Two Slit Interference

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Objective

The objective of this experiment was to study the behavior of light passing through single and double slit devices.

Theory

Light exhibits both wave-like and particle-like properties. This experiment best displays the wave nature of light.
For a monochromatic plane wave incident normally on two parallel slits of width a and distance d between slits. The intensity of the light that reaches the screen is given by:

$$I = I_o \cos^2 \left[\pi d \sin(\theta/\lambda)\right] \left(\frac{\sin\left[\pi a \sin(\theta/\lambda)\right]}{\left[\pi a \sin(\theta/\lambda)\right]} \right)^2$$

Here θ is the angle from the ray perpendicular to the slits to the angle made by the light reaching the screen. Making the small angle approximation we say that $\sin\phi \approx \phi$ leaving us with

$$I = I_o \cos^2 \left[\pi d \sin(\theta/\lambda)\right]$$

This dual nature of light is exhibited even when we take cases where single particles are shot at a screen i.e. even when we have photons passing through the two-slit setup one at a time, we see the same interference pattern we would if they were all passing through together. This experiment effectively illustrates superposition of light and since particle mechanics involves collisions rather than superposition, this demonstrates the wave nature of light.
In this setup, we first use the detector to record interference pattern using a laser source. We use a mask with a slit on it to block first one slit and then the other and also record the two-slit pattern between them (when neither slit was blocked). In this manner we are able to capture different components of the interference pattern and compare them with the complete pattern for the two-slit setup.
For the next part of this experiment, we used the detector to measure the frequency of photons (in terms of voltage). Using this, we calibrated our detector to record intensity (voltage) at the frequency of incidence of photons. A light bulb with a variable intensity was used to give us a reasonable frequency to take measurements at. The resulting effect was that of having a single photon being shot at the screen at any one time. A comparison of this "single particle" pattern with the pattern produced on shining the light all at once demonstrates the properties we were searching for.

Procedure

1. The box was assembled and the laser was set in place such that the laser passed through the various slits and was centered on the detector. The initial positions of the blocker slit and the detector slit were measured to ensure the measurements were being made from the central maximum.

2. The box was covered to avoid interference due to ambient light, and the voltage due to

residual ambient light was recorded so our measurements could be corrected for it.

3. The laser was turned on and the position of the detector slit was recorded with respect to the detected voltage by moving the detector slit away from the central maximum position, first in one direction, then in the other.

4. This process was repeated for the setup with the blocker slit blocking light coming through one of the two slits, starting from the maximum for this slit.

5. The laser source was replaced with the bulb source, and the setup was calibrated so that the bulb source was, once again, centered on the detector and passing through the two slits.

6. The intensity of the bulb was increased until the detector detected a frequency of 0.5 kHz. The photon count was recorded over 1 second intervals.

7. The intensity of the bulb was increased until a frequency of 1 kHz was detected. The photon count was recorded again to corroborate the number of photons hitting the detector every second. This process gave us a way to quantitatively define our uncertainty using the standard deviations in these initial measurements.

Data

For all measurements below, uncertainty in voltage was approximately ±0.02 volts and uncertainty in position was approximately ± 0.01 mm. Uncertainty in position comes from the fact that the micrometers used to measure distance were finely adjustable with 0.01 mm being the smallest marked measurement. It is therefore reasonable to assume that any inaccuracy was within 0.01 mm. The background voltage (voltage due to ambient light) was measured at 0.07 volts. All measurements were corrected for this background voltage.

Double Slit Interference with Laser Source

Multimeter reading	0·128	0·178	0·228	0·278	0·328	0·378
Micrometer reading	2·19	2·14	2·11	2·09	2·04	2·03

Multimeter reading	0·428	0·478	0·528	**0.578**	0·528	0·478	0·428	0·378
Micrometer reading	1·98	1·94	1·91	**1.83**	1·74	1·71	1·68	1·66

Multimeter reading	0·328	0·278	0·228	0·178	0·128	0·078
Micrometer reading	1·62	1·60	1·57	1·53	1·46	1·38

Single Slit Interference with Laser Source

Multimeter reading	0·022	0·072	0·122	0·172	0·222	0·272	0·322	0·372
Micrometer reading	0	0·52	0·84	1·10	1·37	1·62	1·92	2·23

Multimeter reading	0·422	0·372	0·32	0·272	0·222	0·172	0·122	0·072	0·022
Micrometer reading	3·07	3·72	4·06	4·32	4·61	4·85	5·17	5·49	5·57

Double Slit Interference with Bulb Source

Micrometer reading	2·19	2·29	2·39	2·49	2·59
Counter reading	117·550	110·938	87·578	64·409	56·726

Micrometer reading	2·69	2·79	2·89	2·99	3·09	3·19	3·29
Counter reading	73·407	124·708	166·129	146·825	85·058	40·879	95·662

Micrometer reading	3·39	3·49	3·59	3·69	3·79	3·89	3·99	4·09
Counter reading	197·982	208·255	138·386	85·426	33·088	51·678	133·978	199·255

Micrometer reading	4·19	4·29	4·39	4·49	4·59	4·69	4·79	4·89
Counter reading	213·273	177·423	111·631	42·408	36·098	59·785	85·783	98·558

Micrometer reading	4·99	5·09	5·19	5·29	5·39	5·49	5·59
Counter reading	91·327	70·709	53·762	44·773	34·944	24·527	23·856

Micrometer reading	5·69	5·79	5·89	5·99	6·09	6·19
Counter reading	25·585	24·198	21·973	17·551	14·381	11·960

The following measurements tell us the accuracy of the frequency of photons incident on the screen for the second part of this experiment and they allow us to be certain (statistically) that there is at most 1 photon in the box at any given time.

Trial	0.5 kHz	1 kHz
1	0.489	0.978
2	0.463	0.946
3	0.516	0.979
4	0.511	0.998
5	0.492	0.984
6	0.529	0.920
7	0.513	0.923
8	0.501	0.994
9	0.503	0.963
10	0.496	0.937

Frequency	**mean**	**standard dev. (σ)**	**variance**	**percentage within σ**
0.5kHz	0.5013	0.0181	3.3×10^{-4}	80%
1kHz	0.9622	0.0289	8.4×10^{-4}	70%

Analysis

Data

The interference pattern for the double slit configuration (for blocker slit position of 4.13 mm) and one of the single slit configurations (for blocker slit position of 3.78 mm) was recorded. Wave superposition tells us that the maximum of the double slit interference pattern should be found at a point where the difference in path length between the two single slit patterns is $\pi/2$. For the second plot below, the single slit plot was translated such that the double slit maximum would be at an angle of $\pi/4$ from both slits.

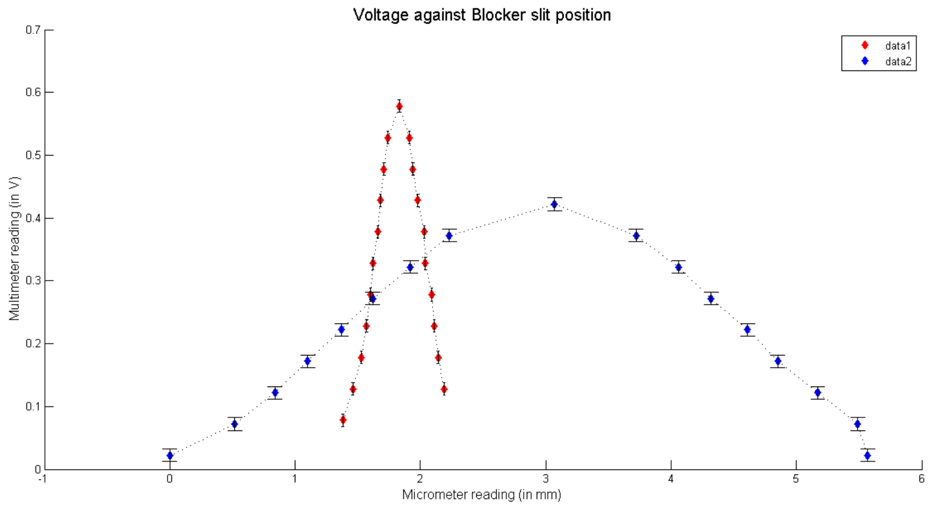

Figure 1: Double slit against one single slit

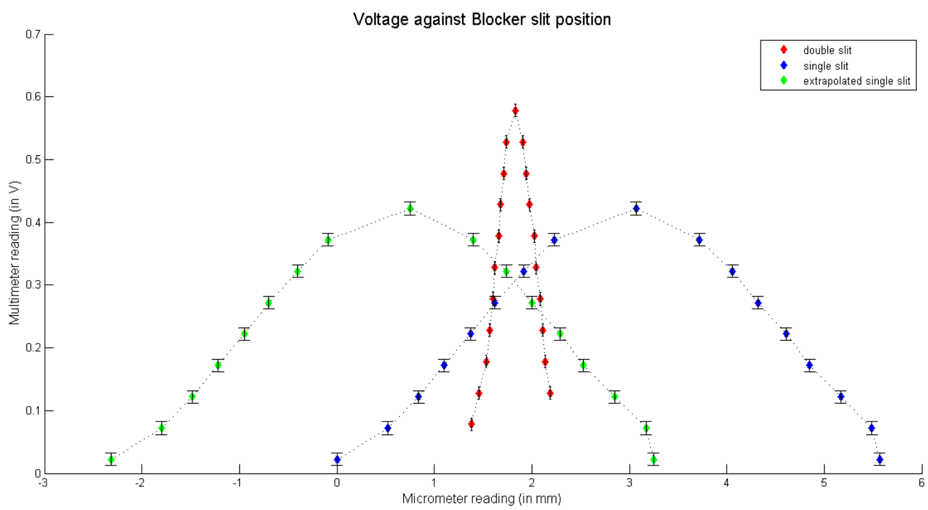

Figure 2: Double slit with both single slits

The following plot represents the detected voltage against the position of the detector slit. This clearly shows a sinusoidal pattern of light fringes. The lack of symmetry in this pattern suggests some kind of misalignment in the setup of the apparatus. Since the apparatus was very sensitive to minor disturbances, this may have been due to the table moving or the masking slit being displaced between moving the detector slit in different directions. We were unable to pinpoint the exact source of this error since the asymmetry of the pattern was not noticed during the lab session.

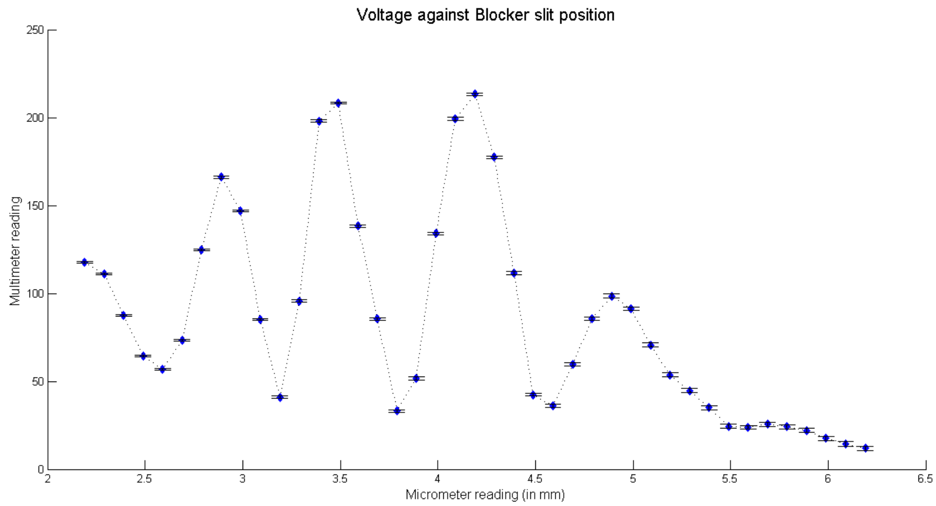

Figure 3: Single slit Pattern with bulb source

We noted that for the laser source, the maximum voltage for the single slit was $0.422 \pm 0.02\,\mathrm{V}$ while the maximum intensity of the two-slit pattern was $0.578 \pm 0.02\,\mathrm{V}$. This gives us a ratio of (0.730 ± 0.030):1 which agrees with the expected ratio of $(\frac{1}{\sqrt{2}} = 0.707) : 1$

Uncertainties

Uncertainty in position was estimated at $\pm$ 0.01 mm. Uncertainty in position arises from the fact that the micrometers used to measure distance were finely adjustable with 0.01 mm being the smallest marked measurement. It is therefore reasonable to assume that any inaccuracy was within 0.01 mm.

For the measurements of voltage for the entire experiment, uncertainty in voltage was estimated at ± 0.02 volts. The background voltage (voltage due to ambient light) was measured at 0.07 volts. All measurements were corrected for this background voltage, however since this background voltage could not be assumed constant, the uncertainty in voltage was considered non-negligible for the experiment.

All calculations based on measured values were calculated with uncertainties propagated according to:

$$\delta_y = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i}\right)^2 \delta_{x_i}^2}$$

Questions

For what values of θ is the intensity I is the intensity zero?

The points of zero intensity should be at points where $\pi d\theta/\lambda = (2n+1)\pi/2$ which would mean $\theta = (2n+1)\lambda/2d$

What is the ratio of the maximum intensity for the two slit pattern to the maximum intensity for the one slit pattern? Can you explain your result?

The maximum intensity of the two slit pattern should be $\sqrt{2} \approx 1.41$ times the maximum intensity of the single slit pattern. For our recorded values this ratio was $0.578/0.422 \approx 1.369$ Which falls within the margin of error. This would be because the point of maximum intensity for the double slit lies between the points of maximum intensity for the two single slits, and the maximum intensity for a position with constructive interference would be at a position where the intensity from each single slit is $1/\sqrt{2}$ which, by superposition, gives a total intensity of $\sqrt{2}$

You should find positions of the detector slit for which the intensity of the two slit pattern is less than that for the one slit pattern. As less light is being transmitted in the latter case, how do you explain this?

There are positions of lower intensity on the two slit pattern at points where the two single slit patterns interfere destructively. At these points the energy due to one single slit pattern is negated by the other. This is an elegant illustration of the wave nature of light.

What is the separation between between the two slits?

The separation of the two slits can be calculated using the fact that in the small angle approximation, $x = L\theta = L\frac{m\lambda}{d}$. Plugging in 650 nm for λ for the red laser, 1 for the index m, and 0.6 m for the length of the box. Using the distance between the first minimum on either side, $4.59 - 3.79 = 0.8$mm for x. This gives us a slit separation of:

$$d = \frac{L\lambda}{x} = \frac{0.6 \times 650 \times 10^{-9}}{0.0008} = 3.9 \times 10^{-4}\text{m}$$

The uncertainty in the length of the box was about 0.05m, while, the uncertainty in the positions of the two minimums was 0.01mm which sum in accordance with the equation:

$$\delta_y = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i}\right)^2 \delta_{x_i}^2} \implies \delta_d = \sqrt{(\delta_L \frac{\partial d}{\partial L})^2 + (\delta_x \frac{\partial d}{\partial x})^2} = \frac{\lambda}{x}\sqrt{(\delta_L)^2 + \left(\frac{L\delta_x}{x}\right)^2} = \pm 3.2 \times 10^{-5}$$

so:

$$d = 3.9 \times 10^{-4} \pm 3 \times 10^{-5}\text{m}$$

Calculate the average time between photons and the time one photon spends in traveling between the source and detector slits. Is there likely to be more than one photon in the apparatus at any given time? If not, how is it possible that a two slit interference pattern is produced? Does it make any sense to ask which slit the photon goes through?

Since the average number of photons striking the screen per second were 1000 (≈ 962), and the time taken for a given photon to traverse the length of the box would be $\frac{L}{c} = \frac{0.6\text{m}}{3\times10^{8}\text{m s}^{-1}} = 2\times10^{-9}$s. This means that for all of the recorded photons to travel the length of the box, assuming they were to pass through one at a time, would require 2×10^{-6}s which tells us that, assuming the detector detects more than 0.1% of the photons passing through the box (a total of 10^6 photons, which would require 0.002s), it is unlikely that there is more than a single photon traveling in the box at any time during this experiment.

Are there regions where the one slit pattern is more intense than the two slit pattern?

Yes, there are regions where the one slit pattern is brighter, as discussed above, this is due to destructive interference in the two-slit pattern, where the phase difference between the two single light waves results in a dark spot.

How does the two slit pattern differ from the one you obtained using the laser? Why?

The two slit pattern for the bulb and the laser differ in that the peaks obtained for the bulb source were much closer together. This is because the peak separation is directly proportional to the wavelength of ray and the light from the bulb has a lower wavelength. The bulb pattern also appeared to be asymmetric, which was not the case with the laser source.

What is the width of each slit?

The width of each slit can be found using the equations used to find the distance between the centers of the slits, and using the angle between rays from the ends of each individual slit. This gives us $5.51 - 0.00 = 5.51$mm for x and therefore:

$$d = \frac{L\lambda}{x} = \frac{0.6\times650\times10^{-9}}{0.00551} = 5.6\times10^{-5}\text{m} = (56\pm9)\mu\text{m}$$

This uncertainty was found using the error propagation equation mentioned earlier in this section.

Conclusions

There seemed to be no significant qualitative difference between the patterns recorded using the laser source and the bulb source which can be viewed as a test of consistency in the interference patterns of single photons and those of simultaneous photon beams. This corroborates our theory that wave-like interference takes place whether the wave nature of light dominates during transmission of light or particle nature.

We found that the positions of maximum (or minimum) intensity of the two-slit pattern did not align with those on the single slit pattern, as is to be expected when constructive or destructive interference takes place.

We determined that the width of the slits was $(56\pm9)\mu$m and the distance between the two slits was $(3.9\pm0.3)\times10^{-4}$m

Examination of the data recorded revealed that the voltage peaks on the plot for the bulb source were asymmetrical along the central maximum. This suggests some kind of asymmetry in the setup of the experiment or an unaccounted for change in the apparatus. This might also represent an asymmetrical filtering of frequencies along the detector slit which would lead to a sharp drop in perceived voltage at (or beyond) a specific position. This seemed to be corroborated by our data which revealed noticably sharper drops in recorded voltage near the 5.4 mm mark on the micrometer screw.