Single Photon Interference Laboratory

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Abstract

The purpose of our laboratories was to observe the wave-particle duality of photons. We observed this in the first lab through Young’s double slit experiment and through Mach-Zehnder Interferometer experiment. For the first lab we used a 632.8nm He-Ne laser to produce our coherent light beam and used filters to attenuate it in order to be used for the Young’s double slit experiment. Using a very sensitive EM-CCD camera we were able to detect a single photon showing its particle nature and also to record the interference pattern showing its wave nature. For the second lab we used the Mach-Zehnder interferometer to observe the fringe visibility dependence to the angle of the polarizer. This experiment indicated that without removing the “which path” information there would not be interference. These two experiments prove the wave-particle duality of the light and its complexity.

Background and Theory

The human race has been fascinated by light and its complexity since ancient times. Light studies have began in ancient Egypt and Mesopotamia, then Greece and Rome, to continue in the middle age in the Islamic world, then the European industrial age up to the modern 20-21st century. In the beginning light was studied as a ray and Geometrical optics described the properties of light. Geometrical optics has been used and still is being used in lens design and illumination but has many limitations and the wave + particle nature of light has helped overcome this limitations. With the passing of the centuries the studies went more in depth and in the 17th century Huygens expressed his theories on the wave nature of light. In the 18th century Newton for the first time introduced the world with the idea that light had a particle nature. In modern physics acclaimed physicists like Max Planck and Albert Einstein theorized that light is emitted in small energy packets called photons, which explained the photoelectric effect. There is a lot of confusion about the nature of light and Young’s double slit experiment with single photons combines these two theories and introduces the wave-particle duality of light [2]. In order to demonstrate this duality experiments showing the wave nature of light through interference and diffraction, and experiments showing the particle nature of light through single photon counting should be performed. The wave effect is due to the fact that photon particles are represented as a wave function, where the amplitude of the wave function represents the probability of where the photon is at any given time. The photon in a double slit experiment can go through any of the two apertures but the uncertainty principle makes it hard to know. The photon particle theoretically can interfere with itself, but when you try to record which path the photon will go the photon doesn’t interfere. The last example is known as “which path information” and it interrupts the interference pattern [3]. Using a Mach-Zehnder Interferometer and a polarizer we study this phenomenon.
**Experiment**

The first laboratory consisted on performing Young’s double slit interferometer experiment. In this experiment we used a Helium-Neon (HeNe) laser with a wavelength of 632.8nm, a cooled electron multiplying charge-coupled device (EM-CCD) camera, spatial filter and neutral density (ND) filters as attenuators. The laser had a measured power of 0.62μW. We calculated the N(photons/second) to be $1.9 \times 10^{12}$ photon/sec and N(photons/meter) to be $6.577 \times 10^{3}$ photons/meter. In order to achieve the desired 1 photon/m, the beam was attenuated using 4 orders of magnitude ND filters. The double slit had a slit width of 10μm and separation of 90μm. The EM-CCD camera had a high sensitivity to single photons level of 512*512 pixels.

![Young’s Double Slit Interferometer schematic](image)

Figure 1: Young’s Double Slit Interferometer schematic [1].

Using the Andor iXon program of the EM-CCD camera we were able to record images of the interference pattern with different gains, different orders of magnitude for the ND filters and different recording types.

The second laboratory consisted on aligning a Mach-Zehnder Interferometer in order to observe the fringes and comprehend in more details the wave-particle duality of light. In this experiment we used a Helium-Neon (HeNe) laser with a wavelength of 632.8nm, ND filter, spatial filter, polarizing beam splitter (PBS), non-polarizing beam splitter (NPBS), 4 polarizers, two mirrors and the EM-CCD camera [1].
The laser had a measured power of 87μm. We calculated N (photons/meter) to be 0.923*10^6 photons/m. In order to achieve an attenuation of 1 photon/m, 6 order of magnitude ND filters were used. This setup allowed us to observe the wave-particle duality of light under the right polarization. Polarizes B and C were used to check the polarization in Path 1 and Path 2. We used a rotating polarizer in front of the EM-CCD camera to change the angle of the polarization in order to analyze the “which way” information. The dependence of visibility of the interference pattern shows us the existence of a quantum eraser that cancels which-way information, allowing the photon particle to interfere with itself.

**Procedure**

For Young’s Double Slit

1- System was aligned for the spatial filter and the ND filters part.
2- Aligned the double slit and the camera to the incoming beam.
3- Opened Andor iXon camera software program and took 11 pictures while varying the exposure time, gain, order of magnitude of attenuation and accumulation.

For Mach-Zehnder Interferometer

1- System was aligned up to the polarizing beam splitter (PBS).
2- Aligned the PBS so that the incoming laser beam would hit the center of the two mirrors and the non-polarizing beam splitter in order to make upcoming steps easier.
3- Aligned the aperture size and polarizers so that the intensity and polarization of the beam allowed us to align the beam close to the exit point (beam splitter) and align the beam at a distance (wall).
4- Aligned PBS, NPBS and the two mirrors in order to observe interference fringes on the screen (this was the trickiest part of the alignment). When the beam close to the exit and the beam far to the exit were overlapping at the same time we knew the alignment was done correctly.
5- Attenuated the laser light with 6 orders ND in order to have 1 photon/meter.
6- Inserted rotating polarizer in front of the EM-CCD camera.
7- Opened Andor iXon camera software program and took 22 pictures while varying the angle of orientation of the polarizer every 10 degrees.

Results

For Young’s double slit experiment

Figure 3&4: Left image is a double slit interference pattern with 0.1s exposure time, 2 orders of magnitude of ND filters and no gain. Right image is a double slit interference pattern with 0.1s exposure time, 4 orders of magnitude of ND filters and no gain.

Figure 5&6: Left image is a double slit interference pattern with 0.005s exposure time, 6 orders of magnitude of ND filters, 10 accumulations and 255 gain. Right image is a double slit interference pattern with 0.005s exposure time, 6 orders of magnitude of ND filters, single and 255 gain.
The pictures above were taken using an EM-CCD camera with a 0.1, 0.05 and 0.005 s exposure time in order to record the double slit interference pattern. We used a 4 order ND filter in the beginning and then a 6 order ND filter in the other recordings. We can observe that the visibility of the fringes decreases as the order of magnitude of the ND filters increases. Measurements were taken changing the exposure time, the gain of the camera and the accumulations. Some of the pictures were not clearly visible but after amplifying the signal with the gain we were able to enhance the visibility of the fringes. These images of the interference fringes confirm our theory about the wave-particle duality of light.

**For Mach-Zehnder Interferometer**

Using the Mach-Zehnder interferometer for single photon interference allowed us to analyze the which-way information through the measurements of fringe visibility.
In order to measure the fringe visibility we use the given formula: \( Fringe \ Visibility = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \), where \( I_{max} \) and \( I_{min} \) are the maximum intensity and the minimum intensity [1].

Figure 9: Twenty Mach-Zehnder interference patterns with polarizer set from 160° to 10°, with increments of 10°. We can see the interference pattern without fringes at 110° and 20°.
We made 21 measurements of the interference pattern visibility starting with the polarizer at a rotation at $0^\circ$ up to a polarization rotation of $200^\circ$, with increments of $10^\circ$. We used the software ImageJ to measure the visibility of the images. The measurements were made using 6 order of magnitude of attenuation to achieve 1 photon per meter, an exposure time of 0.1 seconds and gain of 255.

The dip in the graph indicates the interference pattern visibility dependence on the polarization, meaning that the which-way information is noticeable at the dips and canceled at the peak of the visibility. From the above plot at $20^\circ$, $110^\circ$ and $200^\circ$ which are a $90^\circ$ (dip-dip) difference, we can see that the which-way information is present and interference pattern starts to disappear. We also have the visibility oscillation peak-dip every $45^\circ$. 

Figure 10: Plot profile of the intensity of the captured images analyzed using ImageJ. The left plot is the interference pattern of the polarizer at $0^\circ$. The right plot is the interference pattern of the polarizer at $30^\circ$.

Figure 11: Plot of the Fringe visibility vs. polarizer angle of the Mach-Zehnder interferometer. We can observe the variation in fringe visibility with the variation in polarization angle.
Conclusion

These experiments confirm the wave-particle duality of light. We observed that the photons interfered with themselves resulting in an interference pattern in both of our experiments. The dependence of the polarization angle in the Mach–Zehnder interferometer describes quantum interference and which-way information. We were able to calculate the fringe visibility by using the cross section of the images.

References