Single Photon Interference

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Abstract:

The purpose of this lab was to explore the wave-particle duality of light through the usage of two interferometers—Young’s double slit and Mach-Zehnder. Young’s double slit involves sending a beam of light, attenuated to the single photon level, at a pair of slits and observing interference patterns. The Mach-Zehnder interferometer uses two beamsplitters to separate an attenuated beam of photons into two, and then recombines them to form an interference pattern. Different parameters such as exposure time, angle of the polarizers (for Mach-Zehnder only), and gain were altered for observation. Based on our results, we confirm that photons do exhibit wave-like properties.

Introduction:

If we were to treat photons as merely a stream of particles, we would expect that they would act like particles. With this assumption, when a stream of photons is sent through a double slit setup, we expect that the photons would go straight through and not form any sort of interference pattern, such as in Figure 1. However, this is not the case—an interference pattern emerges, showing the wave-particle duality of photons.

Figure 1: Classical Predicted Outcome of the Double Slit Experiment [1]

If a stream of ordinary particles were sent through a double slit, the resulting pattern would resemble Figure 1. If photons solely had particle properties, this is what we would expect the result of the double slit experiment to be.

Instead of a stream of photons, let us consider a single photon at a time. Classically, it seems obvious that one photon must act like a particle, and cannot exhibit wave properties on its own. However, when single photons are sent through an interferometer, the same interference pattern emerges as when there are many. When the photons encounter the slits, they travel through only one slit as a particle. This only occurs, however, so long as we do not try to observe which slit (or path) the photon is taking. If we make any kind of observation that allows us to determine the photon’s position, then the photons no longer exhibit interference—they hit the detector in the same way that a stream of particles would, forming only two bands as in Figure 1. This information is known as ‘which-way’ information. When we try to gather ‘which-way’
information about a photon, the mere act of observing collapses the wave function, and the individual photons cease to interfere. If we do not directly observe the photons going through the slits, then we do not have ‘which-way information’ and we allow for the photon to interfere with itself upon encountering the double slit, resulting in the conventional interference pattern.

In our experiment, we will test the wave-particle duality of light by forming interference fringes with single photons.

Procedures:

Young’s Double Slit Interferometer

The first experiment used the Young’s Double slit interferometer (Figure 2). The laser used was a HeNe laser (wavelength=633 nm) with a power of .7 uW. In this setup, single photons from the laser hit the double slit, consequently interfered, and hit hit the EM-CCD.

![Figure 2: Young’s Double Slit Interferometer Setup [1]](image)

Procedure:
1. Set up the double slit setup.
2. Determine laser power and attenuate to one photon per meter using neutral density filters in order to achieve single photons.
3. Place the EM-CCD so that the beam hits the center

To determine how much we should attenuate the beam, we first must calculate the energy of each photon.

\[
E = \frac{hc}{\lambda} \quad \text{Equation 1}
\]

The energy of the photons from our laser is \(3.14*10^{-19}\) J. Next, we can determine the number of photons that are being emitted per second using Equation 2.

\[
\frac{\text{photons}}{s} = \frac{P}{E} \quad \text{Equation 2}
\]

Where \(P\) is the power of the laser, given above. We calculated that \(2.23*10^{12}\) photons are being emitted per second. Lastly, we calculate from that the number of photons per meter.
\[
\frac{\text{photons}}{\text{m}} = \frac{\text{photons}}{c}
\]

Equation 3

Where \(c\) is the speed of light. We calculated that there are \(7.43 \times 10^3\) photons/m in our beam. Therefore, in order to attenuate the beam so that there is only one photon per meter and therefore one photon hitting the camera at a time, we want to reduce the photons by \(10^4\), so we use a 4\(^{th}\) order magnitude filter.

**Mach-Zehnder interferometer**

The second experiment used the Mach-Zehnder interferometer (Figure 3). Light from the laser (633 nm, 98 uW) enters the polarizing beam splitter (PBS in diagram) and is separated into two beams—one with horizontal polarization, one with vertical polarization. The two beams are recombined at the non-polarizing beam splitter (NPBS in diagram) and sent to the EM-CCD. By changing the angle of the polarizer, we are theoretically acquiring ‘which way’ information due to the two beams being perpendicularly polarized. As ‘which way’ information is ‘acquired’ (i.e. the polarizer’s angle altered), the fringe visibility will change due to observer interaction.

![Mach Zehnder Interferometer Setup](image)

1. Alignment: align the two beams such that the bright spots overlap at far and close distances in order to insure that they are collinear.
2. Determine laser power and attenuate to one photon per meter using neutral density filters in order to achieve single photons
3. Following proper safety techniques, place the EM-CCD so that the beam hits the center.
4. Polarizers A and D were both set to 45 degrees
5. Alter the polarizations of polarizers B and C to optimize fringe visibility
6. Change parameters such as gain, angle of Polarizer D, accumulations, and exposure time—record data
7. Analyze results using imageJ—calculate fringe visibility

Using Equations 1, 2, and 3, we calculated that we needed a 6\(^{th}\) order magnitude filter in order to obtain single photons on the detector.
Results + Analysis - Young's Double Slit:

The fringes formed from a .7μW 633nm HeNe laser. The beam was attenuated using 2-order magnitude filters. The camera was set to take single images with a .1s exposure time.

Our first image was not on the single photon level - we merely used it as a reference to figure out what our pattern should look like. The fringes in Figure 4 at first don’t seem correct, as the expected, traditional double slit diffraction pattern looks like a modulated single slit diffraction pattern, as shown in Figure 5. Our fringes have a series of extra vertical dark fringes in the middle of the bright fringes. This is due to reflections between the front and back surface of the glass slit object. The extra reflections interfere with one another, resulting in the striped pattern from Figure 4.

Figure 5: Ordinary Double Slit Diffraction Pattern [2]
The same laser beam from Figure 4 was attenuated with a 6th order magnitude filter. Camera was set to .007s exposure time and 255 gain with the photon counting function.

Although we initially calculated that we wanted 4th order magnitude filters, we chose to increase the number of filters in front of the camera because there was too much background noise in the system to obtain good images of the single photon interference. The intensity plot for Figure 6 is still too noisy to distinguish any kind of pattern. In the image, a faint double slit pattern is discernible. We experimented with several other image capturing functions and exposure times in order to collect good data.

Figure 7 has a clear diffraction pattern both in the image and in the intensity plot. As this image was produced with only one photon reaching the detector at a time, we can conclude that the single photons were interfering with themselves in order to produce the fringes. This verifies the wave-particle duality nature of light, as single particles normally would not interfere with each other.
Results + Analysis: Mach-Zehnder Interferometer:

Figure 8: Mach-Zehnder Interferometer Fringes
All fringes formed using 98μW laser power and 7th order magnitude filters. Exposure time was 1s with 255 gain. Each image was taken with a different angle of polarization of Polarizer D. The fringes vary in clarity depending on the angle of polarization.

As with the Young’s Double Slit experiment, we chose to increase the filter magnitude in order to block out extra noise in the system. After attenuating the beam to 1 photon/m, we were able to create an interference pattern. This once again verifies the particle-wave duality of light. For
further experimentations, we collected the images in Figure 8 by varying the angle of Polarizer D in order to determine how polarization affects the quality of the fringes.

Obviously, some of the images in Figure 8 are of higher quality than others. One way we can quantitatively measure the difference in quality between each set of fringes is by finding the fringe visibility (FV) for each image. The fringe visibility is calculated with the following equation:

$$FV = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

Equation 4

Where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensity values across the fringes. To calculate this, we took a cross sectional analysis of each set of fringes using ImageJ and from that data extracted $I_{\text{max}}$ and $I_{\text{min}}$.

<table>
<thead>
<tr>
<th>Image</th>
<th>Polarization Angle (º)</th>
<th>FV</th>
</tr>
</thead>
<tbody>
<tr>
<td>8(a)</td>
<td>81</td>
<td>0.920</td>
</tr>
<tr>
<td>8(b)</td>
<td>90</td>
<td>0.975</td>
</tr>
<tr>
<td>8(c)</td>
<td>100</td>
<td>0.911</td>
</tr>
<tr>
<td>8(d)</td>
<td>102</td>
<td>0.860</td>
</tr>
<tr>
<td>8(e)</td>
<td>120</td>
<td>0.984</td>
</tr>
<tr>
<td>8(f)</td>
<td>140</td>
<td>0.959</td>
</tr>
<tr>
<td>8(g)</td>
<td>150</td>
<td>0.932</td>
</tr>
<tr>
<td>8(h)</td>
<td>160</td>
<td>0.929</td>
</tr>
<tr>
<td>8(i)</td>
<td>180</td>
<td>0.938</td>
</tr>
</tbody>
</table>

Figure 9: Fringe Visibility of Mach-Zehnder Fringes
Calculated from a central vertical cross section of each image.

One can easily see that the images with the lowest calculated FV (8(c) and 8(d)) are clearly the blurriest images with the least well-defined fringes. However, other images, such as 8(i), appear blurry but still give a relatively high FV. FV is a limited value to calculate since it is a measurement of relative intensity in the image. The FV measures the maximum contrast across the cross-section, which can still be high even without well-defined fringes.

The general trend that can be gathered from the images in Figure 8 and the data in Figure 9 is that the quality of fringes hits a low point around 100º polarization. The fringe quality peaks at 140º. The pattern of fringe quality seems to be on a 90º cycle, where the angles of the best fringes are 90º away from each other, and the same for the angles of the worst fringes.

**Conclusion**

Both the Young’s Double Slit interferometer and the Mach-Zehnder interferometer yielded interference patterns from single photon beams. As both interferometers yielded the same interference patterns with unattenuated beams, we can conclude that the single photons interfered with themselves similarly to how groups of photons interfere. The Young’s interferometer did not yield exactly the interference pattern we expected, however, the final pattern was still an interference pattern, meaning that the single photons still exhibited the wave properties. For the Mach-Zehnder interferometer, fringes were formed so long as the two paths
were equal, although the fringes became almost indistinguishable depending on the angle of polarization of the final polarizer. The polarizer controls the clarity of the final fringes, and the quality increases and decreases on a 90° cycle. These experiments show that photons exhibit both wave properties and particle properties when isolated, and hence have wave-particle duality.

Contributions of Each Student

Ben primarily wrote the Abstract, Introduction and Theory, and Procedures. Kara did the FV calculations and wrote the Data + Results sections. Both Kara and Ben proofread the lab report to maintain continuity between the independently written sections.
References
