Calculating Planck's Constant

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Abstract

The aim of the project is to determine Planck's constant by conducting a multi-slit experiment using a diffraction grating with 1000line/mm. Planck's constant appears in energy formula of the photons, which are the particles forming light. Therefore, we need are going to measure the energy of the light using LEDs and multimeter. Additionally, we know that energy is also multiplication of the Planck's constant with frequency of the light which will be determined calculated with the values measured from the multi slit experiment. Equalizing these two energy formula and leaving the Planck's constant alone, we will be able to determine its value. Since the experiment will be done for three different colored light waves which are red, blue and green. Reliability of the project will be determined by comparing the Planck's constants obtained from these three experiments.

I Introduction

Max Planck was a physicist lived at the end of 19^th and beginning of the 20^th century. He mainly proceeded his studies in thermodynamics. After his discovery of "energy quanta" he won 1918 Nobel prize [3, p. 788].

After the Kirchhoff introduced the "notion" of "black body", scientist tried to came up with ideas attempting to explaining the radiation those "black bodies propagate. Wien's law were made it possible to calculate energy density of this radiation [3, p. 789]. On the other hand, Wien's law was only valid for short wavelengths[3, p. 789], and Planck was managed to came up with a formula that was applicable for both short and long wavelengths[3, p. 790]. One of the constants taking part in his formula was called "Planck's constant(h)"[3, p. 790]. Wien's law was dependant on "molecular disorder". Planck wanted to correlate this disorder with "entropy", and he did this by expressing energy of each "oscillator" with the formula E=hf. This formula is significant because contrary to what "classical" physics says, it claims that energy is not continuous but rather it is quantized[3, p. 790].

Discovery of quantization of energy led to foundation of quantum mechanics.

Quantum mechanics undertakes an important role in development of modern technology. Especially, technological devices that are used in every day life such as mobile phones or in research laboratories such as "computers" and "lasers" are enhancing using quantum mechanics. Very significant and current problem of the world is that running out of energy sources, contributing to development of the "solar cells" quantum physics provides solutions to global environmental problems, too. Moreover, "photo detectors" that are used in emergency sensors in houses and other public places are also the products of quantum physics [2].

II Theory & Mathematics

I Wavelength Calculation

When light waves pass through a very thin slit, they begin to propagate circularly since the slit behaves as though the slit is a point source[5, p. 114,115,116][6, p. 444,445,448]. In double or multi-slit experiments, these circular waves create an interference pattern on the surface they fall onto [5, p. 114,115,121].

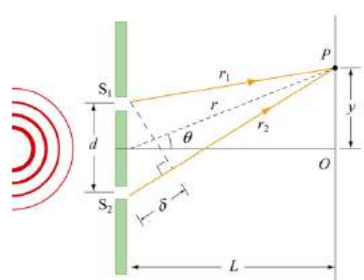

Figure 1: [7, p. 14-5]

From the cosines theorem with given variables in Fig. 1 [7, p. 14-5], one can produce following two formulas:

$$r_1{}^2 = r^2 + \frac{d}{2}^2 - 2\frac{d}{2} r \cos(\frac{\pi}{2} - \theta)[7, p.\ 14-5] \quad (1)$$

which is also

$$r_1{}^2 = r^2 + \frac{d}{2}^2 - dr \sin(\theta)[7, p.\ 14-5] \quad (2)$$

$$r_2{}^2 = r^2 + \frac{d}{2}^2 - 2\frac{d}{2} r \cos{(\frac{\pi}{2} + \theta)} [7, p.\ 14-5] \quad (3)$$

which is also

$$r_2{}^2 = r^2 + \frac{d}{2}^2 + dr \sin{(\theta)} [7, p.\ 14-5] \quad (4)$$

When Eq. 2 is subtracted from Eq. 4 [7, p. 14-6], remaining formula is following:

$$r_2{}^2 - r_1{}^2 = 2dr \sin{(\theta)} [7, p.\ 14-6] \quad (5)$$

In Figure 1, when d is taken remarkably smaller then L [8][7, p. 14-6], r_1 and r_2 can be considered as if they are parallel, and their sum is equal to 2r: $r_1 + r_2 = 2r$ [7, p. 14-6]. Then, following simplification can be done:

$$(r_2 + r_1)(r_2 - r_1) = 2dr \sin{(\theta)} [7, p.\ 14-6] \quad (6)$$

$$2r(r_2 - r_1) = 2dr \sin{(\theta)} \quad (7)$$

and the remaining formula becomes

$$r_2 - r_1 = d \sin{(\theta)} \quad (8)$$

In addition, when r_1 and r_2 accepted as they are parallel [7, p. 14-6], the distance indicated with δ becomes the difference between r_1 and r_2.

$$\delta = d \sin{(\theta)} [7, p.\ 14-6] \quad (9)$$

Considering the two alongside slits of the grating, the light fringes occur just like in the Fig. 2.

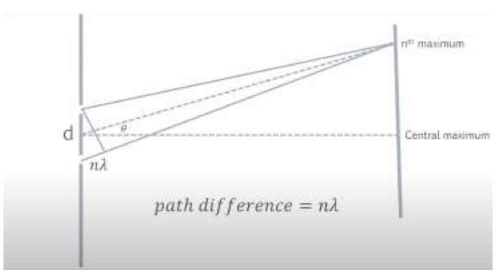

Figure 2: [9]

As it is seen (after applying an approximation since d is so tiny compared to the distance between the slits and wall) from the similarity between triangles, the angle between d and the line perpendicular to the longer line that goes to nth maximum from the bottom slit is the same with the angle theta as shown in the Fig. 3. Hence, it is seen that δ is proportional with nλ.

Therefore, there is a proportionality between d and λ as well. With this information, one can quickly achieve the equation.

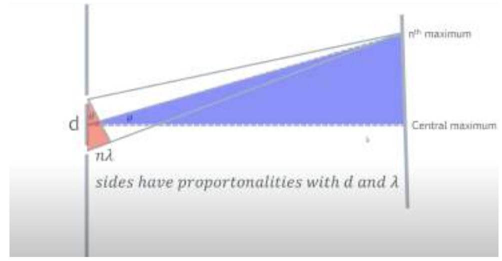

Figure 3: [9]

$$d \sin \theta = n\lambda \quad (10)$$

Hence, the wavelength of the light waves can be found using this pattern obtained from a light source passing through a diffraction grating. Diffraction patterns also have some dark points. However, for this experiment, since the wavelength will be measured, the "constructive interference" pattern is needed, which can be determined by the light lines on the screen on which the pattern appears [7, p. 14-6]. The formula above gives information about these light ones, also called the maxima. For constructive pattern, here, "n" takes only zero and other integer values [7, p. 14-6]. The sign is determined based on the brightest point in the center, depending on whether the point interested is in the +x or -x direction [**?**]. After assigning specific values for d, θ, and n, this formula will be used to find the wavelength of the light source.

This formula was derived using double slit experiment. However, it can also be used for diffraction grating as if it will be done in this project [8].

Einstein came up with the idea that the light is transported via particles called photons, and these photons have the energies proportional to their frequency [5, p. 251,][11, p. 8]:

$$E = hf \ \ [4] \quad (11)$$

Frequency of a photon can also be given with the formula below:

$$f = c/\lambda \quad (12)$$

Therefore, through the relations above, the energy of a photon can be obtained:

$$E = hc/\lambda \quad (13)$$

II Knee Voltage Calculation

The knee voltages of each red, green, and blue LED will be calculated through a multimeter to determine the specific energies required to light the LED by using the equality

$$E = eV \quad (14)$$

where e is the electric charge of a single electron (basically, calculating eV).

III Planck Constant Calculation

Through equating the two energy equalities above, we conclude with

$$h = eV\lambda/c \tag{15}$$

IV Proper Distance Determination (d)

For the wavelengths, length measurements will be held on the pattern reflected on the screen. Schematically, it can be said that the separation between x_1 and x_2 in Fig. 4 will be used for that purpose. However, since the setup is pretty small, the separation x_1 - x_2 would better be large enough for an easier measurement. Since this separation depends on the angle and the value of d, firstly, these values should be calculated.

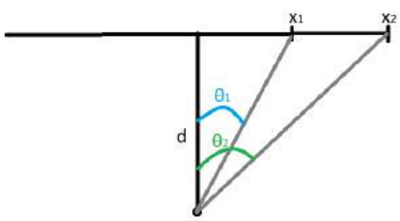

Figure 4: A Basic Diffraction Diagram

Using trigonometric relations one can basically say that

$$x_1 = d \cdot \tan\theta_1 \tag{16}$$

and similarly

$$x_2 = d \cdot \tan\theta_2 \tag{17}$$

We got the value of $\theta = \theta_2$ - θ_1 for a particular wavelength using the Eq. 18

$$|n \cdot \sin\theta| = |-m \cdot \frac{\lambda}{\Lambda}|[14, slide\ 20] \tag{18}$$

This equation is called "grating equation for planar diffraction" [14, slide 7]. In the equation, n is the "refractive index", θ is the angle given in Fig. 4 for a particular order m, λ is the wavelength for a particular color in m^{th} order spectrum, and lastly Λ is the "period" of the diffraction grating [14, slide 6].

This equation is derived using the "phase matching condition" [14, slide 5]:

$$k_x(m) = k_{x,inc} - mK_x[14, slide\ 5] \tag{19}$$

Following figures are also giving an idea of what Eq. 19 refers to :

In the Eq. 19, k's are "propagation vector"s for the light rays and K is the "grating vector" [16].

$$|\vec{K}| = \frac{2\pi}{\Lambda}[16] \tag{20}$$

$$|\vec{k}| = \frac{2\pi}{\lambda}[16] \tag{21}$$

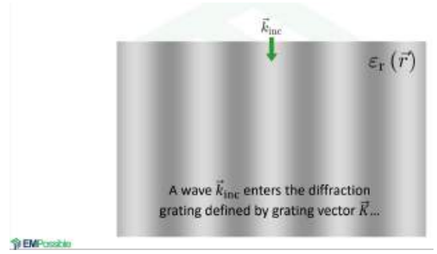

Figure 5: [15, slide 9]

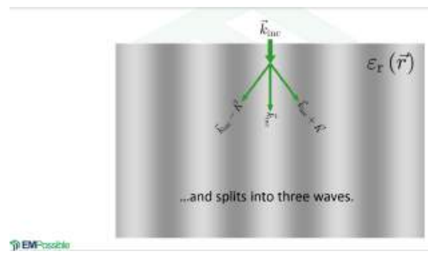

Figure 6: [15, slide 10]

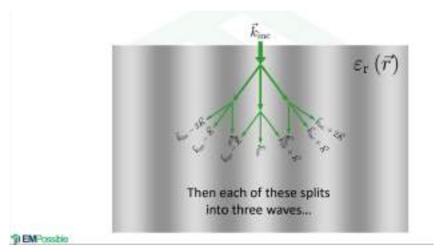

Figure 7: [15, slide 11]

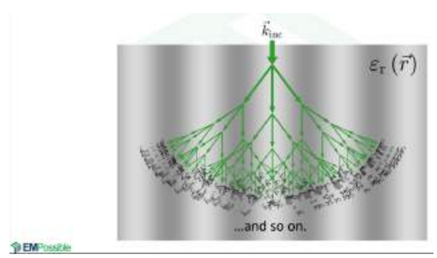

Figure 8: [15, slide 13]

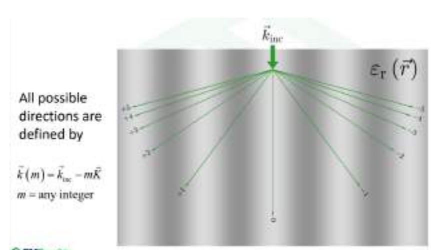

Figure 9: [15, slide 15]

Taking angles and reflective indexes into account, Eq.

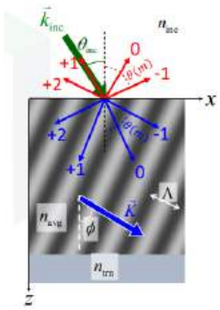

Figure 10: [14, slide 5]

19 can be rewritten as:

$$k_0 n_{avg} \sin[\theta(m)] = k_0 n_{inc} \sin\theta_{inc} - mK_x [14, slide\ 5] \tag{22}$$

$$n_{avg} \sin[\theta(m)] = n_{inc} \sin\theta_{inc} - m\frac{K_x}{k_0} [14, slide\ 5] \tag{23}$$

Since $k_0 = \frac{2\pi}{\lambda_0}$ and $K_x = \frac{2\pi}{\Lambda_x}$[14, slide 5], formula becomes

$$n_{avg} \sin[\theta(m)] = n_{inc} \sin\theta_{inc} - m\frac{\lambda_0}{\Lambda_x} [14, slide\ 5] \tag{24}$$

When the incident ray comes perpendicularly to the grating, θ_{inc} will be zero [14, slide 5]; therefore $\sin\theta_{inc}$ will also be zero. Then, the final version of the formula can be written as

$$n_{avg} \sin[\theta(m)] = -m\frac{K_x}{k_0} [14, slide\ 20] \tag{25}$$

In this experiment, the light ray coming from the LED will tried to be fallen perpendicularly to the diffraction grating. Therefore, Formula 25 is valid for the experiment.

In the Eq. 25, n and m were taken as 1 and 1, as the angle for one of the first order spectrum were tried to be calculated. (At 20°C and under 101.325kPa pressure, air's reflective index(n) is ≈ 1.0002718 [17]. Therefore, in this experiment, it is taken as 1.) For calculating the diffraction period, the formula

$$\Lambda = 1/1000[lines/mm][18] \tag{26}$$

should be applied for our diffraction grating [18]. However, since the wavelength is given in terms of nm, it should be converted Λ from mm to nm [18], then the result will be $\Lambda = 1000nm$. The λ expresses wavelength of the light with particular color in given spectrum with order m. For the example plot given in Fig. 11, the value of 760 nm was used.

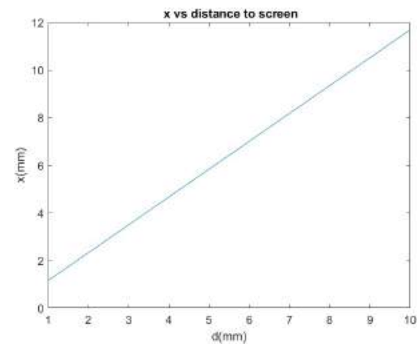

Figure 11: x vs distance to screen (d)

V Error Estimation

There are three main reasons for minor errors:

1. Location of the Light Source: Since the angle of light coming out of the box is affected by the position of the LED, any deviation in the placement of the LED will affect the diffraction pattern so the measurement.

2. Blurry Diffraction Pattern: Either reflecting the light that just passed through the diffraction grating to a wall or a telephone camera, the image comes out blurry and may affect the wavelength measurement's precision.

3. External and Internal Factors in Knee Voltage Calculation: After working the LED for a time, it starts to heat up, and it may affect both the brightness of the LED and its resistance. Also, due to the charge accumulation of the oscilloscope probes, there might be errors in the knee voltage measurement again (in future trials).

Regarding the error percentage, by denoting the measured h as h', V as V', and λ as λ', one can derive

$$error\ \%\ in\ h = (\frac{h'}{h} - 1) \cdot 100 \tag{27}$$

$$error\ \%\ in\ h = (\frac{V'}{V}\frac{\lambda'}{\lambda} - 1) \cdot 100 \tag{28}$$

Calculated Planck's constants will be compared with the theoretical value of Planck's constant which is $6.62607015 \cdot 10^{-34} JHz^{-1}$ [20].

III Equipments

1. Arduino UNO R3

2. TSL2561 Brightness Sensor

3. A digital multimeter

4. A variable voltage power-supply source

5. A breadboard and jumper wires
6. LED with colors red (620-637 nm), green (503-539 nm) blue (449-473 nm) and white (mixture of the frequencies 465 THz, 525 THz and 635 THz) [13]
7. A diffraction grating ($\Lambda = 1$ μm)
8. A resistor (varies from 220Ω to 3.3KΩ)
9. A spectrometer or wavelength meter (to measure the wavelength of the LEDs)
10. White cardboard
11. A Ruler
12. Pencil
13. Duct tape
14. Cardboard
15. Baking paper
16. Phone stand

IV Methodology

The methodology was prepared based on videos [4], and [12].

I Knee Voltage Measurement

In the project, value of Planck's constant calculated for three different colors, red, blue and green. Therefore, it had to be known the energies of these three colors. It was known that knee voltage would give the energy. For the measurement of knee voltage, firstly, red LED, DC voltage source and multi meter were connected to a bread board. Then, the voltage started to increase until LED started to emit light, and using a multimeter, potential of the red LED was measured. This measured data was noted as its knee voltage. Then, the applied voltage were increased by 0.02V steps, and in total 30 data points were recorded. The procedures were repeated for other two colors.

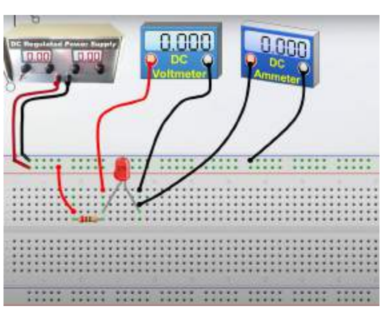

Figure 12: Sketch of the Voltage Measurement Setup

Experimental data were shared by another person in the internet were showing that after the knee voltage value, measured voltage values increases with increasing applied voltage values and they are forming a linear function [1]. Recording further data points, it was aimed to observe this pattern to detect whether the knee voltage value was accurate and data points were giving a similar pattern.

II Multi Slit Experiment

For the left side of the energy equation, wavelength should be calculated. For this purpose, using a diffraction grating, a multi slit experiment was conducted. In the first trial, firstly, a cardboard box was taken and a slit was opened on one side of this box. Then, inside the box circuit including the white LED was placed with in alignment with the slit. On the other side of the box, diffraction grating was placed, and the light coming out of the slit, first, passed through the slit and then the grating.

For this part of the experiment, three setups, with only few adjustments between them, were used.

In setup 1, the slit was wider than other two setups. The possible consequences of wider slit were not searched. However, it was planned that the slit itself should have behaved like a light source. On the other hand, when light came from the wider slit, slit's narrowing effect on light was eliminated and the distance between the slit, and as far as it was observed correctly the distance between the light source and slit started to be required to be considered in measurements. Therefore, for the other setups, slit were narrowed.

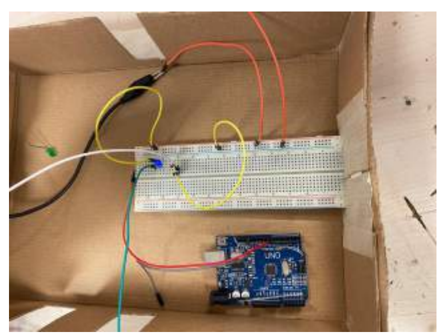

Figure 13: Multi Slit Experiment - First Setup

White light passed through the grating was diffracted and separated to colors forming it, in other words, as a result of diffraction an interference pattern occurred. All system was placed in front of a white wall to be able to see this pattern on the wall. The experiment was done several times and only once the pattern had been managed to be reflected on the wall (Figure 15). On the other hand, the setup was not including a scale and the pattern had a skewed shape that would add error to the measurements. However, it was significant to see

Figure 14: Multi Slit Experiment - Second Setup (narrow slit

Figure 15 because it was demonstrating that multi slit experiment setup was managed to be done.

Figure 15: Interference pattern reflected on the wall

In other trials, the pattern appearing on the surface of the diffraction grating was recorded. Since those photos were only ones that clear and even enough to make the measurements they were decided to be used (Figures 16, 17 and 18). Using the scale on the diffraction grating, the separation distance between the zero maximum point of the pattern and first order maxima of the red, blue and green lines were measured. For the measurements, it was significant to use a scale since the photos were used and camera and zooming would misguide about the lengths; therefore, a reference point was required.

Figure 16: Interference pattern reflected on the wall

Figure 17: Interference pattern reflected on the wall

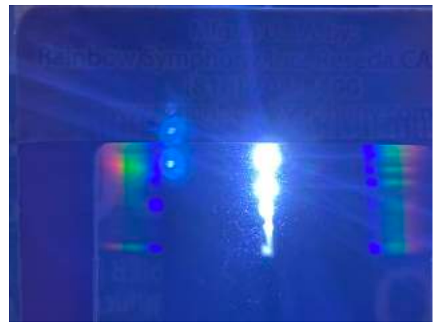

Figure 18: Interference pattern reflected on the wall

Taking the photograph of the pattern appearing on the surface of the grating, distance measurements were done. For obtaining further data and confirming the precision of the experiment, latest setup were constructed again with being more careful to alignment and perpendicularity of the elements of the setups. Additionally, baking paper were added to the system as a reflected surface as it can be seen in Figure 19. As it was stated previously, even though the images appearing on a reflected surface are not used to make measurements, they provide evidence that the project is successful in terms of doing the multi slit experiment properly. Especially, baking paper is not very good to make measurements since it distorts the lines appearing on the surface and it considerably decreases the intensity.

Figure 19: Multi Slit Experiment - Third Setup (narrow slit and baking paper)

In previous trials, only once it was managed to reflect the interference pattern on the wall. In other trials, the interference pattern were not observed, and it was thought that either the environment the experiment were done was not dark enough to be able to see the pattern or the light source was not powerful enough to be able to create a pattern. However, in the last trial, while constructing the setup, the phone light was used while the light was tried to be placed on the right spot inside box, it was positioned with a very small angle unintentionally. However, that resulted in observing the pattern on the surface of the baking paper.

III Intensity Plots

Also from the interference pattern images, the intensity of the lights wanted to be examined. For the determination of the intensities, Matlab code was used. Image was uploaded to the program and intensity-distance graph were drawn. Codes of the program is added to the Appendix section. Then, re-scaling the graph with wavelength range of the visible light, the wavelengths of red, blue and green color were obtained.

V Results

I Knee Voltage Measurement

The voltage data is shown in table 21 with the knee voltage values marked with green color. In the previous knee voltage measurement, while increasing the applied voltage measured voltages had started to decrease at some point which is denoted with red color in ??. When it was realized measurement had been repeated and new data recorded after red data points and this situation had been observed for all three LEDs. It might have been because of possible damages occurred due to applying over-voltage to LEDs, and their obsolescence. On the other hand, in recent second measurement no anomaly was observed.

For the final calculation of the Planck's constant knee voltage values were recorded as 1.568V for red light, 2.727V for blue light and 1.917V for the green light.

II Multi Slit Experiment

Plugging in each measured separation, distance and the distance between the slit and diffraction grating to the formula 9, diffraction angle for each color were found. Then, using diffraction formula 10 wavelength calculations were done. Results with error rates were given in Figure 22.

III Intensity Plots

Intensity graph shown in Figure 24 was obtained using one of the images of the interference pattern appeared on the surface of the grating (Figure 23)is given in 23.

Red LED		Blue LED		Green LED	
Applied Voltage	Measured Voltage	Applied Voltage	Measured Voltage	Applied Voltage	Measured Voltage
1.6	1.68	2.35	2.36	1.74	1.80
1.7	1.8	2.40	2.41	1.76	1.88
1.8	1.88	2.50	2.51	1.80	1.88
1.9	1.96	2.60	2.59	1.89	1.96
2.0	2.00	2.70	2.66	2.00	2.04
2.1	2.08	2.80	2.73	2.10	2.08
2.2	2.12	2.90	2.78	2.20	2.12
2.3	2.20	3.00	2.83	2.30	2.16
2.4	2.24	3.10	2.88	2.40	2.20
2.5	2.28	3.20	2.92	2.50	2.24
2.6	2.32	3.30	2.97	2.60	2.24
2.7	2.35	3.51	2.85	1.80	1.79
2.8	2.40	3.6	2.91	1.90	1.89
2.9	2.40	2.38	2.39	2.00	1.94
3.0	2.44	2.50	2.50	2.10	1.98
3.1	2.48	2.59	2.56	2.20	2.01
3.2	2.48	2.70	2.62	2.30	2.03
3.3	2.52	2.79	2.65	2.40	2.04
3.4	2.54	2.89	2.68	2.50	2.05
3.5	2.56	3.30	2.72	2.60	2.06
3.6	2.56	3.2	2.80	2.70	2.07
3.7	2.68	3.39	2.82	2.80	2.06
3.8	3.76	3.49	2.86	2.90	2.07
3.9	3.84	3.59	2.88	3.00	2.07
4.0	3.96	3.70	2.93	3.10	2.08
4.1	4.04	3.80	2.97	3.20	2.09
4.2	4.08	3.91	3.25	3.30	2.09
		4	3.27	3.40	2.09
				3.50	2.08
				3.60	2.07

Figure 20: First Voltage Measurement

Red LED		Blue LED		Green LED		White LED	
Applied Voltage	Measured Voltage	Applied Voltage	Measured Voltage	Applied Voltage	Measured Voltage	Applied Voltage	Measured Voltage
1.56	1.568	2.26	2.272	1.91	1.917	2.24	2.249
1.58	1.589	2.28	2.293	1.93	1.943	2.26	2.273
1.60	1.609	2.30	2.313	1.95	1.958	2.28	2.292
1.62	1.629	2.32	2.330	1.97	1.983	2.30	2.308
1.64	1.649	2.34	2.355	1.99	2.003	2.32	2.333
1.66	1.669	2.36	2.370	2.01	2.024	2.34	2.349
1.68	1.689	2.38	2.392	2.03	2.044	2.36	2.369
1.70	1.709	2.40	2.411	2.05	2.059	2.38	3.394
1.72	1.724	2.42	2.432	2.07	2.079	2.40	2.408
1.74	1.744	2.44	2.449	2.09	2.100	2.42	2.434
1.76	1.768	2.46	2.468	2.11	2.120	2.44	2.450
1.78	1.782	2.48	2.488	2.13	2.140	2.46	2.468
1.80	1.804	2.50	2.513	2.15	2.160	2.48	2.489
1.82	1.821	2.52	2.527	2.17	2.180	2.50	2.513
1.84	1.835	2.54	2.546	2.19	2.200	2.52	2.530
1.86	1.854	2.56	2.565	2.21	2.220	2.54	2.550
1.88	1.868	2.58	2.583	2.23	2.239	2.56	2.569
1.90	1.878	2.60	2.601	2.25	2.254	2.58	2.589
1.92	1.894	2.62	2.617	2.27	2.278	2.60	2.608
1.94	1.910	2.64	2.634	2.29	2.297	2.62	2.626
1.96	1.918	2.66	2.650	2.31	2.311	2.64	2.644
1.98	1.930	2.68	2.666	2.33	2.335	2.66	2.662
1.100	1.942	2.70	2.682	2.35	2.349	2.68	2.680
1.102	1.954	2.72	2.698	2.37	2.369	2.70	2.698
1.104	1.965	2.74	2.713	2.39	2.386	2.72	2.715
1.106	1.975	2.76	2.727	2.41	2.403	2.74	2.732
1.108	1.985	2.78	2.742	2.43	2.426	2.76	2.745
1.110	1.997	2.80	2.753	2.45	2.440	2.78	2.765
1.112	2.005	2.82	2.767	2.47	2.459	2.80	2.777
1.114	2.014	2.84	2.781	2.49	2.475	2.82	2.797

Figure 21: Second Voltage Measurement

Additionally, intensity graph in Figure 26 was obtained using the Figure 25, which was image of the pattern reflected on the baking paper.

Matlab code detected several data points from the image of the interference pattern. Evaluated the intensities of those points and then created a intensity-positions

Colours/Distance (slit-diffraction grating)	1 cm	2 cm	3 cm
Blue	458 nm (θ=27.2)	407 nm (θ=24)	326 nm (θ=19)
Green	541 nm (θ=32.7)	500 nm (θ=29.9)	392 nm (θ=23.1)
Red	650 nm (θ=40.5)	586 nm (θ=35.8)	457 nm (θ=27.1)
Error percentages (according to the av values of the corresponding colour)	-0.65% 3.84% 3.42%	-11.71% -4.03% -6.76%	-29.28% -24.76% -27.29%

Figure 22: Wavelength Calculations 1

Figure 23: Pattern on Diffraction Grating

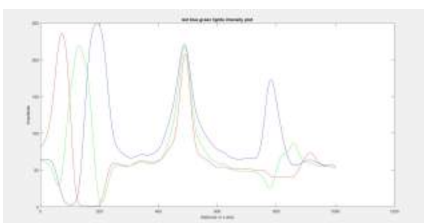

Figure 24: Intensity Graph for Image of Diffraction Grating

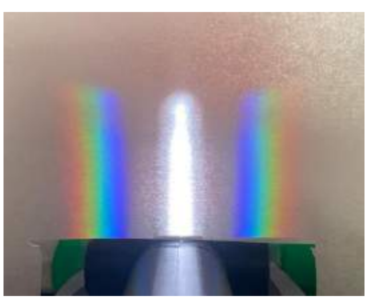

Figure 25: Pattern on Baking Paper

graph. The graph were comprised of 1000 data points. It was accepted that the wavelengths of the visible light starts from 380nm and reaches out to 780nm. Then, 1000 was divided to 400nm, and distance scale converted to wavelength scale. (Intensity-wavelength graph given in Figure 27.)

From the graph, each colors peak value was determined, and corresponding wavelength to those values

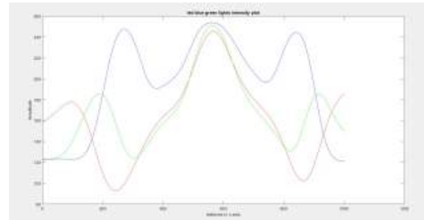

Figure 26: Intensity Graph for Image of Baking Paper

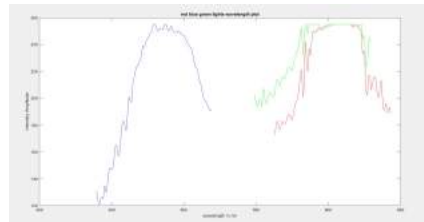

Figure 27: Intensity-Wavelength

were found. Values were 601.0317nm for red light, 587.1429nm for green light and 478.4127nm for the blue light.

Analyzing 24, it is seen that the three lines indicating red, blue and green colors all have peak points at the same point in the middle. Since the white color comprised of this colors, it makes sense that the lines overlap.

IV Planck's Constant Calculation

Trial 1

In this trial, the wavelengths were found using the formula 10, and as separation distance between the slit and grating were taken because it provided the least amount of error. For the knee voltages, values marked with green color in Figure **??**.

1. Red: $\lambda = 650$ nm, $V_k = 1.68$ V, h $= 5.824 \cdot 10^{-34}$, error% $= 12.1\%$

2. Green: $\lambda = 541$ nm, $V_k = 1.8$ V, h $= 5.194 \cdot 10^{-34}$, error% $= 21.6\%$

3. Blue: $\lambda = 458$ nm, $V_k = 2.36$ V, h $= 5.765 \cdot 10^{-34}$, error% $= 12.9\%$

Trial 2

In this trial, the wavelengths were obtained from the intensity graph. For the knee voltages, values marked with green color in Figure 21.

1. Red: $\lambda = 601.0317$ nm, $V_k = 1.568$ V, h $= 5.0331\text{x}10^{-34} \cdot 10^{-34}$, error% $= 24.0415\%$

2. Green: $\lambda = 587.1429$ nm, $V_k = 1.917$ V, h $= 6.0111\text{x}10^{-34} \cdot 10^{-34}$, error% $= 9.2808\%$

3. Blue: λ = 478.4127 nm, V_k = 2.272 V, h = 5.805x$10^{-34} \cdot 10^{-34}$, error% = 12.3919%

Several reasons that could contribute to the error rate:

1. Scale placed on the grating were mm scale, more precise scale could have been used
2. Even though we were careful about placing the elements as if they were aligned and perpendicular to the surface, skewness on the setup might have contributed to the error rate
3. For the multi slit experiment white LED was used. On the other hand, for the knee voltage measurement red, blue and green colored LEDs were measured separately
4. Since the image was more clear, the pattern appearing on the diffraction grating's surface was used. On the other hand, pattern reflected on a flat, plain surface should have been used
5. The images were recorded by phone camera. Quality of the camera may have been limited and lens of the camera might have distort the original appearance of the pattern on the reflected surface
6. During the knee voltage measurements, LEDs were applied increasing voltages. Changing voltage may adversely contribute to the life time of the LEDs and other components of the circuit and may have added extra error on the knee voltage measurement

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VI Appendix

Matlab codes used to obtain intensity-wavelength graph (Figure 27), and also to calculate the wavelengths were given below:

```
% Step 1: Read the Image
img = imread('Screenshott123.png');

imshow('Screenshott123.png');
x=[0 1000];
y=[180 180];
% improfile(img,1000,yi=0,n = 100);
% c=improfile(100);
asd = improfile(img,x,y);

red = asd(:,:,1);
green = asd(:,:,2);
blue = asd(:,:,3);
plot(blue);
blue = blue(2:length(blue),1);
red = red(2:length(red),1);
green = green(2:length(green),1);

% Example using smoothdata with a moving average
% smoothed_blue = smoothdata(blue, 'movmean');
blue_power = trapz(blue);
red_power = trapz(red);
green_power = trapz(green);

% Example using smoothdata with a Gaussian window
% smoothed_blue_gaussian = smoothdata(blue, "gaussian");

% Plot the results
% figure;
% plot(blue, 'b', 'DisplayName', 'Original Data'); hold on;
% plot(smoothed_blue, "g", 'DisplayName', 'Smoothed Data (Moving Average)');
% plot(smoothed_blue_gaussian, 'm', 'DisplayName', 'Smoothed Data (Gaussian)');
% legend show;
% xlabel('Index');
% ylabel('Value');
% title('Data Smoothing Comparison');
% smoothed_red_gaussian = smoothdata(red, 'gaussian');
% smoothed_green_gaussian = smoothdata(green, 'gaussian');

figure;
plot(blue, 'b', 'DisplayName', 'blue'); hold on;
plot(red, "r", 'DisplayName', 'red');
plot(green, 'g', 'DisplayName', 'green');
title("led blue green lights intensity plot")
xlabel("distance in x axis")
ylabel("Amplitude")
[maxIntensity_blue, idx_blue] = max(blue);
[maxIntensity_red, idx_red] = max(red);
[maxIntensity_green, idx_green] = max(green);
wavelengths = linspace(380,780,1000);
hold off;

peakWavelength_blue = wavelengths(idx_blue);
peakWavelength_red = wavelengths(idx_red);
peakWavelength_green = wavelengths(idx_green);

fprintf('Peak wavelength for blue light: %d nm n', peakWavelength_blue);
fprintf('Peak wavelength for red light: %d nm n', peakWavelength_red);
fprintf('Peak wavelength for green light: %d nm n', peakWavelength_green);
blue_array = blue(idx_blue-100:idx_blue+100,1);
red_array = red(idx_red-100:idx_red+100,1);
green_array = blue(idx_green-100:idx_green+100,1);

wavelengths_blue = wavelengths(idx_blue-100:idx_blue+100);
wavelengths_red = wavelengths(idx_red-100:idx_red+100);
```

```
wavelengths_green = wavelengths(idx_green-100:idx_green+100);

blue_array_new = blue_array./255;
red_array_new = red_array./255;
green_array_new = green_array./255;

figure;
plot(wavelengths_blue,blue_array_new,”b”);
hold on;
plot(wavelengths_red,red_array_new,”r”);
plot(wavelengths_green,green_array_new,”g”);
title(”Wavelength”)
title(”red blue green lights wavelength plot”)
xlabel(”wavelength in nm”)
ylabel(”Intensity Amplitude”)
hold off;
```