Abstract:
In this lab we investigated the wave-particle duality of light. We verified light’s wave properties by conducting both a double slit experiment and constructing a Mach-Zehnder interferometer. In each case we recorded interference patterns at both high intensities and single photon levels. By building up interference patterns gradually over time, we demonstrated that single photons can indeed interfere with themselves. The interference patterns we observed provide direct evidence that light can behave both as a particle and a wave.

1. INTRODUCTION AND THEORETICAL BACKGROUND:

The wave-particle duality of light is one of the basic tenets of quantum mechanics. Stated simply, wave-particle duality means that in certain conditions light will behave as a wave, while in others it will behave as a particle. Any direct measurement of light collapses the wave function and results in particle behavior. When light is allowed to travel uninhibited, however, we observe wave-like properties. These wave-like properties are evident even in the case of single photons, which can interfere with themselves.

In this lab we repeated the classic Young’s Double Slit Experiment. We also built a Mach-Zehnder interferometer. Young’s Double Slit Experiment serves as a basic way of demonstrating the wave property of light. In any situation where coherent light is split into two paths and subsequently recombined, we would expect to see interference (as long as no direct measurements of the light are performed along the way). Additionally, when light passing through the two slits is attenuated to the single photon level we would expect to still observe an interference pattern being built up over time. This is a result of single photon interference. The implication of single photon interference is that as experimenters we can only think of photons as particles when they arrive at specific points of interaction. As long as no measurement has been performed, light behaves as a wave, even at single photon intensity levels. In the Mach-Zehnder interferometer experiment, this fact can also be clearly observed. As soon as which path information is destroyed, we observe an interference pattern. If we preserve which path information
meaning we know where an individual photon has been), no interference pattern can be observed because we have already verified light’s particle nature.

In this lab we used a 633nm He-Ne laser as a light source. In order to attenuate the beam to single photon levels we used a series of filters to bring the laser intensity down to an average of 1 photon/300 meters. A cooled CCD camera was used as a detector. This experiment provided verification of a fundamental prediction of quantum mechanics: wave-particle duality.

2. PROCEDURE

![FIG 1. Mach-Zehnder Interferometer](image)

![FIG 2. Young’s Double Slit Experiment](image)
1. We measured the laser intensity to be 0.27μW. Since we were using a 633nm He-Ne laser, the power per photon was calculated to be $3.14 \times 10^{-19}$ J. Thus, at 0.27μW the number of photons arriving at the detector was $8.5 \times 10^{11}$ photons/second. A spacing of 300 meters between photons corresponds to a rate of $1 \times 10^6$ photons/second. Thus we needed attenuation of roughly $10^{-6}$ in order to reach the desired average inter-photon spacing. This was accomplished using neutral density filters.

2. We placed a double slit in the path of the laser and positioned the CCD camera to collect light passing through the two slits (See FIG 2).

3. We captured images of double slit interference at high intensity levels.

4. We placed neutral density filters in front of the laser source to achieve our desired photon spacing of 1 photon/300 meters.

5. We captured images of the two slit interference pattern for various exposure times in order to show that the high intensity interference pattern is identical to a low intensity interference pattern gradually accumulated over time (i.e. a collection of single photons).

6. We then built a Mach-Zehnder interferometer (shown in FIG. 1) and directed the beam from the interferometer towards the CCD camera using two mirrors.

7. A polarizing beam splitter was used to split the light into two paths, each with opposite polarization. After redirecting the light with mirrors, the light was recombined using another beam splitter (FIG 1).

8. In order to align the Mach-Zehnder interferometer we first carefully aligned the individual components in order to ensure that the laser beam was close to level throughout the interferometer. We recombined the split beams using a beam splitter. Further alignment was achieved by tilting/rotating the beamsplitter slightly in order to get the two beams to closely overlap.

9. We used the CCD Camera to capture images of the recombined beams both with a 45 degree polarizer at the exit of the interferometer and without any polarizer at all.

10. We captured images of the interference pattern from the Mach-Zehnder interferometer at both high intensity and single photon levels to show that the interference pattern is preserved even when photons are passing through the system.
one at a time, and that high intensity patterns are similar to low intensity patterns built up over time. This demonstrates wave-particle duality.

RESULTS AND ANALYSIS

Our results confirmed that interference patterns can be built up gradually from single photon interference. In FIG 3 it is possible to see double slit interference first in a well defined interference pattern (image 1) and then in gradually more fuzzy interference patterns (images 2-4). Image 4 clearly shows that light was arriving at the CCD in the form of particles (we can see individual dark pixels), and yet an interference pattern was still present. This is a clear demonstration of wave-particle duality. The intensity patterns corresponding to images 2-4 all show the intensity variations characteristic of a double slit arrangement.

The visibility of the double slit interference patterns can be calculated using the simple equation (max-min)/(max+min) x 100. In FIG 4, the visibility of the Image 2 is very close to 100%, but decreases with increasingly short exposure times. The visibility of Image 3 is about 60%, and the visibility of Image 4 is approximately 25%. Our results clearly indicate that visibility increases with greater exposure times.

Our preliminary results from the Mach-Zehnder interferometer confirmed that when which-path information is preserved no interference pattern is present. In the two images from FIG 5 the only thing that was changed was the presence of a polarizer. When a polarizer was present we observed interference fringes because all which-path information was destroyed (the wave function was not broken down). As long as no polarizer is present the path that a photon took is encoded into its polarization state. Thus, it is not free to take both paths and cannot interfere with itself. As soon as another polarizer is introduced at the exit of the system, the information about which path the photon took is destroyed because it has a new polarization.

In FIG 6 it is evident that the same single photon interference that was observed in the double slit experiment is present in the Mach-Zehnder interferometer experiment. By capturing a series of images with different exposure times, we observed the way an interference pattern gradually builds up as photons pass through the system and interfere with themselves.
FIG 3. Double slit interference patterns.
FIG 4. Intensity cross sections of double slit interference patterns.

We observed that without a polarizer no interference pattern was observed because light exiting the interferometer contained which-path information. When the 45 degree polarizer was placed at the exit of the interferometer an interference pattern was observed.
FIG 6. Images from Mach-Zehnder interferometer at varying exposure times.

<table>
<thead>
<tr>
<th></th>
<th>Attenuation</th>
<th>Acquisition Time (s)</th>
</tr>
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<tbody>
<tr>
<td>Image 1</td>
<td>$3.0 \times 10^{-6}$</td>
<td>1</td>
</tr>
<tr>
<td>Image 2</td>
<td>$3.0 \times 10^{-6}$</td>
<td>2</td>
</tr>
<tr>
<td>Image 3</td>
<td>$3.0 \times 10^{-6}$</td>
<td>5</td>
</tr>
<tr>
<td>Image 4</td>
<td>$3.0 \times 10^{-6}$</td>
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</tr>
<tr>
<td>Image 5</td>
<td>$3.0 \times 10^{-6}$</td>
<td>25</td>
</tr>
<tr>
<td>Image 6</td>
<td>$3.7 \times 10^{-3}$</td>
<td>~ 5</td>
</tr>
</tbody>
</table>

FIG 6 CONTINUED.

DISCUSSION AND CONCLUSION

The double slit interference pattern we observed was not the shape of a theoretical double slit interference pattern. This was due to the type of double slit used (photolithography on a glass substrate). The glass led to additional reflections and interference which created the additional smaller fringes we captured in our images.

In the Mach-Zehnder interferometer experiment the difference observed between the with/without polarizer cases was drastic. When a polarizer was present we observed a clear interference pattern, while absence of the polarizer resulted in no interference pattern. This is because as long as a polarizer was absent, the information about which path a photon took was encoded in its polarization state. Thus, since each photon must have taken one path or the other, it could not interfere with itself as a wave. When a 45 degree polarizer was placed at the exit of the interferometer the path information encoded in each photon’s polarization state was destroyed. This meant that each photon was free to travel along both paths as a wave before being absorbed as a particle at the CCD.

We were able to confirm wave-particle duality in both the double slit experiment and the Mach-Zehnder interferometer experiment. In both cases we observed interference patterns even in the cases where photons were separated by an average distance of 300 meters. This indicates that even when photons passed through the interferometer systems one at a time they were still interfering with themselves. By capturing images of interference patterns created by a low intensity laser beam we showed that interference patterns ultimately consist of single photon probability...
distributions. Thus, we observe the wave property of light by observing the probability distributions of individual photons.

REFERENCES

