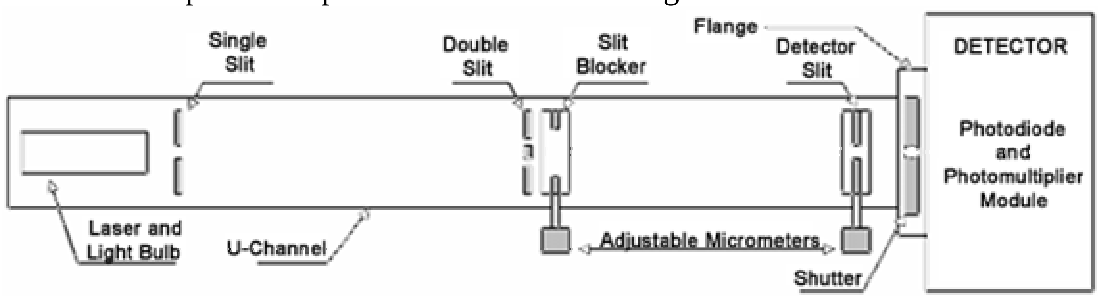
Photon Interferometry

Introduction

In this experiment you will explore the classic Young's double slit interferometry experiment. It demonstrates the wave-particle duality of the electromagnetic radiation. One can also demonstrate some simple effects from quantum measurement theory. You will explore commonly used optical components.

The basic setup of the experiment is shown in the figure



The system is enclosed in a light-tight box to allow measurements at single photon level. The experimental setup provides a number of options to explore:

Light source

Two sources are provided: a diode laser (similar to a red laser pointer) and an incandescent light bulb. You can compare the interference pattern for coherent vs. incoherent light.

Slits

Several options can be explored: Single slit, double slit, and double slit with separate linear polarizers over each slit with orthogonal polarization orientations.

Optical elements in the beam path

You can insert various elements in the path of the beam to explore their effect: Linear polarizers, a dielectric beamsplitter, and optical glass. You can also selectively insert elements into the path for only one of the two slits using a slit-blocker.

Detectors

Two detector systems are setup: A photodiode and a photomultiplier tube. A photodiode provides a voltage proportional to the light intensity, while the photomultiplier tube works in single photon counting regime. The data are collected by scanning the detector slit with a motorized drive.

For more technical details you can consult the instrument manual.

Analysis of interference pattern.

Quantitative analysis of the interference lineshapes can be obtained following Huygens principle, in which each point acts as a source for a spherical wave:

$$E(r) \propto E_0 \frac{e^{ik.r}}{4\pi\, r}$$

where $k=\omega/c$ is the wavenumber and time dependence $e^{-i\omega t}$ is assumed. One can also think of this as Green's function for the wave equation. Therefore the total wave is an integral over all source points:

$$E(r) \propto \iint_{slit\ plane} E_{inc}(r') \frac{e^{ik|r-r'|}}{4\pi|r-r'|} d^2 r'$$

We are interested in the far-field interference pattern, where $r >> r'$, and $|r-r'| \approx r - \hat{\mathbf{r}} \cdot \mathbf{r}'$,

$$E(r) \propto \frac{e^{ikr}}{4\pi\, r} \iint_{slit\ plane} E_{inc}(r') e^{-ik\,\hat{\mathbf{r}}\cdot\mathbf{r}'} d^2 r'$$

The interference pattern is effectively a Fourier transform of the slit shape. This formalism can also be extended to include polarization and phase delay of the electromagnetic wave by treating E_{inc} as a vector with a complex value. The detected intensity is proportional to $|E(\mathrm{r})|^2$. For example, for a single slit of width $2a$ we get an intensity pattern given by the square of the sync function:

$$I(\theta) \propto \left| \int_{-a}^{a} e^{-ikx'\sin\theta} dx' \right|^2 \propto \frac{\sin(ak\sin\theta)^2}{(k\sin\theta)^2}$$

as a function of an angle θ away from the axis normal to the slit plane.

Remarkably, the same formalism applies in quantum mechanics, replacing E with the photon wavefunction Ψ. The probability of detecting the photon is Ψ^2. Therefore you can explain the effects you observe both in terms of classical fields and in terms of quantum mechanical wavefunction. The results will always be consistent, but the reasoning might be slightly different.

Experimental procedure

1. Setup a basic configuration using the laser, a single initial slit, a simple double slit, and a single detection slit. Align the laser so the beam goes through the center of all three slits. You scan see the interference pattern by putting a white card into the beam path. You might need to adjust the tilt of the double slit to make sure the interference stripes are vertical and are well aligned with the detection slit.

2. Close the cover of the interferometer and take a scan using the photodiode. Make sure the manual control knob of the micrometer is in the center position (yellow light is off) to enable computer control. You should see a clear interference pattern with amplitude of a few volts and good contrast.

3. Move the laser out of the way and turn on the lightbulb. Close the interferometer cover and switch to the photomultiplier tube by pulling the photodiode up out of the way. You need to turn on the HV for the photomultiplier tube and adjust the discriminator threshold setting until you can see clear signals from single photons on the oscilloscope. Record the data on the computer using the counting mode, now the scan speed needs to be

significantly slower. Before opening the interferometer cover, close the PMT by pushing down on the photodiode. Otherwise, the experiment will make a warning beep, the PMT can be damaged by exposure to bright light.

4. Once you become familiar with the apparatus, you can explore many conditions:

a) Diffraction pattern from a single slit. To get the whole pattern you might need to shift the slits manually to increase the range of the scan.

b) Dielectric beamsplitter in the path of both slits. It reflects about 40% of the light. What can you say about the probability of photon reflection on each of the two paths?

c) A half-silvered mirror in the path of only one slit. It needs to be carefully aligned by watching the pattern on the white screen before recording it.

d) A linear polarizer in the path of only one slit. See what happens if you put an additional linear polarizer before it. Compare the signals for linearly polarized light from the laser and unpolarized light from the bulb.

e) A double slit with orthogonal polarizers over the slits. At first the interference pattern will disappear, but there is a way of getting it back using linear polarizers before and after the slits. Check for differences between the laser and the light bulb.

f) A piece of optical glass in the path of one of the slits. Compare the signals from the laser and the light bulb.

g) Feel free to explore other configurations of the optical elements

5. Analyze quantitatively the shape of the interference patterns from one and two slits. Check for wavelength differences between the laser and the lightbulb.

6. Interpret your observations under different conditions. Explain the presence or absence of the interference pattern using both classical EM fields or measurement principles from quantum mechanics.