Experiment 3: Dual path interference

PHYS-C0258: Quantum Labs

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Objective of the Experiment is to investigate the impact of indistinguishability of the system states on the measurement result in a Mach-Zehnder interferometer and to get the basic understanding of performing experiments in quantum optics.

Tasks:

1) Demonstrate the influence that photon "path" information has on the measurement result with photons in a coherent state (instead of a single-photon one).

2) Compare the results with theoretical values from a simulation.

Introduction

Discussion on the nature of light dates back to the philosophers of the ancient Greece, and started to be actively supported by experiments in Newtonian times. What is now known as wave-particle duality is a paradigm that propagating light behaves as a wave, while the absorption of light energy takes place at single locations the way particles are absorbed. One of the most prominent manifestations of wave-like nature of light is interference.

Interference of optical waves can be observed if the interacting waves are of the same frequency, polarization, and when the phase difference between them is constant. A basic experiment illustrating the phenomenon is a Thomas Young's double-slit experiment, where a coherent light passes a double slit forming an interference pattern on a screen. Striking feature of the experiment is that reducing the light source intensity to a single-photon level does not destroy the interference pattern. One can pose a question: which path does a single photon take? If this information is unknown, then an interference pattern is observed. If we somehow determine which of the paths does the photon take, the interference pattern is lost. This experiment illustrates the fundamental feature of quantum mechanics, namely the rule for combining probability amplitudes. For indistinguishable outcomes, the resulting probability is the absolute square of the sum of two amplitudes:

$$P = |\Psi_1 + \Psi_2|^2$$

while for distinguishable outcomes one first squares the amplitudes for all possible outcomes, and then takes the sum.

$$P = |\Psi_1|^2 + |\Psi_2|^2$$

This Experiment demonstrates, using classical principles, how the presence or absence of information about the path of a photon supports or destroys the interference of probability amplitudes for path-entangled photons. It is also demonstrated that, even if information about the path of the photon is available at the initial stage, if this information is then later destroyed ("erased"), the interference pattern will be observed again.

Experimental set-up

The experimental set-up shown in fig. 1 is analogous to the double-slit interference experiment and is based on a Mach-Zehnder interferometer (MZI). Incident light is split into one of two optical paths by a beamsplitter. Relative phase between light beams propagating in two arms of the interferometer varies with the optical path length in the arms. The beams are recombined by a second beamsplitter, and complementary interference patterns are observed on the screens. To distinguish between the two paths that a photon can take in the interferometer, two polarizers are introduced into the arms.

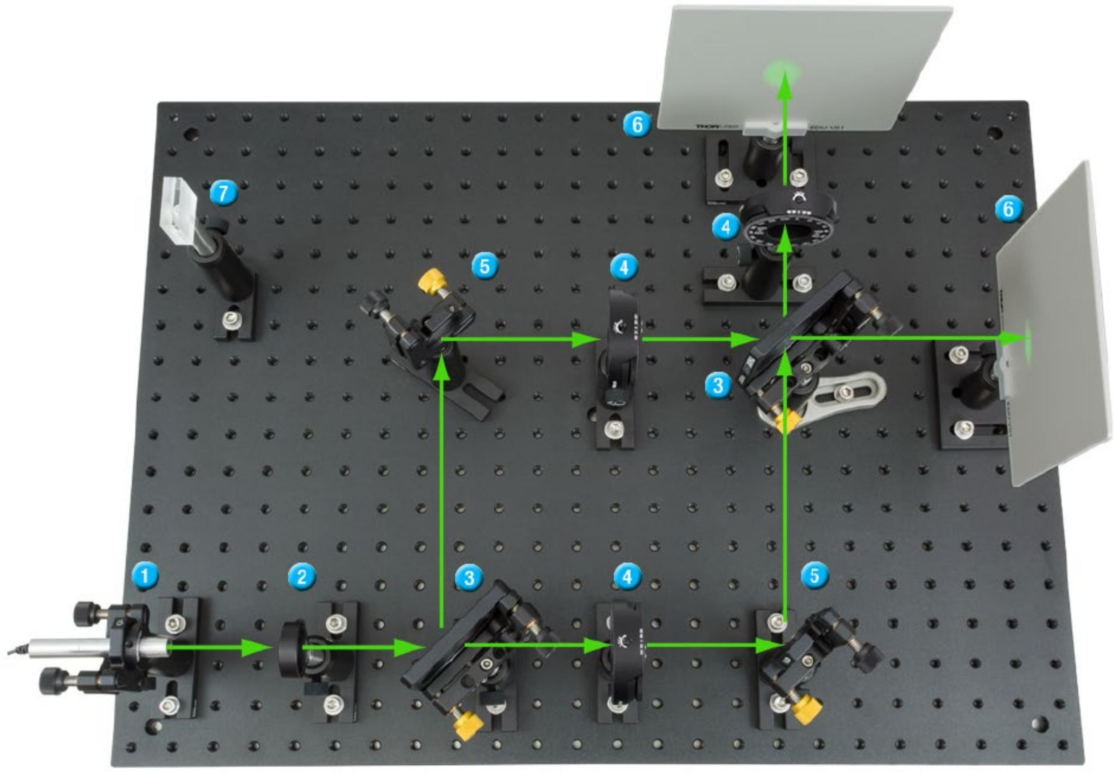

Figure 1. Schematic of the experimental set-up.
1 – laser diode module; 2 – lens; 3 – beam splitters; 4 – polarizers; 5 – mirrors;
6 – observation screens. In the experiment, the top screen is replaced with a CMOS camera for data acquisition purposes. Image by Thorlabs [1]

The data is acquired with a camera that replaces the upper screen in fig.1. The software extracts 1D stripes form the camera image and averages them over multiple frames. The data can then be saved as a .csv file along with the full image from the camera for data analysis and processing.

Theoretical description

In a quantum mechanical description for a single photon, the interferometer without the polarizers can be thought of a two state system. We can then choose a basis where the photon in the upper path is $|U\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ and in the lower path $|L\rangle = \begin{pmatrix}0\\1\end{pmatrix}$. Similarly, we can construct a 2 dimensional Hilbert space for the polarization and denote a vertically polarized photon by $|V\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ and a horizontally polarized by $|H\rangle = \begin{pmatrix}1\\0\end{pmatrix}$. The Hilbert space involving both the polarization and the path is the product of the two separate spaces, $H = H_1 \otimes H_2$. This product space is therefore 4 dimensional, with the basis vectors $|U\rangle \otimes |V\rangle = |UV\rangle$, $|U\rangle \otimes |H\rangle = |UH\rangle$, $|L\rangle \otimes |V\rangle = |LV\rangle$, and $|L\rangle \otimes |H\rangle = |LH\rangle$. As shown in fig. 1, the photon starts in the upper path, and since the laser has a preferred polarization set at 45 degrees, the initial state of the photon is

$$|I\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\\0\end{pmatrix}$$

All the optical components on the beam path can then be described by operators operating on the photon state. For example, the first beam splitter conserves the polarization, and has a 50/50 chance to flip the path of the photon:

$$BS_1 = \frac{1}{\sqrt{2}}\begin{bmatrix}-1 & 0 & 1 & 0\\ 0 & -1 & 0 & 1\\ 1 & 0 & 1 & 0\\ 0 & 1 & 0 & 1\end{bmatrix}.$$

The final state of the photon can be found by operating on the initial state with all the components in the proper order.

$$|F\rangle = [P_3][BS_2][PS][M][P_U][P_L][BS_1]\,|I\rangle$$

Here P_3 is the third polarizer in front of the detector, BS_2 the second beam splitter, PS describes the phase shift due to unequal lengths of the two paths, M is the mirrors, P_U and P_L are the polarizers on the upper and lower paths, and BS_1 is the first beam splitter. The probabilities of detecting the photon on either screen can then be calculated from the final state $|F\rangle$.

Implementation of the Experiment

1) Design an experimental procedure to acquire the necessary data for the report. The first question you should answer is: What is the impact of the angle of the two polarizers on the interference pattern?

2) Perform the measurements according to the design from 1).

3) Perform the so called "quantum eraser" experiment: introduce a third polarizer in front of the camera. What happens to the interference pattern? Why?

4) [optional] If there is extra time, practice aligning the interferometer and see how the other components influence the interference pattern.

Questions for the report:

1) How is the photon "path" information encoded in this Experiment? How does the path information relate to the visibility of the interference?

2) How does the interference pattern visibility change with changing the relative orientation of P1 and P2 polarizers? Plot the visibility of the pattern as function of the relative angle. A good metric for the visibility is the prominence of the peaks of the interference pattern, the Matlab function `findpeaks()` can be useful for this. Similar functions are available for other languages as well, e.g for python `scipy.signal.find_peaks()`.

Another option is to calculate the interferometric visibility $V = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$, where V is the visibility, I_{max} the intensity at the bright part of the pattern and I_{min} the intensity at the dark part.

2) How does introducing the third polarizer affect the interference pattern? What should its orientation be for best results?

3) Compare the experimental results to theoretical prediction from the provided simulation. Do they match? If not, why? What are the largest error sources? Some errors were already mitigated during the experiment, how was this done?

References:

[1] Thorlabs Quantum Eraser demonstration kit:

https://www.thorlabs.com/drawings/7de2f8d008b05750-ABB62716-B23D-7F02-6B2A14913D740C97/EDU-QE1_M-EnglishManual.pdf