

Lab 2: Single Photon Interference

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ABSTRACT

We experimentally illustrate the wave-particle duality of light, one of the most fundamental aspects in the nature of light, which cannot be clearly understood under classical approaches. We explained our experimental results using modern ideas supported by quantum mechanical fundamentals such as "which-way" information.

As in the early years, our experimental study is performed using Young's double slit and Mach-Zehnder interferometers at a light wavelength of 633 nm, attenuated up to a single photon level.

Keywords: Wave-particle duality, Mach-Zehnder Interferometer, Young Interferometer, Which-path information.

1.- INTRODUCTION

1.1.- Introduction

There is no doubt that the nature of light is one of the most fascinating issues in the history of science. It is well known that light has been studied under different formalisms [1], historically the Greek philosophers started with ray optics, and then in 1690 Christian Huygens proposed a wave theory. This idea brought heated discussions along hundreds of years, in spite of that, the Newtonian corpuscle theory of light was generally accepted until 19th century when Thomas Young and Augustin-Jean Fresnel conducted interference experiments that allowed them to conclude the light wave nature. This was completely accepted after James Clerk Maxwell supported this idea with his equations, and the electromagnetic optics was considered as the correct optical theory.

The previous formulations on the nature of light are classical theories. In fact the electromagnetic optics theory is widely used at this moment and many novel phenomena are being studied under this formalism. Besides those behaviors, there are others, whose nature falls into the quantum mechanical realm and therefore they cannot be explained classically. That was the situation in the early twenty-century when Quantum Theory was being formulated, and Max Planck, Sommerfeld, Bohr and others dealt with problems such as black body radiation and quantization rules. These facts brought a huge impact in the understanding of light nature, therein the wave-particle duality paradox, successfully solved by De Broglie.

In this experiment we focus our attention on the wave-particle duality of light, and our tools to study such behaviors are the double slit Young interferometer and the Mach-Zehnder interferometer. In fact, it is not unusual to use interferometry arrangements to study inherent characteristics and properties of light, such as coherence and polarization. This can be illustrated in the A. T Friberg *et al* article [2], which studied polarization states of light using the Young double slit experiment.

We used the Young double slit interferometer to illustrate the wave particle duality. First we used our regular source of light and we obtained the expected interference fringes, which is the typical wave behavior, then after we attenuated near to single photon level we observed that the photons just hit the detector as particles apparently at random, but if the exposure time was

increased they produced an interference pattern similar to the one obtained without attenuation. This means the existence of an interference term and therefore we can say that the ensemble of photons can be described by a wave function, therefore the light behaves like a particle and wave. Then we used a Mach-Zehnder interferometer to prove the wave-particle duality by producing a wave-function collapse known as the knowledge of "which path" information.

1.2 Ideas of Single Photon Interference

It is well known that interference can be understood in the simplest way as a superposition of coherent waves, that is the main idea behind Young and Mach-Zehnder interferometer. If we use the Young interferometer shown in figure 1, where it is assumed that the source of light is symmetrically positioned between the slits, and each slit is acting as a new source described by $\psi_n = E_n e^{ikr_n}$ where E is the amplitude of the electric field, k is the propagation constant, and r is the position vector, then the total intensity in the screen will be given as follows:

$$\begin{aligned}
 I &= |\psi_T|^2 = (E_1 e^{ikr_1} + E_2 e^{ikr_2})(E_1 e^{-ikr_1} + E_2 e^{-ikr_2}) \\
 &= I_1 + I_2 + E_1 E_2 e^{ikr_1 - ikr_2} + E_1 E_2 e^{ikr_2 - ikr_1} \\
 &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[k(r_1 - r_2)]
 \end{aligned} \tag{1}$$

Where $r_1 - r_2$ can be easily determined from figure 1 equal to cy/s .

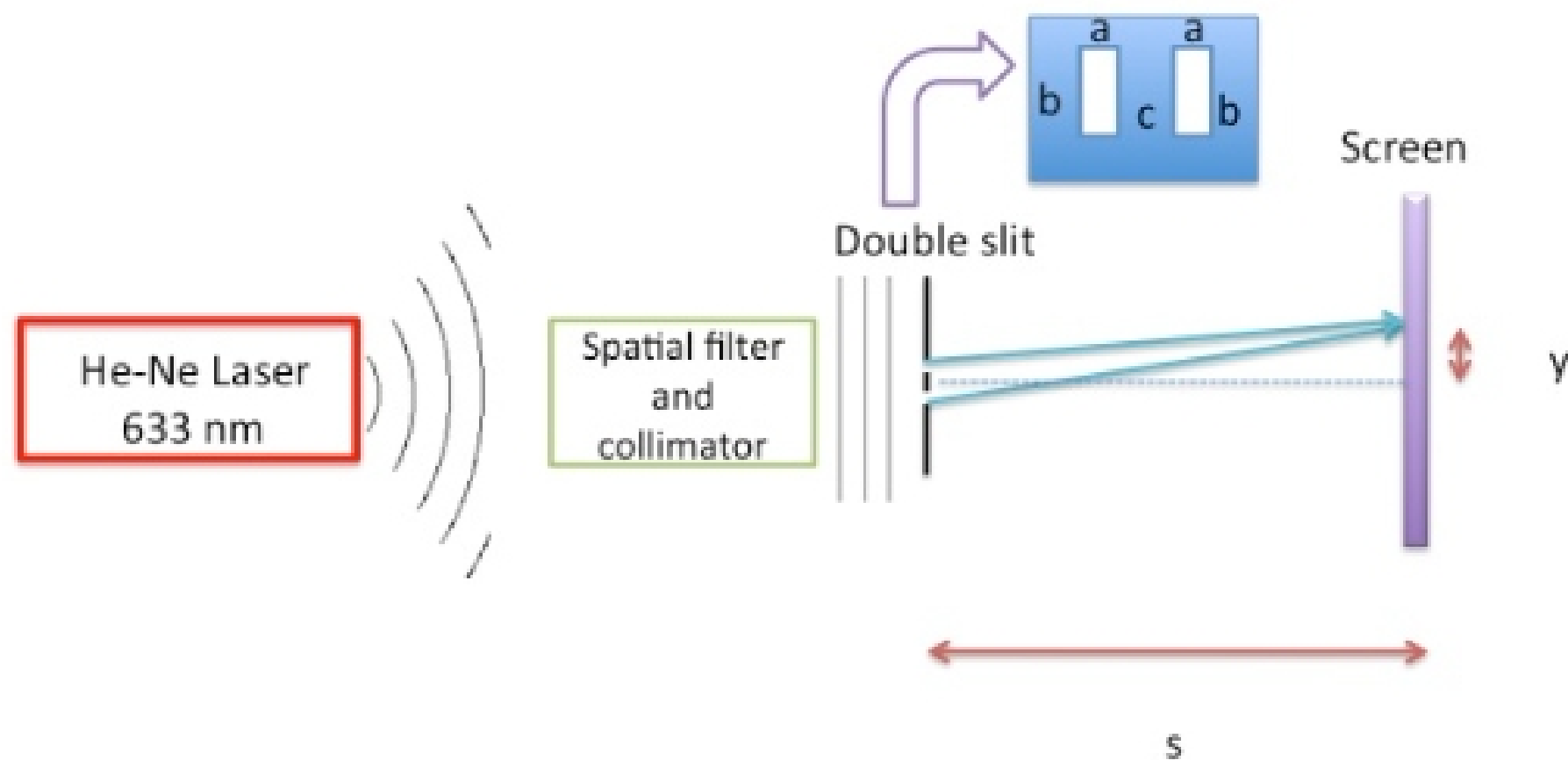


Fig. 1. Schematic of the typical Young's double slit interferometer.

It is clear that this experiment, which has been considered as one of the most beautiful experiments, proves the wave nature of light. However, in spite of that, something quite interesting happens if we attenuate the beam close to a single photon level and we try to know through which slit the photon actually goes through, such effect is called "which-path" information [3]. Before going into our "which-path" information discussion, it is convenient to point out how the transmittance of the attenuators can be calculated in order to attenuate the light to a single photon level.

The filter transmittances needed to attenuate the beam to such level can be calculated determining the number of photons per second that we have from our source with certain power "P". We know that the energy "E" of one single photon is given by " hc/λ ", then " P/E " gives the number of photons per second, Therefore we can calculate the transmittance by " E_c/PL ", where L is the total length of the interferometer.

The determination of which slit the photon goes through implies a measurement, that in the microscopic word implies a collapse of the wave function which describe such photon, then the photon will act like a particle. This can be experimentally done by measuring the photons polarization after the slits; such measurement implies the knowledge of which information. Therefore, in the same terms, one can destroy the wave behavior in a Mach-Zehnder interferometer, but in this case measuring the polarization in any of the arms.

2.- EXPERIMENT

2.1 Experimental Setup

As we have previously mentioned, our tools are a Young interferometer and a Mach-Zehnder interferometer. We will use this section to show detailed about the experimental setups.

The common elements in our experiment are the light source, the spatial filter and the detection instrumentation. As was illustrated in figure 1, we used a 5-mw He-Ne laser with a wavelength of 633 nm, then in order to spatially clean the beam and easily detect interference fringes we used a spatial filter and a collimator respectively. We used an Electron Multiplying CCD camera for a low light level to perform the fringes observation. In our experiment we used an Andor's iXon DV887 EMCCD. This camera needs to be used under certain conditions such as -60°C and in a dark room.

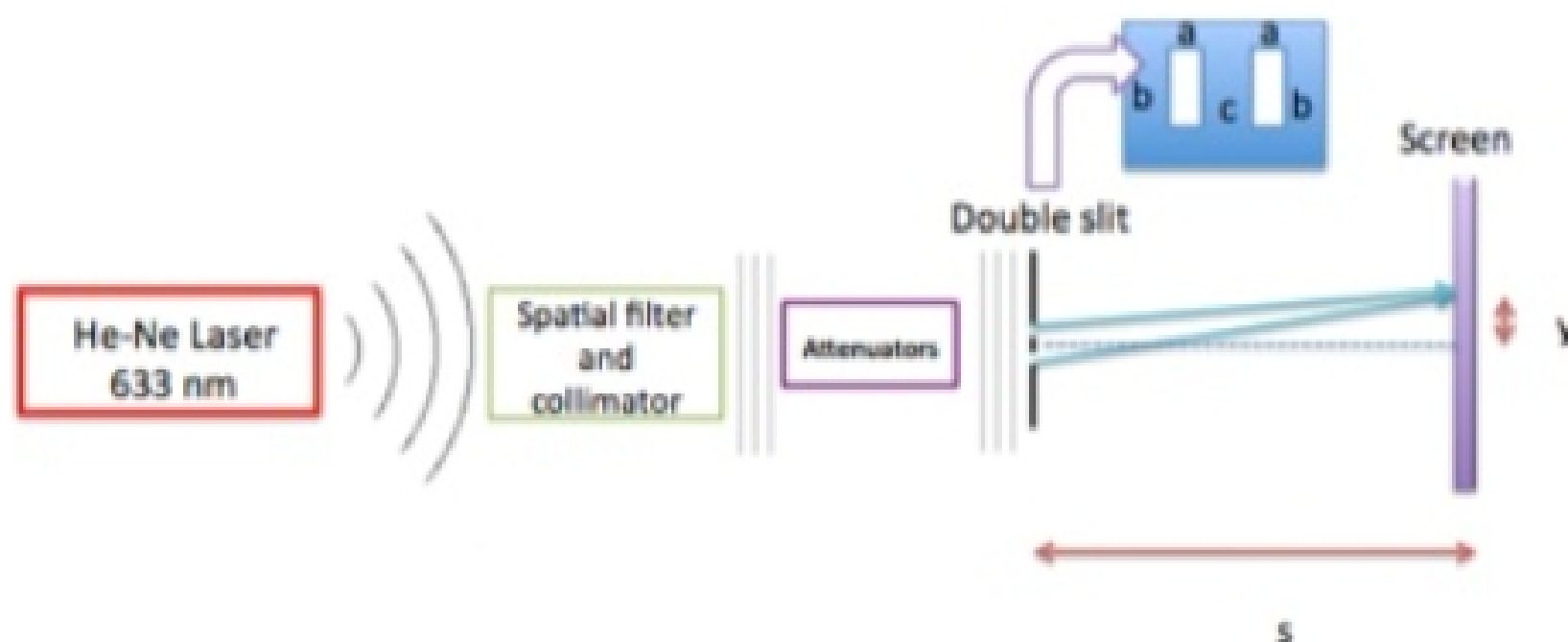


Fig. 2. Schematic of Young double slit experiment used in this laboratory

Now we will start describing our experimental systems, first we will describe Young's double slit interferometer, shown in figure 2.

- As we already mentioned one of the common parts of the experiment is the spatial filter that allows improving the beam quality and the optimal spot size for our experiment, as a