Lab 2. Single Photon Interference

Roshita Ramkhalawon

OPT 253

Department of Physics & Astronomy

University of Rochester

Rochester 14627

Abstract

The purpose of this experiment is to investigate the effects of the wave-particle duality of light and better comprehend what causes photons to act both as particles and waves under different situations. Both multiple photon and single photon interference is carried out using Young’s double slit setup and a Mach-Zehnder interferometer. The results show that interference occurs with a multiple photon source as well as a single photon source, proving that a single photon can interfere with itself to form an interference pattern. We also show that an interference pattern only occurs in the absence of “which-path information”.

1. Introduction

The study of quantum mechanics has brought forward many odd phenomena which happen at the atomic level of matter. The wave-particle duality of light is one such phenomenon, and different observations have been made in the past to prove that light has a two-fold nature: it can act both as a particle and as a wave, depending on the circumstance. Young’s double slit experiment is one such experiment which elegantly demonstrates several counterintuitive results of quantum mechanics.

When light from the He-Ne laser is incident on the double slit, we observe that light exhibits wave-like properties and an interference pattern is created on the screen. This is also the case when the light from the He-Ne laser is attenuated to a single-photon level, suggesting that each photon interferes with itself to create the interference pattern. However, if we try to determine exactly which slit the photon went through or which photon creates the interference, the photon starts behaving like a particle, and instead of an interference pattern, we observe a Fraunhofer diffraction pattern which occurs when light passes through each single slit. Knowledge about the path followed by the photon requires us to make a measurement on the photon, and according to quantum mechanics, making a measurement collapses its wavefunction which results in the photon then behaving as a particle. The same phenomenon can be replicated using the Mach-Zehnder interferometer which is a setup where the light from the laser is separated into two beams using a polarizing beam-splitter and recombined with a non-polarizing beam splitter to create an interference pattern. The Mach-Zehnder interferometer
allows us to observe the appearance and disappearance of interference fringes as “which-path information” is respectively destroyed and restored using a polarizer before the screen.

A 632.8 nm He-Ne laser is used as the light source in both parts of this experiment. High light levels were achieved easily by using no neutral density filters. The laser source was attenuated to the single photon level by placing neutral density filters in front of the CCD camera which is used to image the interference patterns. Those filters were also helpful in eliminating any background when they were placed in front of the camera. To ensure that the CCD camera can only detect one photon per resolution time-period, there must be only one photon in the length of the interferometer at any given time. When the Young’s double slit experiment is carried out, the measured power output of the He-Ne laser is found to be 7 nW and we used 6 neutral density filters to achieve 4.5 orders of magnitude attenuation and ensure single photon level. Similarly, with the Mach-Zehnder interferometer, the power input in front of the PBS is measured and found to be 0.8 µW. Given that the length of the interferometer was 66 cm, we calculated that an attenuation of $10^{-3}$ was needed in this case. The two sketches of the experimental setups are shown in Fig 2 and 3.

2. Procedure

Fig 1. Combined experimental setup of Mach-Zehnder Interferometer and Young’s double slit
Fig 2. Young’s double slit interferometer

[Distance between slits = 90 μm, Distance to camera from slits = 22.86 cm, slit width = 10 μm]

Fig 3. Mach-Zehnder Interferometer as aligned in the lab
1. The He-Ne laser supply was turned on and the power output was measured using a power meter. The measured power output from the He-Ne laser was 7 nW after the slits.

2. The setup was aligned as shown in the figure above to carry out Young’s double slit experiment. We first observe the interference pattern created for CW (continuous wave) He-Ne laser light.

3. Then, the same Young double slit experiment is carried out for single photon interference. Single photons are obtained by using filters to attenuate the light such that there is only one photon per meter in the optical path.

4. The number of photons per meter in the CW laser was calculated to be able to predict how many orders of magnitude of attenuation should be used. It was calculated that $2.2 \times 10^4$ photons were present (for at least 300m distance between 2 photons) and therefore at least 4 orders of attenuation were needed.

5. The filters are now placed in front of the camera such that the beam is being attenuated by 4.5 orders of magnitude.

6. The CCD camera is placed at the output of the beam and the interference patterns are photographed for several acquisition times. As expected, it is shown that the interference patterns get clearer as the acquisition times get longer. The pictures taken are shown below.

7. The next step is to set up the Mach-Zehnder interferometer as shown in Fig 3.

8. We check that the laser beam is traveling parallel to the optical table. Since the laser beam is found to be sloping downwards, we use a 3-mirror setup in order to control the height, tip and tilt of the laser beam.

9. In order to adjust the tilt of the beam between each optical component, two irises of the same height were used. The beam was made to go through two irises, one which was placed closer to the component and another one further away. If the beam goes through both irises perfectly, we know that it is then travelling straight across.

10. This procedure was repeated between each component (mirrors and polarizers).

11. Polarizer A was oriented at 45 degrees to make sure that the beam is evenly split between horizontally and vertically polarized photons. The power output of the two beams was measured and it was ensured that the two beams were of equal power.

12. Polarizer B at the output of the Mach-Zehnder interferometer was set at 45 degrees – this destroys “which-path” information.
13. The alignment of the interferometer is adjusted until the interference fringes are visible on the screen – these fringes can be made clearer and rotated using the mirror adjustments.

14. The fringes are viewed using the CCD camera and the interference pattern created by single photons is recorded for different settings: the acquisition time, gain level and attenuation are respectively changed.

15. When polarizer B is oriented at 0 or 90 degrees, the interference fringes are seen to disappear. This is because orienting the polarizer at 0/90 degrees only allows vertically or horizontally polarized photons to come through – this restores “which-path” information, hence the interference fringes disappear.

3. Results and Analysis

Interference patterns obtained from Young's double slit experiment are shown below. The presence of the fine structure in the interference pattern is explained in the conclusion (section 4).

![Interference pattern](image1)

*Above picture is the interference pattern obtained using the non-attenuated laser beam. The pictures which follow are all taken with 4.5 orders of magnitude attenuation and gain 255. The different acquisition times are labeled.*

![Interference pattern](image2)

Acquisition time 0.02s

![Interference pattern](image3)

Acquisition time 0.1 s
Calculation of fringe width in Young’s double slit experiment:

Using the formula \( \Delta y = \frac{L}{a} \lambda \), where \( \Delta y \) is the fringe width

- \( L \) is the distance from the double slit to the camera = 0.2286 m
- \( a \) is the slit separation = 90 µm
- \( \lambda \) is the wavelength of the light = 632.8 nm

The fringe width is calculated to be 1.6 mm.

Calculation of attenuation to be used in the Mach-Zehnder interferometer

We calculate how many orders of attenuation we need so that there is only one photon in the interferometer at any given time. The length of the interferometer is measured to be 66 cm. The power before the interferometer is measured to be 0.8 µW. The energy of one photon is \( \frac{hc}{\lambda} \) which is calculated to be \( 3.14 \times 10^{-19} \) J. The energy per meter is \( 2.67 \times 10^{-15} \) J/m, hence the number of photons per meter is \( 8.5 \times 10^3 \). In 0.66m, there are \( 5.6 \times 10^3 \) photons. Therefore we need at least 3 orders of attenuation so that the He-Ne laser acts as a single photon source. Calculations are shown below in more detail.

Wavelength of light \( \lambda = 632.8 \) nm

Energy of one photon \( \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}) (3.0 \times 10^8)}{(632.8 \times 10^{-9})} = 3.14 \times 10^{-19} \) J

Length of interferometer = 66 cm

Energy per meter = \( 3.14 \times 10^{-19} / 0.66 = 2.67 \times 10^{-15} \) J

Number of photons per meter = Energy per meter / Energy per photon

\[ = \frac{2.67 \times 10^{-15} J}{3.14 \times 10^{-19} J} \]

\[ = 8.5 \times 10^3 \]

Number of photons in interferometer = Number of photons per meter \times 0.66 m

\[ = 8.5 \times 10^3 \times 0.66 = 5.6 \times 10^3 \) photons.\]
Below are the interference patterns for the Mach-Zehnder interferometer.

- **0.1s exposure time, No Gain, 2.5 orders of attenuation before camera**
- **0.001s exposure time, 255 gain, 1 order of attenuation before camera**
- **0.0001s exposure time, 255 gain, 2 orders of attenuation before camera, 2 orders of attenuation before interferometer, polarizer at 45 degrees**
- **0.1s exposure time, 255 gain, 2 orders of attenuation before camera, 3 orders of attenuation before interferometer, polarizer at 90 degrees: fringes destroyed**
Below are the intensity profiles of a few of the images from the Mach-Zehnder interferometer.

**1: 0.1 s acquisition time 255 gain and 2.5 orders of attenuation**

\[
\text{Fringe visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{250 - 40}{250 + 40} = 0.72
\]

**2: 0.01 s acquisition time 255 gain and 3 orders of attenuation**

\[
\text{Fringe visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{250 - 125}{250 + 125} = 0.33
\]
3: 0.001 s acquisition time 255 gain and 3 orders of attenuation

\[ \text{Fringe visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{240 - 175}{240 + 175} = 0.16 \]

From the above intensity profiles, we can see that as the acquisition times become smaller, the fringe pattern still exists. Plot 1 can be thought as the summation of several plot 3's. This further confirms that interference occurs at single-photon level.

4. Discussion and Conclusion

From the above data collected, we can conclude that the experiment verifies our predictions. We see that there is an interference pattern present both when high light level and a single photon source are used. We see that as we diminish acquisition times, the interference pattern becomes less visible, but the photons nevertheless accumulate in the same pattern. This suggests that interference pattern obtained using high light level is simply a sum of the pattern obtained from single photon source. The same is true for Young’s double slit experiment – the pattern on the images obtained at single photon level corresponds with those obtained with high light. If the acquisition time is increased, the interference pattern obtained with single photon source looks almost exactly like the one obtained with high light level.

We can also confirm that interference fringes only occur in the absence of “which-path information”. In the images obtained from the Mach-Zehnder interferometer setup, we can see clearly that the interference fringes are destroyed when the polarizer is set at 90 degrees. Since one arm of the interferometer transmits only horizontally polarized photons and the other arm only vertically polarized photons, the polarizer at the output must be set such that it transmits both polarizations equally (at 45 degrees). When it is set at 90 degrees, only one polarization of photons is allowed to go through which means the path of the photon is known; hence no fringes are observed.

It is worth noting that the images obtained with Young’s double slit experiment are not exactly what we expected, since the fringe width in the center differs from those on the ends. This can be explained by calculations which show that the beam diffracted from the slits interfered with a plane wave formed by reflections from the metal and glass surfaces of the screen. Also, regarding the images collected from the Mach-Zehnder interferometer, we can observe some “blotches” on the patterns which are due to imperfections in the glass of the polarizers. High quality polarizers were not available to us due to price limitations. Otherwise, the experiments conducted confirm our predictions in every way.