Optics Laboratory

Young's Two-Slit Experiment

1. OBJECTIVES

- Analysis of Young-type two-slit interference patterns in regimes of both high and low light intensity.
- Estimation of the number of photons coexisting inside the interferometer.
- Analysis of the dependence of the interference pattern on the polarization state of the light diffracted by each slit.
- Study of the relationship between the optical phenomena analyzed and their implications in the context of Quantum Optics (single-photon experiments, quantum erasure).

CAUTION: A laser source is used. To avoid serious injuries in your eyes, be careful not to look directly into the beam or to let a direct reflection of the beam enter your eye.

2. THEORY

In this practice, we are going to study the formation of Young's interferences by using a metal screen with two slits. We will emphasize two features that allow us to establish a relationship between this experiment and quantum aspects: the wave-corpuscle duality and the principle of complementarity.

On the one hand, we are going to see that as the light intensity reaching the slits becomes lower, a series of apparently uncorrelated scintillations will be observed instead of smooth interference fringes. This observation allows us to establish a connection between this phenomenon with the corpuscle nature of light (photon). In this low-intensity regime, the continuous interference pattern can be recovered after accumulating enough patterns, none of which show interference. To some extent, this experience allows us to recreate or simulate a situation analogous to a quantum "photon-by-photon" experiment: although individual photon detections are randomly detected at any place on the detector surface, after some times the statistical distribution of these detections starts mimicking a high-intensity distribution. It is worth noting that in the experiment here each scintillation should not be directly associated with a single photon, which avoids us to conclude that this is a quantum mechanical experiment (photon by photon). This is due to the uncontrollability of the production and detection methods. Standard detectors are based on the photoelectric effect: each detected photon produces a change in the state of an electron, which acquires some energy and eventually either contributes to an electrical current or to charging a capacitor. However, the scintillations observed in the CCD camera are not uniquely related to one of such single events, but they are a multiple of the minimum current unit generated in a pixel of the camera, namely, a "count". Each count corresponds to an incident intensity of the order of 1,000. Therefore, each observed scintillation corresponds to a relatively large photon number.

On the other hand, it is also going to be studied the effect on the pattern observed of having information about the path followed by light when it travels from the source to the detector, which allows us to get a deeper insight into the concept of complementarity: if the pathway is known, there is no interference pattern, while if this phenomenon is to be observed, then any which-way information should be removed or "erased". In this latter regard, in order to achieve which-way information, the beams diffracted by each slit are going to be "marked" with mutually perpendicular polarization states.

In this laboratory experience, a CCD camera plays the role of the detector. The interference pattern recorded by this device is described by the intensity spatial distribution:

$$I(\boldsymbol{r}) = E_1^2(\boldsymbol{r}) + E_2^2(\boldsymbol{r}) + 2\,\boldsymbol{u}_1 \cdot \boldsymbol{u}_2 E_1(\boldsymbol{r}) E_2(\boldsymbol{r}) \cos(2\pi \Delta l/\lambda)\,, \tag{1}$$

where E_1 and E_2 denote the amplitudes of the beams diffracted by each slit (1 and 2, respectively), Δl is the difference between paths going from the center of each slit to the observation point $\boldsymbol{r} = (x, y)$ on the detection plane, and λ is the wavelength of the incident beam that is assumed to be linearly polarized. In expression (1), the first two terms correspond to the intensities associated with each diffracted beam (if one of the slits is covered, the diffraction pattern produced by the other one will be observed, and vice versa). The third term describes the interference arising from the overlapping of the beams coming from each slit. This term is accompanied by a pre-factor $\boldsymbol{u}_1 \cdot \boldsymbol{u}_2$, where $\boldsymbol{u}_1$ y $\boldsymbol{u}_2$ denote unit vectors along the polarization directions of each diffracted beam. In this practice, we can control $\boldsymbol{u}_1$ y $\boldsymbol{u}_2$ by attaching linear polarizers after each slit. Depending on the orientation of these vector, we have the following:

a) If they are parallel or anti-parallel ($|\boldsymbol{u}_1 \cdot \boldsymbol{u}_2| = 1$), the interference pattern is observed. Moreover, if the amplitudes of the diffracted beams are the same, then the pattern visibility is maximal (vanishing minima, except for fluctuations due to random noise).

b) If they are mutually perpendicular ($\boldsymbol{u}_1 \cdot \boldsymbol{u}_2 = 0$), there is no interference pattern and the total intensity is just the bare sum of the intensities of each diffracted beam (in this case, the intensity distribution is pretty similar to the one displayed by a single-slit diffraction pattern).

c) In any other case ($0 < |\boldsymbol{u}_1 \cdot \boldsymbol{u}_2| < 1$), the fringe visibility is partial (non-vanishing minima).

From the quantum-mechanical point of view, cases (a) and (c) represent a situation similar to have no information about the slit crossed by each photon, while in case (b), due to the presence of the polarizers on each slit, with their transmission axes being mutually perpendicular, it is possible to determine whether the photon has gone across one slit or the other by looking at its polarization state after having crossed the interferometer.

In this latter case, though, it is still possible to "erase" the which-way information by inserting a new linear polarizer behind the interferometer. In this case, the intensity recorded by the CCD camera is no longer described by Eq. (1), since the electric field amplitude has to be first projected along the direction of the transmission axis of the new polarizer. Hence, the detected intensity reads now as:

$$I(\boldsymbol{r}) = \cos^2 \alpha \, E_1^2(\boldsymbol{r}) + \mathrm{sen}^2 \, \alpha \, E_2^2(\boldsymbol{r}) + \mathrm{sen} \, 2\alpha \, E_1(\boldsymbol{r}) E_2(\boldsymbol{r}) \cos(2\pi\Delta l/\lambda) \,, \quad (2)$$

where α is the angle formed by the directions of the axis of the new polarizer and the unit vector $\boldsymbol{u}_1$ (taken here as reference). It is worth emphasizing here that the phenomena following the "marking" and the "erasing" of which-way information for light can be explained with both classical optics and quantum optics.

3. EXPERIMENTAL METHOD

3.1 Description of the experimental setup

The setup to be used here is shown in Fig. 1. The light source is a laser diode, which produces a linearly polarized beam with a wavelength $\lambda = 635$ nm. After, one or two polarizers (A, B) can be accommodated to control the amount of light incident onto the two-slit metal mask. An additional polarizer (C) that could be inserted or removed follows the two-slit mask. Behind polarizer C, there is a positive lens (with a +125 mm focal length for setup 1, and +150 mm focal length for setup 2) and the CCD camera (detector), which should be placed at the lens focal plane. Polarizers A and B, as well as the two-slit mask, can be easily released from their frames (only in case they are not needed or should be replaced) by gently unscrewing the top locking screw.

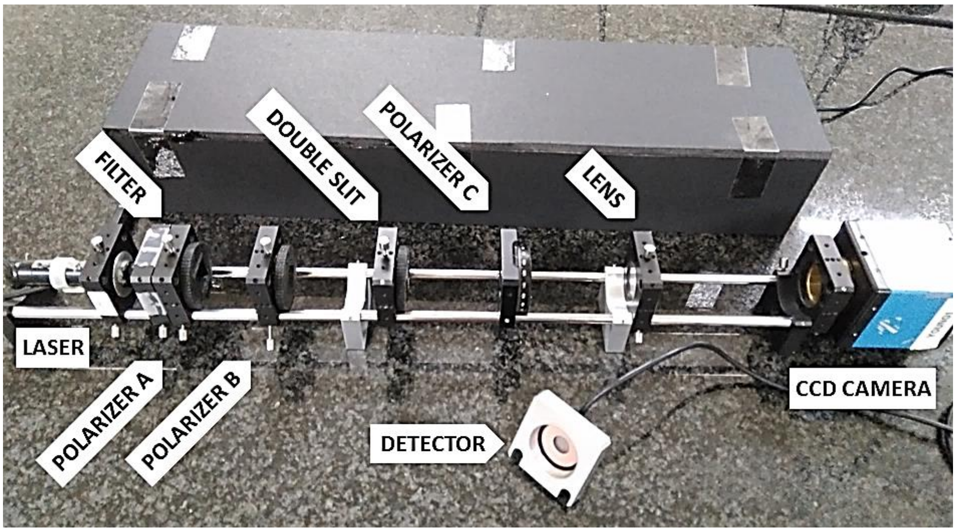

Figure 1. Picture of the experimental setup.

3.2 Instructions for data acquisition and analysis

The CCD chip consists of square pixels with square pixels with 3.75μm side for C1 camera or 4.64 μm side for C2 camera. The CCD is connected to a laptop, where the visualization, recording and analysis of images is carried out with the aid of the Matlab **CCDYoung.m** executable file (double-click on the **Matlab R2013b** desktop icon). The main commands of this simple code are:

- **Configure:** to open the configuration screen. The default exposition time (**Exposure**), which will be used during the whole experience, should be 0.1 ms.
- **CCD: START/CCD: STOP:** to initiate/stop the option that allows us to visualized 2D images, frame by frame, of the interference pattern on the large left-hand side screen (the corresponding 1D profile arising after integration of the pattern along the vertical coordinate can be seen in the lower screen).

- **ACUMULATE:** to show the interference pattern (large right-hand side screen) resulting from accumulating a sequence of frames (equivalent to integrating in time). The corresponding 1D profile (after integration along the vertical coordinate) is shown in the respective lower screen. To stop the data acquisition, click again on this command.
- **Colormap:** assigns a color map to the 2D intensity plots.
- **Save:** to save in a file individual frames.
- **SaveAcum:** to save in a file both an individual frame (I) and the accumulated intensity pattern (I_s).
- **Profile Right:** to select a portion of the accumulated pattern and then obtain the 1D profile along a chosen direction. The option **Data cursor** allows to obtain the intensity value (y-coordinate) at a given position (x-coordinate). The same kind of information is provided by **Profile Left**, although referred to the frames shown in the larger left-hand side screen.

CAUTION. Before starting to measure, cover the setup with the black box to avoid that light coming from other sources in the lab reaches the CCD camera, thus spoiling your measures. Furthermore, if the intensity maxima observed on display are saturated (they appear truncated at some point), use polarizers A and B to attenuate the incident beam.

3.3 Measure of the light power

Light power is measured with the circular detector (inserted in the aluminum frame). In order to perform a measurement, accommodate the detector in the optical bench right behind the slits, in such a way that it blocks the passage of light immediately after having crossed the slits. In the laptop, double-click on the **Thorlabs Optical Power Monitor** desktop icon. Since the detector is connected to the laptop, data reads will start being displayed on screen automatically. Once open, a left-hand side menu bar and three measure screens are displayed. In the menu bar, select "**High**" from the "**Resolution**" option. One of the measure screens (the larger one) occupies most of the graphical environment, while the other two are smaller. La larger screen provides with the instantaneous read of the power detected, while the two lower ones render the maximum (left) and minimum (right) detected reads. These two latter values can be restarted by clicking on the reset icon, just on top of the large screen.

4. EXPERIMENTS

4.1 Adjustment of the setup

The observation of the effects of this practice is greatly improved by a small preliminary adjustment, which is also very illustrative of the physical processes involved.

To adjust the amount of light avoiding saturation of the camera in the first steps, insert B polarizer with no slits and no auxiliary lens, so it avoids saturation of the camera. You should move the other lens until it focus the light as much as possible in the CCD plane. After adjusting the lens, it must remain in this position.

Secondly, the visibility of the interference is maximized if the same amount of light pass through each slit, thus, the polarizer B must be adjusted. To this end, place the double slit with polarizers, which is labeled with CP. Attached to each slit there is a different polarizer, with their axes approximately perpendicular.

Place the auxiliary lens and move it until you have a good image of the double slit on the screen. Place the polarizer C and rotate it at will. You will see that the amount of light in the image of each slit varies. Set the polarizer C in the position where the image of any of the slits disappears. Then the axis of the polarizer C will be perpendicular to the axis of the polarizer of the disappearing slit. From this position rotate the polarizer C 45º, regardless of the direction. Remove the slits and the auxiliary lens and rotate the polarizer B until the intensity on the screen disappears or is minimal. At this point the light coming out of polarizer B will form 45º with the axes of the slit polarizers when the slits are positioned as specified (vertical images).

Polarizer B will remain in the described position for the whole practice. Annotate this position of the polarizer C, because it will serve as a reference for the last part of the practice. Remove the auxiliary lens which will no longer be used. If you want to adjust the amount of light, insert a polarizer that we will call A between the laser and polarizer B and rotate it at will.

4.2 Observation and interpretation of the interference pattern in the high-intensity regime

1. Introduce the SP slits in the setup. Adjust the position of polarizer A in such a way that the detected signal is intense enough, but without reaching saturation. In this experience, polarizer C should not be mounted, but remaining aside. Rotate the screen with the slits until the interference fringes (maxima and minima) are aligned along the x-axis.

2. Determine the light power at the plane of the slits by accommodating the detector right after the slits (in order to minimize errors, the detector should remain stuck to the slits plane and, moreover, the setup covered by the black box.

4.3 Observation and interpretation of the interference pattern in the low-intensity regime

1. In order to attenuate the intensity of the incident beam as much as possible, rotate A polarizer until appears a series of random-like distributed scintillations.

2. Activate **ACUMULATE** and observe in the right-hand side screen the gradual emergence of Young's interference pattern from the accumulation of seemingly random detections. Provide a rough measure of the time interval necessary to observe a smooth intensity distribution.

3. Repeat point 2 from Section 4.2.1

4.4 Path distinguishability with polarizers and which-way information erasure

1. Get back to the initial configuration of the setup, i.e., as in the high-intensity regime (see Section 4.2).

2. Substitute the **SP** two-slit mask by the **CP** one, with its slits covered by polarizers with (nearly) perpendicular transmission axes (one axis is parallel to the slits, while the other is perpendicular).

3. Check that no interference pattern can be observed. Click on **ACUMULATE** and collect a number of frames in order to minimize noise-type contributions.

4. To achieve **which-way information erasure**, making indistinguishable the polarization state of the beams diffracted by each slit, accommodate polarizer C in the optical bench. Rotate this polarizer until the interferential pattern is observed under optimal conditions (maximal erasure).

5. Try now to rotate polarizer C in the opposite direction. Observe and annotate any change undergone by

the interference pattern with respect to the result obtained in point 4.

6. Gradually rotate polarizer C until completing a full turn. Annotate the angular positions where the polarizer produces maximum and minimum visibility of the interference fringes.

5. BIBLIOGRAPHY

[1] A. Ghatak, *Optics* (McGraw-Hill, 6th Ed., 2017).

[2] F. L. Pedrotti, L. M. Pedrotti and L. S. Pedrotti, *Introduction to Optics* (Pearson Int'l Edition, 2006).

[3] J. F. James, *An Introduction to Practical Laboratory Optics* (Cambridge University Press, 2014).

[4] P. Roger, G. Grangier and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: A new light on single-photon interferences," Europhys. Lett. **1**, 173-179 (1986).

[5] T. L. Dimitrova and A. Weis, "The wave-particle duality of light: A demonstration experiment," Am. J. Phys. **76**, 137-142 (2008).

[6] R. S. Aspden, M. J. Padgett and G. C. Spalding, "Video recording true single-photon double-slit interference," Am. J. Phys. **84**, 671-677 (2016).

[7] Interference pattern built up photon by photon: https://www.youtube.com/watch?v=MbLzh1Y9POQ

[8] R. Hillmer and P. Kwiat, "A do-it-yourself quantum eraser," Scientific American **296** (5), 90-95 (2007). https://www.physlab.org/wp-content/uploads/2016/07/diy-quantum-eraser.pdf

[9] W. Rueckner and J. Peidle, "Young's double-slit experiment with single photons and quantum eraser," Am. J. Phys. **81**, 951-958 (2013).

QUESTIONNAIRE

- **In this practice, <u>uncertainties are optional</u>.**
- **For an easier identification of the answers, please, specify in a visible place the number of the question responded (unless you have included explicitly the question).**

Adjustment

1. Roughly measure the distance from the slits to the optimal position of the auxiliary lens. Is it related to the focal value? Why?
2. Annotate the position of polarizer C for which the image of one of the slits disappears.

High-intensity regime

3. Determine the average photon number from the measured light power. Note that this quantity represents the number of photons that reach the CCD detector over a time interval equivalent to the exposure time of 0.1 ms (assuming there are no losses in the way from the slits to the CCD).

Low-intensity regime

4. Annotate how long it takes to observe a well-defined interference pattern starting from a random-like scintillation distribution. Although this is a somehow qualitative measurement, use it to briefly comment on your observations compared to the high-intensity regime.
5. Determine the average photon number from the light power measured in this scenario. Compare with the result obtained in point 3 and discuss it.
6. From the results obtained in points 3 and 5, estimate the number of photons that coexist between the two slits and the CCD chip in an instant in each scenario.

Which-way information erasure

7. Explain the intensity diagram observed when the diffracted beams are distinguishable.
8. Rotate gradually the graduated polarizer in front of the two slits and annotate the angular positions where you observe conditions of maximum and minimum fringe visibility. Discuss these results in relation to Eq. (2).

Additional comments

9. If you have observed or thought about something else that has not been previously considered in any of the above points, you can add it here.