Single Photon Interference
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Abstract

The purpose of this experiment was to study the dual wave-particle nature of light. Using a Mach-Zehnder and double slit interferometer, we successfully observed single photon interference. The double slit interferometer demonstrated that when a laser beam of monochromatic light was attenuated to a single photon level, i.e., one photon goes through the slit at a time, an interference pattern was produced. Additionally, the Mach-Zehnder interferometer demonstrated the principle of “which-way” information, in which case, the interference pattern was destroyed when the path of the photon was known, and preserved when the path was completely ambiguous. This was accomplished using a polarizer to destroy the “which-way” information.

Introduction

Photons exhibit wave-particle duality; they behave as both a wave and a particle. In Young’s double slit experiment it is possible to see a stream of particles interfere with one another, photons or not. It’s also mathematically sound as the wave nature of the photons or small particles can be expressed. But what were to happen if only one photon were to pass through these slits? One would expect to see a particle-like pattern in which the majority of photons are opposite of the slits they pass through. This is not the case. Instead an interference pattern is observed; the photon has interfered with itself. This explains the wave-nature of the light, however the particle part of wave-particle duality deals with the detection method (i.e. a CCD) and how photons are detected at single locations (a single pixel).

A peculiar nature of photon behavior lies with the amount of information known about the system. With such results that indicated a photon is interfering with itself we would like to see how this would happen, naturally we would like to know the path a photon has taken. Unfortunately for scientist knowing this path destroys the wave nature of the photon and when observed the photon behaves as a particle with no interference pattern. The “Which-path” scenario is also developed in this lab, and we shall see how polarization is used to designate this.

Procedure

Mach – Zehnder Interferometer

\textbf{Figure 1 - This setup is known as the Mach-Zehnder interferometer. It was used to single photon interference.}
The experimental apparatus for the Mach-Zehnder interferometer consists of a HeNe laser (633 nm monochromatic light source), a spatial filter, several neutral density filters for attenuating the laser light, a circular aperture to further attenuate the light, four polarizers, a non-polarizing beam splitter, a polarizing beam splitter, a red band pass filter to remove the second order diffracted laser light (~1266nm wavelengths), several mirrors to align the apparatus, and an EM-CCD camera.

The following equations were used in the lab to determine the power output of the laser at the time the experiments were performed. This was primarily used to calculate the order of magnitude necessary to attenuate the laser beam to the appropriate power level using the neutral density filters.

\[
\frac{N}{s} = \frac{P\lambda}{hc} \quad \text{(Equation 1)}
\]

\[
\frac{N}{m} = \frac{P\lambda}{hc^2} \quad \text{(Equation 2)}
\]

1. A set up of the Mach-Zehnder interferometer in Figure 1 is built and aligned. Alignment was controlled by superimposing the two beams at two spots; one close to the CCD camera’s lens, and one very far away.
2. The He-Ne laser was activated and a power reading was obtained from the output beam using a power meter. The number of photons per meter was calculated using equation 2 and this, along with the CCD camera’s refresh rate allowed us to calculate the amount of Neutral Density filters needed to allow a ‘one-photon-per-meter’ adjustment.
3. Polarizer A is oriented to a 45 degree mark. Allowing the transmitted beam (lower path) through the PBS to be horizontally polarized, and the reflected beam to be vertically polarized.
4. For security Polarizer B was placed at a near zero degree mark to make sure the lower path only contained an almost horizontally polarized beam.
5. For the same security as step 4, polarizer A was placed at a mark perpendicular to Polarizer B to make sure the upper path only contained an almost vertically polarized beam.
6. Polarizer D was oriented such that its orientation was halfway between Polarizers B and C, which was the 60 degree mark. Thus not allowing us to know which path our photons were traveling, and we observed fringes on the CCD.
7. We aligned the camera based to the interference fringes to ensure the CCD captures the interference pattern.
8. The attenuation filters were placed next to the laser source as well as in front of the camera.
9. We recorded this interference pattern using the highest possible contrast of the fringes.
10. Polarizer D set to its zero degree mark. With 10 degree increments of this polarizer, the interference pattern (if any) was recorded.
Young’s Double Slit Interferometer

![Diagram of Young's Double Slit Experiment](image)

*Figure 2 - This figure is the setup for Young’s Double Slit Experiment. It should be noted that this setup was done on a different day from the Mach – Zehnder Interferometer.*

The experimental apparatus for Young’s Double Slit Experiment consists of a double slit interferometer (it should be noted that the interferometer in figure 2 is not to scale, the width and separation of the slits are 10 and 90 microns, respectively), a HeNe laser (633 nm monochromatic light source), a spatial filter, several neutral density filters for attenuating the laser light, a circular aperture to further attenuate the light, a red band pass filter to remove the second order diffracted laser light (~1266nm wavelengths), several mirrors to align the apparatus, and an EM-CCD camera.

1. Since this experiment was done on a different day of the Mach-Zehnder interferometer, the power output of the laser had to be measured again to calculate the order of attenuation required to prevent overload to the EM-CCD.
2. The apparatus was aligned as shown in the diagram above and the appropriate filters were selected to attenuate the laser for a mult-photon beam.
3. The EM-CCD was cooled using the computer software and the intensity of the interference fringes were recorded and saved.
4. The parameters such as gain and contrast were varied in the software to obtain the best image possible.
5. Now the attenuation was increased to obtain an approximate single photon beam (~1 photon per meter) according to our calculations.
6. The interference pattern was again imaged using the EM-CCD and adjusted with the parameters in the software.

Results

Mach – Zehnder Interferometer

Our He-Ne Laser source produced a power output of 87 milliwatts. Our goal was to produce an ideal setup where one photon will be present per meter. With the current power, there are around 9*10^8 photons per meter, meaning that an attenuation of ~10^8 will be needed to make sure we are getting single photons. A six order attenuation was used in the experiment. The Mach-Zehnder Interferometer split the laser source beam, oppositely polarized (i.e. vertically and horizontally) the beams and recombined them. An interference pattern was only formed with this recombined beam when the polarization of this recombined beam was disoriented by a Polarizer at a 60 degree mark.
As the angle of polarization was varied, the pattern produced was recorded using the EM-CCD camera and shown below in figure 3.

![Figure 3 - The above collection of images shows how the angle of polarization changes the interference pattern on the screen.](image)

We are able to empirically determine the visibility of the fringes using equation 3 as shown below and the ImageJ software to compute the intensity of the fringes in a cross section of the pattern as a numerical value. These values were then used to determine the visibility.

\[
Visibility = \frac{GL_{\text{max}} - GL_{\text{min}}}{GL_{\text{max}} + GL_{\text{min}}} \quad \text{(Equation 3)}
\]

![Visibility of Fringes](image)

*Figure 4 – This plot represents the visibility of fringes versus the amount of which way information determined by Polarizer D's angle. The visibly was calculated using ImageJ and Equation 3.***
Double-Slit Experiment

In this experiment, the laser power output was measured to be 0.62 microwatts so we attenuated the laser about $10^2$ to get an appropriate level for a multi-photon beam. Figure 5 below shows the captured image of the interference pattern.

Since photons have a specific energy of and thus can be considered particles, yet produce an interference pattern like we would expect a wave to, we hypothesize the photons may be colliding with each other to cause this effect and so we attenuate the beam to a single photon level. To do this we calculate that a $10^6$ order of magnitude of attenuation is required to separate the photons to 1 photon/meter. If the photons were colliding with each other, this should theoretically eliminate that effect by allowing one photon to travel through either slit at a time. The gain amplification had to be set to maximum (255 gain) and the intensity distribution was captured as shown below in figure 6.

![Figure 5a](image1.png) The above image shows the interference pattern of the double slit interferometer.

![Figure 5b](image2.png) The intensity of an arbitrary cross section of the image in figure 5.a is shown above.

![Figure 6a](image3.png) The above image is the intensity distribution of the interference pattern produced by the single photon beam. Note that even with single photon source, the interference pattern is still observed.

![Figure 6b](image4.png) The above is the intensity profile of a cross section in image 6a.
It may be difficult to observe the interference pattern from one cross section of the intensity profile but with ImageJ image software we can create a 3D plot of the entire interference pattern and it becomes clear as shown in figure 6 below.

Discussion

Mach – Zehnder Interferometer

Our results were consistent with theory! When Polarizer D (in reference to Figure 1) was aligned in such a way that the polarizations of the recombined beam were indistinguishable we saw an interference pattern. This proves that knowing the path of the photon will collapse the wave function. One would ponder if the collapse wasn’t due to which way phenomena but rather for interference the beams needed to be polarized; however this isn’t the case as other, non-polarizing, interferometers produce interference patterns.

The results also prove a geometrical phenomenon of angles (or vectors) are constructed from, and likewise broken down into, components. This is proved because of the visible interference pattern at multiple orientations of polarizer D, a component of the polarization is still is still at 60 degrees, allowing us to not know the path and thus making an interference pattern. We notice the interference pattern is cancelled at 20, 120, and (slightly) 200 degrees. Through the discussion of components it is reasonable to theorize wave collapse only occurs when extinction of one of the beams beam occurs, which is due to the polarizer being perfectly perpendicular to one of the beams.
Double-Slit Interferometer

The Double slit experiment confirms the dual wave-particle nature of photons. The results from the multi photon beam in figure 5 confirm that photons act as waves since they interfere with each other like classical waves in a pond of water. The waves produce large intensity when the maxima of the overlapping waves meet, and cancel each other out when the minima of a wave meets a maxima of another. The result is an interference pattern. Strange enough however, when we attenuate the beam so that only one photon hits the detector at a time, the interference pattern is still preserved. This eliminates the hypothesis that photons can collide with each other at the multi photon level to somehow produce the fringes and requires that we treat the photons as waves. On the other hand, by approximately attenuating the beam to a single photon level, we must also simultaneously treat the photons as particles, since one photon goes through the slits at one instant and hits the screen with energy, $h\nu$. So the only complete theory of the photon must be that it is a wave when it goes through the slits, interferes with itself and then hits the detector one photon at a time as a particle with a packet of energy. The photon must be both a wave and a particle at the same time!

Further experiments could be done to precisely fire one photon at a time and “anti-bunch” the particles. The laser used in this experiment can only be approximately attenuated to a single photon level since classical lasers cannot achieve complete separation of photons. This error, however, can be neglected because we only need an approximate single photon beam to conduct this experiment since the precision of our EM-CCD detector doesn’t resolve to that level of single photon detection.