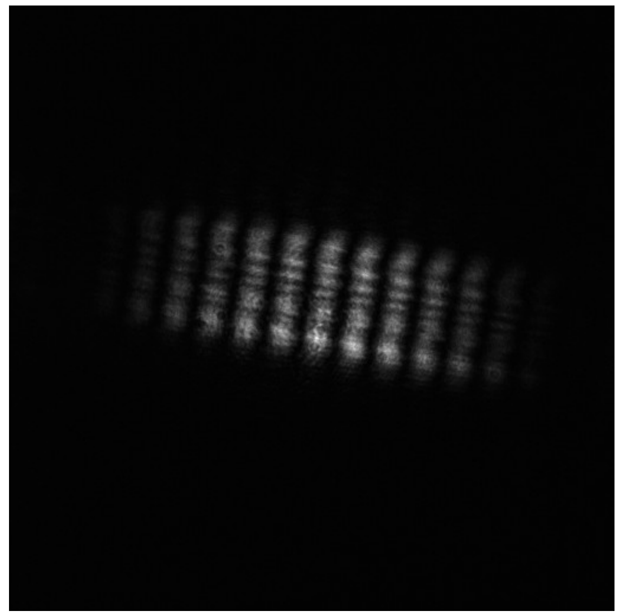

FIG. 5: 4 OD filter, single accumulation, 100ms exposure, cooled

We see in figures (5, 4) that the higher the exposure the better the resolution is. Not only is the image clearer, the edge noise is almost disappeared in the higher exposure . Next we try the other setting, accumulation capture, and vary the number of points to see how more number of points affect the image resolution. We see in n figures (6, 7) that the image quality is not changed by much, but the noise is more pronounced in the 20 accumulation point image, so for accumulation we choose 100 points going ahead. Additionally, we see that there is more edge effects in the accumulation images as compared to the single image for the same 1ms setting.

2. Five Optical Density Filters

5 OD filters correspond to 1 photon per 10 meters level. In general it is harder to image the signal for the same settings as 4 OD as photons are much more scarce in this case. The exposure time as the most effect in terms of resolution regardless of the single or accumulation settings, or the number of accumulation points. It can be clearly seen from the increased quality as we move from 1 to 10 to 100 ms exposure time. Also notice, how for 5 OD there is hardly anything visible at 1ms level for single, and some barely traceable fringes for 100 accumulation point image, with a significant edge noise. Overall we see an overall decrease in the resolution as lesser photons are

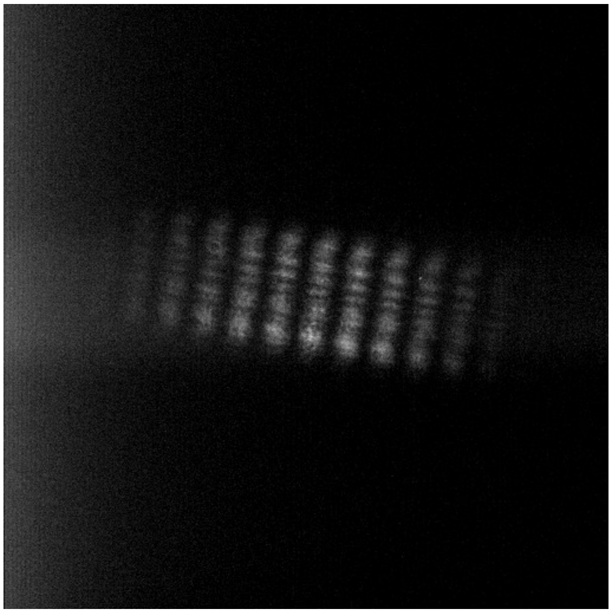

FIG. 6: 4 OD filter, accumulation of 20 images, 1ms exposure, cooled

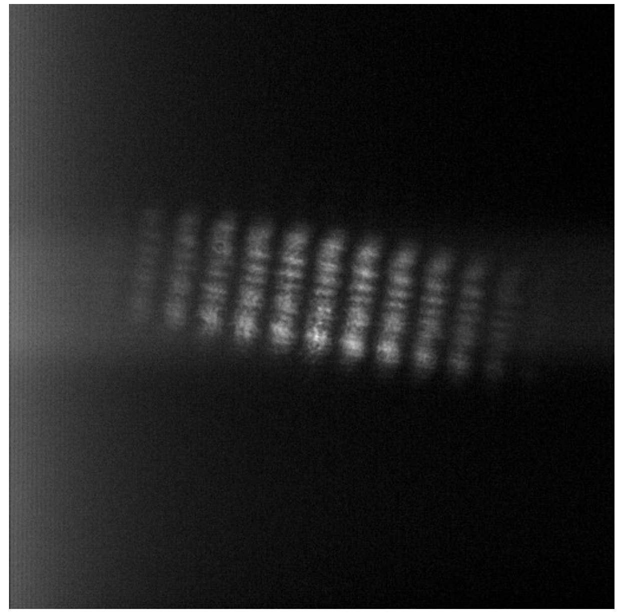

FIG. 7: 4 OD filter, accumulation of 100 images, 1ms exposure, cooled

available now then before making noise levels more apparent. At the 100 ms exposure level we can hardly distinguish the images based on the clarity as they all look very good.

3. Six Optical Density Filters

6 OD filters correspond to 1 photon per 100 meters level. In general it is harder to image the signal for the same settings as 4 OD and 5 OD as photons are much more scarce in this case. We start with 10 ms because it can be clearly inferred that we will not see anything at 1ms exposure from our 5OD experience. Additionally, we take only accumulation images based on what we saw for 10ms exposure setting for 5 OD.

We notice that the exposure time has a huge effect in terms of resolution regardless of the accumulation settings. It can be clearly seen from the increased quality as we move from 10 to 100 to 1000 ms exposure time. As we can see that in the 10 ms, 100 accumulation image there are traces of double slit interference pattern. We raised the temperature from -65°C to 20°C to see what effects does raising temperature have. We can clearly see the incomprehensible image as we move to a higher temperature for the same configuration. Also notice in figure (27), how for 6 OD there is hardly anything visible at 10 ms level for 20 accumulation points, and some barely traceable fringes for 100 accumulation point image, with a significant edge noise. Overall we see a decrease in the resolution as lesser photons are available now then before decreasing the signal-to-noise ratio. At the 100 ms exposure level the more accumulation point image seems to do considerably better. However, we do not see any increase in the quality

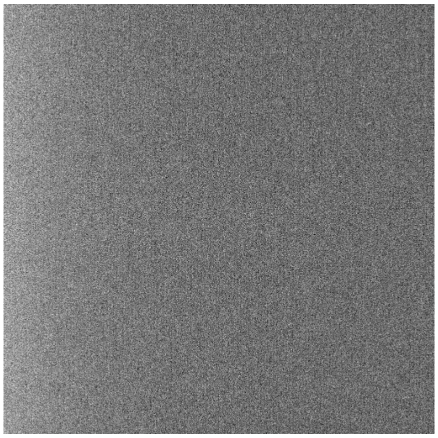

FIG. 8: 5 OD, single, 1ms exposure, cooled

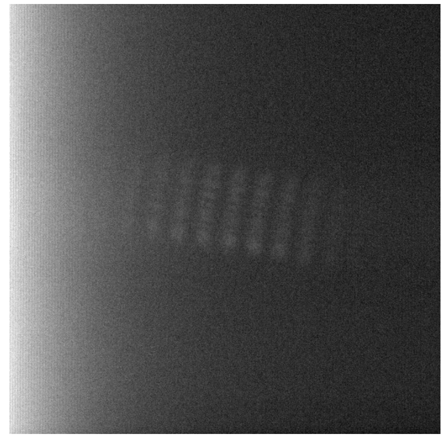

FIG. 9: 5 OD, accumulation of 100 images, 1ms exposure, cooled

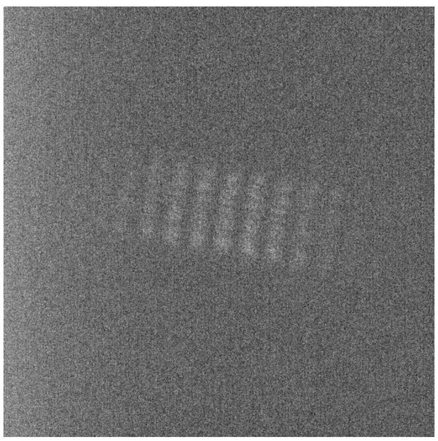

FIG. 10: 5 OD, single, 10ms exposure, cooled

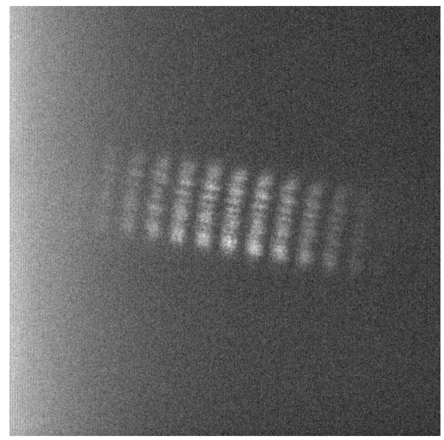

FIG. 11: 5 OD, accumulation of 100 images, 10ms exposure, cooled

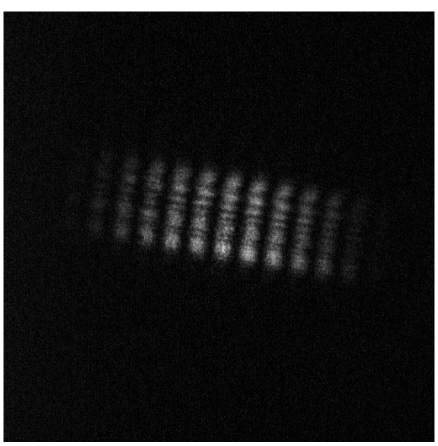

FIG. 12: 5 OD, single, 100ms exposure, cooled

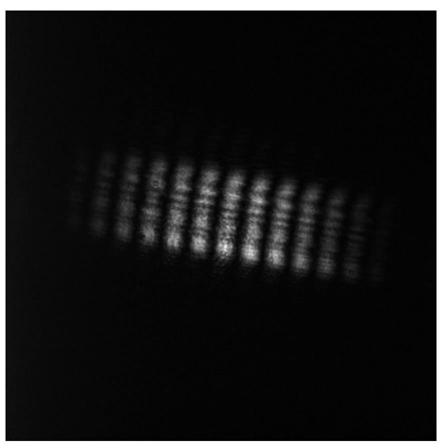

FIG. 13: 5 OD, accumulation-100 images, 100ms exposure, cooled

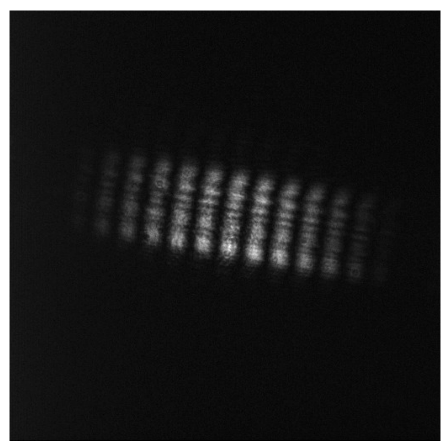

FIG. 14: 5 OD, accumulation-20 images, 100ms exposure, cooled

FIG. 15: Interference pattern image for different imaging settings with 5 OD filters

We noticed that there appeared to be slight changes in the location of the fringes between different measurements, which indicates that our experimental setup was very sensitive of the environment, and this may have been the cause of the poor image quality over longer integration times.

B. Experiment 2: Mach-Zehnder interferometer

In this section we analyse how visibility and Polarization B Angle are related to each other. To do so, first with the images obtained, we plot the figures 17 . We can see that the fringe contrast is better as the angles approach even multiples of 45°. Then using ImageJ we analyse the images by taking rectangular slices and then getting 3 values of I_{max} and I_{min}, as shown in the figure below. We span one horizontal block around the center of the circular pattern we see in the images.

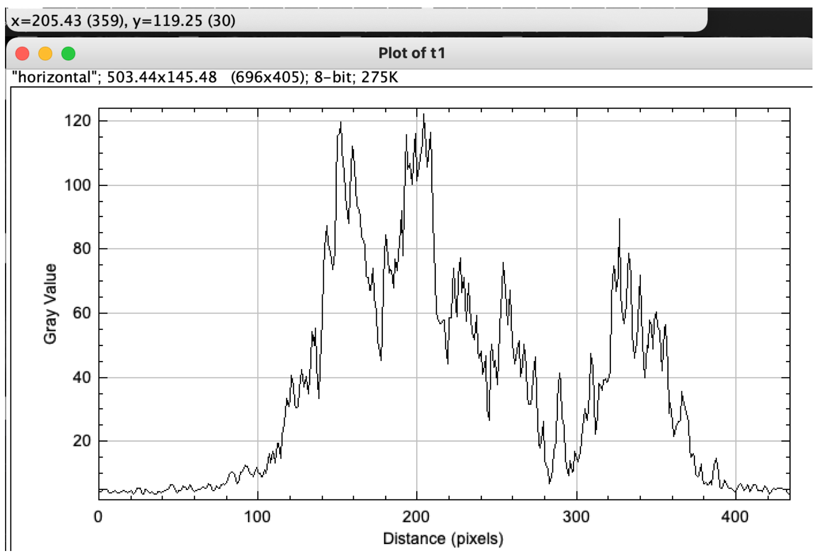

FIG. 16: Gray Scale value vs pixel distance in the rectangular slice

As it can be seen from Figure 16, we can get the Y pixel grey scale values which correspond to the intensity. Now, from the plot we got the I_{max} and I_{min} values. Using the average of the three values we get $I_{avg-max}$ and $I_{avg-min}$ and the corresponding error in them. These values were recorded and used for plotting fig 18. The error in visibility is given by the following expression:

$$\sigma_V = \sqrt{\left(\frac{\partial V}{\partial I_{max}}\right)^2 \sigma^2_{I_{max}} + \left(\frac{\partial V}{\partial I_{min}}\right)^2 \sigma^2_{I_{min}}} \tag{14}$$

$$\frac{\partial V}{\partial I_{max}} = \frac{2I_{min}}{(I_{max}+I_{min})^2} \tag{15}$$

$$\frac{\partial V}{\partial I_{min}} = \frac{-2I_{max}}{(I_{max}+I_{min})^2} \tag{16}$$

$$\sigma_V = \sqrt{\left(\frac{2I_{min}}{(I_{max}+I_{min})^2}\right)^2 \sigma^2_{I_{max}} + \left(\frac{-2I_{max}}{(I_{max}+I_{min})^2}\right)^2 \sigma^2_{I_{min}}} \tag{17}$$

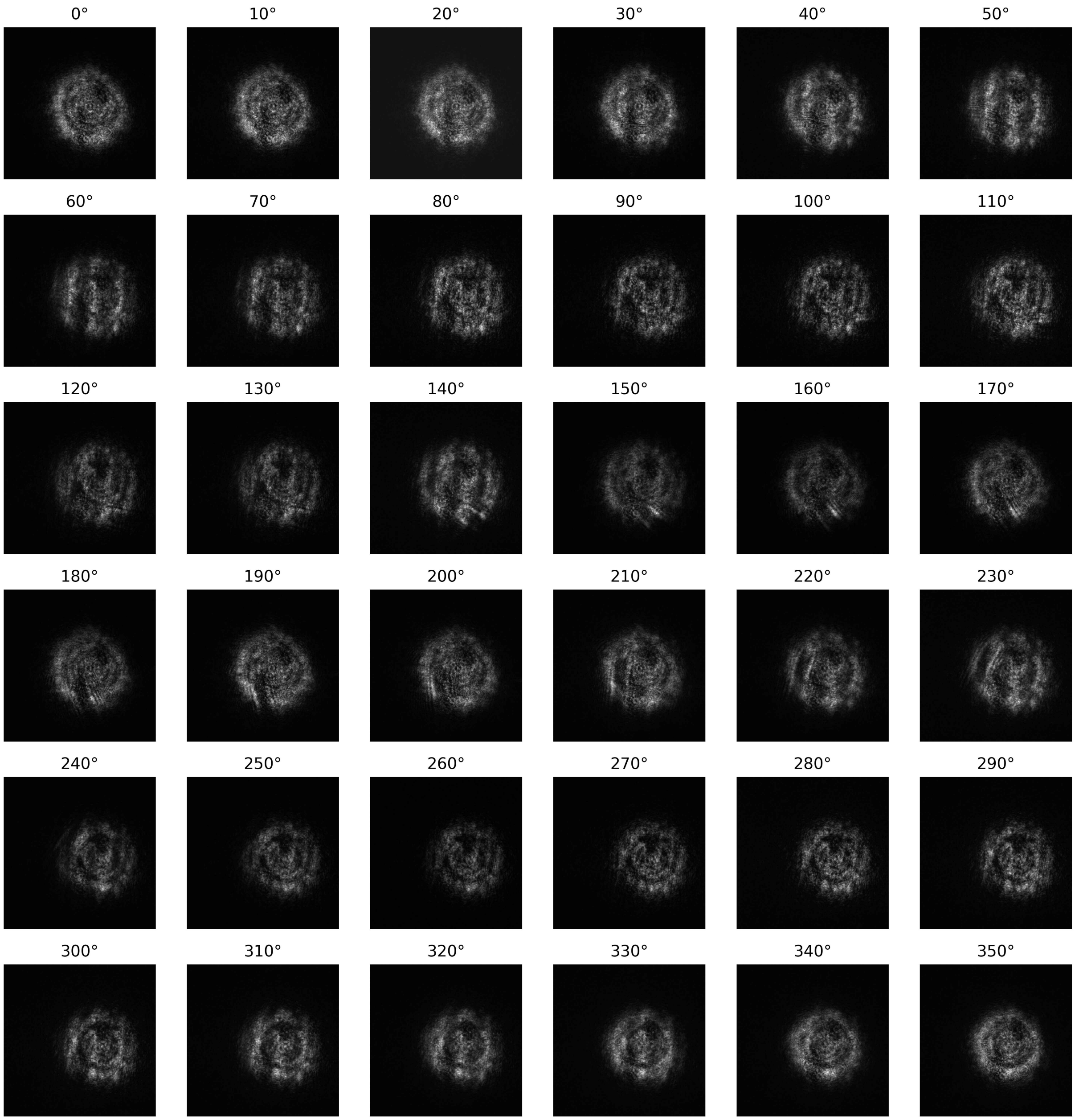

FIG. 17: Pictures from the EMCCD at the Mach-Zehnder system when rotating polarizer B every $10°$ from $0°$ to $350°$

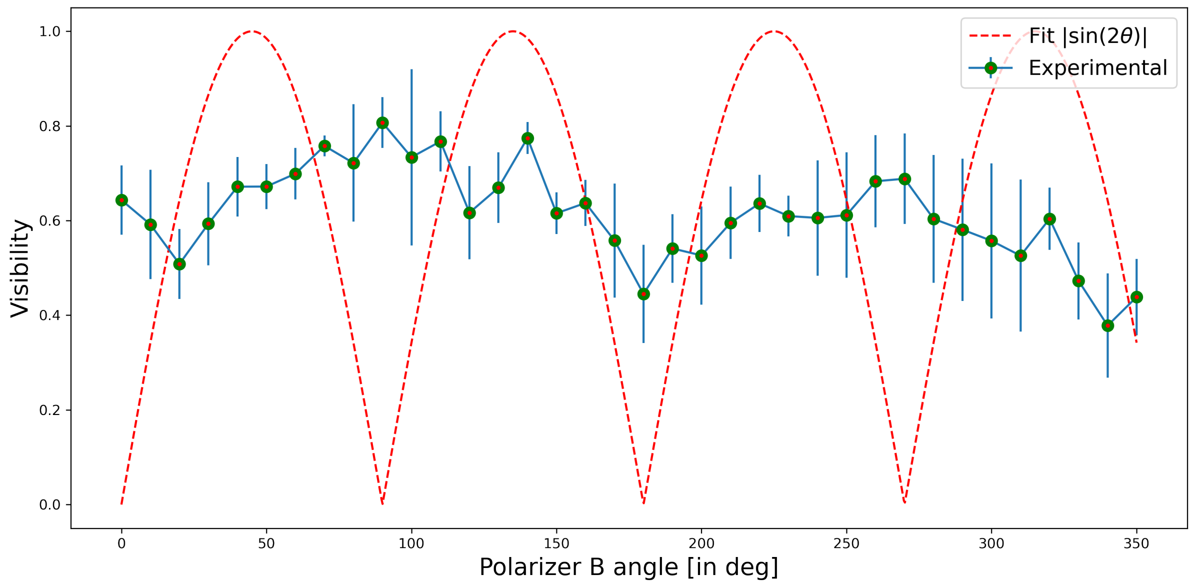

FIG. 18: Plot of visibility vs polarizer B angle which ranges from 0° to 350°

We see that the experimental data does have maxima around the odd multiples of 45 degrees and it follows the general structure. However, we see that the experimental data collected is quite far from the predicted. The visibility does not drop down to around zero as we would expected from the theoretical prediction of $\sin|2\theta|$; the curve's amplitude is also smaller than expected. This suggests a systematic error in the experiment - which can be attributed to the background brightness that we have due the presence of the monitor in the room. Additionally, it can be explained if we look at the uncropped images and the edge effects that give non zero pixel brightness for the other pixels. Additionally, it was noted by the lab instructor that the fluctuations were unusually high and could have been due to the heating system inside the room which will also affect our measurement given how sensitive it is to external noise. This decrease in stability might be because a double slit apparatus is more stable than a Mach-Zehnder interferometer setup, thus vibrations and noises in the are more prone to shift the fringe pattern during the duration of the integration time.

IV. CONCLUSION

In this lab, we explored wave particle duality and the various lab settings for better understanding this rather unintuitive phenomena. Both experiments in this lab demonstrated important and unintuitive aspects of quantum mechanics. Young's double slit demonstrated that single photons can actually pass through both slits and interfere with themselves, therefore we cannot think of photons as just particles. The Mach-Zehnder interferometer (quantum eraser experiment) demonstrated that the photon's decision to act as a particle or wave depends on if the observer has "which path" information. In this lab, we also learnt about the alignment of Mach-Zehnder interferometer.

For the first experiment, while imaging the interference pattern we saw how increasing the accumulation number and exposure time greatly improves the quality of image and the contrast between the fringes. Additionally, we see how the effect of increasing the attenuation of the laser and increasing the temperature of EM-CCD; the quality of image contrast is significantly decreased. The results demonstrate the general structure that we expect: the maximum at the odd multiples of 45° and minimum at the even multiples. However, the data is far from the theoretical fit; this can be attributed to the various channels of noise we have in the system: the background, thermal fluctuations, possible misalignment. This analysis can be improved by taking into account the background count and using Fourier transform techniques rather than selecting three peaks by manual investigation. The former is less prone to error as compared to the latter.

[1] R. Nave, Hyperphysics double slit.
[2] S. Lukishova, "lab 2 lectures" opt253 and opt 453/phy 434 quantum optics and nano-optics laboratory, 2021 (2021).

Appendix A: Data Collected

We also recorded the fringe separation image for the setup used in 7

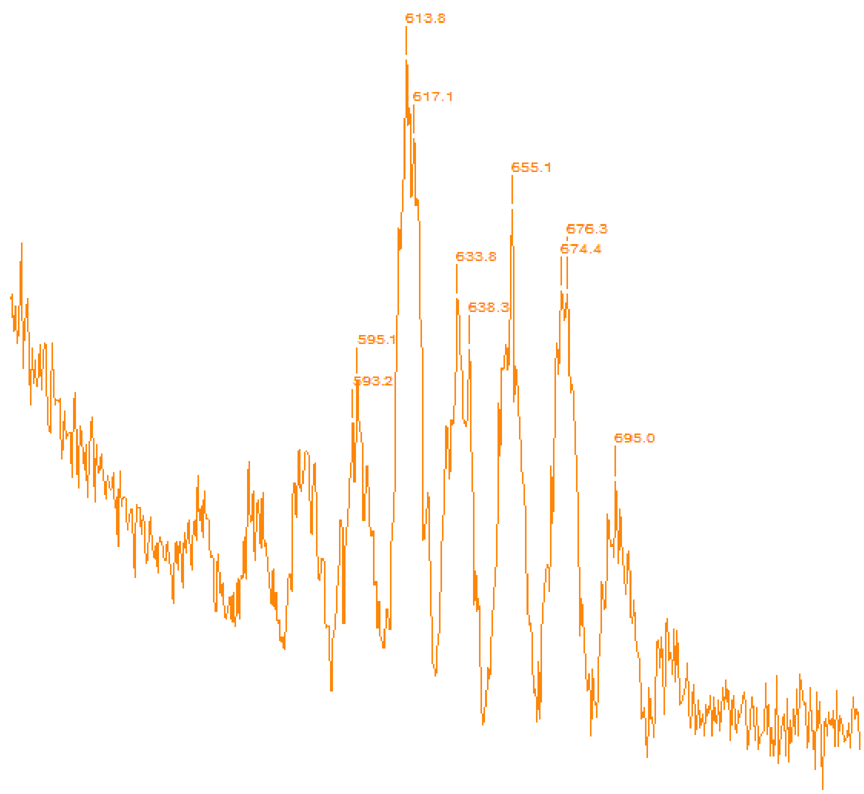

FIG. 19: Fringe separation/ resolution as seen through Solis

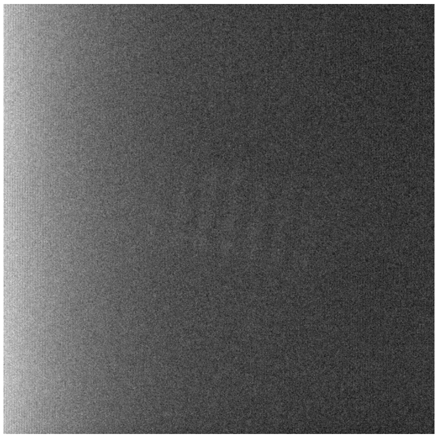

FIG. 20: 6 OD, accumulation of 20 images, 10ms exposure, cooled

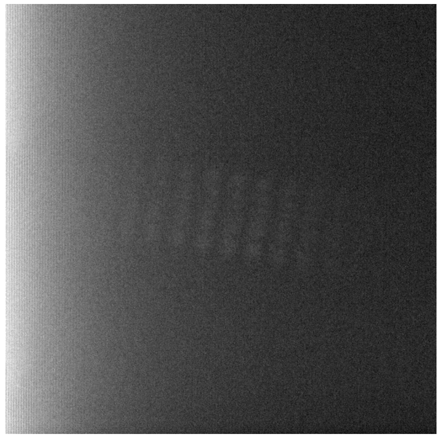

FIG. 21: 6 OD, accumulation of 100 images, 1ms exposure, cooled

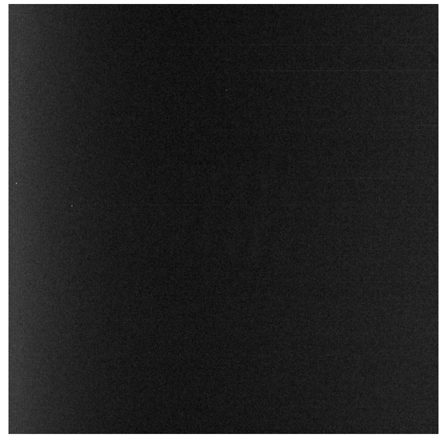

FIG. 22: 6 OD, accumulation of 100 images, 1ms exposure, warm

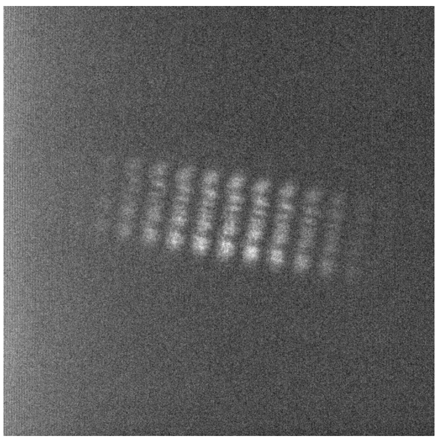

FIG. 23: 6 OD, acc of 20, 100ms exposure, cooled

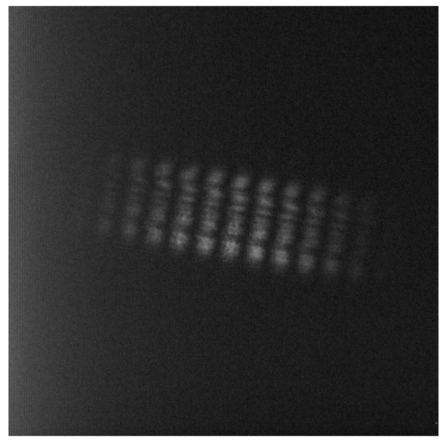

FIG. 24: 6 OD, acc of 100, 100ms exposure, cooled

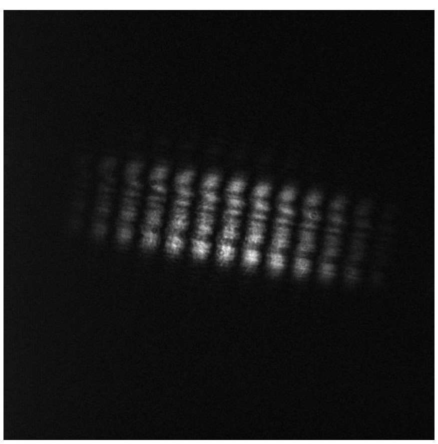

FIG. 25: 6 OD, acc of 1000, 1000ms exposure, cooled

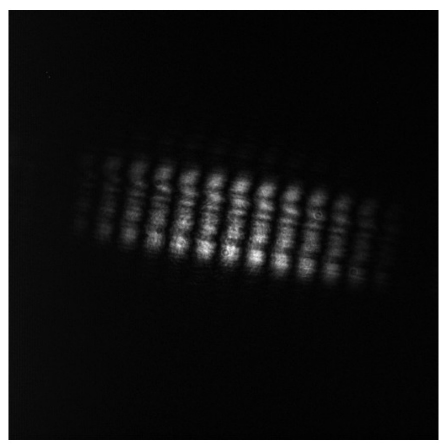

FIG. 26: 6 OD, acc of 100, 1000ms exposure, cooled

FIG. 27: Interference pattern image for different imaging settings with 6 Optical Density filters

Appendix B: Acknowledgments

Regards to Professor Lukishova, the TAs, and my lab partner for their time and help throughout this lab.