Lab2: Single Photon Interference

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ABSTRACT

The wave-particle duality of light was verified by multi and single photon interference both through Young's double slit and Mach-Zehnder interferometer. In these two sets of experiments, the interference in the single photon level is the same as that at multi photons level with long enough exposure time. In the Mach-Zehnder interferometer, the "which-path" information can be identified by measuring the polarization of each path. With the knowledge of this information, there is no interference, which proves the duality of light as particle and wave.

Keywords: Wave-particle duality, Young's double slit, Mach-Zehnder interferometer, "which-path" information

1. INTRODUCTION

1.1 Introduction of background

Study of light began very early in the history, and there were different kinds of theory about optics. Beginning in 1670, Isaac Newton developed his theory that light is particle, and the straight line of reflection of light supports his theory. However, the particle theory can't explain refraction of light. Robert Hooke, Christian Huygens, and Augustin-Jean Fresnel found out the medium-depended of light when it travels in the medium, and their theory interprets refraction very well. And the Huygens-Fresnel theory was proved by Thomas Young's double slit interference experiment. Later James Clerk Maxwell developed four simple equations which describe that visible light, ultraviolet light, and infrared light are electric-magnetic wave with different frequency. Though it seemed that the optics wave theory prevailed, the birth of quantum turned out to be an important milestone. Albert Einstein explained the photoelectric effect based on Planck's formula for black-body radiation model. The photoelectric effect points out that electron can only receive energy from electromagnetic field in discrete amount energy portion which is denoted as photons, and this theory is a good support of light particle theory. Then De Broglie solved this paradoxical problem by claiming that all matter has a wave-like and particle-like nature. Later his theory was proved by the electron interference experiment and also supported by Heisenberg's uncertainty principle. So currently scientists widely believe the wave-particle duality of light.

In this lab, we used the Thomas Young's double slit to understand the wave-particle duality of light. The interference in the multi photons level proves the wave aspect of light. While in the single photon level, and at very short exposure time, the photons will hit the detector as particles[1]. These particles distributed according to the maximum of interference pattern which is not clear to observe at very short exposure time. Only when exposure time accumulated, the interference fringe becomes visible. The interference in the single photon level shows that light is both particle and wave. And by Mach-Zehnder interference, we studied the problem of "which-path" information, which further proved the wave-particle duality of light.

1.2 Theory

In the Young's double slit, the absence of "which-path" information is an essential criterion for interference. Thomas Young ingeniously used double slits to make two coherent light sources. Here we will use a coherent laser light and double slits to get two coherent sources for the interference. If we use some method, to know which of the two slits one single photon took in the Young's double slit interference, there will be no interference fringes[2]. In Fig. 1 (a), suppose that we put a polarizer after each slit to make us knowing the exact that photons take which path of the slit, the photons

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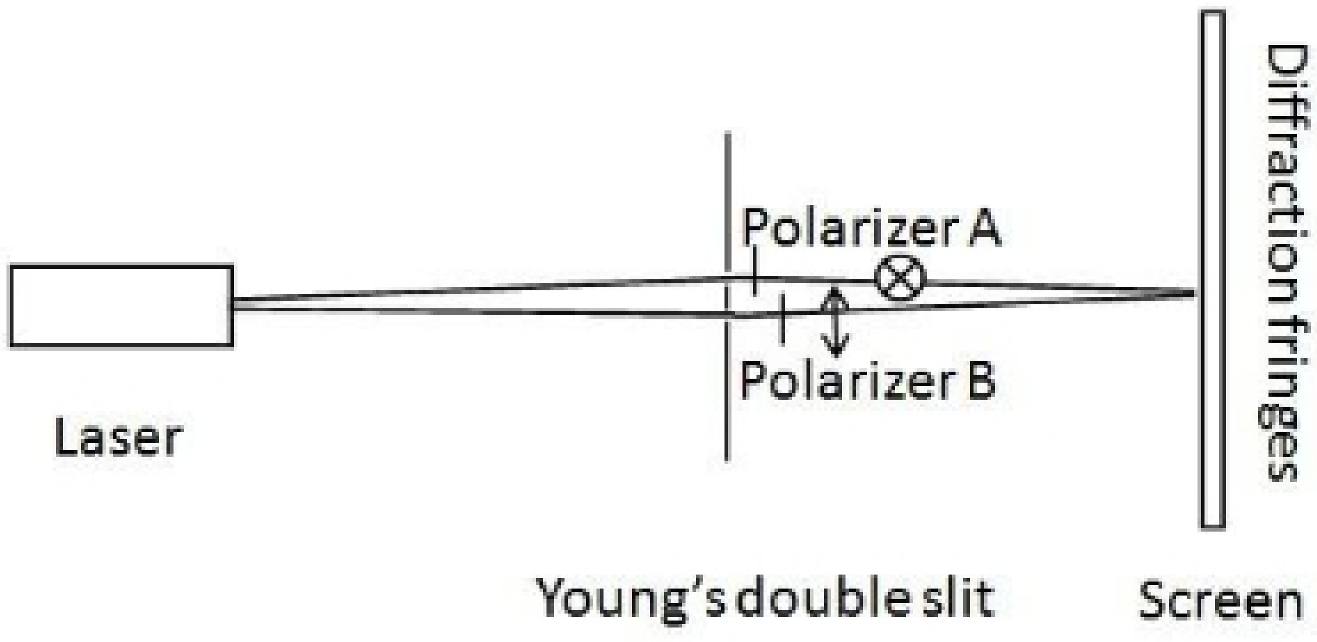
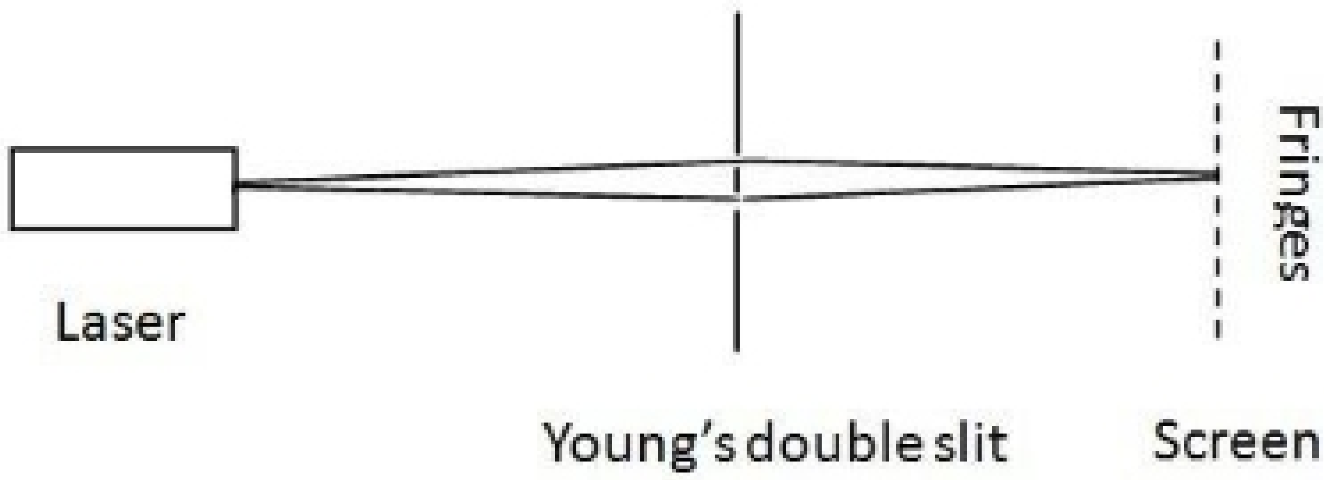
behave totally as particles, then they will distribute in the screen according to the shape of the slit, and we will have two sets of diffraction fringes rather interference fringes[3]. And as shown in Fig.1 (b), without the polarizer, we lose the information of which path the photons take, we do have interference fringes from the double slits. In the Mach-Zehnder interference, the "which path" information can be easily attained by measuring the polarization of two arms.



(a) With "which path" information



(b) Without "which path" information

Figure 1, Scheme of Young's double slit interference

To study photons in single photon level, we need single photon source. There is a trick to have the single photon source with normal laser. As we only demand that "one photons one time in the interference", we can attenuate the laser to single photon level. If here is a laser with wavelength of λ / nm, power of P/w, the number of photons per meter can be calculated as follows:

$$\frac{Photons}{M} = \frac{P\lambda}{hc^2} \qquad (1)$$

And if the total length of interferometer is L, so to get one photon in the interferometer, the attenuation α should be:

$$\alpha = \frac{hc^2}{P\lambda L} \qquad (2)$$

2. EXPERIMENT

2.1 Experimental equipment

A red He-Ne laser was used in the experiment, with wavelength of 632.8nm, output power of about 5mw. Though the power is low, looking into the laser beam is still dangerous. Observing the beam by projecting the beam on the wall or on a paper is suggested.

Andor's iXon DV887 back illuminated EMCCD used in the experiment is capable of single photon capture. The camera is internally cooled, and ideally works at the internal temperature of -60 degree centigrade. The shutter of CCD should be turned off when the light is on.

2.2 Experimental arrangement

Young's double slit interference experiment (the experiment arrangement is showed in Fig. 2) in normal laser intensity and single photon level was performed in the following way:

1) Turn on the laser. Spatial filter was introduced to improve the beam quality and also to enlarge the diameter of beam spot, so that the fringes can be observed in a larger area. Make sure that the beam transmits in the same height and passes through the center of each optical element.

2) Put the double slit after the spatial filter, and vertical to the light beam. The distance between the centers of each slit is 90um, and the slit widths are 10um. Then the interference could be observed if we put a screen after the double slits. Using EM-CCD camera to record Young's double interference pattern in multi photons level.

3) Calculate the attenuation α to get one photon one time in the interferometer using equation (2), where L equals to 9 inch in our situation, and the laser power before double slit is about 7nw. So we should add attenuator with $\alpha = 6.543\times10^{-3}$ attenuation to imitate a single photon source. In the experiment, we chose neural density filter with attenuation $\alpha = 4.5\times10^{-4}$ for convenience.

4) We capture single photon interference at different exposure time and gain by the EMCCD.

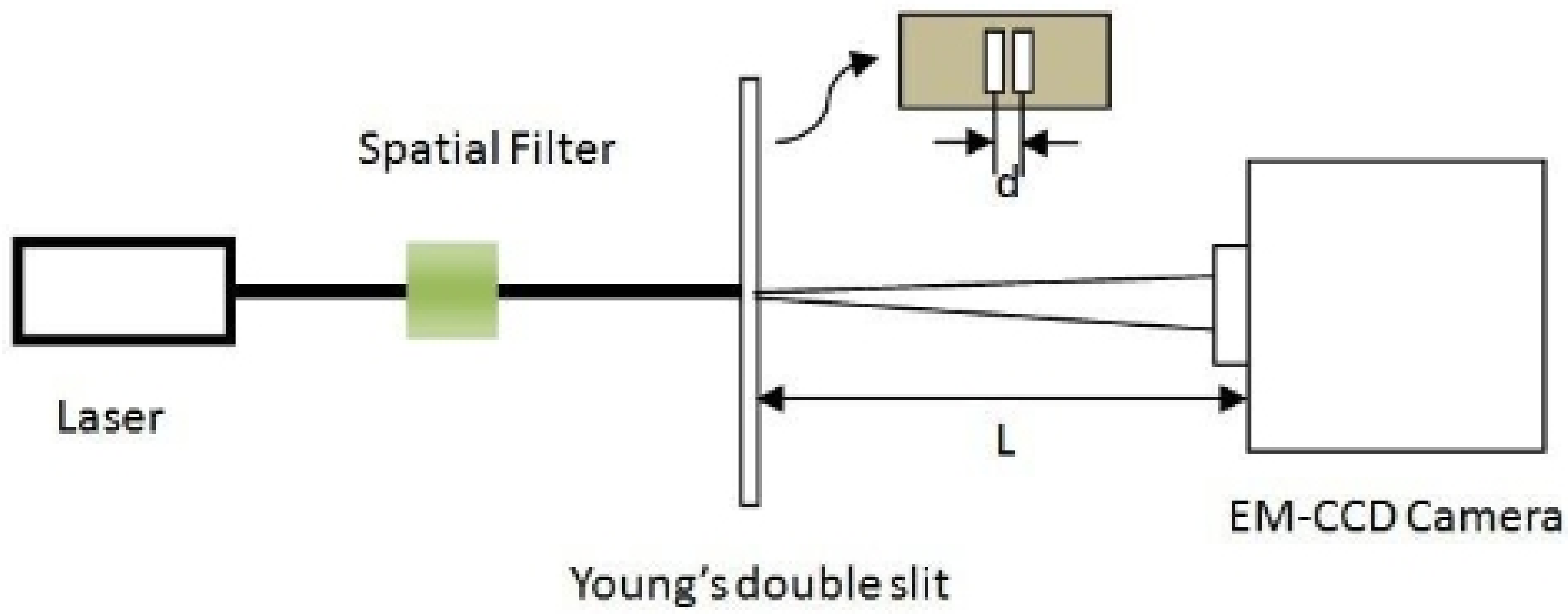


Fig. 2 Young's double slit interference experiment arrangement

Mach-Zehnder interference experiment is showed as Fig.3 and Fig. 4. The same laser, N. D. Filter and spatial filter are used as that in the Young's double slit experiment. The procedure of the experiment is as follows:

1) Using Mirror 1, 2, 3 to align the system, make sure the beam after Mirror is parallel to the surface of optical table and the edge of the table.

2) Put polarizer 1 and polarizing beam splitter (PBS) right after the Mirror 3, and let the beam travels at the same hight. The PBS is a beam splitter which splits light according to its polarization. It will reflect light of vertical polarization