Lab Report 2: Optical Diffraction

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Contents

1 Abstract

Following Experiments explore the phenomenon of optical diffraction through a series of experiments. The experiments investigate the diffraction patterns generated by slit, circular, and multiple slit grating apertures The apparatus includes a semiconductor diode laser, an optical bench, CCD camera, and various optical components which aim to record and analyze Fraunhofer diffraction. Specifically angular positions and relative intensities of peaks and minima. The findings are compared with theoretical predictions, demonstrating the correlation between experimental and theoretical results. Throughout the experiments, sources of error are identified, including challenges in maintaining ideal beam alignment. Despite these limitations, the results generally align with theoretical expectations, confirming the observation of Fraunhofer diffraction under the given conditions. Overall, the experiments outlined provide valuable insight into optical diffraction and specifically demonstrate the potential similarity between theory and experimental findings.

2 Theory and Introduction

A property of waves is that they diffract as in they spread out and change direction as they pass through or around obstacles. As light behaves as a wave; In order to investigate this property we must observe light as it passes through apertures and take the projection of such a motion at a particular plane perpendicular to the incident motion. This results in observing peaks and troughs of intensity along the horizontal axis alongside the beam as the constructive and destructive interference occur. An equation which outlines the angular dependence of this phenomenon is outlined below:

$$I(\theta) = I(0)\left(\frac{\sin(\beta)}{\beta}\right)^2, \text{ where: } \beta = \left(\frac{kb}{2}\right)\sin(\theta), \quad k = \frac{2\pi}{\lambda} \tag{2.1}$$

In order to quantify this phenomenon a sensor may be used instead of the optically reflected intensity along a screen. In order to perform such a measurement, the experiments outlined below use a CCD camera with a specialist software specifically designed with this purpose in mind. In the experiments to be outlined, a laser with emitted light wavelength λ 650 nm was utilized to examine diffraction for both its close (Fresnel) and far (Fraunhofer) phenomenology. The angular position which is calculated using the following expression:

$$\text{Angular Position} = arctan(\frac{x}{L}) \tag{2.2}$$

where x is the horizontal displacement of the observed occurrence from the central order beam observed and L is the distance between the diffracting aperture and the sensor. Assuming that diffraction behave similarly invariant of total intensity, measurement of angular position and relative angular intensity will be sufficient to make observations for the purposes of the experiments outlined below:

3 Apparatus

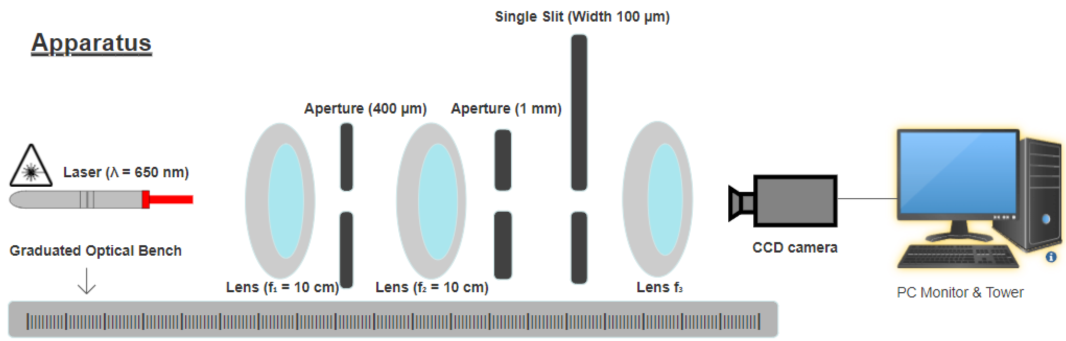

Figure 1: *The Apparatus*

The apparatus associated with this experiment includes:

- Semiconductor diode laser (wavelength: 650 nm)
- Optical Bench (Graduated with mounts)
- CCD camera with noise reduction cap
- Neutral Density Filters
- PC Monitor and Tower (with VideoCom software installed)
- Lenses (Focal lengths 10, 20 and 30cm)
- Circular apertures (of diameter 1, 1.2, 1.4, 1.6mm, and 400, µm)
- Single Slit (Width 100 µm)
- Multiple slit diffraction grating (with 25 slits, with width 40 µm and spacing 80 40 µm)

4 Methodology

4.1 Experiment 1 - Part 1:

The purpose of this experiment is to record the Fraunhofer diffraction produced by a slit of width 100 μm (without using the lens L_3).

The apparatus was configured as shown in Figure 1 (excluding lens L_3) in order to record the Fraunhofer Diffraction and determine:

- Their angular positions
- The relative intensities of the peaks

This was achieved in order to compare it with the theoretical expression for the Intensity (I) at an angular displacement θ on the CCD camera:
$I(\theta) = I(0)\left(\frac{\sin(\beta)}{\beta}\right)^2$, where: $\beta = \left(\frac{kb}{2}\right)\sin(\theta), \quad k = \frac{2\pi}{\lambda}$

Each row of the CCD camera sensor was made of 2048 pixels with a total width of 0.02867 m such that each pixel had a width of $\sim 14\mu m$.

In this case: the wavelength of the laser was: $(\lambda = 650nm)$, the width of the slit was: $(b = 100\mu m)$, and the distance between the CCD sensor and the slit was: $(L = 0.21m)$.

This information was used to determine the displacement of each peak from the central peak and then used to determine their relative angular positions.

The intensities of the peaks were noted and the theoretical expression was adjusted relative to the intensity of the central peak relative to the maximum intensity the CCD could measure.

The data was tabulated and used to compare the experimental data with the intensities mapped by the theoretical expression.

4.2 Experiment 1 - Part 2:

The purpose of this experiment is to record the Fraunhofer diffraction produced by a slit of width 100 μm while using the lens L_3 where the focal length of the lens is $\sim$ 0.4 m. The distance between the CCD sensor and the slit was: $(L = 0.48m)$. All other factors were controlled.

The data was tabulated and used to compare the experimental data with the intensities mapped by the theoretical expression. This information was used to determine the displacement of each peak from the central peak and then used to determine their relative angular positions.

The intensities of the peaks were noted and the theoretical expression was adjusted relative to the intensity of the central peak relative to the maximum intensity the CCD could measure.

The data was tabulated and used to compare the experimental data with the intensities mapped by the theoretical expression and the result determined in the prior experiment.

4.3 Experiment 1 - Part 3:

The purpose of this experiment is to record the Fraunhofer diffraction produced by a $400\mu m$ circular aperture

The apparatus was configured similar to shown in Figure 1 in order to record the Fraunhofer Diffraction of the circular aperture and determine:

- Their angular positions
- The relative intensities of the peaks

This was achieved in order to compare it with the theoretical expression for the Intensity (I) at an angular displacement θ on the CCD camera:

$I(\theta) = I(0)\left(2J_1(ka\sin\theta)\cdot\frac{ka\sin\theta}{2}\right)^2$

where a is the hole radius, and J_1 is the first-order Bessel function being: $J_1 = \frac{\sin(*)}{*^2} - \frac{\cos(*)}{*}$

In this case: the distance between the CCD sensor and the slit was: $(L = 0.48m)$

This information was used to determine the displacement of each peak from the central peak and then used to determine their relative angular positions.

The intensities of the peaks were noted and the theoretical expression was adjusted relative to the intensity of the central peak relative to the maximum intensity the CCD could measure.

4.4 Experiment 2:

The purpose of this experiment is to record the Fraunhofer diffraction pattern produced by a multiple slit grating:

The apparatus was configured similar to shown in Figure 1 in order to record the Fraunhofer Diffraction of the multiple slit grating and determine:

- Their angular positions
- The relative intensities of the peaks

This was achieved in order to compare it with the theoretical expression for the Intensity (I) at an angular displacement θ on the CCD camera:

4.5 Experiment 3 - Part 1:

A spatial filter is an aperture or pinhole. This aperture is placed in the path of the laser precisely such that defined hole or slit through which the laser beam must pass. The incident light travels through the aperture grating, though the objective lens (f = 0.2 m) and the transform lens and was used to produce three images being those with:

1. zero order diffraction only
2. zero and first order diffraction only
3. first order diffraction only

These measurements were then compared and their intensities noted.

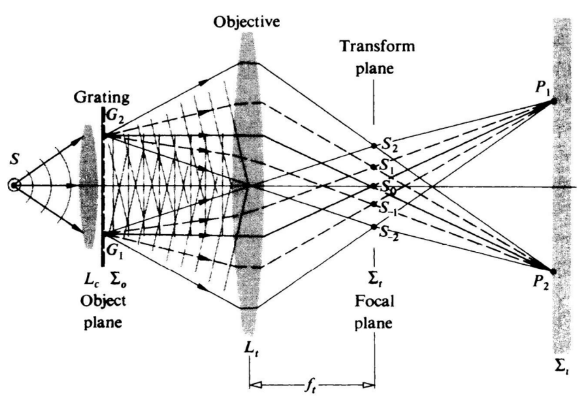

Figure 2: Image Formation in Spatial Filter

4.6 Experiment 3 - Part 2:

Plane waves incident on a circular aperture will project Fresnel patterns according to the following equation: $R_m^2 = mr_0\lambda$ The radiance is determined by the number of zones exposed by the aperture.

Choose conditions such that two separate images are determined: Select an aperature between 1.2, 1.4, and , 1.6 mm and record the associated lengths r_0 determined.

5 Data

5.1 Experiment 1 - Part 1:

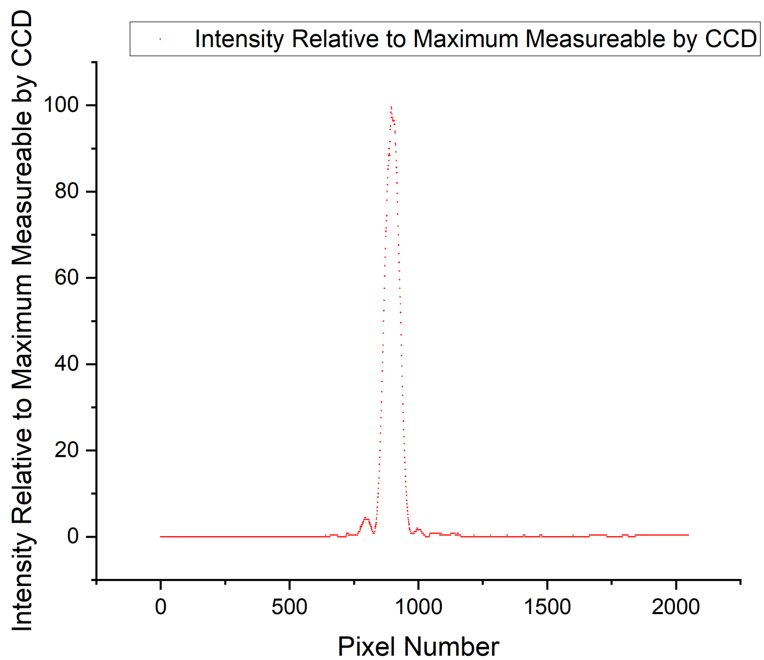

Figure 3: *Single Slit Fraunhofer Diffraction Without* L_3

Extremum Type	Pixel Range	Median Pixel	Displacement from C-P	Relative Intensity
Peak	722-728	725.5	-169.5	0.8%
L-Min	729-764	781.5	-113.5	0%
Peak	792-796	794	-101	4.4%
L-Min	824-829	831.5	-63.5	0.8%
C-P	895	895	0	99.6%
L-Min	970-983	976.5	81.5	0.8%
Peak	995	995	100	2%
L-Min	1027-1042	1049.5	154.5	0%
Peak	1045-1082	1063.5	168.5	0.8%

Table 1: Experimental Fraunhofer Diffraction without L_3

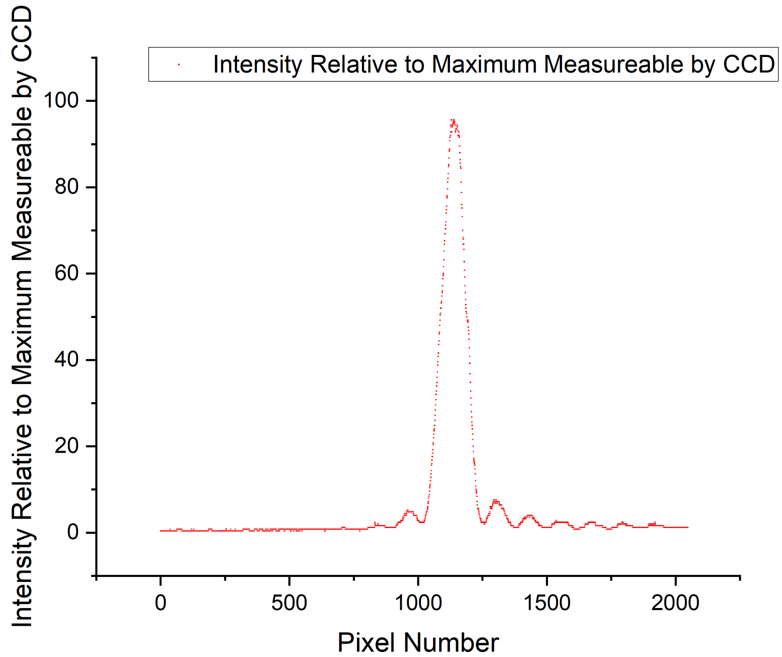

Figure 4: *Single Slit Fraunhofer Diffraction with L_3*

5.2 Experiment 1 - Part 2:

Extremum Type	Pixel Range	Median Pixel	Displacement from C-P	Relative Intensity
Peak	832	832	- 207	2.4%
L-Min	872-913	892.5	- 146.5	1.2%
Peak	959-962	960.5	- 78.5	5.2%
L-Min	1005-1024	1014.5	- 24.5	2.4%
C-P	1138-1140	1039	0	99.6%
L-Min	1258	1258	219	2%
Peak	1294-1304	1299	260	7.6%
L-Min	1371-1390	1380.5	321.5	1.2%
Peak	1424-1443	1433.5	394.5	4%

Table 2: Experimental Fraunhofer Diffraction with L_3

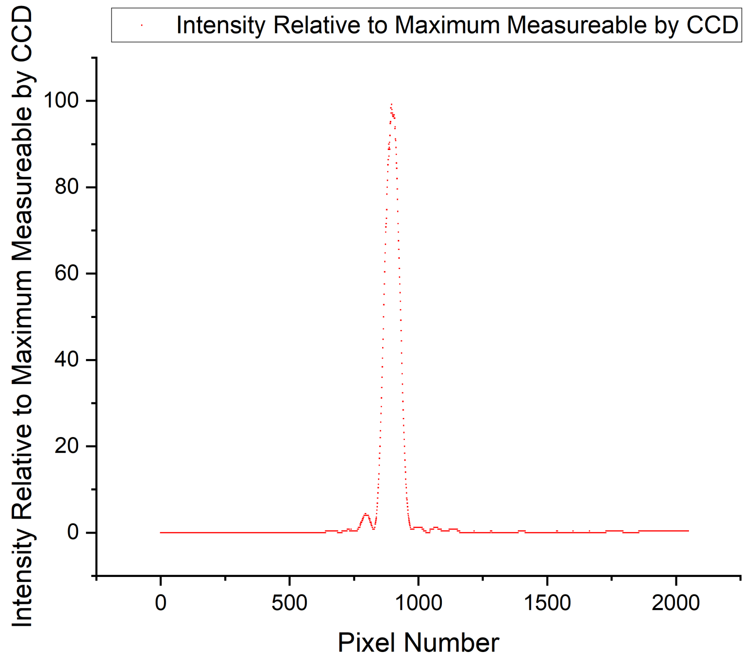

Figure 5: *Circular Aperature Fraunhofer Diffraction*

5.3 Experiment 1 - Part 3:

Extremum Type	**Pixel Range**	**Median Pixel**	**Displacement from C-P**	**Relative Intensity**
Peak	724-739	731.5	- 165.5	0.8%
L-Min	740-763	751.5	- 145.5	0.4%
Peak	795-797	796	- 101	4.4%
L-Min	823-829	826	- 71	0.8%
C-P	897	897	0	99.2%
L-Min	971-983	977	80	0.8%
Peak	984-1014	999	102	1.2%
L-Min	1030-1044	1038.5	141.5	0%
Peak	1060-1075	1067.5	170.5	1.2%

Table 3: Experimental Fraunhofer Diffraction by Pinhole

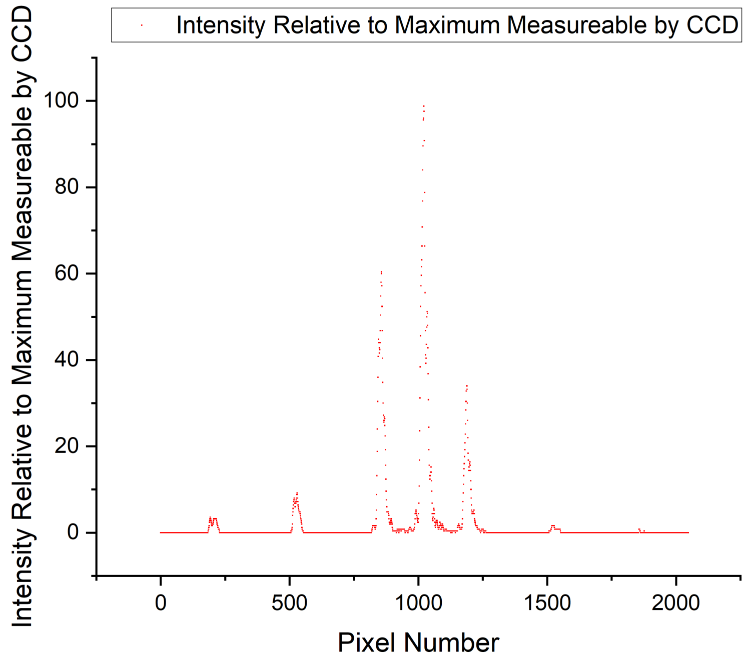

Figure 6: *Fraunhofer Diffraction by Multiple Slit Grating*

5.4 Experiment 2:

Extremum Type	Pixel Range	Median Pixel	Displacement from C-P	Relative Intensity
Peak	529	529	- 399	9.2%
L-Min	554-817	685.5	- 242.5	0%
Peak	856	856	- 72	60.4%
L-Min	915-927	921	-7	0%
C-P	928	928	0	98.8%
L-Min	1126-1144	1135	207	0%
Peak	1187	1187	259	34,0%
L-Min	1263-1506	1384.5	456.5	0%
Peak	1519-1528	1523.5	595.5	1.6%

Table 4: Experimental Fraunhofer Diffraction by Multiple Slit Grating

5.5 Experiment 3 - Part 1:

5.6 Experiment 3 - Part 2:

6 Results

6.1 Experiment 1 - Part 1:

There is acceptable correlation between the theoretical values and the experimentally derived values of angular position and relative intensity.

As the the distance L = 0.15 m, L ¿¿ $\frac{a^2}{\lambda}$ a is the width of the aperture, the diffraction observed

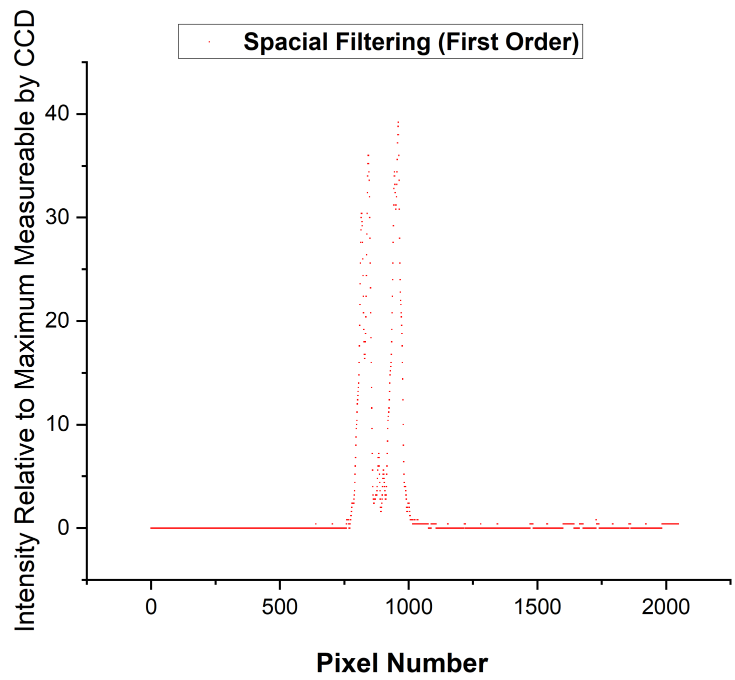

Figure 7: *Spacial Filtering (First Order)*

was Fraunhofer by definition.

The observed diffraction pattern aligns well with the theoretical predictions.

Extremum Type	Relative Displacement (mm)	Angular Position rad	Theoretical Angular Position (rad)	Theoretical Relative Intensity
Peak	-2.373	-0.01508	-0.01598	- 1.614%
L-Min	-1.589	-0.01059	-0.013	0%
Peak	-1.414	-0.009426	-0.0093	4.7%
L-Min	-0.8890	-0.005927	-0.0065	0%
Peak	0	0	0	undefined $\rightarrow$ 99.6%
L-Min	1.141	0.007607	0.0065	0%
Peak	1.400	0.009333	0.0093	4.7%
L-Min	2.163	0.01442	0.013	0%
Peak	2.359	0.01573	0.01598	1.614%

Table 5: Single Slit Fraunhofer Diffraction Without L_3

6.2 Experiment 1 - Part 2:

There was better correlation between the theoretical values and the experimentally derived values of angular position and relative intensity for the Fraunhofer diffraction with the lens l_3 which is contrary to that predicted by theory as theory would suggest that the presence of the lens would better collimate the beam such that it is better in line with theory in both angular position of the peaks and minima. This is likely due to a systemic error present in the measurement technique undertaken in these experiments as the beam was not kept straight

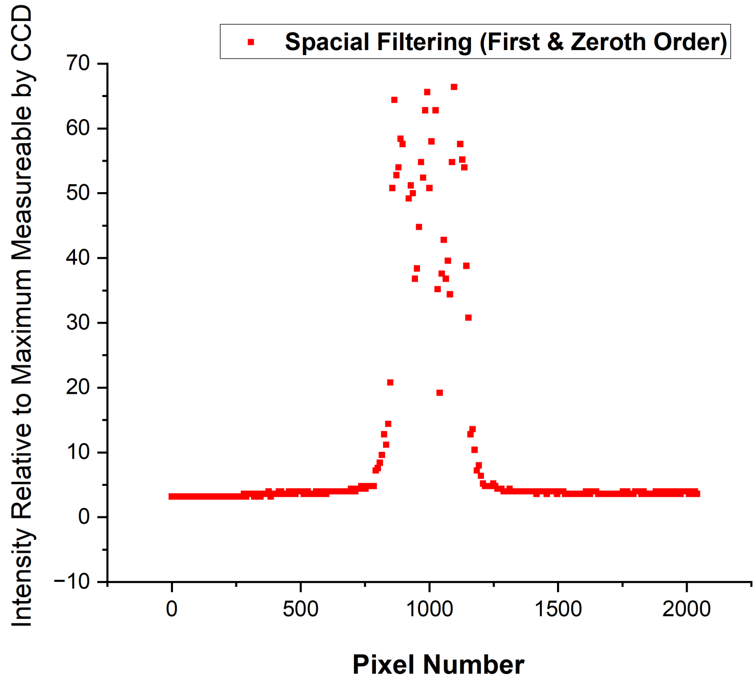

Figure 8: *Spacial Filtering (First & Zeroth Order)*

on the target of the CCD sensors and therefore the order of such a systematic error dwarfs the measurement error that can be propagated through the calculated values.

overall the observed diffraction pattern aligns reasonably well with the theoretical predictions.

Extremum Type	**Relative Displacement (mm)**	**Angular Position rad**	**Theoretical Angular Position (rad)**	**Theoretical Relative Intensity**
Peak	- 2.898	- 0.01380	- 0.01598	1.614%
L-Min	- 2.051	- 0.009766	- 0.013	0%
Peak	- 1.099	- 0.005233	- 0.0093	4.7%
L-Min	- 0.343	- 0.001633	- 0.0065	0%
Peak	0	0	0	undefined $\rightarrow$ 99.6%
L-Min	3.066	0.01460	0.0065	0%
Peak	3.64	0.01733	0.0093	4.7%
L-Min	4.501	0.02143	0.013	0%
Peak	5.523	0.02629	0.01598	1.614%

Table 6: Single Slit Fraunhofer Diffraction with L_3

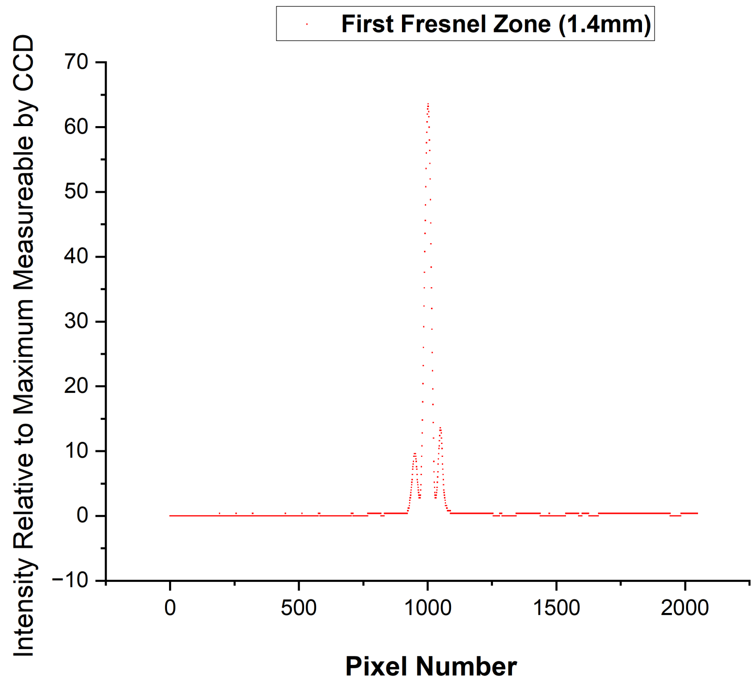

Figure 9: *First & Fresnel Zone (1.4mm)*

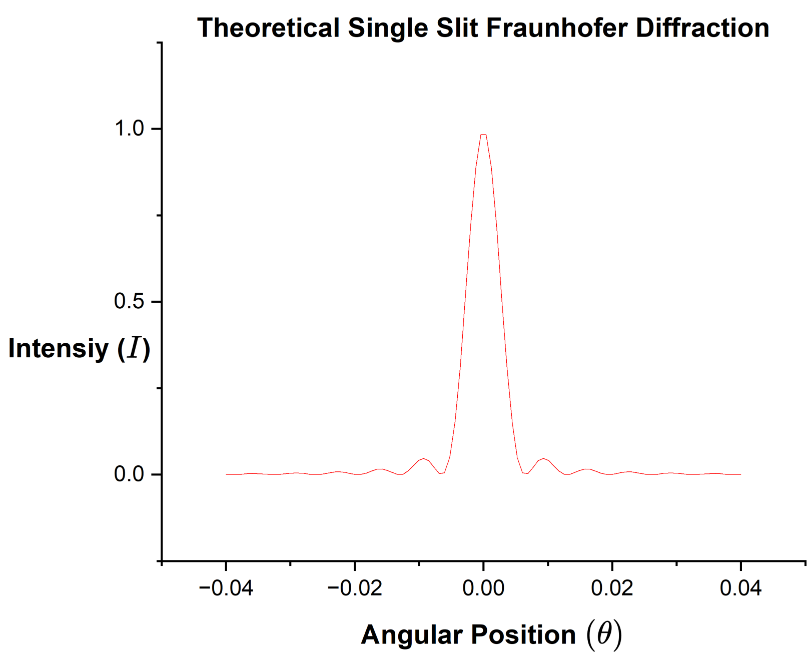

Figure 12: *Theoretical Single Slit Fraunhofer Diffraction With* L_3

6.3 Experiment 1 - Part 3:

There is acceptable correlation between the theoretical values and the experimentally derived values of angular position and relative intensities.

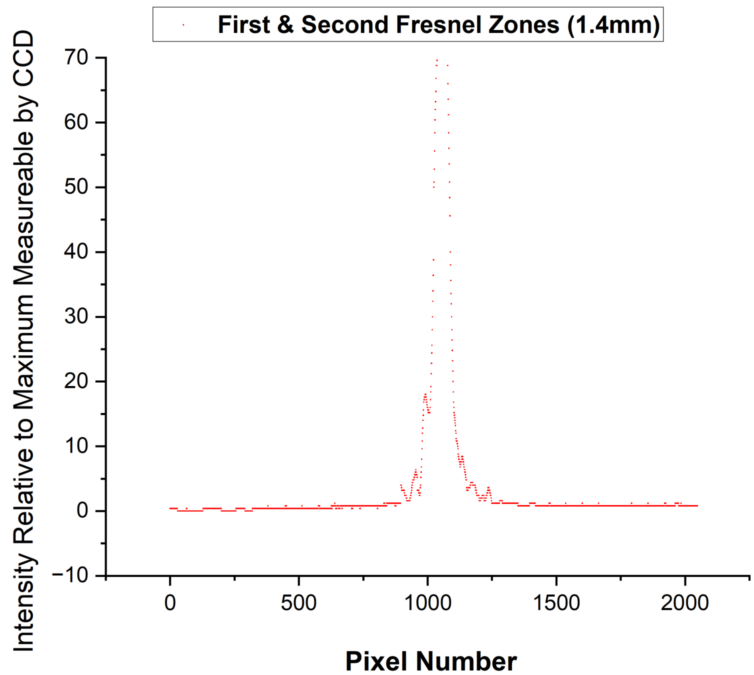

Figure 10: *First & Second Fresnel Zone (1.4mm)*

.The observed diffraction pattern aligns well with the theoretical predictions but error analysis performed across the tabulated results would be able to better determine the whether or not the experimentally derived values versus the theoretical but this is difficult due to the systematic error likely introduced in the collimation of the beam changing the angle of incidence to one that is less than face-on in each of the measurements.

Overall the Fraunhofer diffraction through a circle aperture was shown to behave similarly to the behaviour of the theoretical light wave.

Extremum Type	**Relative Displacement (mm)**	**Angular Position rad**	**Theoretical Angular Position (rad)**	**Theoretical Relative Intensity**
Peak	- 2.317	- 0.004827	- 0.004704	0.1258%
L-Min	- 2.037	- 0.004244	- 0.00396	0%
Peak	- 1.414	- 0.002946	- 0.002981	0.7366%
L-Min	- 0.994	- 0.002071	- 0.002324	0%
Peak	0	0	0	undefined → 99.2%
L-Min	1.12	0.002333	0.002324	0%
Peak	1.428	0.002975	- 0.002981	0.1258%
L-Min	1.981	0.004127	0.00396	0%
Peak	2.387	0.004.9729	0.004704	0.7366%

Table 7: Circular Aperture Fraunhofer Diffraction

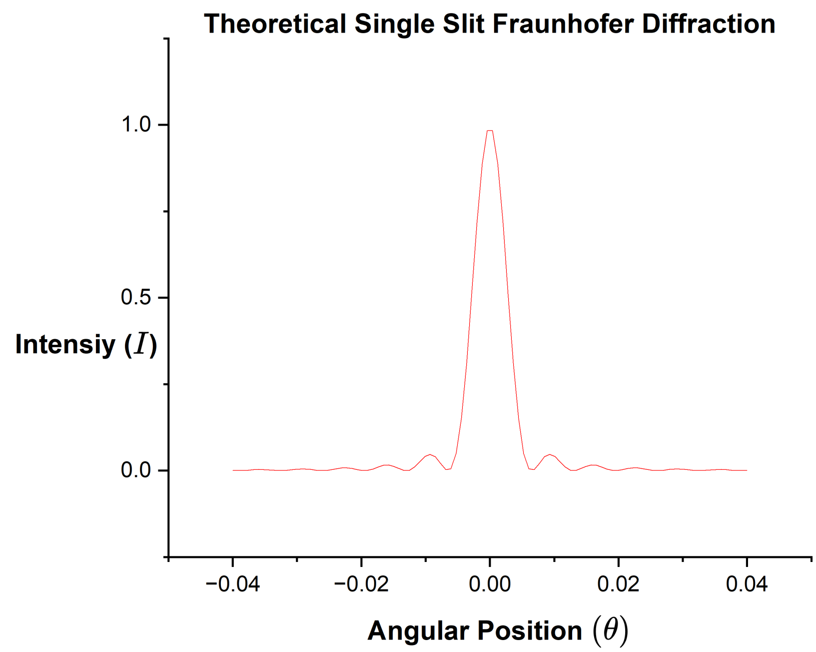

Figure 11: *Theoretical Single Slit Fraunhofer Diffraction Without* L_3

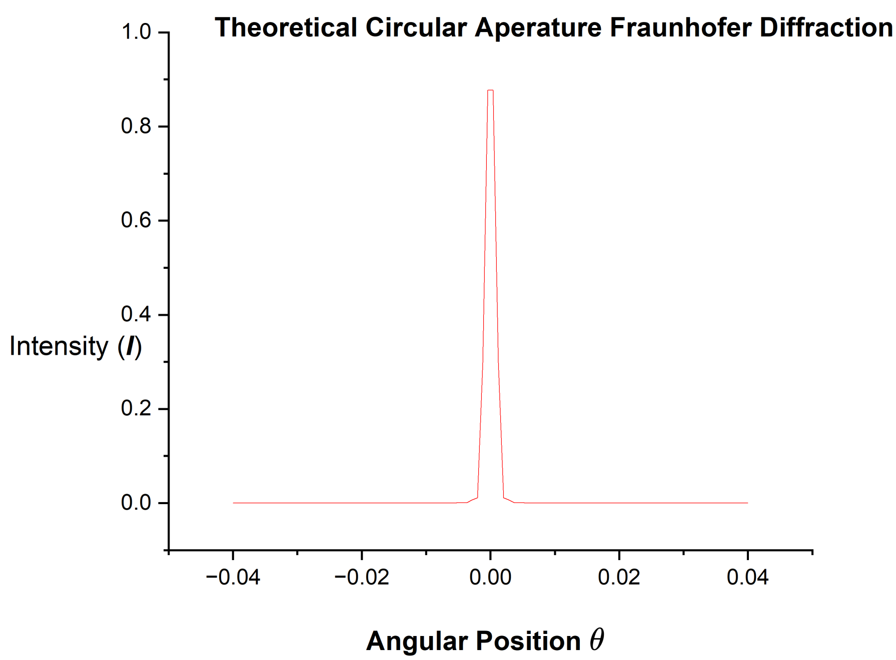

Figure 13: *Theoretical Circular Aperature Fraunhofer Diffraction*

6.4 Experiment 2:

For multiple aperture grating diffraction there is acceptable correlation between the theoretical values and the experimentally derived values of angular position and relative intensities but it is quite obvious for this example the systematic error which was introduced to measurement as there is a huge intensity bias towards one side of the measured intensities whilst the other half lags below theoretically derived predictions.

Overall the Fraunhofer diffraction through a multiple aperture was shown to behave similarly to the behaviour of the theoretical light wave with a similar overall (excluding systemic error in measurement technique)

Extremum Type	**Relative Displacement (mm)**	**Angular Position rad**	**Theoretical Angular Position (rad)**	**Theoretical Relative Intensity**
Peak	- 5.586	- 0.01048	- 0.0244	4.37%
L-Min	-3.395	- 0.006370	- 0.001713	0%
Peak	-1.008	- 1.891	- 0.008121	40.06%
L-Min	-0.098	- 0.1839	- 0.004387	0%
Peak	0	0	0	undefined → 98.8%
L-Min	2.898	0.05437	0.004387	0%
Peak	3.626	0.006803	0.008121	40.06%
L-Min	6.391	0.01199	0.001713	0%
Peak	8.337		0.0244	4.37%

Table 8: Single Slit Fraunhofer Diffraction with L_3

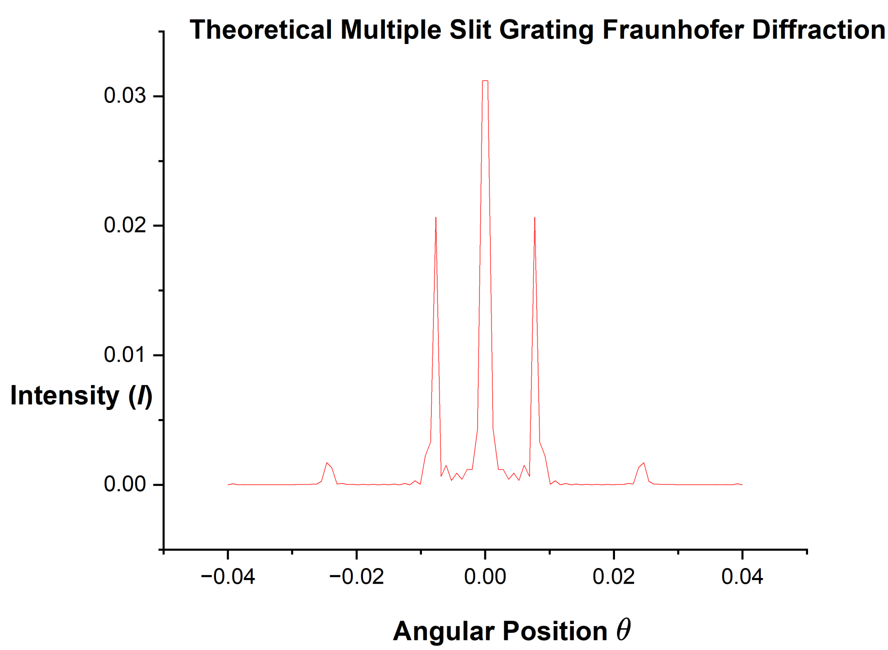

Figure 14: *Theoretical Multiple Slit Grating Fraunhofer Diffraction*

6.5 Experiment 3 - Part 1:

A spatial filter "cleans up" a laser beam by selectively allowing a well-behaved central portion to pass through, blocking aberrations and irregularities at the edges of the cross-section of the laser, resulting in a more uniform, collimated beam suitable for precision usage.

A parallel to this is apparent in analysis as the first and zeroth image together was much higher in intensity which is in line with theory as the more images that are transferred through the aperture, the more intensity is achieved.

Spatial Filtering was used to find the First and Zeroth and the First Order itself. Possibly due to the error in experimental method, the image of the Zeroth order alone was not found.

6.6 Experiment 3 - Part 2:

The 1.4mm aperture was used for both the first and second fresnel zones were captured successfully with r_0 equalling R0 = 0.878 m for the image with the first fresnel zone which lead an estimated radius of $7.554 \times 10^{-4} m$.

7 Sources of Error:

The beam was not kept straight with its path focused squarely on the CCD sensors which resulted in huge directional intensity biases which affected many of the diffraction patterns measured.

While still in general useful for determining many aspects of uncertainty throughout the experiments, error propagation was not carried out as the huge source of systemic error present in the method carried out during this experiment made the errors which woukd have been propagated too large to be particularly useful.

8 Conclusions

In conclusion, the experiments outlined above on both Fraunhofer and Fresnel diffraction present a detailed investigation into various diffraction phenomena. The experiments conducted with different apertures and lens configurations exibited behavior of light waves when interacting with slit, circular, and multiple slit grating apertures.

Despite encountering sources of error, such as deviations from ideal beam alignment, the results generally exhibited a reasonable correlation with theoretical expectations. Notably, the experiments demonstrated that single slit Fraunhofer diffraction was observed, as expected, due to the experimental conditions and configurations.

The content of the experiments above bolster understanding of optical diffraction and serve as a basis for further research and analysis in the field of optics. Additional error analysis and improvements in experimental techniques could enhance the accuracy of future experiments in this domain.

Overall, the experiments outlined above provide valuable insights into optical diffraction phenomena and the possibility of creating circumstances where the theoretical models are practically indiscernable from the the experimentally derived measurements.

9 Bibliography:

Hecht Eugene - Optics-Springer Verlag (2002) Chapter 10 Diffraction

List of Figures