

UNIVERSITY OF ROCHESTER
THE INSTITUTE OF OPTICS

OPT 253, OPT 453, PHY 434

Lab. 2. Single Photon Interference

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Important Safety Tips

Laser safety

You will use red He-Ne laser (~633 nm wavelength, ~ 5 mW power) in this lab. Despite its low output power, He-Ne lasers may still represent a significant hazard to vision.

One should never look into the beam of any laser - especially if it is collimated. Use an indirect means of determining proper operation such as projecting the beam onto a white paper or laser power meter.

Equipment safety

The CCD camera used in this lab is internally cooled, and ideally works at an internal temperature of -60° C. Never block the vent on the camera since doing so can disrupt the cooling mechanism. The temperature inside the camera is displayed at the bottom left of the screen when the Andor iXon software is open. If the camera ever reaches a temperature too high to operate safely, a buzzer will sound from inside the camera. If one ever hears this buzzer, it is extremely important to turn off the internal cooling in the camera and make sure that the internal fan is on and turned to 'High'. This can be done in the iXon software by first click on the 'Hardware' drop down menu, and then choosing 'Temperature'. Turn the cooling option to off and click 'Ok'. Next click on 'Hardware' again and choose 'Fan Control'. Make sure that 'High' is selected and press 'Ok'. Make sure to stop any data collection. The camera should then be left alone to cool off before usage continues.

PREPARATORY QUESTIONS

You should answer two sets of questions:

- (1) before your first laboratory session and
- (2) within each section of this Manual. All questions have a blue-color font.

Answer these questions before your first laboratory session

1. What should be a filter transmission value to attenuate a 5 mW, 633 nm laser beam to a single-photon level (e.g., for a ~ 300 -m distance between photons)?
2. Will you expect to obtain an antibunching histogram from the attenuated laser beam?
3. Draw the interference pattern from a single slit and a double-slit. Provide the equations for these patterns.
4. Draw the schematics of a Mach-Zender interferometer.
5. How will you align the interferometer?
6. Explain what is a “which-way information”.

References and recommended literature:

1. G. Greenstein and A.G. Zajonc, *The Quantum Challenge*, Jones and Bartlett Publ., Boston, 2006.
2. M.B. Schneider and I.A. LaPuma, "A simple experiment for discussion quantum interference and which-way measurement", *Am. J. Phys.*, **70** (3), 266-271 (2002).
3. The Feynman Lectures on Physics. Vol. 3, Chapter 1, R. P. Feynman, R. B. Leighton, & M. Sands, Addison-Wesley, 1965.
4. Technical University of Delft, Optics Research Group: :
<http://www.optica.tn.tudelft.nl/education/photons.asp>
5. <http://www.physics.brown.edu/physics/demopages/Demo/modern/demo/7a5520.htm>
6. W. Rueckner and P. Titcomb, "A lecture demonstration of single photon interference", *Am. J. Phys.* **64**, No. 2, 184-188, Feb 1996.
7. <http://www.fas.harvard.edu/~scdiroff/lds/QuantumRelativity/SinglePhotonInterference/SinglePhotonInterference.html>

Introduction

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. The particle nature of light is explained by considering light as massless energetic particles called photons.

It is only recently that people have been able to generate and detect single photons. The main driving force behind single-photon research has been the possible applications in the field of quantum information. During the last few decades, this field has revealed a number of possibilities where quantum physics could be used to achieve tasks that were not possible with classical physics. Among these tasks are quantum computing, quantum teleportation, and quantum key distribution. The latter is the most technically mature application, and has been one of the most important motivators for the increased interest in the generation and usage of single photons.

Interference of light is a well-studied phenomenon. One way to observe interference is by using an interferometer. In an interferometer, light from a single source is divided into two paths that are then recombined to produce an intensity pattern on a screen or a detector. The most commonly used interferometers are Young's double slit, Michelson, and Mach-Zehnder interferometers. This Laboratory uses the Mach-Zehnder and Young's double slit interferometers to explain some important optical concepts, specifically the wave-particle duality of light.

Interference is usually understood in terms of waves and does not have an adequate explanation in terms of particles. Thus, if a stream of single photons being modeled as particles were incident on the two slits of a Young's double slit interferometer, one might expect that the photons would first pass through one of the two slits (or hit the screen), then travel to the screen resulting in the superposition of the two intensity patterns formed as a result of geometry of each slit, as in Fig. 1 below:

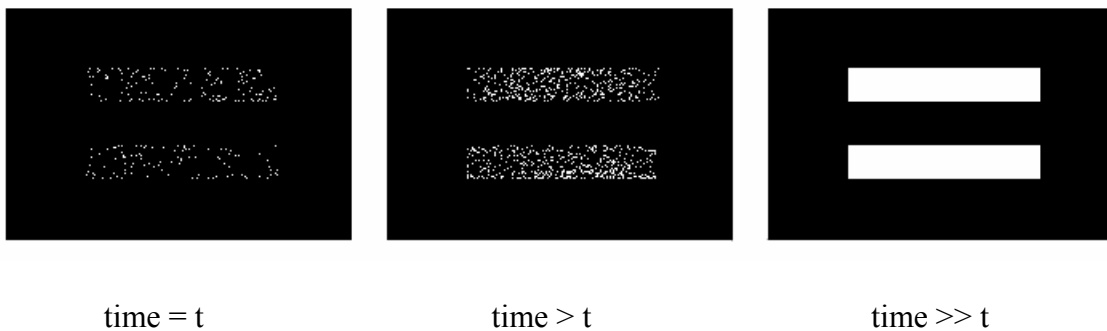


Fig 1: Theoretical intensity pattern observed at distant screen caused by single photons modeled as particles incident on two slits. Images are over increasing accumulation time.

This, however, is not the case unless one does now know which slit the single photons goes through, referred to as “which-path” information. As long as one does not have “which-path”

information, the pattern seen in fig. 2 is created when a stream of single photons is incident on the slits in a Young's double slit interferometer (the setup described above) even though only one photon is incident on the slits at a time. The interference pattern observed would be a sinusoidal function, whose amplitude is modulated by an envelope function corresponding to diffraction from a single slit, as in Fig. 2. The absence of "which-path" information is the essential criterion for single-photon interference. For example, if one had a way of knowing (even in principle) which of the two paths a photon took in a Young's double slit interferometer, one would not see any interference fringes. Knowing the path that a photon takes is equivalent to performing a measurement on the photon. As dictated by quantum mechanics, performing a measurement collapses the photon's wave function, causing it to behave like a particle (a particle cannot interfere with itself).

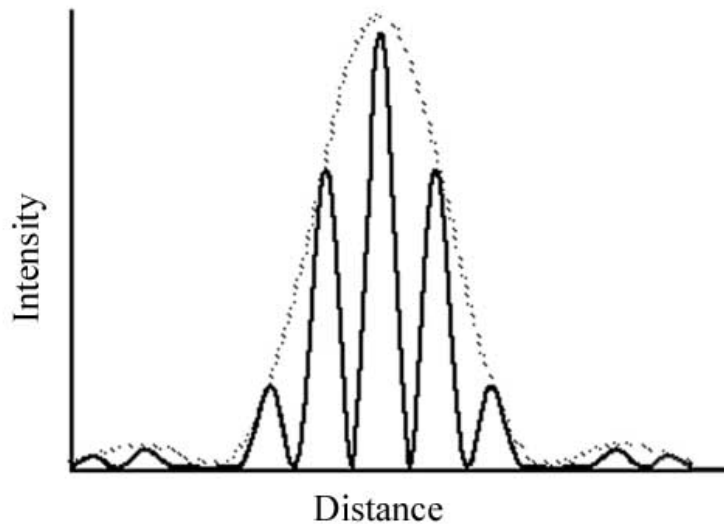


Fig 2: Interference pattern observed at distant screen resulting from single photons incident on the two slits of a Young's double slit interferometer.

But if a photon is a particle, not a wave, how can it interfere with itself? Suppose one had a "perfect" two-dimensional detector. After only one single-photon event, one clearly would not see interference fringes. Here, an "event" is understood to mean a single photon incident on the double-slit. The photon would hit the detector at a single point, thus the photon behaves like a particle. However, as one records more and more single-photon events, an interference pattern begins to form. Fig. 3 illustrates the emergence of single-photon interference fringes. This clearly demonstrates that the particle-like photons behave like waves. This is what is known as the wave-particle duality.

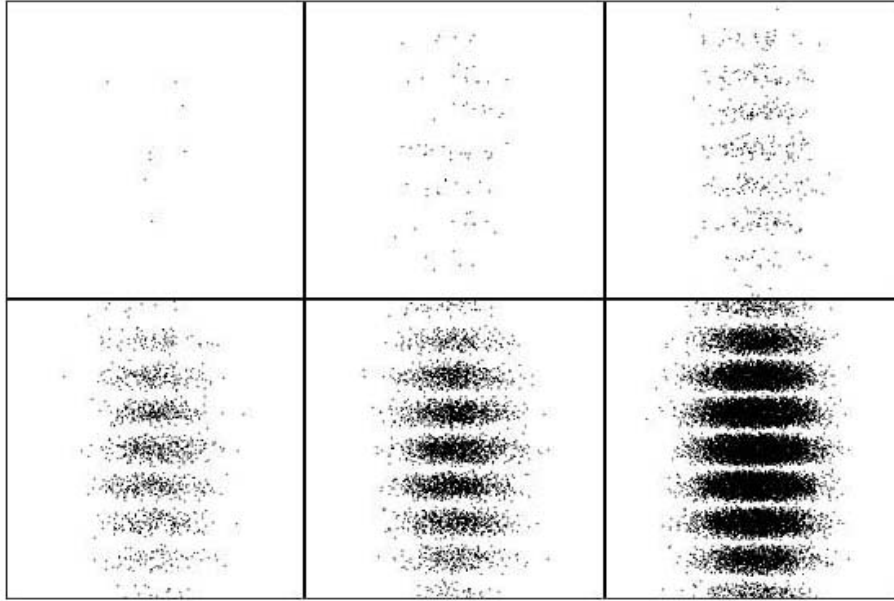


Fig. 3: Single-photon interference over increasing time intervals.¹

Associated with each point in space is the probability that a photon emerging from the double-slit will go there. Dark fringes in Fig. 3 correspond to high probability regions and light fringes in Fig. 3 correspond to low probability regions. The parameters of the double-slit determine the probability distribution (i.e. the fringe pattern). The classical interference pattern produced by light waves can therefore be regarded as the sum of a great number of single-photon interference patterns.

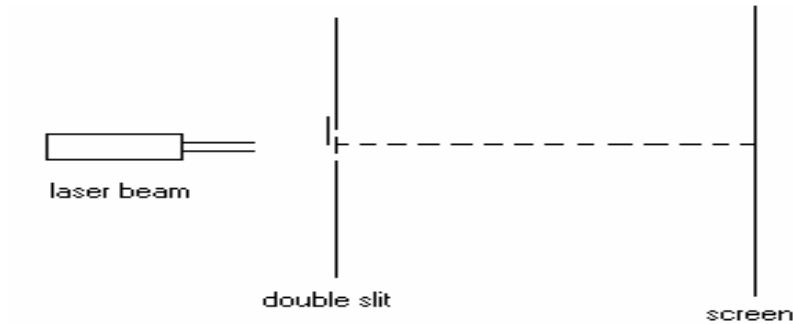
This laboratory provides a visual demonstration of the appearance and disappearance of interference fringes, both at high light and single-photon levels, by carefully destroying and restoring “which-path” information using a polarizer in a Mach-Zehnder interferometer. It also demonstrates the wave-particle duality and by observing interference fringes created by single photons incident on a Young’s double slit interferometer.

¹ <http://www.optica.tn.tudelft.nl/education/photons.asp>

Activity 1. Photon : a Particle or a Wave ?

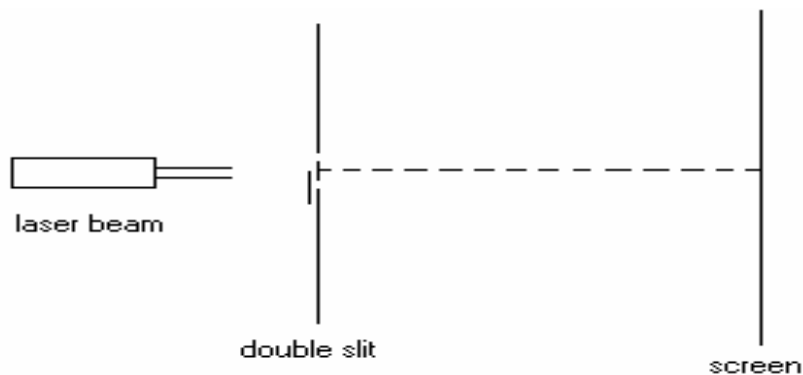
To better understand the importance of “which-path” information, consider the simple example of Young’s double slit experiment. The principles involved are the same as those in a Mach-Zehnder interferometer.

Question 1: Sketch on the figure below the intensity pattern you would see if the top slit were blocked.



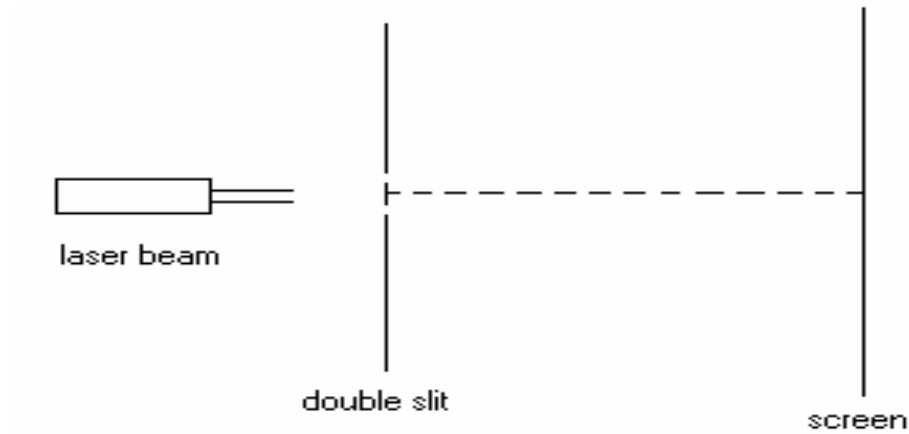
Young’s double slit experiment with top slit blocked.

Question 2: Sketch on the figure below the intensity pattern you would see if the bottom slit were blocked.



Young’s double slit experiment with bottom slit blocked.

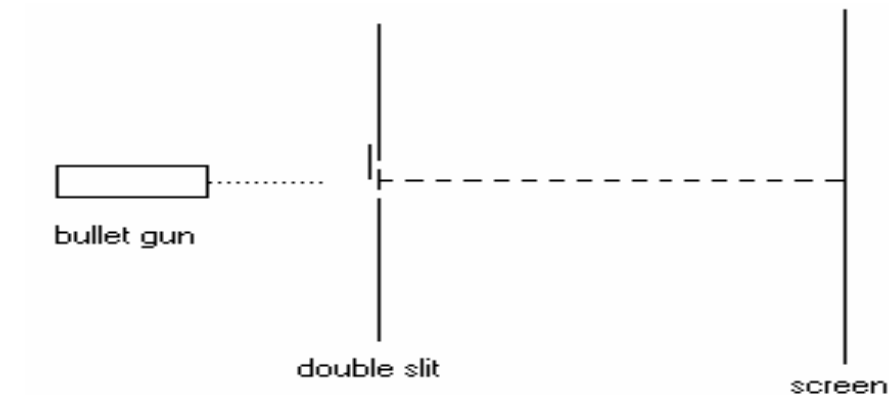
Question 3: Sketch on the figure below the intensity pattern you would see if both the slits were open.



Young's double slit experiment with both slits open.

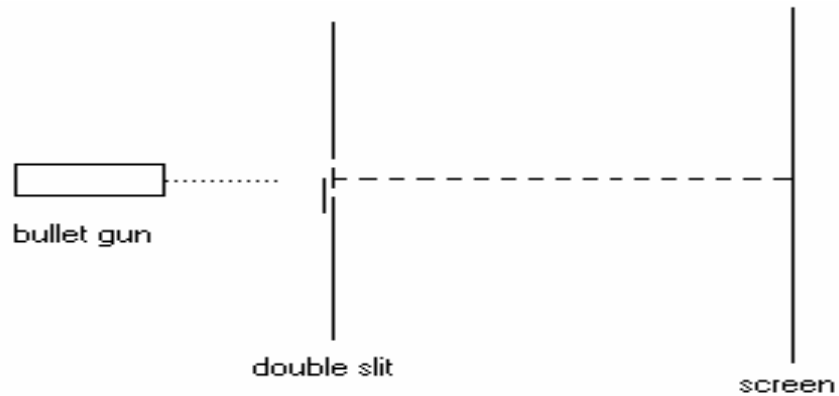
Next consider Young's double slit experiment with a bullet gun instead of a laser. (Assume that the bullets are about the same size as the slit width).

Question 4: Sketch on the figure below the accumulation pattern (intensity pattern) of bullets that you would see if top slit were blocked.



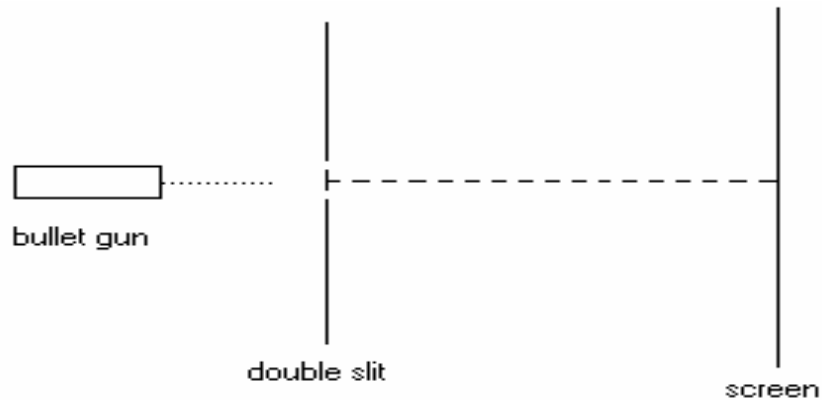
Young's double slit experiment with bullets (top slit closed).

Question 5: Sketch on the figure below the accumulation pattern (intensity pattern) of bullets that you would see if bottom slit were blocked.



Young's double slit experiment with bullets (bottom slit blocked).

Question 6: Sketch on the figure below the accumulation pattern (intensity pattern) of bullets that you would see if both the slits were open.



Young's double slit experiment with bullets (both slits open).



SEE YOUR TA to make sure you correctly answered the above questions before proceeding further.

Question 7: If light is nothing but a stream of particles (called photons), why doesn't a stream of bullet give rise to an interference pattern similar to that of photons? (Take your time to answer this question and then check with the answer below).

Answer: “Which-path” information and wave particle duality. A bullet is a **massive** object and one can always find out for sure which slit or path, a bullet happens to take. Since interference is a wave phenomenon and it is impossible for a bullet to act like a wave on a measurable scale, one never sees an interference pattern with bullets.

On the other hand, photons are massless particles and act like waves as long as there is no measurement performed on them. The moment a measurement is performed on the photons, they start behaving like particles.

Making a measurement is the same as finding the path or slit that a photon happens to take. In the above double slit experiment, one has no way of knowing which path a photon takes. So individual photons can act like waves and interfere with themselves. In Activity 2 we’ll actually see how a “which-path” measurement destroys the interference in a Mach-Zehnder interferometer.

Activity 2. “Which Path” Puzzle

In this activity, you will experimentally observe the effect of “which-path” information using a Mach-Zehnder interferometer. The experiment is set-up as shown in the schematic diagram (Fig. 5). You will assemble this interferometer from the scratch.

Experimental Set-up: (for a description of the optical elements used, see Appendix 1)

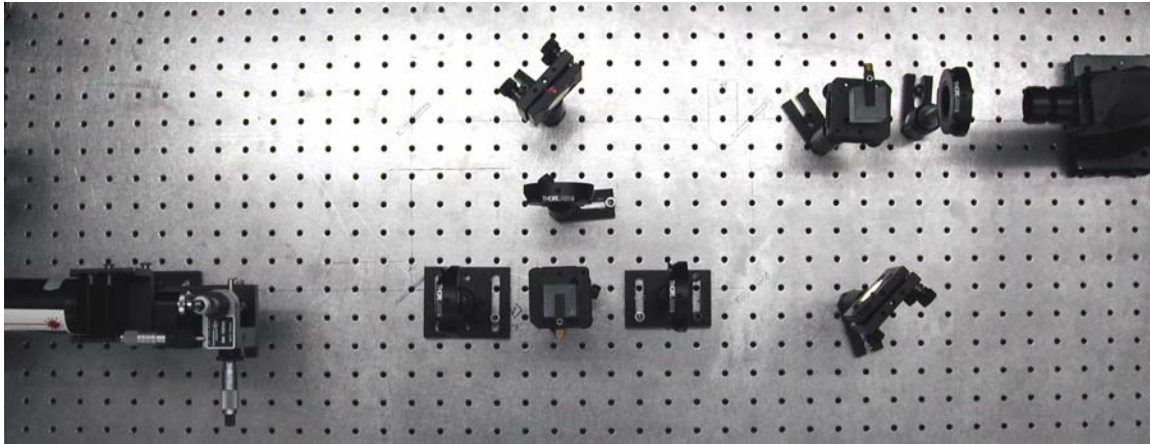


Fig. 4: Photograph of experimental set-up (Mach-Zehnder interferometer).

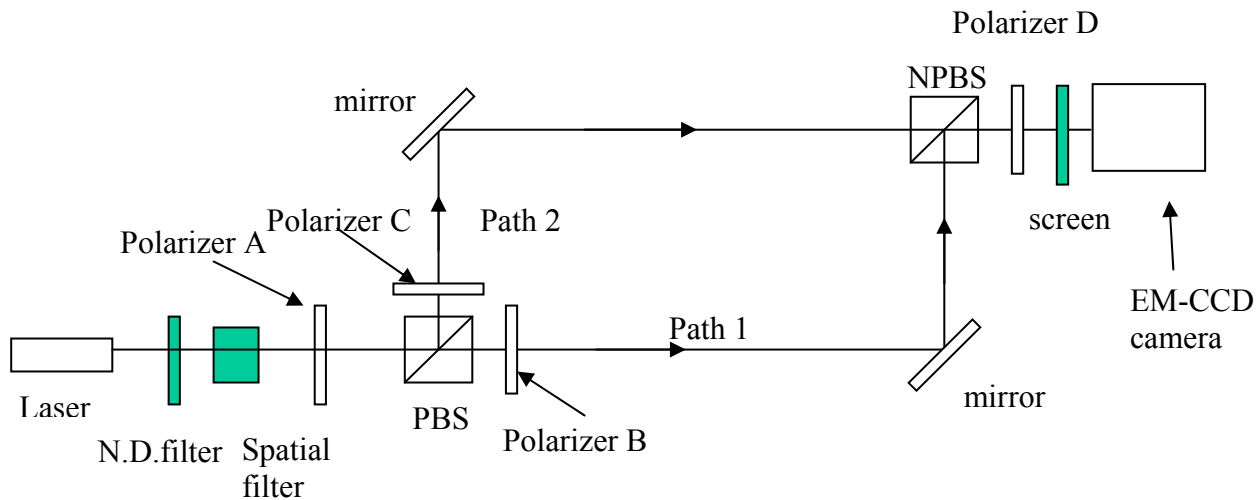


Fig. 5: Schematic of the experiment with a Mach-Zehnder interferometer.

As shown in the schematic diagram (Fig. 5), light from the laser passes through a spatial filter, increasing the beam diameter from a few mm to a few cm. It then enters into the PBS, which

transmits the horizontal polarization while reflecting the vertical polarization. A polarizer is placed before the PBS to adjust the polarization of incoming light such that it gets equally divided between horizontal and vertical polarizations after passing through the PBS. Polarizer B and polarizer C are put in path 1 and path 2, respectively, to make sure that there are only horizontally polarized photons in path 1 and only vertically polarized photons in path 2.

The beams in path 1 and path 2 are then combined at the NPBS via reflection from the mirrors. The resulting light is observed on a screen to the right of the NPBS. Polarizer D is used to demonstrate the appearance and disappearance of fringes, which can be observed with the naked eye on the screen at high light level. To demonstrate the same effect at single photon level, an EM-CCD camera is used to collect data.

Before you start the experiment, remove Polarizer D if it is there. Verify that you have only horizontally polarized photons in path-1 and only vertically polarized photons in path-2.

1. Switch the laser on. Turn the room lights off.
2. Put Polarizer B at 90° and hold a piece of paper right after Polarizer B.

Question 8: Do you see a bright or a dark spot?

3. Put Polarizer B at 0° and hold a piece of paper right after Polarizer B.

Question 9: Do you see a bright or a dark spot?

4. Put Polarizer B back at 90° .

Question 10: What do question-8 and question-9 tell you about the polarization of the photons in path-1?

5. Now put Polarizer C at 0° and hold a piece of paper right after Polarizer C

Question 11: Do you see a bright or a dark spot?

6. Put Polarizer C at 90° and hold a piece of paper right after Polarizer C.

Question 12: Do you see a bright or a dark spot?

7. Put polarizer C 2 back at 0° .

Question 13: What do question-11 and question-12 tell you about the polarization of the photons in path-2?

Polarization of photons in path 1: _____

Polarization of photons in path 2: _____



SEE YOUR INSTRUCTOR to make sure you have the right polarizations.

Prediction:

Now you know the polarization states of photons in both paths. Suppose you had a device that measured polarization (instead of the EM-CCD camera). If this device detected a horizontal photon, you would know for sure that it came through path 1 and if it detected a vertical photon, you would know for sure that it came through path 2. The photons' "which-path" information is completely known.

Question 14: Do you expect to see interference fringes with the present configuration of the Mach-Zehnder interferometer? Why?

Check your prediction: Observe the intensity pattern on the screen.

Question 15: Did your prediction match with the observation?

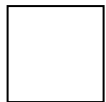
Prediction:

Let us assume that we put a polarizer after the NPBS and set it at 45° . By putting a polarizer at 45° , one will obtain only 45° -polarized photons at the detector. The 45° polarized photons incident on the detector could then have taken either of the two paths. There is no way to tell which path a photon takes. So by putting a polarizer at 45° , one essentially destroys the “which-path” information.

Question 16: Do you expect to see interference fringes if you introduced a polarizer at 45° ? Why?

Check your prediction: Put polarizer D in after the NPBS and set it at 45° . Observe the intensity pattern on the screen.

Question 17: Did your prediction match with the observation?



See your TA if you don't see any fringes in this activity. The set-up may need to be aligned.

Activity 3. Single Photon Interference (Mach-Zehnder Interferometer)

In the previous activity, we found that any attempt to get “which-path” information destroys the wave nature of the photons and therefore, the interference pattern. Removal of any possibility of determining this information brings the fringes back. All this was done at a high light level.

In this activity, you will perform the same experiment, but at the single photon level. Obtaining similar results as before would confirm that a single photon does, in fact, interfere with itself and the interference fringes at high light level are just the combined effect of many single-photon interference patterns.

What we ideally want is a single photon source, so we can be certain that there is only one photon in the interferometer at a time. It seems difficult to have this kind of source, but it is not entirely the case.

“One photon at a time” is a relative concept. Our eye has a resolution time of 0.1 seconds. So if photons were coming at an interval of 0.1 seconds, our eye would call it “one photon at a time”. With the advent of technology we now have detection system (including the counter-timer computer card) with nanosecond resolution time. So for this detection system, photons coming at nanosecond intervals would still be considered as “one photon at a time”.[†]

Question 18: The EM-CCD camera we are using is a single photon detector that has a resolution time of about 100 nanoseconds. If photons are coming at the rate of 100,000 photons/second, how many resolution-time periods (on an average) would the detector have to wait before detecting a photon?

[†] Here we are talking about the probability that the detector would detect only one photon at a time. There is a finite probability with the attenuated laser pulses of detecting two photons at a time. However this probability is much smaller than the probability of detecting just one photon at a time.

As you saw in the above calculation, the detector, on average, detects a photon every couple of hundred resolution times. So we are at a “one photon at a time” level, in the sense that there is only one photon in the interferometer at a given time. You will now replace the screen with an EM-CCD camera and view the fringe pattern. We can now check to see if the results of Activity 2 can be repeated with single photons.

1. There should be two cables going to the CCD camera, a data cable and a power supply cable. Make sure that both cables are properly connected. The power cable simply plugs into the back of the camera whereas one must press in the sides of the silver data cable when attaching or removing it.
2. Turn off the lights if you have not done so.
3. Double click the Andor iXon icon located on the desktop of the computer attached to the camera. On the toolbar, click ‘Hardware’, and a drop down menu will appear. Choose ‘Shutter Control’. Choose ‘CLOSED For Background’ and click ‘ok’. Next choose ‘Acquisition’ from the toolbar, and another drop down menu will appear. Choose ‘Setup Data Type’. Choose ‘Counts (Bg corrected per second)’ and click ‘ok’. Again open the ‘Acquisition’ drop down menu, and choose ‘Setup Acquisition’. Locate the field labeled ‘Exposure time’, and change the current value to 0.1, then click ‘ok’.
4. Next, again choose ‘Acquisition’, and choose ‘Take Background’. The camera should make a clicking sound, and a new window will appear on the screen which displays the camera’s current view. It should resemble static. The purpose of taking a background is to eliminate as much background noise in the image displayed by the camera as possible.

Note: The acquisition time will have to be changed depending on the intensity of the pattern incident on the EM-CCD camera. The gain can also be adjusted if needed. Keep in mind, however, that when changing the acquisition time, a new background should be taken (to be subtracted).

5. Replace the screen used previously for viewing the fringe pattern with the EM-CCD camera. Click the icon with a picture of a video camera to display a live video feed from the camera. Use the image to align the camera such that an acceptable image is visible.
6. When this is the case, stop the live video input and **insert the number of ND filters you calculated previously to be necessary to reach the single photon level**. Click on the picture of a camera to take an image of the fringe pattern present. Again, changing the exposure time and gain may be necessary to receive good results.
7. Change the polarized to 0° and again image the resulting fringe pattern using the camera.

Activity 4. Single Photon Interference in Young's Double Slit Interferometer

In this experiment, you will observe the interference of single photons further exemplifying the wave-particle duality. The interference patterns will be examined with and without knowledge of “which-path” information. The general setup for a Young's double slit interferometer is as follows:

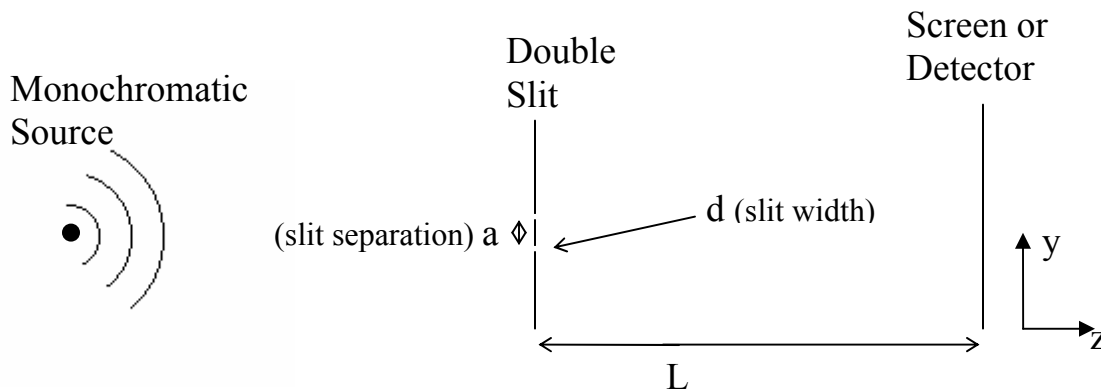


Fig. 6: General Young's Double Slit Interferometer.

The setup to be used in this experiment can be seen schematically below:

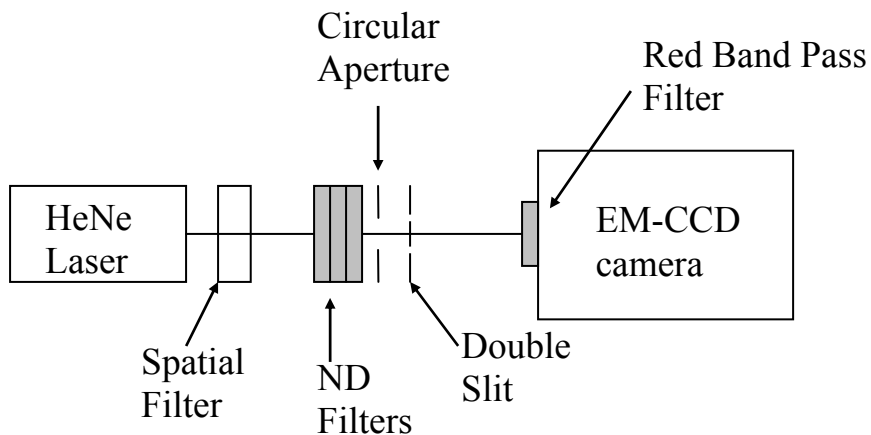


Fig. 7: Schematic Diagram.

1. Given that the fringe separation in the interference pattern (Δy) can be approximated by the following equation:

$$\Delta y \approx \frac{L}{a} \lambda$$

calculate the distance from the double-slit to the EM-CCD camera that would give you a fringe separation of 2 mm. The double-slit is illuminated by a HeNe laser ($\lambda = 632.8$ nm), the slit separation is 90 μm , and the slit width is 10 μm . If any neutral density filters are mounted in front of the spatial filter remove them. Then place a piece of paper at the distance you calculated and observe the interference pattern.

2. Using a power meter, measure the unattenuated laser power at the distance found in step 1. (Make sure the brightest fringes are incident on the power meter head and the room lights are off when performing this measurement). For single-photon interference you want to attenuate the laser power to a single-photon level. For this purpose you need to make a distance between photons larger than a distance between the laser and a double-slit, e.g., ~ 300 m ($\sim 10^6$ photons per second).

The following equations will be useful in your calculation:

$$Power = \frac{Energy}{Time} \quad E_{photon} = h\nu$$

Be sure you take into account that the active area of the camera is different from the area of the power meter head. (Active area of camera is 8.2 x 8.2 mm).

Since too much light can damage the camera, have your TA check your calculations before you proceed.

3. After the TA has approved your selection of neutral density filters, mount them at the output of the spatial filter as (Fig. 7). Position the EM-CCD camera at the distance you calculated in step 1. Turn off the lights and make sure that the camera is properly aligned by viewing the image of the fringes in the live video mode of the camera. Recall that changing the acquisition time and the gain may be necessary and that a new background must be taken when these parameters are changed.
4. When the camera is properly aligned, take multiple exposures of the image with smaller and smaller acquisition times.
5. Shut down the iXon software, turn off and unplug the camera, and turn off the laser.

Reference:

R.P.Feynman, Lectures on Physics, Volume III, Chapter 1.

Appendix 1

- (i) **Non-Polarizing Beam Splitter (NPBS):** This beam splitter splits the intensity of light, transmitting 50% of the light while reflecting 50% of the light as shown in picture.

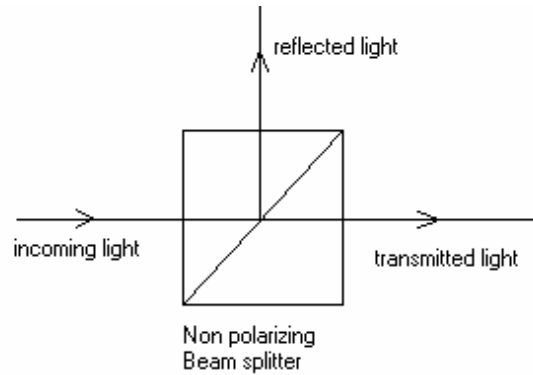


Figure A1.1: Nonpolarizing Beam Splitter

- (i) **Polarizing Beam Splitter (PBS):** This beam splitter does not split the intensity of light rather it splits the polarization of light. PBS transmits the horizontal polarization while reflecting the vertical polarization, as shown below:

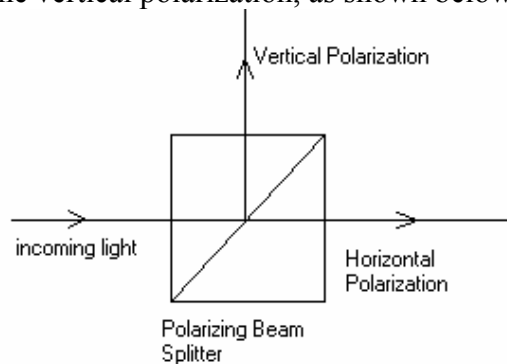


Figure A1.2: Polarizing Beam Splitter.

- (ii) **Laser:** A Helium-Neon (He-Ne), $\sim 5\text{mW}$, 633 nm laser is used in this experiment.
- (iii) **Spatial Filters:** This is introduced to increase the beam size so that interference can be observed over a wider area. It consists of a microscope objective, a pinhole and a lens.

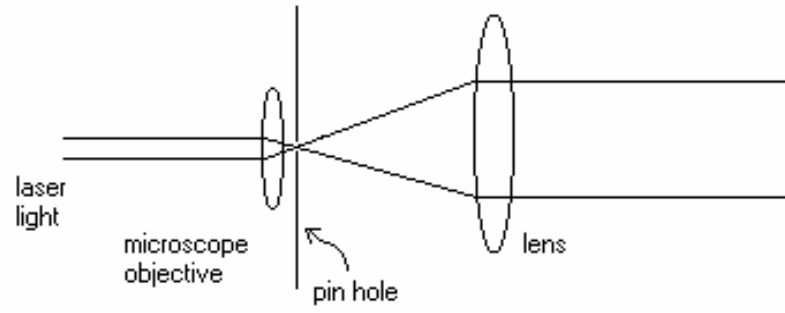


Figure A1.3: Spatial filter

Appendix 2. Previously completed lab report

The goal of this experiment was to investigate the phenomenon of single photon interference. This was performed by analyzing the interference patterns created by both Mach-Zehnder and Young's double slit interferometers. Interference patterns created at high intensity levels and at the single photon level were recorded respectively using cooled EM-CCD camera. They were then compared and used to demonstrate that single photons, barring any knowledge of "which-path" information, interfere with themselves and that interference patterns at higher intensity levels are actually the sum of a large number of single photon interference patterns. These results clearly exemplified the wave-particle duality of photons.

1. INTRODUCTION AND THEORETICAL BACKGROUND

Central to understanding the nature of light is its description as photons, which are governed by wave-particle duality. This description dictates that under different circumstances, photons will act either as particles, which do not experience interference, or waves, which do experience interference. Further, despite perhaps being counterintuitive, when single photons act as waves, they interfere with themselves. These properties of light were examined in this experiment using a Mach-Zehnder and Young's double slit interferometer (see Fig.1R and Fig. 2R). An interferometer is a setup which divides the emitted light from a single source (typically coherent) into two paths, and then recombines the two paths to create an interference pattern. Interference patterns generated by multiple and single photon light levels were imaged and compared to demonstrate that the interference pattern generated at the single photon level, given a longer and longer collection time, will eventually resemble that created at high light levels.

A 633 nm Helium-Neon (He-Ne) laser was used as the illumination source in both parts of this experiment. High light levels were easily achieved by using little or no neutral density filters. To achieve a "single photon source" using the He-Ne laser, enough neutral density filters had to be placed in the beam path so that the CCD camera used for imaging the interference patterns only detected one photon per resolution-time period, or that there is only 1 photon in the length of interferometer at each time. To reach this criterion, two neutral density filters of attenuation totaling $\sim 10^{-7}$ were used together were necessary given the 10 MHz refresh rate of

the CCD camera used to achieve a “single photon source” and 1 photon per 1 meter at any given time.

One necessary criterion for single photon interference is the absence of “which-path” information. Knowledge about a photon, such as the path which it follows, requires performing a measurement on that photon. However, quantum mechanics dictates that if one performs any sort of measurement on a photon, its wave function collapses, and the photon then acts like a particle. In the part of this experiment utilizing a Mach-Zehnder interferometer, single photon interference was first observed without any knowledge of “which-path” information, demonstrating that photons can act as waves and interfere with themselves. “Which-path” information was then acquired during observation, causing the photons to act as particles and thus destroying the preciously observed interference pattern.

Single photon research is becoming increasingly important greatly due to its application in the growing quantum information field. Insight into the nature of single photons as well as the creation of single photon sources has application pertaining to quantum computing, quantum teleportation, and quantum key distribution. Applications such as these rely on quantum physics since classical physics offers no explanation for many of the interesting phenomena involved, such as entanglement of quantum states.

2. PROCEDURE

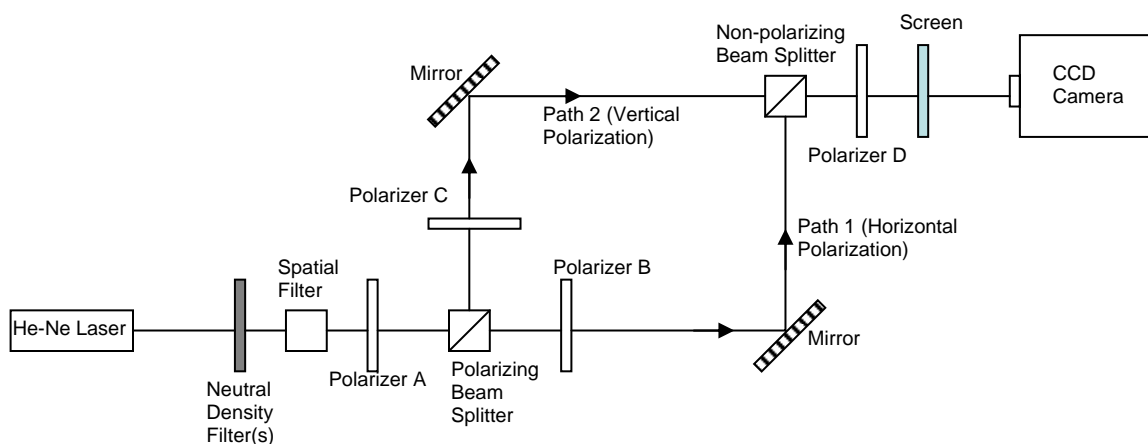


Fig. 1R. Mach-Zehnder Interferometer

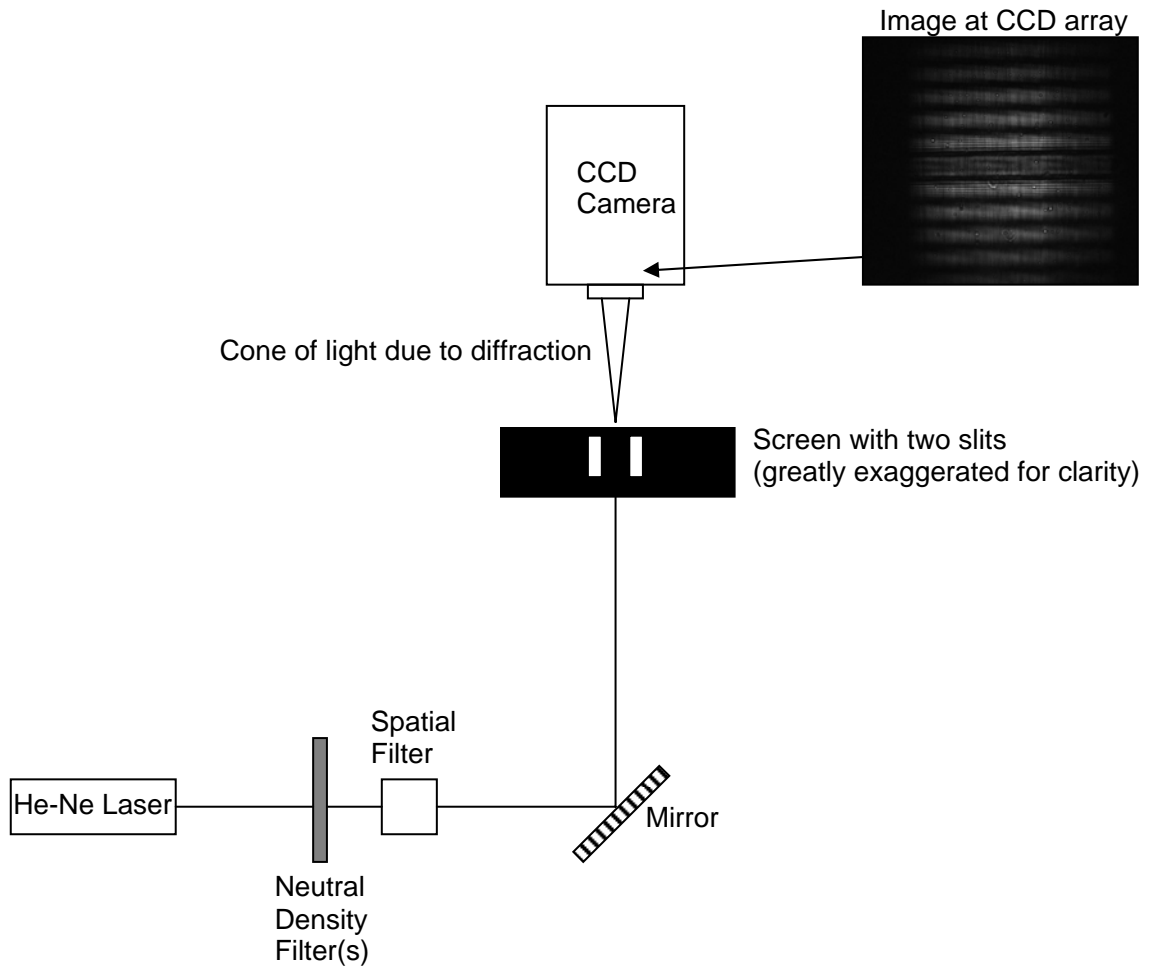


Fig. 2R – Young’s Double Slit Interferometer (The slits used had $10\ \mu\text{m}$ width and were separated by $90\ \mu\text{m}$. Observation plane was located at the $20\ \text{cm}$ from the slits’ plane).

1. The He-Ne laser supply was turned on and the power output was measured using a power meter. The numbers of photons/meter was calculated. Using this calculated value and the given refresh rate of the CCD camera used, the number of neutral density filters required to achieve a “single photon source” was calculated (see below for values). These filters were set aside and not yet used in the system.
2. The CCD camera was placed at the output of the Mach-Zehnder interferometer setup.
3. Polarizer A at the input of the Mach-Zehnder interferometer was oriented at 45° to assure that the polarizing beam splitter directed an equal number of horizontally polarized photons down path 1 and vertically polarized photons down path 2.

4. Polarizer B in the Mach-Zehnder interferometer was then oriented to assure the photons traveling down path 1 were indeed horizontally polarized. Orienting polarizer B at 90° provided maximum transmission, whereas orienting it at 0° provided minimum transmission. Thus it was certain that path 1 contained horizontally polarized photons.
5. Polarizer C in the Mach-Zehnder interferometer was then oriented to assure the photons traveling down path 2 were indeed vertically polarized. Orienting polarizer C at 0° provided maximum transmission, whereas orienting it at 90° provided minimum transmission. Thus it was certain that path 2 contained vertically polarized photons.
6. Polarizer D at the output of the Mach-Zehnder interferometer was then set at 45° , and the alignment of the entire system was checked by assuring that fringes were visible in the combined path on the screen.
7. Polarizers B and C in the Mach-Zehnder interferometer were then adjusted to provide maximum contrast in the interference pattern.
8. With polarizer D at 45° and the screen and filters removed, the interference fringes were viewed using the CCD camera.
9. The filters (total attenuation = $1.41 * 10^{-7}$) were placed in front of the laser and diminished the He-Ne laser enough that the single photon level was achieved.
10. With polarizer D at 45° and the screen still removed, the interference fringes created were again viewed using the CCD camera. Fringes were visible because orienting polarizer D at 45° eliminates any mechanism for establishing “which-path” information.
11. The interference pattern created by single photons was recorded for increasingly smaller acquisition times and with varying amounts of electron multiplier gain on the CCD camera (sees images below).
12. Polarizer D was then oriented at 0° , and it was observed the interference fringes that were visible disappeared. This was because orienting polarizer at 0° provides “which-path” information by only allowing vertically polarized photons (path 2) to reach the CCD camera.

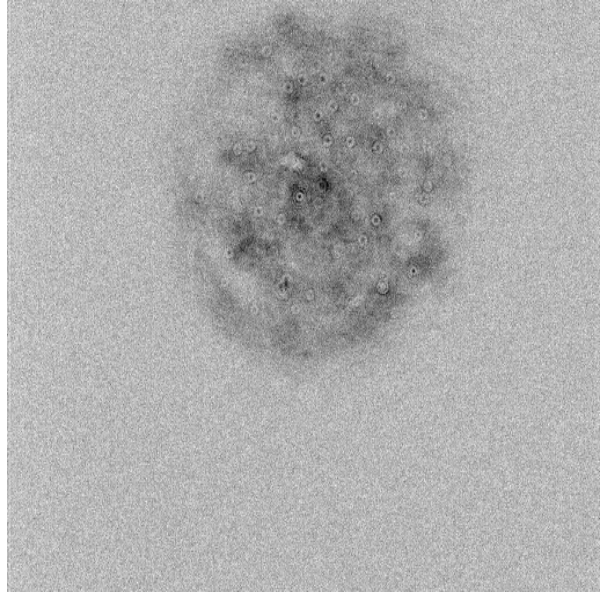
13. Polarizer D was then oriented at 90° . Again, the fringe pattern present on the CCD camera disappeared since “which-path” information was established by assuring that only horizontally polarized photons from path 1 reach the CCD camera.
14. Polarizer D was then oriented at 45° . The interference pattern was once again visible because “which-path” information was lost. Orienting polarizer D at 45° allows for both horizontally and vertically polarized photons to pass, and thus the photons reaching the CCD camera could have come from path 1 or path 2. Thus one cannot attain “which-path” information.
15. The neutral density filters removed, the CCD camera was then moved to the Young’s Double slit interferometer setup.
16. The position of the camera was adjusted until the fringe pattern created by the slits was centered on the CCD array.
17. The neutral density filters were then replaced (total attenuation = $1.41 * 10^{-7}$) to establish single photon source conditions.
18. The acquisition time was then decreased while the electron multiplier gain increased on the CCD camera. A series of images was collected showing the interference pattern created by the slits with fewer and fewer photons. The comparison of these images shows how the interference pattern that results is actually the result of the summation of single photon interference patterns.

3. RESULTS AND ANALYSIS

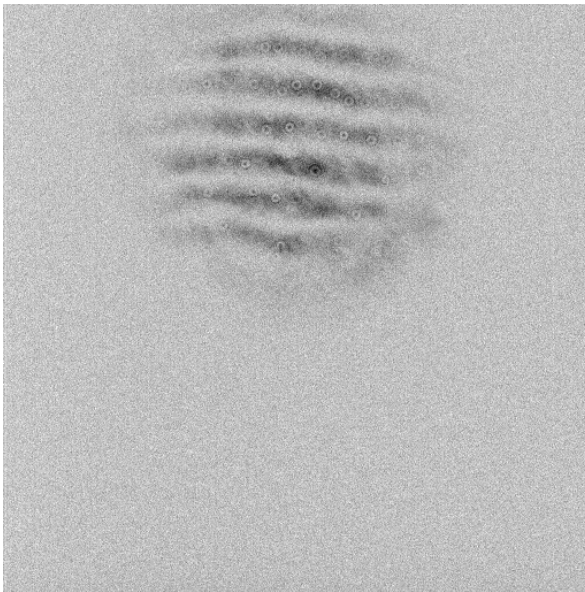
To achieve single photon source conditions: The measured He-Ne laser power output was 1.896 mW. To achieve single photon source conditions, the desired criterion is 1 photon per meter within the optical system. The calculated number of photons/m given the power measurement is $2.012 * 10^7$ photons/m. Thus an attenuation of $\sim 10^{-7}$ is needed to achieve single photon source conditions. Two neutral density filters, with attenuations of $1.24 * 10^{-3}$ and $1.17 * 10^{-4}$ were used, thus providing a total signal attenuation of $1.41 * 10^{-7}$.



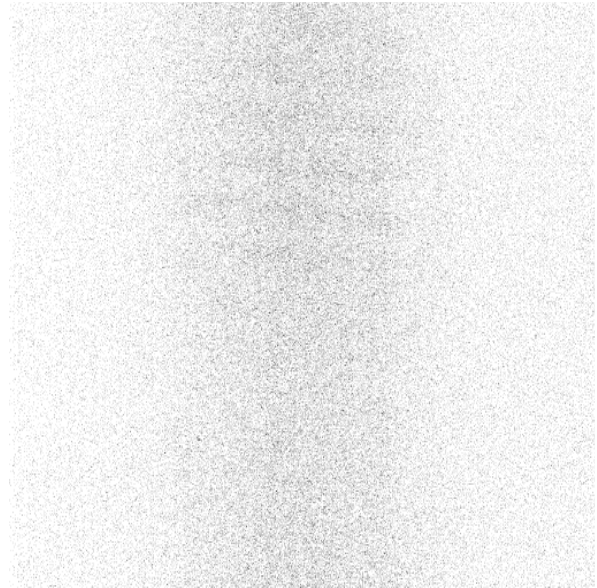
Attenuation: $1.41 * 10^{-7}$, Acquisition time: 1s,
 gain: 0x, Polarizer D = 45°
 Comment: Fringes clearly visible



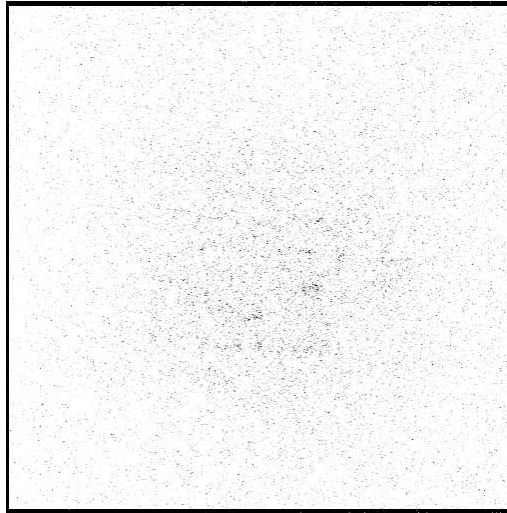
Attenuation: $1.41 * 10^{-7}$, Acquisition time: 100ms,
 gain: 0x, Polarizer D = 90°
 Comment: Fringes destroyed



Attenuation: $1.41 * 10^{-7}$, Acquisition time: 100 μ s
 gain: 255x, Polarizer D = 45°
 Comment: Fringe pattern with small acquisition time



Attenuation: $1.41 * 10^{-7}$, Acquisition time: 60 μ s,
 gain: 255x, Polarizer D = 45°
 Comment: Fringe pattern with smaller acquisition time



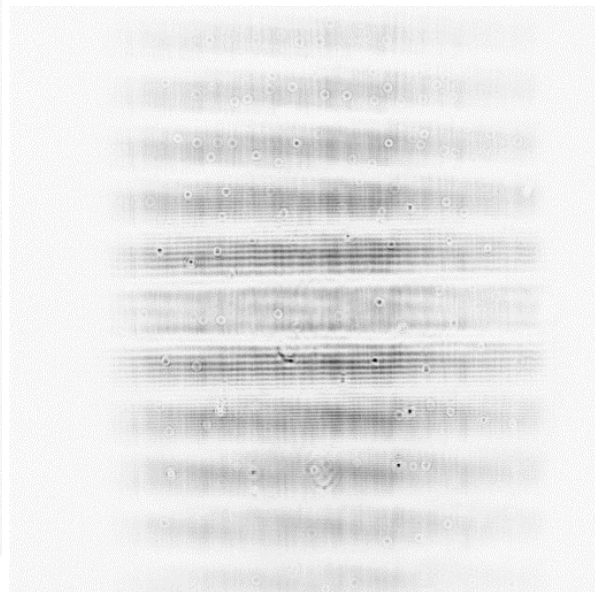
Attenuation: $1.41 * 10^{-7}$, Acquisition time: $20\mu\text{s}$,
gain: 255x, Polarizer D = 45°

Comment: Fringe pattern with smallest acquisition time, single photon interference creating pervious fringe pattern

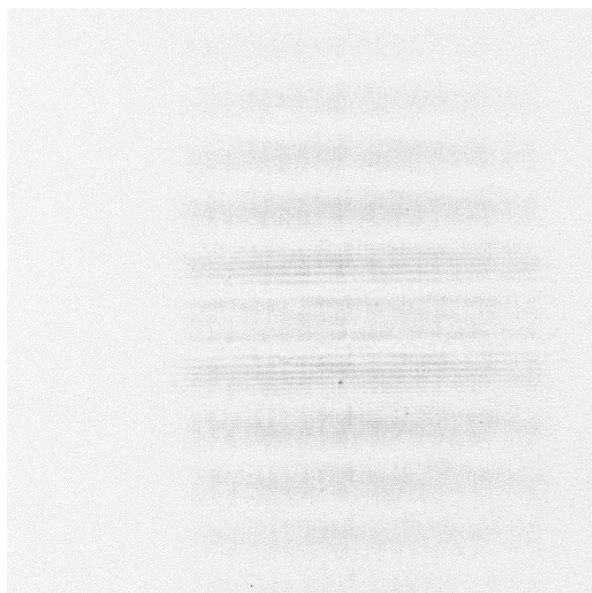
Fig. 3R. Mach-Zender Interferometer Images (see also images on page 27).



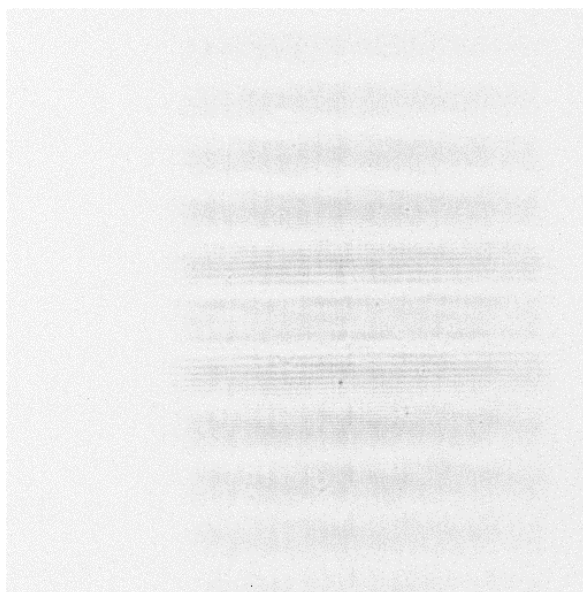
Attenuation: None, Acquisition time: 600ms, gain:0x



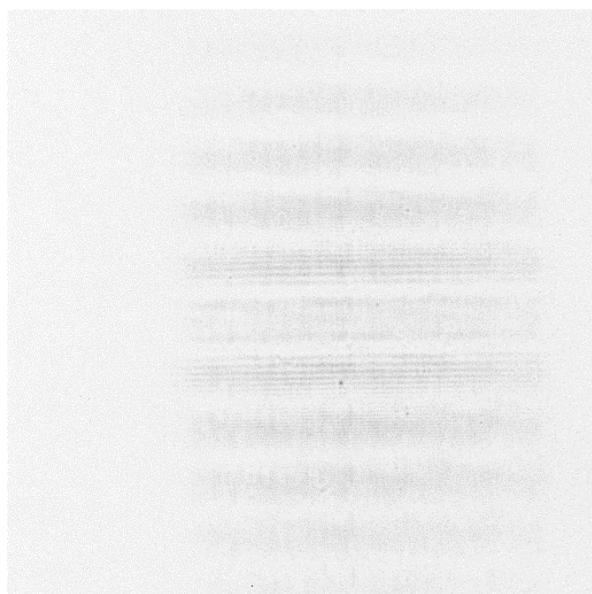
Attenuation: None, Acquisition time: 500ms, gain:0x



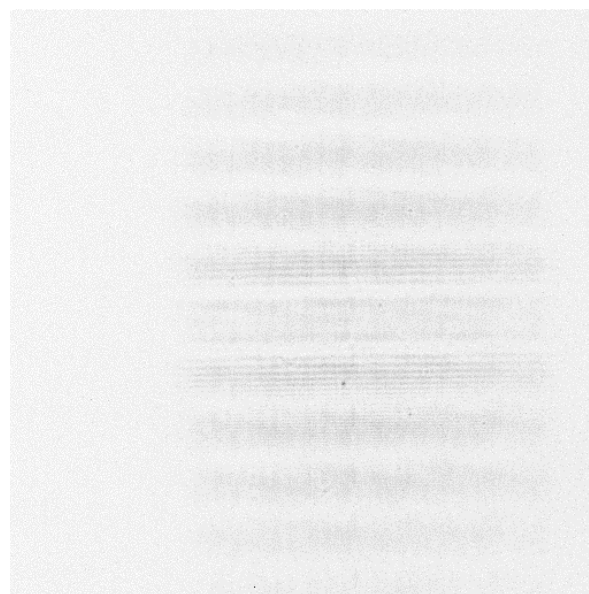
Attenuation: $1.41 * 10^{-7}$, Acquisition time: 3s, gain:255x



Attenuation: $1.41 * 10^{-7}$, Acquisition time: 2s, gain:150x



Attenuation: $1.41 * 10^{-7}$, Acquisition time: 2s, gain:100x



Attenuation: $1.41 * 10^{-7}$, Acquisition time: 100ms, gain:255x

Fig. 4R. Young's Double Slit Interferometer Images (see also page 29).

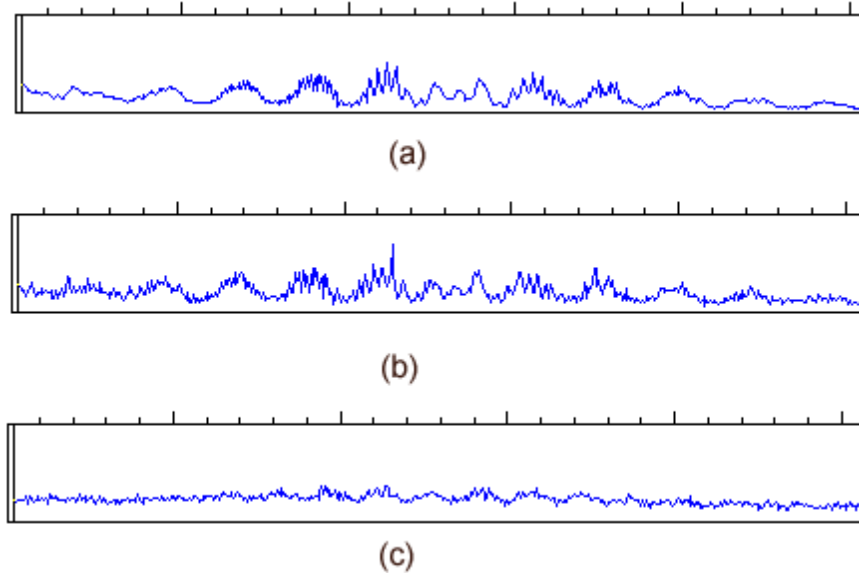


Fig. 5R. Intensity cross sections of interference pattern

Comment: One can see that with decreasing acquisition times (a-c) the fringe pattern created by single photon interference still exists. Thus, plot (a) can be considered a summation of many plot (c)'s.

4. DISCUSSION AND CONCLUSION

The data collected in this experiment generally followed the predictions presented and served as a validation of the underlying theory. The images collected using the Mach-Zehnder interferometer clearly demonstrate that when “which-path” information is present by introducing polarizer D at either 0° or 90° , the interference pattern that was present before is completely destroyed. In addition, as the acquisition time is decreased further and further, one can see that the interference pattern present becomes decreasingly visible, however, the areas where single photons strike are still consistent with the prior pattern. Thus one can see that interference pattern at higher light levels is simply a sum of single photon interference patterns. This was also the case with the images attained using the Young’s double slit interferometer: one can see that the interference pattern created by the interference of single photons will create the interference pattern characteristic of greater light levels given enough time.

There were two properties of the images collected which were not accounted for previously and require explanation. Firstly, on many of the above images, small “dots” and “blotches” are visible. This is most likely due to the fact that the vacuum seal on the CCD camera used is failing, and therefore small water droplets may form on the inside of the lens system within the cooled camera. Also, some of the larger “blotches” visible in the Mach-Zehnder interferometer images are due to imperfections in the glass of the polarizers used. Higher quality polarizers were not used due to price limitations.

Secondly, there is a series of finer fringes within the larger fringe pattern on the images collected from the Young’s double slit interferometer. Calculations showed that it may be due to interference of the beam diffracted on the double slits and a plane wave. This plane wave was formed by reflections from the metal and the glass surfaces of the screen. (Two slit pattern on the screen was made by a photolithography on a glass substrate).

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