Light Diffraction

Distance Version

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***Abstract*—This lab focuses on light diffraction where the students perform experiments regarding how the diffraction occurs when using different types of gratings and also on how a spectroscope can be used with a grating to see the spectral lines and measure from them using a vernier scale. When using the Open Optics Module program with this lab the result is proven to be correct according to the pattern shown in the program and measurements of different variables for light diffraction. With precision, the result from the spectroscope will be theoretically correct according to the database NIST.**

I. Introduction

This lab report covers two separate experiments with light diffraction. The first experiment were to estimate slit-openings based on the diffraction patterns displayed on the screen. This was done both experimentally and theoretically to varying degrees depending on which opening being used at the time. The second experiment was with a grating spectroscope, it was used to determine wavelength for different orders of minima. A telescope was used to properly measure the degree of each. A result could be obtained for all experiments, in the conclusion section we discuss potential errors of our measurements.

II. Theory

The head subject for this lab is diffraction and interference. Diffraction is a phenomenon that occurs when a wave encounters an obstacle or opening (for example a grating) and bends around this obstacle, or spreads out if it passes an opening, in this case light. Interference is another phenomenon in which two waves form a resultant wave of greater, lower or same amplitude which is applied to the superposition principle.

A new type of scale is presented to the students in this lab, called the vernier scale. The vernier scale uses a combination of degrees, arcminutes and arcseconds to get the precise position of where the spectral lines are in the grating. How to determine the angle on the vernier scale consists of reading the degrees and then reading the position of which tick on the scale that matches the lining. The number of ticks is multiplied by $\frac{1}{3}$ to determine the amount of arcminutes and arcseconds. These minutes and seconds are used in the formula below to convert to degrees to retrieve a precise angle.

A. Formulas

A variety of formulas is used during this lab. The formulas are provided in this courses formula collection. Here are the formulas used during this lab:

- Intensity at bending: $I = I_0(\frac{sin(\beta)}{\beta})^2$, where I is the intensity, I_0 is a constant, $\beta = \frac{\pi b}{\lambda} * sin\theta$
- Bending minima with a slit: $bsin\theta = m\lambda$, where b - width of slit opening, θ - angle of consideration, m - order $\pm1, \pm2, \pm3$ etc., λ - the wavelength
- Interference for head max: $dsin\theta = m\lambda$, where d - distance between adjacent columns, θ - angle of consideration, m - order of maxima $0, \pm1, \pm2$ etc., λ - the wavelength
- Bending minima with a circular hole: $Dsin\theta = k\lambda$, where D - diameter of circular opening, θ - angle of consideration, k - order $1.22, 2.23, 3.24$ etc., λ - the wavelength
- Convert vernier scale to degrees: degrees + $\frac{arcminutes}{60} + \frac{arcseconds}{3600}$

III. Equipment

Diffraction experiments with laser: Green laser($\lambda = 532nm$), optical bench, screen(paper), single slit, slit with circular openings, slit mount, gratings (40 lines/mm, 80 lines/mm, N-slits (2,3,4,5)), ruler, camera, computer and software (measure the diffraction).

Experiment with a grating spectroscope: Spectrometer with collimator and telescope, cadmium Lamp, grating (100 lines/mm)

IV. Preparatory questions

For this lab there were some preparatory questions that should be answered. Following is the questions and their answers and a short solution to the questions (due to long calculations) and the answers:

A. Produce a diffraction pattern using the simulation program. Use 5 slits and pay around with the width and spacing. How many secondary maxima do you observe between the principle maxima?

When using the Open Optics Module with Diffraction on a web-based program a pattern can be shown in figure 1 where it is shown that a diffraction pattern with five slits produce three secondary maxima's. This is because of a formula used in diffraction patterns when calculating minima's and secondary maxima's, N-1 (minima's) and N-2 (secondary maxima's), where N equals to number of slits [3].

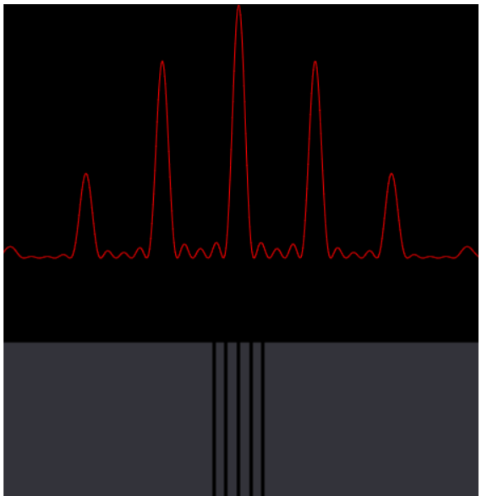

Fig. 1. Diffraction pattern with five slits showing that N-2 secondary maxima's is equals to three

B. A laser beam of wavelength 632.8 nm illuminates a screen through a 0.5 mm wide and long slit. What diameter does a central spot of light get?

By using the bending formula for minima with a slit, $bsin\theta = m\lambda$. The diameter can be achieved by first solve out what the angle degree is which is $\theta = arcsin(\frac{\lambda * m}{b})$. By using trigonometry, the radius of the central spot can be solved, $tan\theta = \frac{x}{L} \Leftrightarrow x = tan\theta * L = 5mm, Diameter = 5mm * 2 = 10mm$. The diameter of the central spot is 10 mm.

C. A laser beam of wavelength 632.8 nm illuminates a screen with a hole of 0.5 mm diameter. The diffraction pattern is studied on a screen 4.0 m away. What is the diameter of the central spot?

The methodology for these questions is the same as the question above, though another formula is used for bending for a circular hole, $Dsin\theta = k\lambda$. By using this formula with the methodology from the previous question, the diameter of the central spot with a circular hole can be solved to be $Diameter = 2 * 6.2mm = 12,4mm$.

D. A laser beam of wavelength 632.8 nm illuminates on a screen through a 50 μm wide slit. Calculate approximately at what angle the first maximum outside the central maximum occurs and calculate the ratio between the intensities of the two maxima.

The formula for bending for minima with a slit, $bsin\theta = m\lambda$, will be used here. However the question asks for the maximum and not the minimum. To calculate minimum for a slit the order must be used which is $m = \pm1, \pm2, \pm3, ...$. To calculate a maximum with this formula m must be modified. As the minima is indicated by 1, 2, 3 etc. then the maximums must be identified as $m = \pm1.5, \pm2.5, ...$. By using $m = \pm1, 5$ in the formula above the angle can be solved out, which is $\theta = 1.087° = 0, 019rad$.

To solve the intensity ratio between the first maxima and second maxima the methodology with m can still be used here. If $m = \pm1.5, \pm2.5, ...$ then m can be converted to radians where 1 = π. Therefore $m = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, ...$. The next question is after the ratio of the first and second maxima, which an angle for the second maxima is needed $\frac{3\pi}{2}$. By using these angles in the intensity with bending formula, $I_1 = I_0(\frac{sin(\beta)}{\beta})^2$ the ratio can be achieved by divide I_0 to the left side, $\frac{I_1}{I_0} = (\frac{sin(\beta)}{\beta})^2$ and insert $\beta = \frac{3\pi}{2}$ in the formula the ratio will be 0,045 which is 4,5%.

E. Parallel light illuminates a grating with 600 slits/mm. The third order of the wavelength λ is observed at an angle of 64.16°. Use the grating formula in Appendix 2 and determine λ.

The formula used here is the same as the previous questions with a slit, $bsin\theta = m\lambda$. To determine the wavelength divide m to the other side and insert the value known, $\lambda = \frac{b * sin\theta}{m} = 4,99 * 10^-9 = 500nm$

V. Methods

A. Diffraction experiments with laser

All the openings, referring to the diffraction parts, were put on the mount and it was made sure that the light was properly aligned with the opening for clear diffraction patterns. For the single slit a picture was taken of the pattern shown through the paper-screen, this was then plotted on a computer. We then used a software [4] to estimate the width of the slit. For the circular openings we only calculated on the smallest opening, that is also when the minima rings were the most visible and patterns larger, thereby easier to measure. This was done by hand. The gratings were used both individually and simultaneously. For the last N-slits all openings were used. The 2 and 3 slits were measured with the camera and used in software. Similar to single.

B. Experiment with a grating spectroscope

The diffractions (spectral lines) were examined for all minima orders to determine their respective wavelength, measuring from the central line (m=0). We used the telescope in order to determine at what angle the different lines entered, the telescope was then moved till the vertical line lined up with the displayed cross with the help of the fine adjustment screw on the spectroscope. This was done for all lights of all orders, the degree was read on the vernier scale.

VI. Results

Following is the result for the questions from the lab tutorial in exact order. The questions that need to be discussed are analysed in the next section.

A. Diffraction experiments with laser

In this first experiment the task was to calculate the width of the slits using the software [4] with values measured with the camera or for the slit with circular hole measuring the distance minima rings to calculate the width. This formula can be found in the theory section.

1) Single slit: Comparing the real values with the theoretical on the software [4]. We believed width = 120 µm was the most accurate. Used spacing = 400µm.
This is shown in Fig.2 below. The white lines are the theoretical while red is real values.

2) Circular hole: For the circular opening we had to use the formula listed. $Dsin\theta = k\lambda$

x = 0.7 cm= 0.007m , k = 2.23 (second order)

$tan\theta = \frac{x}{L} = \theta = arcsin(\frac{0.007}{1.79})$ = 0.224 °

$d = \frac{k*\lambda}{\sin\theta} = \frac{2.23 \cdot 532 \cdot 10^{-9}}{\sin 0.244} = 3.034 \cdot 10^{-4}m = 0.3034m$

3) Transmission gratings: 40 lines/mm and 80 lines/mm
When combining two gratings the first grating will curve the light horizontally and the second grating (turned 90 degrees) will curve the light from the first gratings vertical angle. This will cause diffraction in the light and creates the pattern shown in the video for the lab.

4) Diffraction in N slits: For two slits the estimated data is, width = 80µm and spacing = 310µm. For three slits the estimated data is, width = 80µm and spacing = 310µm This is shown in Fig.3 and Fig.4 below. The white lines are the theoretical while red is real values.

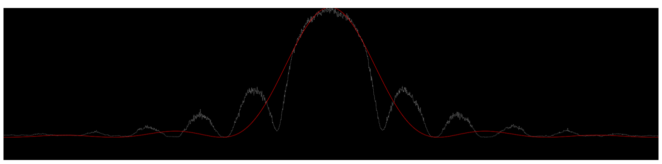

Fig. 2. Single slit

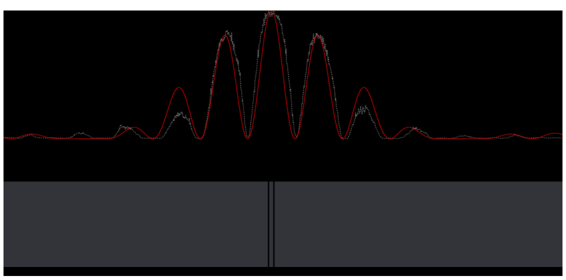

Fig. 3. Two slits

B. Experiment with a grating spectroscope

Wavelength Measurement: In this part the task was to calculate the wavelength of each spectral line in the grating using the formula for interference for head max: $dsin\theta = m\lambda$. Using this formula combined with the angle in degrees with the vernier scale will give the wavelength. The calculations will not be shown, however the result will be shown in different tables for this task. First the angle in degrees need to be known for each spectral line. The formula for vernier scale is used here and together with it the angle for each spectral line in order 0, 1 and 4 is calculated. The order of 1 and 4 is the ones were after however to get the angle the angle for the specific order needs to be calculated from the zeroth order.

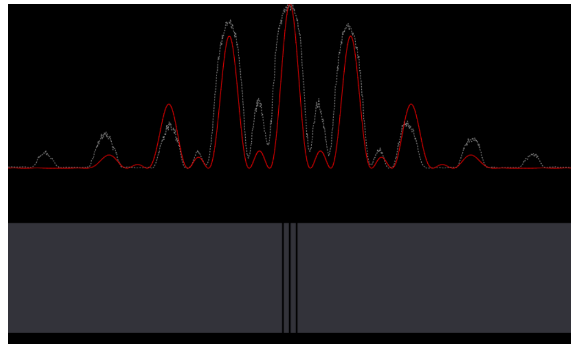

Fig. 4. Three slits

Order	Blue 1st	Blue 2nd	Green	Red
0	265°1'20"	265°1'20"	265°1'20"	265°1'20"
1	260°19'40"	260°15'0"	260°6'40"	259°20'0"
4	252°13'20"	251°56'40"	251°16'40"	248°10'0"

TABLE I
THE DATA OF EACH SPECTRAL LINE USING THE VERNER SCALE

The data from the vernier scale is known and after converting it with to degrees and subtracting it from the zeroth order angle the following angles of the spectral lines in order 1 and 4 is achieved:

Order	Blue 1st	Blue 2nd	Green	Red
1	2,695°	2,772°	2,911°	3,689°
4	10,8°	11,078°	11,745°	14,856°

TABLE II
THE ANGLE (DEGREES) OF EACH SPECTRAL LINE IN ORDER 1 AND 4 AFTER CONVERTING THE VERNER SCALE TO DEGREES AND CALCULATED THE DIFFERENCE WITH THE ZEROTH ORDER

When paraphrasing the formula $dsin\theta = m\lambda$ to get the wavelength the formula will look like this $\lambda = \frac{dsin\theta}{m}$. When inserting the known variables the wavelength for each spectral line in order 1 and 4 will be calculated to:

Order	Blue 1st	Blue 2nd	Green	Red
1	470nm	484nm	508nm	643nm
4	468nm	480nm	509nm	641nm

TABLE III
THE WAVELENGTH λ FOR EACH SPECTRAL LINE IN ORDER 1 AND 4

By using the wavelengths collected by NIST [2] in the following table the deviation can be calculated (note that the NIST wavelengths are rounded):

Blue 1st	Blue 2nd	Green	Red
468nm	480nm	509nm	644nm

TABLE IV
THE WAVELENGTH λ GIVEN BY NIST

Order	Blue 1st	Blue 2nd	Green	Red
1	2nm	4nm	1nm	1nm
4	0nm	0nm	0nm	3nm
Percentage (1)	0,43%	0,83%	0,20%	0,16%
Percentage (2)	0%	0%	0%	0,47%

TABLE V
THE WAVELENGTH λ DEVIATION BETWEEN THE LAB RESULT AND NIST

VII. DISCUSSION

A. Diffraction experiments with laser

The software gave a graph for how the diffraction patterns would look in theory and also one with the measured values from the lab. It does look similar so we can probably say with certainty that the right equipment has been used and that the measurement was done correctly. It will never be identical to the theoretical one. If one were to guess why it is not identical, we believe perhaps the most uncertain factor leading to the biggest source of errors is our measuring, this goes for all parts of the lab but perhaps most significant on the circular hole part, where we had to manually measure instead of the computer software. There are of course many candidates leading to potential errors, another one we discussed is that there might have been light from another source that disturbs the diffraction, but this most likely does not lead to greater error than our measurements.

If we stay on diffraction from a single slit we can clearly see differences compared to N-slits. The central maximum is clearly larger than those on either side, the intensity of the maxima's from the center also decreases rapidly. We could see similar effect on N-slits but not as drastic. In the formulas in the theory section we see "Intensity at bending", I_0 is the intensity at the center of the pattern. With L'Hôpital's Rule [5] we know that for the central maximum m=0,β is also 0.

$$\lim_{\beta \to 0} \frac{\sin \beta}{\beta} = 1$$

$$\lim_{m \to 0} I = I_0$$

Perhaps to understand the above you might have to see the steps to the final formula. Basically, β is dependent on various variables including the order [6] We believe it would add little to the discussion of the phenomenon to list all the steps of the definition. From this we know that max intensity is indeed in the middle and it is supposed to be substantially larger than the other maxima's to each side. Since the $\sin \beta$ is restricted to [-1:1] and not the rad angle in the denominator, this is then squared for even larger effect. We can also see that those points with no patterns are seen located where $\sin \beta = 0$.

For the double slit we got a diffraction pattern similar to the theoretical one too, this experiment has been done before and is called the Young's double slit experiment [7], this proves that light was indeed a wave. If there were no diffraction and interference the light would just show two lines on the screen, instead we see multiple lines with different intensity as shown in the results above. The reason we see more clear maxima's here is because the waves interact with each other and amplitudes of waves add. If two waves are in phase pure constructive happens (amplitudes double) and pure destructive interference happens when the waves are completely out of phase, meaning one waves max interfere with the other ones min, resulting in cancellation of the wave. No diffraction. If we look at the formula "Interference for head max" from theory-section, so if λ (for good light source) and m is fixed. Then a small d (width) would have to result in larger θ, this is something that can be observed with all these experiments but perhaps most notable here. Perhaps good to mention although θ becomes larger that should not be confused with that these angles are large, they are relatively small, especially for the single slit. As mentioned in the paragraph regarding intensity for singular slit, the same pattern and formula can be used here. The intensity falls off.

The last opening we will mention in the discussion is diffraction gratings. We saw maxima's outside the screen across the room simply when doing the experiment with high number of slits, the maxima's with high angle had so low intensity before that they were not seen.

B. Experiment with a grating spectroscope

When looking through a grating without a telescope many pairs of spectral lines are shown. The reason for this is because of diffraction when light goes through the grating. This is because this kind of grating separates the polychromatic light into its corresponding wavelengths and with some distance to the next order of light. This kind of diffraction is caused by waves of light being shifted by a diffraction object, in this case a grating, which causes the incoming light to diffract and the pattern shown depends on the diffracting object and the size of the wave of light [8]. One can wonder why they are called spectral lines and not called after other types of shapes. The gratings with slits contains the shape of lines which is the reason for the shape.

The experiment when doing the wavelength measurement is pretty straight forward, however a good question to ask here is what is the biggest error when you try to get the wavelength on the spectroscope? This is probably a human error as if the setup is correctly placed and configured the spectroscope should give the correct visual effect on the spectral lines. However as this is a physical setup and not made by some kind of computer program or online the human error is a big part here during this experiment. To read the vernier scale can be quite difficult, especially if this tool is new to the person who does the experiment. To find the right angle on the vernier scale a tick must be aligned correctly to the scale, which can give the wrong number of ticks for the calculation if the person is reading the scale from the wrong angle.

The wavelengths retrieved from NIST can be used in the wrong way. During the calculation to retrieve the deviation between the measured wavelengths and NIST the wavelengths from NIST is rounded. The reason for this is because for easier calculations with no decimals, which could give some source of error of the result. However as shown in figure 5 the difference between the wavelengths is not that large. The difference is more visible in the first order of the diffraction. This small difference could be the cause of human error on the vernier scale or from rounding up the wavelengths. The question is why the first order is so much different from the fourth order as the fourth order contains three of four wavelengths that are the same as NIST. This could be pure coincidence but the most logical explanation is that the vernier scale has been read wrongly and of course that the lab result is done one time when probably NIST have done these tests several times and extracted an average value from it.

VIII. Conclusions

Our result for both parts of the lab appear to be aligned with the theoretical answers. There were some differences between the results gathered experimentally compared to the theoretical result. This was mostly noticed from the singular slit in experiment one and experiment two with the spectroscope. Some potential errors such as potential outside light, error in reading were mentioned in the discussion.

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