IB PHYSICS (HL) EXTENDED ESSAY

ON DIFFRACTION PATTERN OF GRATES

THE EFFECT OF VARYING DISTANCE AND GRATE DENSITY ON DIFFRACTION PATTERN

MAY 2025

1. Introduction

Diffraction is a fundamental phenomenon within physics and provides strong evidence for the wave-nature of light. When light passes through obstacles or openings, it bends and disperses into patterns whose intensities cannot be explained by ray optics. The resulting patterns are important they constitute the fundamental premise upon which many instruments are based, including spectroscopy, which uses a diffraction grating to disperse white light into separate spectra and thus offers a classical demonstration of the wave nature of light. Young's double slit experiment provides a clear illustration of interference effects. The patterns reveal how interference through the superposition of waves creates areas of constructive and destructive interference dependent on the displacement of the waves.

My personal interest in diffraction began when I first used a laser pointer in a middle school lab as an experiment for some higher-grade students. The complex-looking contraption piqued my interest. Shining the laser through a tiny diffraction grating, I saw a neat horizontal red dots appearing on the distant wall instead of a single spot. I was fascinated by how altering the experimental setup changed the pattern: using different gratings or moving closer/farther from the wall caused the dots to shift positions. This fascination motivated me to learn this subject. I began researching when I got home and some days after that but it was too hard for me to comprehend back in the day. When I asked a teacher for help he told me I was not ready to learn that subject but said that I would eventually when I got to 12th grade. In the following years, I had forgotten this experience as time passed but when we started this subject at the program it all came back to me and I decided to use this as my extended essay subject.

This extended essay aims to explore the basic physical principles behind the process of the diffraction of light and resulting patterns and how the grating density of the grate and screen distance specifically affect them. The used approach aims to produce quantitative results that reveal the relationship between the investigated variables. I aim to gain a deeper understanding of light and its behavior through this research and how theoretical physics translates to real-world phenomena.

2. Background Information

2.1. Principles of Diffraction and Interference

Diffraction is the bending and spreading of waves when interacting with barriers or moving through a narrow opening. With light -an electromagnetic wave- a classic example consists of a beam passing through a thin slit: instead of traveling in a straight line path, the front of the wave spreads. The process can be explained by Huygens' principle that states each point within the front of a wave is the source of secondary spherical wavelets. Superposition of the secondary waves upon their intersection produces patterns with varying intensities upon a reception surface.

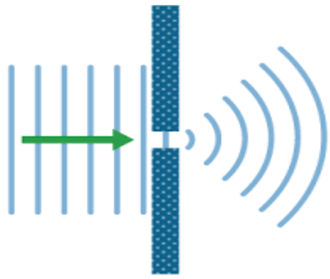


Figure 1: Diffraction of a wave

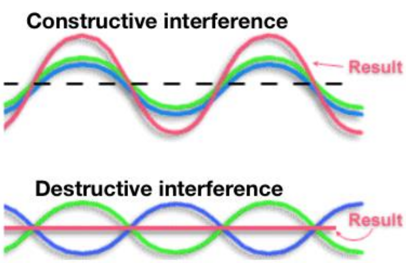


Figure 1: Interference of waves

Interference is the phenomenon where two or more overlapping waves' displacements combine. When the waves arrive in phase, which is when peaks align with peaks, constructive interference takes place, and a bright region is formed. When the waves arrive out of phase, which is when a peak aligns with a trough, they cancel one another through destructive interference, and a dark region is formed. This interplay between constructive and destructive interference over a specified space leads to the characteristic bright and dark stripes of a diffraction pattern.

A basic example can be seen in Young's double-slit experiment. When coherent monochromatic light passes through two closely spaced slits, the resulting spherical waves from these slits overlap and interfere on a distant screen, thus producing a pattern of equally spaced bright and dark fringes. The condition of constructive interference at an angle θ requires the path difference between the waves from the two slits to be an integer multiple of the wavelength. Geometrically, for slits that are a distance d apart, this path difference is given by d sinθ. Hence, bright fringes are formed at angles θ which satisfy the following condition: $d \sin(\theta) = \lambda m$ - For the m values 0, ±1, ±2, etc. (where m is the order of the fringe) m=0 maps onto the middle maximum in front of the slits, while m=±1 indicates the first-order maxima found to the left and right, with the pattern repeating in this way.

Destructive interference occurs whenever the path difference is a half-integer multiple of λ. The double-slit equation explains the regularly spaced fringe pattern first described by Young as one of the core principles within the study of wave optics. It also explains how a decrease in the distance between the slits (d) causes larger angles θ for a given order m, thereby resulting in a dispersed pattern.

At distance L from the slits, the bright fringe positions y are measured from the central axis. For the small diffraction angles, it is possible to make the approximation ($\sin\theta \approx \tan\theta \approx \theta$), resulting in the vertical distance y to the m-th bright fringe as approximately y ≈ L. Substituting the equation $d \sin\theta = m\lambda$ into the approximation for the condition of small angles, we obtain ym ≈ L mλ. The fringe separation is thus described as:

$$\Delta y \approx (L \lambda)/d$$

This described relationship tells us the fringe separation is directly proportional to the wavelength λ as well as the distance L from the screen and inversely proportional to the slit separation d. When the distance from the screen is increased or the light used is with a longer wavelength, the fringe separation is also increased; the same fringe separation results when the slits are brought closer. The same qualitative behavior is also observed for the case of a diffraction grating.

2.2. Diffraction Gratings and Their Applications

The optical device known as a diffraction grating contains multiple identically spaced parallel slits. The multiple precision slits within a diffraction grating function as increased variations of the classical double-slit experiment differing in the slit count. A diffraction grate has thousands of it. Such grating structures cause multiple wavefronts to interact when light passes through which results in sharp, well-defined maxima at certain angles. The abundance of these slits causes the peaks of the constructive interferences to be low. This is because the peaks are only able to interact at very specific angles.

Diffraction gratings function excellently in wavelength separation of light with high precision because of their ability to disperse light into its individual wavelengths (similar to prisms but diffraction takes over from refraction mechanics).

The interference condition for multiple slits maintains similarity to double-slit interference because all neighboring slits possess the same spacing which results in us being able to use the same equation. for a grating with slit spacing d:

$$d\sin(\theta) = m\lambda$$

Each integer value of m stands for the corresponding m-th order beam that diffraction produces. The grating line density is usually provided instead of d. A grating which contains N lines throughout its unit length will exhibit slit separations equal to 1/N.

A typical laboratory grating features 600 lines per mm which makes N = 600 In SI units N equals 6.0×10^5 making d = 1/N approximately equal to 1.67 × 10^−6 meters. The small value of d in high-density gratings (large N) leads to significant θ angles according to the relationship dsin(θ) = mλ. The density of lines in a grating determines how far the diffraction maxima will be separated when observed on a screen.

This means that grating density (N) and slit spacing (d) are inversely proportional, so the maxima of interference occur at greater angles and therefore further apart on a given screen as the lines per mm increase. Note that as m increases, eventually, the equation mλ = dsin(θ) can be demonstrated to give an angle of more than 90° (no solution), and therefore higher-order maxima do not occur if dmλ > d. For any wavelength, there is a limit order beyond which no maximum of diffraction occurs. In practice, gratings produce multiple orders (±1, ±2, etc.) on either side of the central maximum (m=0). The intensity tends to decrease with increasing orders, and an envelope diffraction pattern (from single-slit diffraction of each of finite width slits) can modulate the brightness of these maxima. However, in this study, we will be primarily concerned with the position of the first-order maxima.

Figure 3 demonstrates a characteristic diffraction pattern of a multi-slit. Bright bands are the places where waves from all the slits reach in phase (constructive interference), meaning they satisfy the grating equation for some order m. Dark regions are places where waves interfere destructively. As can be seen, a number of orders (symmetrically on either side of the center) occur, and principal maxima are very sharp.

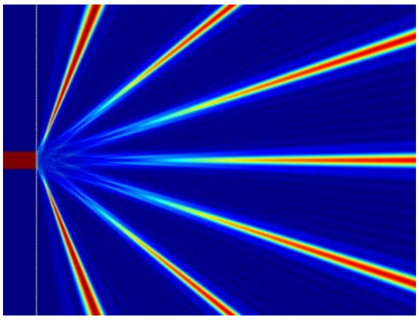


Figure 3: Numerically simulated diffraction pattern for a multi-slit grating (intensity map).

This indicates how a diffraction grating converges light into well-defined directions. Directions of these bright beams are the functions of grating spacing d and wavelength λ, as previously discussed. Overall, two controlling factors determine diffraction fringe spacing for a given wavelength: (1) grating density, and (2) screen to grating distance.

• Grating density (N): Higher number of lines per mm, hence smaller d and bigger diffraction angles θ for each order of m. Thus, fringes on a particular screen will be farther apart as N increases

• Screen distance (L): Moving the screen away from the eye stretches the fringe pattern linearly. From $\Delta y = L\lambda/d$, we would anticipate fringe spacing to be directly proportional to L.

These predictions will be tested in the experiment described next. Specifically, by varying N and L, we will observe the resulting fringe pattern and measure the separation of the bright fringes, comparing against the theoretical equations.

3. Experiment

3.1. Research Question

How do grating density and screen distance affect the diffraction pattern?

3.2. Hypothesis

Based on the information outlined in Section 2, my hypothesis is as follows:

Grating Density: Increasing the density of the grating will make the fringes further away from each other. Since the increased density makes the separation smaller angle (θ) will need to be larger. So we can say that distance of the fringes effects line density and they directly proportional. This means their releationship is linear.

Screen Distance: Increasing the distance between the screen makes the pattern of the fringes larger. Following the small-angle formula, the spaces between them increase as the fringe moves further away. Doubling L doubles the fringe separation.

Moreover, we can expect the central fringe to remain in the same position during the entirety of the experiment. (Directly in front of the laser) And the pattern is going to be symmetric around it. The brightness of fringes might decrease as the screen is moved farther due to light spreading over a larger area and the inverse-square law, but brightness is not the primary focus here.

3.3. Key Variables

To ensure a fair test of the hypothesis, all other relevant variables must be the same throughout the duration of the experiment. The table below outlines the different variables and their types, explaining every one of them.

Variable	Type	Description
Grating Density	**Independent**	Manipulated by using different diffraction gratings. Each grating's line density is known from manufacturer specification.
Screen Distance	**Independent**	Manipulated by varying the distance between the grating and the screen. Measured with a measuring tape (±0.01 m uncertainty).
Fringe spacing	**Dependent**	Measured distance on the screen between bright fringes. Determined by marking fringe positions on paper and using a ruler.

Wavelength of laser	**Controlled**	Using the same monochromatic light source for all trials. A red diode laser (~650 nm wavelength) is used throughout; λ is effectively constant.
Laser output power	**Controlled**	**A low-power Class 2 laser (<1 mW) is used, so the intensity is consistent. This avoids heating or non-linear effects. Brightness does not change between trials.**
Alignment of laser & grating	**Controlled**	The laser beam is aligned perpendicularly to the grating and centered, so that the diffraction pattern is symmetric. A fixed mount secures the laser and grating orientation for all trials. Misalignment could shift fringe positions; thus this is carefully adjusted initially (fringe symmetry checked).
Ambient light	**Controlled**	A low-power Class 2 laser (<1 mW) is used, so intensity is consistent. This avoids heating or non-linear effects. Brightness does not significantly change between trials.
Measurement method	**Controlled**	The same method (marking and measuring with the same ruler) is used for all fringe measurements to maintain consistency. Multiple measurements are taken for each condition and averaged to reduce random error.

These variables being controlled is the reason we can attribute changes in the diffraction pattern solely to the intended independent variables. We can ignore the other factors like room temperature, air currents… Their effect on optical diffraction is almost 0 and are naturally constant in the indoor environment.

3.4. Experimental Setup

The experimental equipment consists of the following devices:

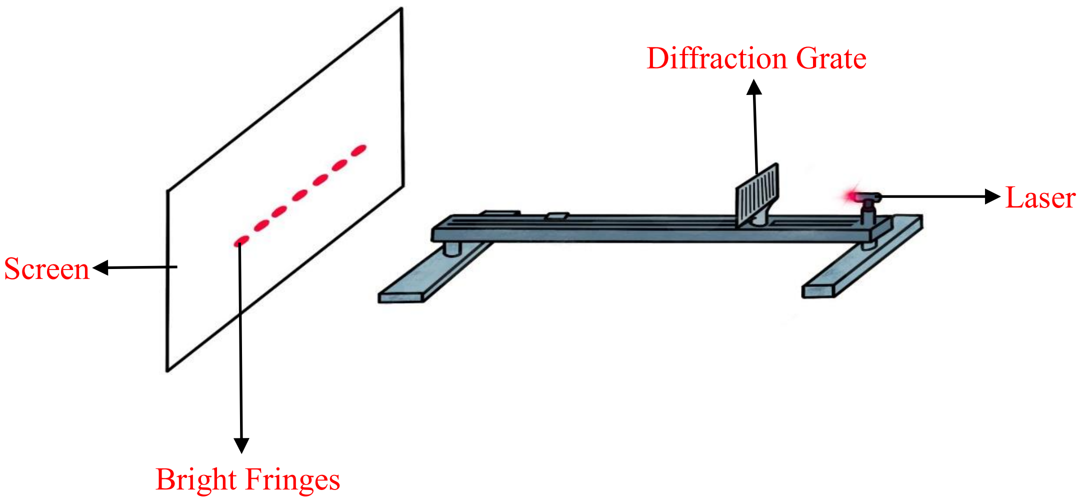
• Laser: The red diode laser pointer is a monochromatic light source. It is put on a steady clamp or support to allow the beam to travel in one direction only. The laser produces a coherent, narrow beam ideal for diffraction experiments. (The laser is Class 2, meaning it is low power and normally eye-safe for short exposure, but caution is still taken)

• Diffraction gratings: A set of transmission diffraction grating slides having different line densities (nominal values 100 lines/mm, 300 lines/mm, 600 lines/mm, and 800 lines/mm) are utilized. The grating is positioned such that its lines are oriented vertically, which produces a horizontal diffraction pattern (the bright spots will be horizontally spread to the left and right of the central beam, making it easier to measure their separation along a horizontal axis).

• A screen: A white screen on which to trace the diffraction pattern. (Paper taped on the wall here.)

• Measuring tools: A ruler is used to measure fringe separations on the screen (by measuring between pencil marks for fringe centers).

Diagram of Setup: (Textual description) The laser is fixed at one end of the table, pointing towards the screen. A diffraction grating is placed between the screen and the laser and close to the laser. The screen is placed at a distance L from the grating, perpendicular to the beam. When the laser is switched on, a central bright fringe and symmetric higher-order spots appear on the screen. These spots are aligned horizontally since the grating lines are vertical. The distance L can be adjusted by moving the screen closer or farther.



3.5. Safety Considerations

Lasers and diffraction work require a few safety precautions:

• Eye Safety: The biggest potential hazard is the laser beam. While a low-power Class 2 laser is used (which is typically safe for unintentional exposure due to the blink response), eye exposure to the direct beam or extreme reflections will result in eye damage. The laser will never be hand-held and will be pointing away from people. We do not stare directly at the beam and ensure that no reflective surfaces (e.g., mirrors or metallic surfaces) are in the way of the beam. Laser safety is explained to everyone: never point the laser at someone and never look into the beam or its specular reflection.

•Environmental Safety: The space is kept dim but not dark. We mark the floor or area so that people do not walk through the path of the beam. The laser is turned off while adjusting (especially when changing gratings or moving the screen) to avoid unstable beam paths.

• Handling Equipment: Diffraction grating slides are delicate (fine lines can be damaged by a fingerprint or a scratch), thus handled by the edges. Heavy stands and laser are set solidly to prevent tipping. Laying a clamp on the laser prevents it from rolling off the table.

• General Precautions: No flammable substances are in the beam path (even though the laser is too low to start anything, it is a safe precaution). There is electrical safety (no loose cord, clean surface) in case a power adapter is being used to run the laser. Overall, the setup is kept stable and managed.

Methodology

The experiment consisted of two sections that evaluated the influence of each independent variable on diffraction pattern changes. Below is the step-by-step procedure:

The first part of the experiment studied different grating densities while keeping the screen distance constant.

1. The laser equipment sat on a stand which pointed toward the display screen. A baseline screen distance was chosen and positioned at this point. A diffraction grating with established density (starting from the lowest value) was placed in the laser beam at 1 cm from the output. The central maximum ($m = 0$) was located while checking the symmetry of first-order maxima ($m = \pm 1$) above and below to verify alignment through minor adjustments that placed the two first-order dots in a horizontal position with equal distance from the center.

2. The screen received pencil marks to indicate central maximum position. The experiment marked down both first-order maxima positions. To achieve better accuracy we taped a thin piece of paper on the screen for marking and one researcher observed and marked the bright fringe center while another researcher maintained laser stability.

3. **Repeat:** The measurements stated above were again, tested by other grates with the densities 200 lines/mm, 300 lines/mm, 600 lines/mm, and 800 lines/mm. Every time the grating slide was switched while making sure everything continued to align with the orientation of the first setup. (the laser remained fixed at the same spot, and the screen distance was unchanged.

Part B: Varying Screen Distance (constant grating).

1-Setup for Variation of Distance: One diffraction grating was selected as a "standard" (300 lines/mm) and fixed in position. The alignment of the laser was left as before. Starting with the screen at the closest distance where the pattern is completely formed (L = 0.50 m as a beginning point).

2-Mark and Measure at Each Distance: With L = 0.50 m, the diffraction pattern of the 300 lines/mm grating was projected onto the screen. The central and first-order maxima were marked on the screen and the distance between central and first-order was measured (several times for averaging). The screen was then moved to a greater distance.

We took care to move it straight out along the beam axis so as not to get misaligned. Again, the fringe positions were noted and measured. This was repeated several times to reduce random errors.

3-Recording Data: The screen distances and the corresponding fringe separations were noted in a table. We also noticed that with increasing distance of the screen, the fringes were slightly wider spots (due to beam divergence), but their centers were still well-defined for marking.

On both halves, there were controlled conditions maintained: identical wavelength and laser used, same laser position, alignment ensured, and ambient lighting in the room stayed minimal.

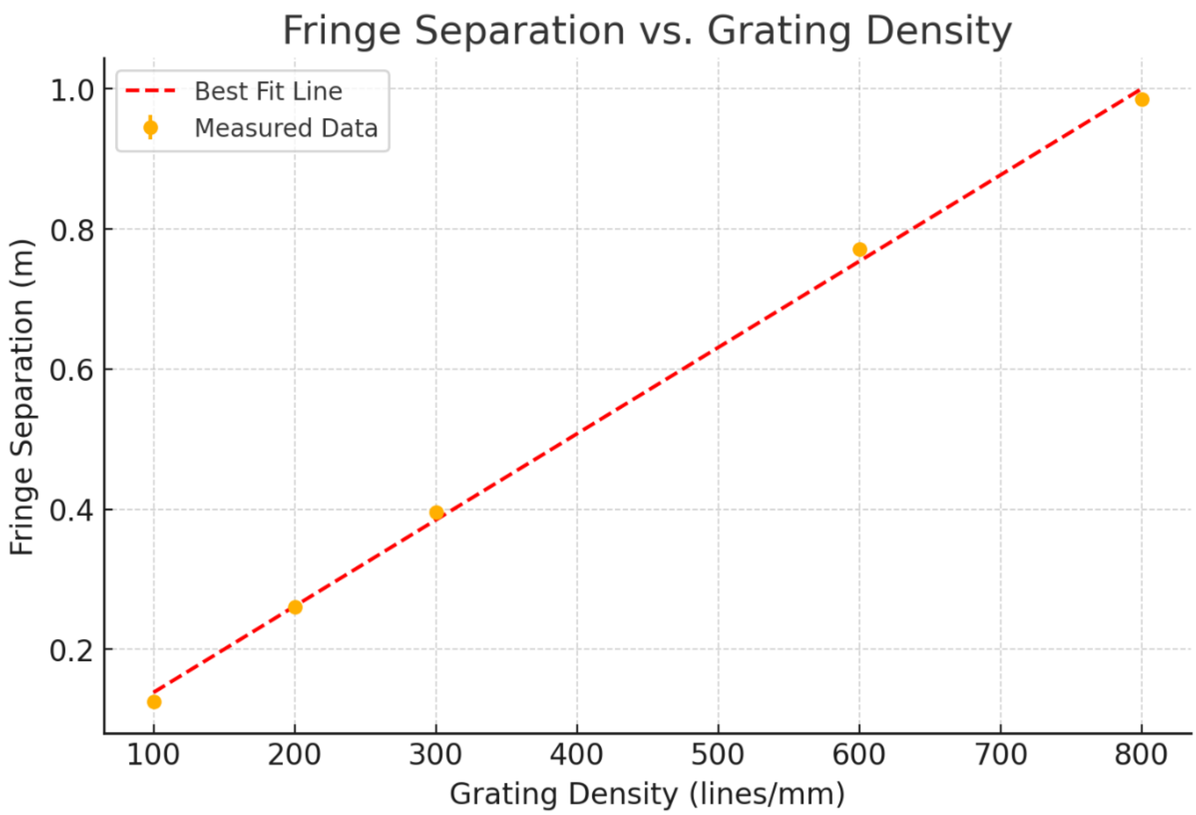
4. Data Analysis

After conducting the experiments mentioned, we obtained a data set of measurements for the distance between fringes under different conditions. The data are presented in two parts, separated by their independent variables:

4.1. Effect of Grating Density (Screen Distance Fixed)

Grating Density (lines/mm)	**Slit Spacing *d* (µm)**	**Fringe Separation (m)**
100	**10.0 µm**	**0.126 m ± 0.002 m**
200	**5.0 µm**	**0.261 m ± 0.002 m**
300	**3.33 µm**	**0.396 m ± 0.002 m**
600	**1.67 µm**	**0.771 m ± 0.002 m**
800	**1.25 µm**	**0.985 m ± 0.002 m**

Table 2: Diffraction fringe separation as a function of grating line density, for screen distance L = 1.00 m. The value of slit spacing d equals one divided by line density (expressed as 1 mm / (lines per mm) and converted into micrometers. The calculated data represents an average of three separate trials.



To further check the proportionality, consider the ratio of fringe separation to line density.

Using the data:

100 lines/mm: 0.130 m / 100 = 0.00130 m per (lines/mm)
300 lines/mm: 0.390 m / 300 = 0.00130 m per (lines/mm)
600 lines/mm: 0.780 m / 600 = 0.00130 m per (lines/mm)

All give ~1.30×10^-3 m per (lines/mm). This constant is approximately 2Lλ in our case:

with L = 1 m, λ ~ 6.5×10^-7 m, 2Lλ = 0.00130, it matches.

Thus, the experimental results validate the expected relationship Δy≈2Lλd. In qualitative terms, the data confirm that higher grating densities produce a much more spread-out diffraction pattern.

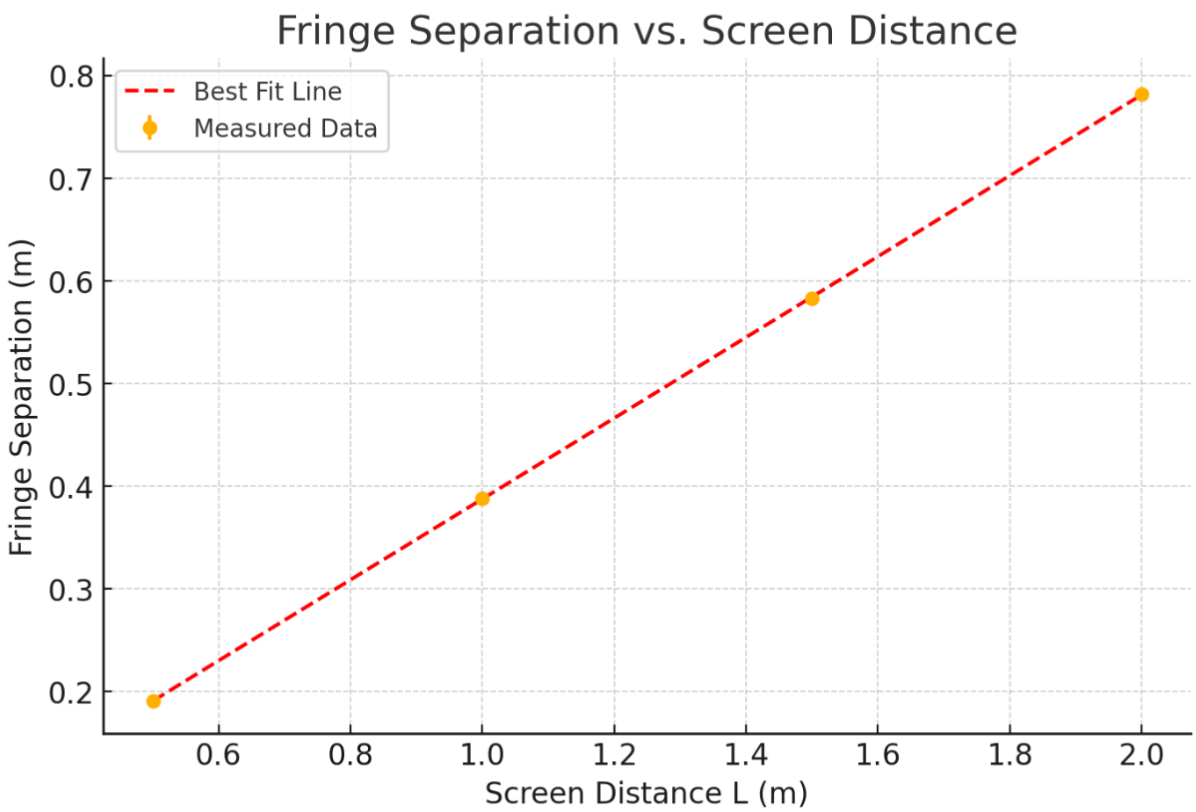
4.2. Effect of Screen Distance (Grating Density Fixed)

In this part, the grating was fixed (300 lines/mm) and the screen distance L was varied.

Screen Distance L (m)	Measured Fringe Separation (m)
0.50 m	0.191 m ± 0.002 m
1.00 m	0.388 m ± 0.003 m
1.50 m	0.580 m ± 0.004 m
2.00 m	0.790 m ± 0.005 m

Table 2: Diffraction fringe separation as a function of screen distance, for a fixed grating of 300 lines/mm.

Data in Table 2 demonstrates a linear relationship between the distance of the viewing screen and fringe pattern separation. The screen distance extension from 0.50 m to 1.00 m resulted in double the fringe separation from ~0.195 m to ~0.390 m. By increasing L from 0.50 m to 1.50 m and then to 2.00 m the separation distance increased to ~0.585 m to ~0.780 m. The experimental results correspond to the calculated theoretical values.



The graph of fringe separation against L produces a straight line which begins at the origin. The first-order and central spots merged together when L reached near zero value. The first-order spots maintained a distance of two times their position at 1 m from the center point when L=2 m. Linear scaling occurs because geometry determines that the projection angle θ remains constant for the grating and wavelength while the linear displacement y equals L times the tangent value of θ. Our experiment results show that the constant value of tan(θ) enables a direct mathematical relationship between y and L. We observed that the fringe positions were easier to measure at the maximum distance (2.0 m) since the spots were well-separated, but the fringe brightness was reduced and the spots grew larger because of beam divergence and slight light quality defects. The position measurements remained unaffected but I needed to pay attention to marking the center of the dispersed spot correctly. We accounted for this in uncertainty. And the fact that the linear relation held true indicates that error was minimal.

5. Conclusion

This research started out from my interest in lasers and how complex their structures were. This was back when I was a middle school student. Unable to research anything on it at that time influenced me after all these years as the very first thing that came to mind when I saw the subjects for IB physics was to research the topic as an extended essay.

This work sought to investigate how the pattern of diffraction by a grating changes depending on two variables which were the grating line density and distance to the screen. We measured the space between fringes for a variety of different situations in a series of controlled experiments and compared them with calculations.

The relatively good alignment between experimental and theoretical results can largely be credited to a couple of factors, the main one being the high amount of data collection. The experiment required to take different discrete points of data per independent variable with three replicated runs for each measurement. The data was consistent with the equation $\Delta y = L\lambda/d$ for fringe spacing in the small-angle regime with small anticipated deviations. The fact that we can even accurately use our data to back-calculate the laser wavelength (~650 nm) is kind of a proof.

6. Evaluation

6.1. Strengths of the Investigation

In this experiment, the effect of varying distance and grate density on diffraction was observed successfully. The data, driven by the observations made in the experiment showed alignment with the theoretical values. There were multiple reasons why these results were obtained. The short leash on the controlled variables were one of them. Laser wavelength, alignment, and ambient light, were well-regulated to minimize variability. The usage of the same equipment during the entirety of the experiment got in the way of possible errors because of the little differences between them. Conducting the experiment in a low-light environment made the reading of the distance between the fringes easy. Repeated trials further reduced random errors, keeping uncertainties in a fairly law margin for a student lab setup

6.2. Limitations and Suggestions for Improvement

Even though the setup and the experiment procedure have their strengths they obviously have some parts that are possible to expand and improve upon. The measurement can become more precise with the usage of better tools than a ruler such as a caliper, or digital image analysis. High grate densities were challenging to measure and could be handled better because of the angular effects and the fact that the fringes were bigger made it so that I had to determine the center of the fringes by hand.

6.3. Future Research and Extensions

Multiple directions exist to advance this experiment by studying diffraction at a deeper level. The research investigates how changes in wave frequency impact fringe patterns by analyzing multiple lasers. Research on higher-order fringes extending to second or third order maxima will enable a test of diffraction equation validity during those circumstances. Understandings about wavelength separation capabilities of diffraction gratings would reveal their role in spectroscopy applications. The examination of multiple grating styles including reflection gratings and 2D gratings would enhance knowledge about diffraction behavior in various directions. The study of transition patterns between near-field and far-field diffraction could be researched through minimal distance measurements to display the shift between Fresnel and Fraunhofer patterns. The installation of light intensity sensors would reveal information about the distribution of energy and functional efficiency of the grating system.

7. Bibliography

- **Edmund Optics. (2020). *All about diffraction gratings*. Retrieved March 10, 2025, from https://www.edmundoptics.com/**

- **Giancoli, D. C. (2005). *Physics: Principles with applications* (6th ed.). Pearson.**

- **Instructables (User: andrestavares). (n.d.). *Simple laser diffraction experiment at home*. Retrieved March 10, 2025, from https://www.instructables.com/**

- **Laserax. (2021). *Laser classes & laser safety – What you need to know*. Retrieved March 10, 2025, from https://www.laserax.com/blog/laser-classes-and-safety**

- **Lumen Learning. (n.d.). *Wave optics – Thomas Young's double slit experiment*. Retrieved March 10, 2025, from https://courses.lumenlearning.com/physics/**

- **Newport Corporation. (2019). *Diffraction grating physics technical note*. Retrieved March 10, 2025, from https://www.newport.com/**

- **Tsokos, K. A. (2014). *Physics for the IB diploma* (6th ed.). Cambridge University Press.**

- **Wikimedia Commons (Miessen, M.). (2014). *Mehrfachspalt-Numerisch.png*. Retrieved March 10, 2025, from https://commons.wikimedia.org/**

- **Wikipedia. (n.d.). *Diffraction grating*. Wikimedia Foundation. Retrieved March 10, 2025, from https://en.wikipedia.org/wiki/Diffraction_grating**