Single Photon Interference
Edward Pei

Abstract

The following report describes the observation of the wave-particle duality of photons by demonstrating that single photons can interfere with themselves. The photon interfered with itself within a Mach-Zehnder interferometer and a Young double slit. An EM-CCD camera sensitive enough to detect a single photon demonstrated that photons are particles. Meanwhile, with a non-zero exposure time, we captured the interference pattern giving evidence of the wave nature of light. With the Mach-Zehnder interferometer, the visibility of the fringes was observed to be dependent on the polarization. The polarizer indicates that photons will not interfere with itself if it knows “which-path” it took through the interferometer.

Background

Light has been viewed from a macroscopic point of view to the microscopic world we observe it today. It was initially defined as a ray when it was studied between planets. Then in 1678, Huygens introduced in his Treatise on Light that light was composed of waves. In 1704, Isaac Newton stated in his book Optiks claiming that light was composed of particles. After much debate on which theory was true, it is generally accepted that all particles exhibit both wave and particle properties called the wave-particle duality. This concept is fundamental of quantum mechanics as it separates classical mechanics and behaviors only possible in the quantum scale.

Theory

When describing light, we categorize its behavior under different physical conditions. When viewed from a macroscopic level, light can be described as rays and waves. While under microscopic level, light is described as massless energetic particles called photons. It is only until recently that people have been able to generate and detect single photons. The main reason behind single-photon research has been the possible applications in the field of quantum communication. The mysteries and measurements in quantum mechanics are probably most simply and elegantly stated in the context of interference. When observing two waves incident to a detection area with two distinctly different paths, the interference between waves is apparent. However, when considering the same scenario with particles, the interference is no longer apparent. When the waves and particles properties happen to belong the same source such as light, the results are ambiguous giving rise to a wave-particle duality. The experiment to showcase this duality would affirm the wave nature of light by interfering the waves and count the single photons to demonstrate light’s particle nature. Consider a particle incident on two slits. The particle can either go through one or the other slit. Classical mechanics would dictate that the particle would only go through one slit. If a wave was incident on the slits, an interference pattern would arise. The scenario above is reproduced in Young’s Double Slit by sending a single photon through the slits and observing wave interference affirming the wave-particle duality.

A particles wavelength is described by deBroglie’s wavelength:

\[ \lambda = \frac{h}{mv} \]  \[1\]

However it is not the sinusoidal behavior of the particle that interferes but the probability of the particle to be on a certain point on its wavelength giving rise to a probability distribution where the particle is most likely to strike on the detector plane when traversing Young’s double slit. The probability is split in
half when the photon is faced with two paths. The split probability waves interferes and changes the 
most likely areas on the detector planes where the photon would land. The appearance of a path choice 
is also introduced in Mach-Zehnder interferometer which also affirms the wave-particle duality. The two 
paths in the Mach-Zehnder is shown to have two different polarization and no interference pattern in 
the detector plane. Only when the polarization of the two incident waves from the two different paths 
are unknown does the interference pattern become visible. The polarization gives information of the 
path taken by the photon destroying the interference pattern. This which-way information shows that 
only the probability waves are interfering since the wave is no longer split when the path is known 
preventing the interference.

Experiment

The first experiment used Young’s Double slit interferometer. The purpose of this experiment 
was to verify that single photons incident on the double slit aperture would accumulate to a double slit 
interference pattern.

The measured power of the He-Ne laser (632.8nm) before the aperture was 1µm which calculates to 
3.18 × 10^{12} \text{photons/sec} and 10^4 \text{photons/meter}. To achieve an average of 1 \text{photon/meter}, we 
attenuated to beam using 4 orders of magnitude of neutral density filters.

The double slit experiment provides no variables to modify simplifying the process while also restricting 
the analysis. The interference pattern was visible under the required condition to confirm the wave-
particle duality nature of light. The condition was that photons would be emitted in average at less than 
1 photon per meter.

Figure 1: Young Double Slit interferometer. The aperture measured 90×10 µm. The laser power is 
attenuated until the average photon per meter is less than 1. The EM-CCD camera detects an interference 
pattern confirm the wave-particle duality.
The second experiment involved a Mach-Zehnder interferometer.

The same He-Ne laser (632.8 nm) is used for the Mach-Zehnder interferometer. When measured, the laser’s output power before the neutral density filters was 2.1 µW which indicates that $2.23 \times 10^4$ photons are emitted per meter. The laser is attenuated so that the average photon per meter is less or equal to 1. An interference pattern with the condition above met will confirm the wave-particle duality of light under the right polarization setting. The modifiable polarizer at the end, near the EM-CCD, will allow analysis of which-way information. The dependence of visibility of the interference pattern informs the existence of a quantum eraser that destroys which-way information allowing the photon to interfere with itself.

Procedure

1. Setup and align the interferometer. Align the beam close to the interferometer exit as well as aligning the beam at a distance. When both section of the beam are overlapping at the two points, the beam should be overlapping at all points along the beam after the exit.

2. Adjust the polarizers and neutral density filters until interference pattern is visible.

3. Measure the power of the laser before entering the optical system and calculate how many filters must be used to achieve less than 1 photon per meter.

4. Align the EM-CCD camera with the beam which shutter is permanently closed. Place the filters.

5. Adjust the parameters of the camera and view/capture interference patterns.

Figure 2: Mach-Zehnder interferometer. Neutral density filters allow for modification of laser intensity before entering the interferometer. The polarizer allows for which-way information analysis.
Results

The pictures above captured using an EM-CCD camera all used a 0.1s exposure time to capture the double slit interference pattern. As the neutral density filter magnitude’s increased, the visibility decreased until figure 5 which a 4.66 magnitude. The EM-CCD camera is capable of capturing and accumulating multiple measurements and captured an interference pattern using 20 accumulations shown in figure 4. To further enhance the visibility, the camera could amplify the signal allowing for much more precise measurements.
The EM-CCD achieves a single photon sensitivity by multiplying the signal when a photon hits the detector. Figure 7 & 8 captures an interference pattern with 4.66 orders of magnitude of neutral density filters. The appearance of an interference pattern confirm the wave-particle duality.

The Mach-Zehnder interferometer allows for analysis of which-way information through the measurements of fringe visibility.

\[ \text{Visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

Where \( I_{\text{max}} \) and \( I_{\text{min}} \) is the maximum and minimum intensity respectively.
The visibility was measured using ImageJ from 0 to 360° with 10° increments. The result was expected with a visibility dip every 90°.

All the measurements was done using 5 orders of magnitude of attenuation for an average one photon per meter. Even under those circumstances, no gain or accumulation was needed to capture visible fringes.

The dip indicate the interference pattern visibility dependence on polarization. In other words, the which-way information is apparent at the dips and erased at the peak visibility.
Conclusion

The experiment confirms the wave-particle duality of light particles. The photons interfered with itself resulting in an interference pattern explainable only through wave like properties. The dependence of polarization angle with the Mach-Zehnder interferometer describes quantum interference and which-way information. By storing the information of path in the polarization, interference is destroyed. Meanwhile, once the polarization erases the aforementioned path information, interference fringes are visible.

Bibliography