University of Rochester

OPT253 Lab 2 Report

Single Photon Interference

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1 Abstract

Wave-particle duality can be demonstrated by observing interference between single photons. In this lab we observed single photon interference in both Young’s double slit experiment and in a Mach-Zehnder interferometer. In the latter, polarizing each arm of the interferometer allowed us to determine which path each photon traveled, collapsing the wave function and thus eliminating the interference pattern. In both experiments we successfully observed interference patterns. Since an attenuated laser beam is a good approximation of a single photon source, these observations are persuasive evidence for the wave-particle duality of light.

2 Introduction

Various historical theories described light as both particles (corpuscles) and waves in order to explain different phenomena. However, the advent of quantum mechanics presented cases in which neither model could independently predict experimental results. Out of these results emerged a new quantum theory of light as both a particle and a wave under different circumstances.

Light interference was one such experiment. Interference of light had long been the quintessential example of its wave nature, while measurements of discrete units of light (such as the photoelectric effect) were examples of its particle nature. Performing interference experiments with single photons forces these models into conflict.

The quantum theory of light describes photons as waves that are capable of interfering with other photons. Upon being measured (for example by a detector recording the diffraction pattern), the wave function collapses to a single point. The photon then behaves like a particle, activating a single pixel on the detector. The observation in the laboratory of such interference patterns confirms the wave-particle duality of light.

Skeptics of wave-particle duality may argue that interference fringes are produced by interactions between multiple particle-like photons. Single photon interference experiments try to defeat this objection by sending only one photon at a time through the apparatus. In this lab we will approximate a beam of single photons by strongly attenuating a laser beam until the average number of photons in the experiment at any given time is less than one. In reality, photon bunching ensures that small groups of photons are likely pass through the experiment at the same time. More sophisticated techniques can produce antibunched (truly separate) photons with which to conduct these experiments. However, since it is quite difficult to imagine how only a few photons could interfere as particles to create interference fringes, our “few” photon interference experiments are still a persuasive demonstration of duality.

Single photon interference experiments can also be used to study the collapse of the wave function after a measurement. If a detector is added to a double slit interference pattern to determine which slit each photon travels through (“which path” information), the wave function will collapse and the photons will exhibit particle behavior. In order to collect this which-path information, we will use an interferometer with arms of orthogonal polarizations. Passing the resulting interference pattern through a polarizer before a detector makes a which-path measurement, collapsing the wave function and forcing the photon to behave like a particle.

3 Double Slit Experiment

In order to produce a quasi-single photon beam, we attenuated a Helium-Neon (HeNe) until the separation between individual photons was greater than one meter. The beam from the HeNe was first cleaned with a spatial filter in order to produce a homogenous beam. This beam was then
split with a fifty-fifty beam splitting cube between the double slit experiment and the interferometer described later in this report. The beam for the double slit experiment then passes through a plate with several pairs of slits etched into it and a set of attenuators before being detected by a camera sensitive to single photons.

In order to persuasively demonstrate single photon interference, the beam must be attenuated to the single photon level before passing through the slits. However, since multiple photons also interfere like waves, attenuating the beam after the slits produces the same interference pattern. Placing the attenuators immediately in front of the camera (after the slits) has the benefit of reducing the ambient light incident on the detector. Since our lab experiment was not designed to minimize ambient light (such as stray reflections from the laser), we were forced to perform our measurements with the attenuators after the slits.

We determined how many attenuators were necessary by measuring the power of the beam incident on the double slits. For a beam of power $P$ and wavelength $\lambda$:

$$\frac{\text{photons}}{\text{second}} = \frac{P \cdot \text{photons}}{J} = \frac{P \lambda}{hc}$$

Since photons travel with speed $c$:

$$\frac{\text{photons}}{\text{meter}} = \frac{\text{photons}}{\text{second}} \cdot \frac{1}{c} = \frac{P \lambda}{hc^2}$$

For our incoming beam of $0.7 \mu W$, we have 7440 photons per meter. Thus we attenuated our beam by a factor of $10^4$ in order to achieve less than one photon per meter. This simplistic calculation assumes that the photons in a laser beam are evenly distributed in space. However, since photons are bosons, they tend to bunch together. As a result, it is more likely that pairs or triples of photons pass through our experiment together. Technically, this limitation means that we have not actually observed single photon interference. Real single photon experiments use sophisticated anti-bunching techniques to resolve this issue.

After the attenuators the interference pattern is observed with an electron multiplying CCD camera. This camera is thermoelectrically cooled to $-60^\circ C$ to minimize thermal background noise. Exposures were taken ranging 1ms to 10s with the best results at approximately 1s.
4 Analysis

Images of the interference patterns were exported as 512px by 512px JPEGs (figure 2 left). These images were then processed in ImageJ to generate a one dimensional pattern. The values of all the pixels in each vertical column were summed to produce a single value. Graphing these values verses the column number produces a graph of the diffraction pattern (figure 2 right).

Several aberrations were apparent in all of our images. Small circular irregularities in the images were likely caused by pieces of dust on the optics or imperfections in the glass lenses of the spatial filter. The interference patterns also exhibit a fine structure of vertical and horizontal lines. These lines are caused by back reflections off the surface around the etched slits, which is reflective. This reflected light interferes with the incoming beam, creating this secondary interference effect.

Fringe visibility can be easily calculated for the pattern using the visibility formula:

$$V = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}}$$

Which will return a value between 0 and 1 depending on the visibility. The higher the value, the more visible our fringes. Doing so, we find obtain the value 0.939 which suggests a high visibility for our fringes.

This data clearly demonstrates that small groups of photons interfere like waves. A more persuasive test of quantum theory would use a single photon source (such as quantum dots) to create an anti-bunched beam as well as minimize ambient light levels so that the attenuators could be placed before the slits.

5 Mach-Zehnder Interferometer Experiment

As noted above, the HeNe beam used for the double slit experiment was also used for the Mach-Zehnder interferometer. After passing through the spatial filter and beam splitter, we passed the beam through a 45° polarizer and then into the interferometer.

As shown in figure 3, the beam gets passed through a polarizing beam splitter which discriminates a beam by horizontal and vertical polarizations. Since the beam has been polarized to
45°, approximately half of the beam will travel on each path after the polarizing beam splitter. We then recombine the beams by guiding them with mirrors to a non-polarizing beam splitter. The recombined beam passes through another polarizer set to 45°, through a series of attenuation filters, and then finally onto the EM-CCD. The final polarizer either removes or transmits which-path information. When the polarizer is set to 45°, the horizontal and vertical polarizations of the two beams is lost and interference can occur. As the polarizer is rotated towards 0° or 90°, which-path information is restored by discriminating the horizontal and vertical components of the combined beams. With the which-path information restored, the wave function collapses, the photon acts as a particle, and no interference is observed.

The overall setup of the interferometer was completed before we arrived in the lab but it was not properly aligned. The recombined beams must be parallel and overlap. Before we realigned the system, the recombined beams intersected but were not parallel. In order to align the interferometer, we narrowed the beam size using irises and used the walk the beam technique to superimpose both beams on top of each other. By adjusting the angle and position of the mirrors, the lab group painstakingly aligned the beams until they were parallel and interference fringes became visible.

Once aligned, we attenuated the beam with neutral density filters. Using the same methods as above, determined that our incoming beam of 98µW had approximately 1,040,000 photons per meter. Thus, we needed 6 order of magnitude attenuation to produce a beam of 1 photon/meter. The majority of the data collected was using 7 orders of magnitude attenuation which produces a 1 photon / 10 meter beam. However, as previously mentioned, photons are bosons and tend to bunch together and as a result, probably pass through the neutral density filters in pairs or triples. Thus, it is difficult to say that we have achieved a beam truly comprised of single photons.

The attenuated beam was passed through the interferometer and to the EM-CCD which was cooled to −60°C. We took several images of the single photon interference fringes while varying the angle on the exit polarizer. We captured images both when the polarizer erased the which-path information and when the polarizer preserved the which-path information.
6 Analysis

Shown below are two interferograms with the polarizer set such that in image $0^\circ$, we have which-path information and in image $60^\circ$, we do not have which-path information.

Figure 4: Interferograms with polarizer angles relative to image with minimum fringes.

Due to time constraints in the lab, our lab group was not able to obtain as many interferograms as we would have liked. Ideally, we would have obtained 20 images at $10^\circ$ increments from $0^\circ$ to $200^\circ$. We did not have enough time to make accurate measurements. Further, as you will see in the fringe visibility analysis in figure 6, we did not obtain any data for which there was 0 fringe visibility. If we had had more time, we would have been able to take more images which would ideally show us that the fringes disappear every $90^\circ$ of polarizer rotation.

However, it is still clear that when we are able to discriminate which-path the photon took through the interferometer, it will not interfere with itself. It is also clear that when we erase the which-path information, we see interference on the single photon level.

Figure 5: Cross sections of some of the interferograms in figure 4
Above are total cross sections of the interferograms. The pixel values in each row were summed to create a total horizontal cross section of the image. This reduces background and artifacts due to aberrations in the optics, as well as amplifies the signal.

Fringe visibility can be calculated using these cross sections and the fringe visibility formula:

\[ V = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} \]

We have calculated this for multiple angles of the exit filter. The results are shown below.

![Figure 6: Fringe visibility vs. exit polarizer angle](image)

The angle of the exit polarizer controls the fringe visibility. When the polarizer is set to zero or ninety degrees, only light from one arm of the interferometer is able to pass through to the detector. Since we then know that all photons detected have passed through that branch of the interferometer, we have which-path information for the photon and no interference pattern can be observed. However, if the polarizer is set to forty five degrees, light from either branch of the interferometer passes to the detector with equal probability. Since we can no longer be sure which path the photons we are recording have traveled, they produce an interference pattern. In this configuration the polarizer is acting as a quantum eraser, destroying information about the state of the photon in order to preserve its wave function.

7 Conclusion

In both experiments, we have attenuated a laser beam to the single photon level and we have observed interference. The double slit experiment has shown that single photons passing through a double slit still disperse and accumulate to produce an interference pattern. The Mach-Zehnder interferometer experiment has also shown that when which-path information of a single photon is unknown, it will interfere with itself and disperse into an interference fringe pattern.

These experiments have relied on the assumption that the attenuated laser beam contains photons that are evenly distributed in space and therefore that we had obtained single photons. This is probably not the case however, because photons are bosons and like to bunch together.
While this is a good approximation for a single photon source, a proper single photon experiment would require an anti-bunching source.

Nick contributed to this report by doing the image processing and writing the Mach-Zehnder sections and conclusion. Peter contributed by writing the abstract, introduction, and double slit sections and typesetting the report in \LaTeX.

8 References