Lab 2: Single Photon Interference

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Abstract

In this lab we exhibit the wave-particle duality of light in the Young double-slit and Mach-Zehnder interferometer setups. We use a 5mW HeNe laser source attenuated to single photon intensity, and image the refracted light of both setups in an EM-CCD camera running Andor Solis Software to observe a time-accumulation of a granular interference pattern. The observed granularity indicates individual photon detections at the EM-CCD, while the overall interference fringe pattern indicates wave-like destructive interference at fixed locations along our detection screen. We next demonstrate “which way” information using the Mach-Zehnder interferometer; by blocking one of the polarizations from either arm of the interferometer using an analyzer polarizer after the beams are recombined, we can selectively allow photons from only one of the interferometer arms to pass to the detector. This process identifies the path of the photons, giving us “which way” information, and thus destroys the interference pattern we observe.

1 Introduction

There are two central figures in establishing the wave-particle duality of light: Thomas Young and Albert Einstein. Though, it is notable that as early as 1670, Isaac Newton developed a theory of light treating it purely as a particle to successfully explain light’s reflection. It was nevertheless Einstein in 1905, in his study of the photoelectric effect and in deriving the Black-body spectrum, who reintroduced the necessity of considering light as coming in packets or particles [1] after a perceived confirmation of the Huygens-Fresnel principle classifying light as wave-like by Thomas Young’s double slit interference experiment a century earlier, in 1803 [2]. In fact, Maxwell, in the late 1800s derived equations for the propagation of electromagnetic radiation that treated light successfully as a wave too. But, during the birth of Quantum Mechanics, Einstein’s work showed the dual particle nature of light. It was de Broglie who initially asserted that light, in addition to all matter, has both wave-like and particle-like properties, which has since been confirmed in modern interference experiments with both photons and electrons (see for recent example [3]).

In this lab, we used Young Double Slit apparatus to observe the interference of laser light with itself traveling through a double slit at single-photon intensities. We observe both single photon detections and an interference pattern characteristic of waves, indicating both the particle and wave-like nature of light. We further used the Mach-Zehnder interferometer setup with highly attenuated laser light to observe granular interference patterns for additional confirmation of the wave-particle duality of light; but, we also observed the effects of “which way” information on the interference pattern – seeing that the wave-like nature of light is only present when there is no observable distinction between light’s possible paths.

![Figure 1: Young’s sketch of double-slit diffraction interference pattern to explain when light behaves like a wave from [2].](image)
2 Experimental Setup and Procedure

2.1 Experiment Setup

We used two setups for this lab: (1) the double slit apparatus, and (2) the Mach-Zehnder interferometer, with a 5 mW HeNe laser source. The laser was first sent through a spatial filter (comprised of a microscope objective, a pinhole, and a converging lens for collimating the beam). Next, the beam was split to our two setups by a non-polarizing beam splitter.

Figure 2: The Young double slit setup.

In the Young Double Slit setup (Fig. 2), the beam was next passed through a series of attenuating filters, which we could place either before or after the double slit apparatus. Our double slits were precision cut in a 2mm-thick glass plate to have a slit width of 10µm and a slit separation of 90µm. When the attenuated laser beam passed through the double slit, the refracted light was observed using a screen (or EM-CCD for single-photon intensities). The diffracted light caused interference between the light waves emanating from each of the slits.

We attenuated our source beam to a single photon level (one photon per second per length of our apparatus). We note, though, that while the average intensity from an attenuated laser may be equivalent to that of a single photon’s energy, the lifetime statistics of a laser source preclude it from being a true single-photon source (i.e. an antibunching source; see Lab 3). What we see then from a laser attenuated to single photon levels is occasions of photon bunches, groups of photons passing through the apparatus together, while at other times we may see individual photons. Thus, we do not always see true single photon interference in this setup. Nevertheless, we may exemplify the wave-particle duality of light with our low-intensity laser source, as at single photon intensities, detections of light in our CCD occur as granulated interference patterns that intensify over time.

Figure 3: The Mach-Zehnder interferometer setup.
Our second setup, the Mach-Zehnder interferometer, is diagramed in Fig. 3. After exiting the spatial filter, a non-polarizing beam splitter sent light to the Mach-Zehnder interferometer. The light passed through a polarizer to set the beam polarization so that the intensity in each arm of the interferometer could be made equal. Then the light was split with a polarizing beam splitter and sent to two mirrors that redirected the light to a non-polarizing beam splitter to recombine the light from each arm. After passing through the interferometer, the light was then sent through an analyzer polarizer at the output of the NPBS before our detector. This polarizer was used to select which polarization could pass to our detector. The analyzer polarizer is a necessary component of our setup, because without it the encoding of path information is present in the photons coming out of the Mach-Zehnder interferometer that are incident on our detector. In other words, there is “which way” information; we do not even need to make a measurement of the photon polarization by setting the analyzer polarizer to one of the polarizations in either interferometer arm [4]. Thus, we set the analyzer polarizer to be 45deg. to the two orthogonal polarizations in the interferometer arms. This eliminates “which way” information by changing the observed polarizations at the detector to one that a photon having traveled in either arm may have with equal probability (by Malus’ Law) after passing through the analyzer polarizer. With this setup we observe interference fringes on our CCD.

2.2 Experiment Procedure

2.2.1 Young’s Double Slit Setup

(1) Calibrate Double Slit Detection: We attenuated the laser by 4 orders of magnitude and imaged with the EM-CCD camera (example image in Fig. 4). The choice of 4 orders of magnitude attenuation reduces the laser source to an average power of 100pW incident on the detection screen. This yields an average photon separation of ~1m, as shown by the following calculation:

\[
\langle N \rangle = \frac{P_{\text{laser}}}{P_{\text{photon}}} = \frac{\langle P_{\text{laser}} \rangle \lambda (d/c)}{hc} = \frac{P_{\text{laser}} \lambda d}{hc^2},
\]

where the HeNe laser power at the output of the double slit was measured to be 1 µW, \( \lambda = 632.8\text{nm} \) is the laser wavelength, \( h \) is Planck’s constant, \( c \) is the speed of light, and \( d \) is the desired spacing between photons. Then, \( 1/N \) gives the needed attenuation to achieve a source-intensity equal to that of photons having energy corresponding to wavelength \( \lambda \), spaced apart on average by a distance \( d \). Our 4 orders of magnitude result yields an average photon separation of 0.94 meters.

We can identify the resultant image as having an overall structure as predicted by the Young Double Slit equation for intensity maxima: \( n \lambda = d \sin \theta_n \); where \( n = 1,2,3, \) etc. is the fringe order, \( \lambda \) is the incident wavelength, \( d \) is the slit spacing and \( \theta_n \) is the angle from the horizontal to the screen location of the \( n^{th} \) intensity maximum. Note also the finer structure in the standard double slit structure. This is due to reflection from the double slit glass plate itself, which is caused light to interfere with the diffracted light passing through the grating.

(2) Test of varied Attenuation and Accumulation Time: The above experimental setup is reproduced for changing levels of attenuation and detector accumulation time. In Fig. 5, we see samples of images taken with an attenuation of \( 0.8 \times 10^{-5} \). At this beam attenuation the average photon separation is about 11 meters, and detection events in our EM-CCD camera occur at approximately 25.6 million/second. Note the positive correlation between visibility in fringe structure and accumulation time. We thus observe a grainy image a low accumulation times with faint interference fringes, but fringes are preserved and become more visible as time elapses, indicating that incident photons are interfering with each other during each detection event. This result serves to demonstrate the wave-particle nature of light.
Figure 4: An image (rotated 90° left) taken of the fringe pattern produced by the double slit using 4 orders of magnitude of attenuation, no gain, and with 0.1-second exposure time. The fine structure is caused by interference between reflected light due to the glass slit used as the Young double-slit apparatus and the regular double slit interference pattern. The plot on the right is a central intensity profile of the image taken at pixel 256. The red curve is sinusoidal fit to the profile as described in the analysis section. We note the fine structure and the overall double slit interference pattern.

Figure 5: Images of double slit intensity patterns taken using an attenuation of $0.8 \times 10^{-5}$, with gain of 255. Exposure times (left to right): 0.5 seconds, 1 second, 5 seconds, and 10 seconds. This accumulation time comparison exemplifies how fringe patterns become more visible over time as more photons are detected and the signal to noise ratio grows. The image visibility for 10-second’s exposure time is likely diminished due to poor signal/background contrast.

2.2.2 Mach-Zehnder Interferometer Setup

(1) **Calibrate Interferometer**: We aligned polarizer A (as labeled in Fig. 3) to set the power in each arm of the interferometer equal. Our measured power was 0.123 mW in each arm. We then attenuated the source beam by 4 orders of magnitude and took sample images in the CCD camera for several analyzer polarization angles, as shown in Fig. 6, which demonstrates the characteristic “which path” information in the interferometer. When the analyzer polarization is set to 45° from the polarization of the interferometer arms, we see maximum interference visibility. When the analyzer is aligned parallel to just one of the interferometer arm polarizations, we know which photons are passed to the detector (as the other arm is totally blocked by this polarizer) and thus we know the path of these photons, and lose the interference pattern totally.

(2) **Test of “Which Path” Information**: The above procedure was then reproduced for various analyzer polarization angles and for higher beam attenuations. Fig. 7 records a 180°-range sample in steps of 10° of how the analyzer polarization affects the Mach-Zehnder interference pattern. We note how “which way” information can be seen for analyzer polarizations of 175° and 265° (measured on the mount scale) as for these angles, we see no interference pattern. We also see interference...
visibility maxima occur about 45° from the two minima (angles 135°, 215°, and 305°), where fringe visibility is defined by:

$$V_{fs} = \frac{N_{max} - N_{min}}{N_{max} + N_{min}},$$

and where max and min refer to the maximum and minimum intensity values of the fringe pattern.

Ideally we expect a properly aligned Mach-Zehnder interferometer to yield a sinusoidal fringe pattern with approximately constant maximum and minimum intensities. But, as we see from Fig. 6 and Fig. 7, noisy signals obscure this result, reducing visibility dramatically. This noise is shown in the central cross section of Fig. 6(a). To attempt to gain information about the correlation between visibility and analyzer polarization angle, we construct a sinusoidal fitting function of the form shown in the analysis; and, by fitting to the cross sections of the CCD images from Fig. 7, compute the visibility of the fitted functions, using these as indications of the desired correlation.

**Figure 6:** Images of Mach-Zehnder interferometer, using an attenuation of 4 orders of magnitude, no gain, and a 0.1-second exposure time. Image (a) shows an interference pattern for the angle 45°. The accompanying plot displays a central cross-section intensity with a sinusoidal fit (as described in the analysis section). Image (b) displays no interference pattern because the analyzer polarization is set only to pass light from one arm of the interferometer at 90° polarization. The accompanying plot here also shows an oscillation in the intensity using the fitting function, however, we note that the magnitude of oscillation,
as indicated by the black rectangles, is smaller than in (a) by an order of magnitude. Thus, oscillations in (b) are negligible and may be an artifact of attempting to fit the data to a sine function. The ring pattern in the bottom left of each image is likely an artifact caused by dirt on the interferometer mirrors.

![images of Mach-Zehnder interferometer](image)

**Figure 7:** Images of Mach-Zehnder interferometer using attenuation 7 orders of magnitude, 255-gain, and 1-second exposure taken on 10/21/2010. The images displayed for analyzer polarizer angles in a range from 175° to 285° in increments of 10°.

### 3 Analysis and Results

As seen in Fig. 7, there are approximately 26 fringes in the CCD-detector 512-pixel region. Thus, we can take the approximate frequency of the fringe pattern in this Mach-Zehnder interferometer setup to be $f = \frac{26}{512}$. Mathematica can be used to fit a sinusoidal function to the cross section of the intensities profiles at the middle of each image (horizontal pixel line 256). We use a fit function of the form:

$$p + q \sin(a2\pi f t + b),$$

where $t$ is the independent variable, and $p$, $q$, $a$, and $b$ are fitting parameters determined by the intensity patterns. The fringe visibility can then be found from the fit as
\[
\frac{\text{Max}\{ p + q \sin(a2\pi f x + b) \} - \text{Min}\{ p + q \sin(a2\pi f x + b) \}}{\text{Max}\{ p + q \sin(a2\pi f x + b) \} + \text{Min}\{ p + q \sin(a2\pi f x + b) \}} = \frac{p + q - (p - q)}{p + q + (p - q)} = \frac{q}{p}
\]

This model allows us to make calculations of the visibility while avoiding the poor visibility introduced by the background noise, seen in Fig. 6 as the rapid fluctuations in the intensity profiles. In Fig. 8, we tabulate and plot the resultant calculated visibilities for each image from Fig. 7.

In Fig. 8 we should expect minima at analyzer polarization angles of 180° and 270°; these correspond to the orthogonal polarizations of the Mach-Zehnder interferometer arms. So “which path” information is achieved by setting the analyzer polarization to these values, and so destroys the interference fringes. We expect maxima at 135° and 315° in our measurement range, as these values are 45° out of phase with the interferometer arm polarizations. Hence, “which way” information is maximally eliminated for an analyzer polarization of this angle; the two outputs from each arm have nearest to the same probability of passing through the analyzer polarizer for this configuration. This result is supported by our results from Fig. 8. However, one observes at 225° a drop in visibility that is not predicted by the above assertions. This is likely due to ambient light contaminating our reading at that angle, or an artifact affecting the middle row of pixels from the EM-CCD that was used to evaluate the intensity spectrum of each image from Fig. 7. One could perform an average of the intensities in each line of the images to attempt to achieve clearer results.

Additionally, we report in Fig. 9 how visibility changes with acquisition time of the EM-CCD. With an attenuation of 4 orders of magnitude and the analyzer polarization set at 135°, the maximum from Fig. 8, we set the CCD camera to no gain and varied the acquisition time. We expect that longer accumulation times yield a better signal-to-noise ratio; so we should observe that longer exposure times yield better visibility of the interference fringes. Approximating the fringe visibility using the same fit as above, we determine approximate values for the visibility as a function of acquisition time, and do indeed observe that fringe visibility increases with CCD detection time.

### Table 8

<table>
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<tr>
<th>Polarizer Angle</th>
<th>Fringe Visibility</th>
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<tbody>
<tr>
<td>135</td>
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<tr>
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</table>

**Figure 8:** Fringe visibility from the Mach-Zehnder interferometer plotted against the analyzer polarization angle, with data taken from table above, where the visibilities are approximated using the curve-fitting method described in the analysis section. These visibilities correspond to the images in Fig. 7, having 7 orders of magnitude attenuation, with 1-second acquisition time, and 255 EM-CCD gain. We remove the
data point at the analyzer polarization angle at 225 deg., clearly an outlier that is due to either a CCD camera error or flaw in the data.

Figure 9: Fringe visibility from the Mach-Zehnder interferometer as a function of detection acquisition time, using 4 orders of attenuation, and an analyzer polarization of 135 deg, with no gain. We observe that fringe visibility does increase with acquisition time, as expected.

4 Conclusion

Our results indicate successful demonstration of the wave-particle duality of light. We used the Young Double Slit setup and the Mach-Zehnder interferometer in two separate experiments to observe how a HeNe laser light attenuated to single-photon intensities can produce grainy and interference-fringed intensity patterns on an EM-CCD camera. The granulated detections in conjunction with the interference fringes are indicative of both single-photon detections and the wave-like interference of light. We also showed the effect of “which way” information on these intensity patterns by rotating the analyzer polarization angle in the Mach-Zehnder setup, yielding the result that “which way” information destroys the wave-like nature of light.

5 Acknowledgements

I would like to thank Dr. Lukishova for her help in this laboratory, and for her kindness and guidance. I would also like our TA, Sophie Vo, for her questions in lab and for grading. Thanks also to the other laboratory students for collaboration.

6 References