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Mach-Zehnder interferometer

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Abstract

In this lab course students set up and operate a Mach-Zehnder interferometer. The interferometer is used to explore interference phenomena of a classical laser beam and at the single-photon level. The results can be interpreted based on the wave-particle duality. Moreover, abstract concepts such as the encoding of 'which-way' information and quantum erasure are realized experimentally.

Contents

1 Description

The Mach-Zehnder interferometer (MZI) is a tool for measuring optical interference and coherence (see Fig. 1). An optical beam is sent onto a 50:50 beam splitter and separated into two arms. The two arms are then reflected off mirrors that direct them onto a second 50:50 beam splitter which recombines them. At the two output ports of the second beam splitter one measures interference patterns that depend on the path length difference between the two interferometer arms. For a classical beam of light, e.g. a laser beam, this interference can be explained by the wave-nature of the electromagnetic field. On the contrary, a single photon will pass through the MZI in a coherent quantum superposition of both paths. Being a particle the photon can only be detected in one interferometer arm or one detector port at a time which is fundamentally different from the classical theory. However, when averaged over many runs of the experiment, the single photon detector signal shows the same interference pattern as the laser.

2 Which-way information and quantum erasure

The MZI is in principle equivalent to a simple double-slit experiment. However, one has the additional possibility to manipulate the two interferometer arms independently. For example, detecting whether the photon has traveled through the upper or the lower arm, a concept known as 'which-way' information, destroys the superposition

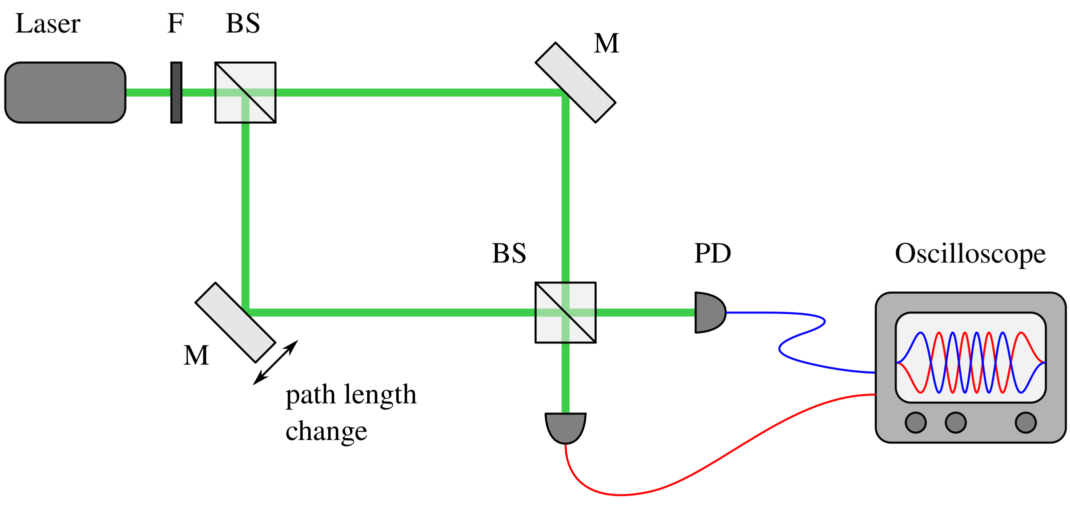

Figure 1: Schematic of a simple Mach-Zehnder interferometer. An interference pattern is recorded as a function of the path length change between the two interferometer arms. F: attenuating filter, BS: 50:50 beam splitter, M: mirror, PD: photodetector.

and the interference. Instead of placing a beam block or detector in one of the arms, one can project the two arms onto orthogonal optical polarizations. Information about the path that the light has taken is then encoded in polarization and the interference pattern vanishes. This can be interpreted as which-way information that allows to distinguish the two paths at the detector. Interestingly, the which-way information can be erased such that the interference pattern reappears. One achieves this by placing another polarizer in front of the detector that projects the beams emerging from the two interferometer arms onto the same polarization again. The second polarizer undoes the encoding of which-way information into polarization, which is called quantum erasure [1].

3 Tasks

In this lab course students set up and align a simple MZI to measure optical interference with both a strong laser beam (many photons in the interferometer on average) and a laser attenuated to a level where on average only a single photon passes the interferometer. In the two regimes interference patterns are recorded using a standard photodiode and a photomultiplier tube, respectively. Students then use linear polarizers to manipulate the interferometer arms in order to encode which-way information in polarization. They explore the conditions under which the interference pattern vanishes or appears.

References

[1] T L Dimitrova and A Weis. Lecture demonstrations of interference and quantum erasing with single photons. *Physica Scripta*, T135:014003, jul 2009. doi: 10.1088/0031-8949/2009/t135/014003. URL `https://doi.org/10.1088/0031-8949/2009/T135/014003`.