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Lab 4 Report

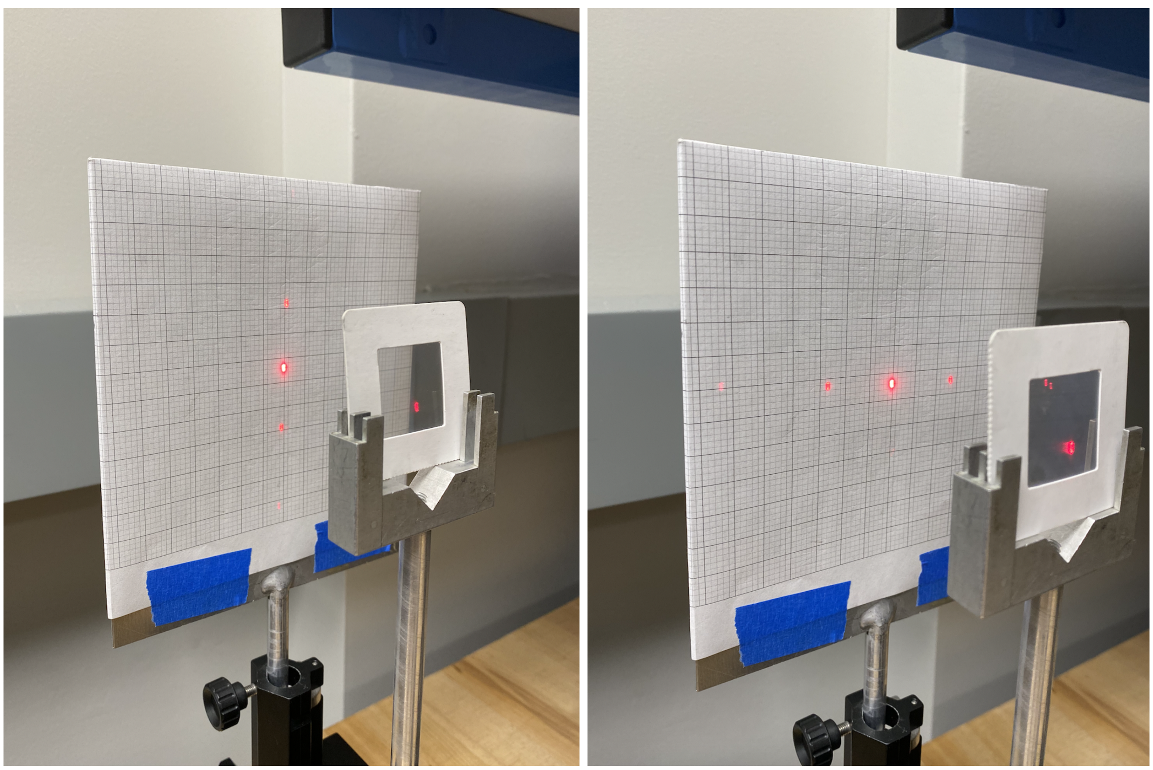
Tier 1

Experiment 1 - Diffraction Gratings

Observation

The diffraction pattern from the red diode laser looks like one central maximum with first order and second order maxima farther out. When we rotate the diffraction grating by 90°, the pattern changes from horizontal to vertical or vice versa. Rotating it by 180° makes no difference to the diffraction pattern.

Vertical and horizontal patterns:



Measure

Distance between central maximum and first order maxima on the right: 2.6 ± 0.1 cm
Distance between central maximum and first order maxima on the left: -2.6 ± 0.1 cm
Distance between the diffraction grating and the screen: 8.1 ± 0.1 cm

We chose 0.1 cm for the uncertainty because each maxima had some thickness. We tried to measure to and from the center of the thickness, but the exact center point was unclear. The pattern was also slightly tilted on the screen, which could have contributed some uncertainty to our measurements.

Angles to the first order maxima: $\tan^{-1}\left(\frac{2.6 \pm 0.1}{8.1 \pm 0.1}\right) = 17.8° \pm 7.3°$ (0.128 rad)

<u>Analysis</u>

Width of the diffraction grating: 2.5 ± 0.1 cm = w

We estimate the slit density of the diffraction grating using the equation $\sin\theta = \pm m\lambda/d$, where m = 1 and λ = 634.6 nm. We solve for d and get $d = 2.08 * 10^{-6} \pm 8.29 * 10^{-7}$ m, which translates to $1.20 * 10^4$ slits in the diffraction grating. This means $1.20 * 10^4$ slits / 2.5 cm = $4.81 * 10^3$ slits per cm, which is around equal to 5000 slits per cm as desired.

We dropped the errors here because we are just estimating the number of slits per cm.

<u>Measure</u>

Second order maxima: 6.78 ± 0.01 cm from central maximum

We used 0.01 cm for the uncertainty because we used the calipers to measure the distance, and 0.01 cm is the reading error of the calipers.

Angle from central maxima: $\tan^{-1}\left(\frac{6.78 \pm 0.01}{8.1 \pm 0.1}\right) = 39.9° \pm 3.9°$

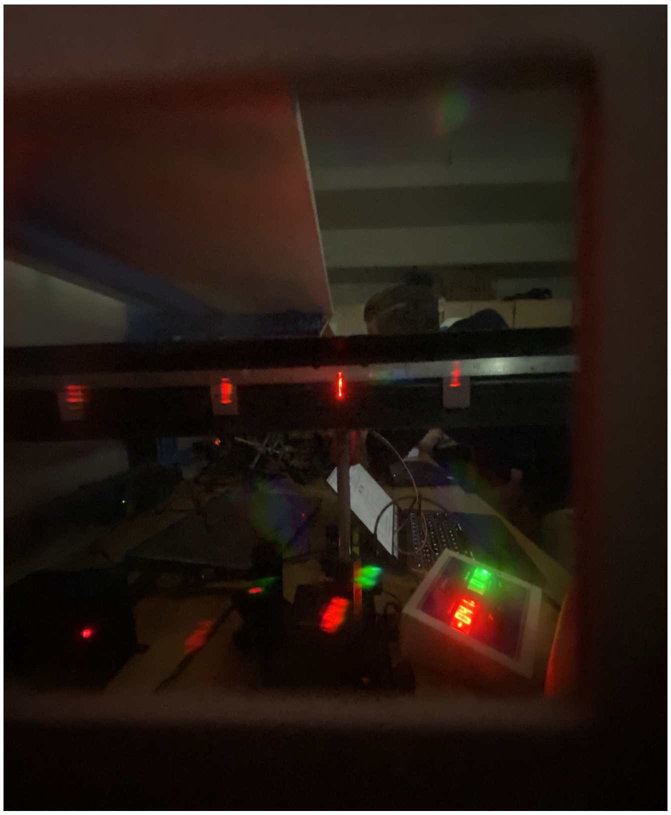
The third order maxima were not easily observable and too difficult to measure, so we did not attempt to measure them.

Experiment 2 - The Spectrum of the LEDs

<u>Observation</u>

We set up the red LED behind the spectrometer scale and looked through the diffraction grating to observe the pattern. The second order maximum on the right side is cut off in the photo, but we saw it during the experiment. We only see up to second order maxima on either side.

Red LED:



Green LED:

Data

The maxima appeared to have some thickness, so obtaining a precise measurement was difficult. We accounted for this by giving each of our measurements an uncertainty of 0.1 cm. For each measurement, we counted the very edge of the light (i.e. where we saw the faintest markings of light) as the near and far edges of the maxima.

For the blue LED, we saw that the color changes near the edges of each maxima, but we still took the near and far edge measurements to be on the edges of the entire range of colors (not at the edge of just the blue). Similarly, for the green LED, we saw a rainbow of colors at the edges of each maxima, but we still took the measurements at the edges of the colors.

Red LED

distance between grating and scale: 27.2 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	-8.2 ± 0.1 cm	-8.6 ± 0.1 cm
m = 1 (right)	8.4 ± 0.1 cm	8.8 ± 0.1 cm

distance between grating and scale: 38.4 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	-11.5 ± 0.1cm	-12.4 ± 0.1cm
m = 1 (right)	11.3 ± 0.1 cm	12.2 ± 0.1 cm

distance between grating and scale: 21.8 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	-6.2 ± 0.1cm	-6.9 ± 0.1cm
m = 1 (right)	6.3 ± 0.1 cm	6.8 ± 0.1 cm

Blue LED

distance between grating and scale: 21.8 cm

maxima	distance (near edge) (cm)	distance (far edge)
m = -1 (left)	4.4	5.0
m = 1 (right)	4.6	5.2

distance between grating and scale: 31.1 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	6.9	7.4
m = 1 (right)	6.8	7.3

distance between grating and scale: 43.9 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	9.5	10.6
m = 1 (right)	9.8	10.8

Green LED

distance between grating and scale: 43.9 cm

maxima	distance (near edge) (cm)	distance (far edge)
m = -1 (left)	10.8	13.9
m = 1 (right)	10.9	13.8

distance between grating and scale: 34.1 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	8.2	10.9
m = 1 (right)	8.5	10.9

distance between grating and scale: 24.2 cm

maxima	distance (near edge)	distance (far edge)
m = -1 (left)	5.5	7.6
m = 1 (right)	5.9	7.7

Analysis

We calculate the range of wavelengths for each pair of measurements for the red LED. The list of near and far numbers are the wavelength calculations for each measurement, and we calculated the overall wavelength range by averaging the near wavelengths for the lower bound and the far wavelengths for the upper bound. We also averaged the errors and divided by $\sqrt{6}$ to get the error for each of the average values.

```
red
near: 600 ± 353 nm
far: 627 ± 358 nm
near: 614 ± 355 nm
far: 640 ± 361 nm
near: 597 ± 352 nm
far: 639 ± 360 nm
near: 587 ± 350 nm
far: 630 ± 359 nm
near: 569 ± 347 nm
far: 628 ± 358 nm
near: 577 ± 349 nm
far: 619 ± 357 nm

wavelength range:
lower bound: 591 ± 143 nm
upper bound: 631 ± 146 nm
```

Similarly, for the blue and green LEDs, we find the following.

```
blue
near: 412 ± 322 nm
far: 465 ± 330 nm
near: 429 ± 325 nm
far: 483 ± 333 nm
near: 451 ± 328 nm
far: 481 ± 332 nm
near: 444 ± 327 nm
far: 475 ± 331 nm
near: 440 ± 326 nm
far: 488 ± 333 nm
near: 453 ± 328 nm
far: 497 ± 335 nm

wavelength range:
lower bound: 438 ± 133 nm
upper bound: 482 ± 136 nm
```

```
green
near: 497 ± 335 nm
far: 628 ± 358 nm
near: 501 ± 335 nm
far: 624 ± 357 nm
near: 486 ± 333 nm
far: 633 ± 359 nm
near: 503 ± 336 nm
far: 633 ± 359 nm
near: 461 ± 329 nm
far: 623 ± 357 nm
near: 493 ± 334 nm
far: 631 ± 359 nm

wavelength range:
lower bound: 490 ± 136 nm
upper bound: 629 ± 146 nm
```

According to the lab manual, the accepted values for the LED wavelengths are:

LED	**Wavelength (nm)**
Blue	462 ± 10

LED	Wavelength (nm)
Green	533 ± 10
Red	618 ± 10

We find that the accepted wavelength value for each of the three LEDs lies within our range of wavelengths for each color. Thus, our data reasonably supports the accepted values. However, we notice that the wavelength range for the green LED was especially large; we think this is due to the green LED being the least ideal out of the three. We saw a lot of rainbow colors when looking at the green LED through the diffraction grating, which likely contributed to measurements that were wider than what they should have been if the LED was pure green light. This also applies to the blue and red LEDs, although to a lesser degree. Another source of error could be that we might have been taking distance measurements while looking through the diffraction grating at different angles. We generally tried to measure when looking straight through the grating, but there might have been slight differences between measurements, especially when Eric and I were taking turns doing the measurements.

Experiment 3 - Measuring h and ϕ with LEDs

Experimental Design

We placed the LED inside the Optika photoelectric effect setup, then connected the LED to the power supply. Then, the intensity of the LED was set to a fixed intensity of L030. We chose this intensity because it was approximately in between the minimum intensity that the LED light was observable (by eye) and L040, which we were told not to exceed. This intensity was used throughout the experiment for the sake of consistency.

We then pressed the "reset" button on the control panel, which set the opposing voltage to zero. Once this was complete, we varied the voltage and recorded the measured current. Both positive and negative voltages were used in order to ensure the accuracy of our theoretical relationship.

Data

The raw data is as follows:

Blue LED

Voltage (mV, ±1 mV)	Photocurrent (nA)
317	6282
225	5556
106	4634

-22	3625
-128	2890
-235	2219
-362	1496
-486	895
-561	613
–639	376
-767	129
-841	50
-916	16
-925	9
-932	9
-940	5
-946	1
-953	-1
-1110	-23

Red LED

Voltage (mV, ±1 mV)	Photocurrent (nA)
830	602
687	560
523	495
408	446
355	382
244	318
111	220
-91	52
-173	21

-242	5
-257	1
-267	1
-331	0
-448	-1
-584	-5

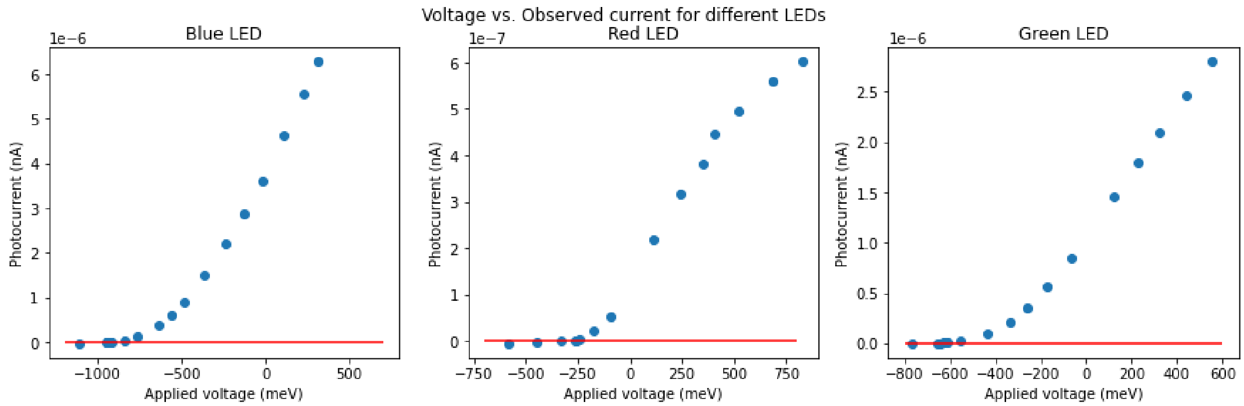
Green LED

Voltage (mV, ±1 mV)	Photocurrent (nA)
553	2797
441	2460
323	2090
230	1801
123	1455
-65	854
-172	557
-258	351
-335	211
-433	92
-552	27
-611	12
-625	5
-627	5
-639	3
-645	3
-652	0
-766	-1

Data Analysis

Without conducting any analysis, we can see the data roughly matches our theoretical model in the sense that once we pass a certain voltage, the measured current is approximately zero. We do measure small currents of about 3-5 nA at certain times, but these fluctuations can effectively be regarded as zero since any slight perturbation could have resulted in these fluctuations.

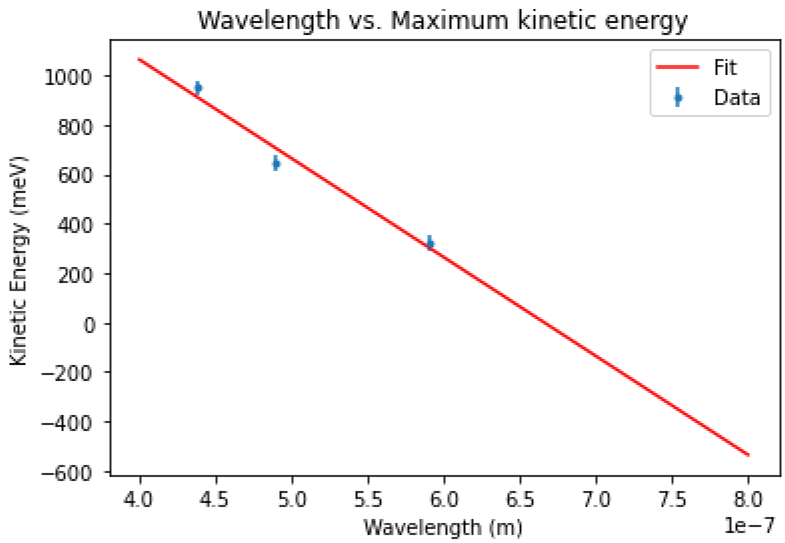
Plotting all these results against their voltages, we obtain:



The red line in each of the plots denotes y = 0. These plots were also concatenated together for the sake of space, but in our analysis they were plotted individually so we could closely examine them. We zoomed into the data to look for the points where the observed photocurrent is zero, and we obtain:

LED	Maximum KE (meV)
Blue	-950 ± 30
Red	-250 ± 30
Green	-645 ± 30

We chose a value of ±30meV as our uncertainty because within this range, we observed that the photocurrent fluctuated rapidly between 0 and 5 nA. Now we can plot maximum kinetic energy vs. wavelength, using the minimum wavelengths we obtained in experiment 2. Justification for why this was done is explained in section 3.2. Doing so, we obtain the plot:



To determine the cutoff frequency, we can instead plot wavelength on the y-axis, then use the y-intercept along with its uncertainty to determine the cutoff wavelength. Doing so, we obtain a critical wavelength of 661.8 ± 27.8 nm.

3.2 Analysis

Throughout this experiment, we were only concerned with electrons which have the highest kinetic energy, and thus are produced by the maximal emitted frequency of the light. From Experiment 2, we obtained an upper and lower bound on the wavelength for the three LEDs. Because we are looking for the maximal frequency, we are looking for the shortest wavelength, and our uncertainty in this measurement will be the uncertainty associated with the lower bound energy. Therefore, applying this procedure we get

LED	Wavelength (nm)
Blue	438 ± 133
Red	591 ± 143
Green	490 ± 136

In terms of the uncertainty, we chose an interval of ±10 mV because within this interval we were obtaining extremely similar readings with the same observed fluctuations, so it naturally made sense that ±10mV is chosen as our uncertainty.

To find physical values, we use our fitted value of the critical wavelength, 661.2 nm and convert it to a frequency. Doing so, we get a cutoff frequency of $f_0 = 4.534 \times 10^{14} \pm 1.9 \times 10^{13}$ Hz. Now, we can use

$$h = \frac{eV_{stop}}{f - f_0}$$

In order to calculate for planck's constant. Doing so for all three lasers (and also propagating the error) we get

LED	Planck's constant
Blue	$4.11 \times 10^{-15} \pm 0.04 \times 10^{-15}$
Red	$4.48 \times 10^{-15} \pm 0.09 \times 10^{-15}$
Green	$4.07 \times 10^{-15} \pm 0.05 \times 10^{-15}$

With these values, we can now find the work function, which is given by hf_0, so therefore

LED	Work Function
Blue	1.86 ± 0.03
Red	2.01 ± 0.04
Green	1.84 ± 0.03

Here, we can see that our theoretical values for the work function as well as Planck's constant are relatively similar to our theoretical values, indicating a good agreement between our theoretical values and our experiment.

Tier 2 Experiments

Experiment 4 - Measuring h and ϕ with Lasers

Objective

In this experiment, our objective was to measure the work function ϕ (for each color) and Planck's constant h using each of the red, green, and violet lasers.

Theory

We know that the maximum kinetic energy of excited electrons is given by

$$h(f - f_0) = K_{max} = eV_{stop}$$

Furthermore, we know that the stopping voltage is related to the wavelength of light by

$$E = hf = \frac{hc}{\lambda}$$

Since the first equation measures the maximum kinetic energy, we know that $K_{max} = E$ in our case. Using this fact, we are able to experimentally determine a value for h from the second equation, then use it to solve for the value of f_0. Therefore, in order to experimentally determine f_0 and h, we will first find the stopping voltage to find Planck's constant, then use the frequency of the laser to determine f_0.

Furthermore, we are also given the theoretical wavelengths of light for the different lasers:

Laser	Wavelength (nm)
Violet	405
Green	532
Red	634.6

Experimental Design

Our setup is as follows:

Pictured is the photoelectric effect optical setup, with the red laser currently being shown. The control panel is to the right of the image, displaying the applied voltage as well as the measured photocurrent. This image was taken before the laser was turned on and calibrated for offset. Furthermore, we also used the lens given on the setup for the green and purple lasers, so that their light could be dispersed, and the entire photodiode could be illuminated. Once the laser was turned on, we recorded the measured photocurrent for a wide range of voltages.

Raw Data

GREEN LASER

Voltage (mV, ±1 mV)	Photocurrent (nA)
623	198
557	185
419	165
325	147
226	127
126	103
34	76
-102	45
-208	23
-320	10
-360	7
-381	5

-430	5
-498	3
-532	3
-568	1
-654	0
-686	0

VIOLET LASER

Voltage (mV, ±1 mV)	Photocurrent (nA)
654	1079
533	979
411	886
307	792
190	681
64	570
-83	420
-178	342
-266	274
-423	176
-531	123
-638	85
-749	49
-875	21
-968	9
-1040	3
-1120	1
-1130	1
-1140	1
-1150	1

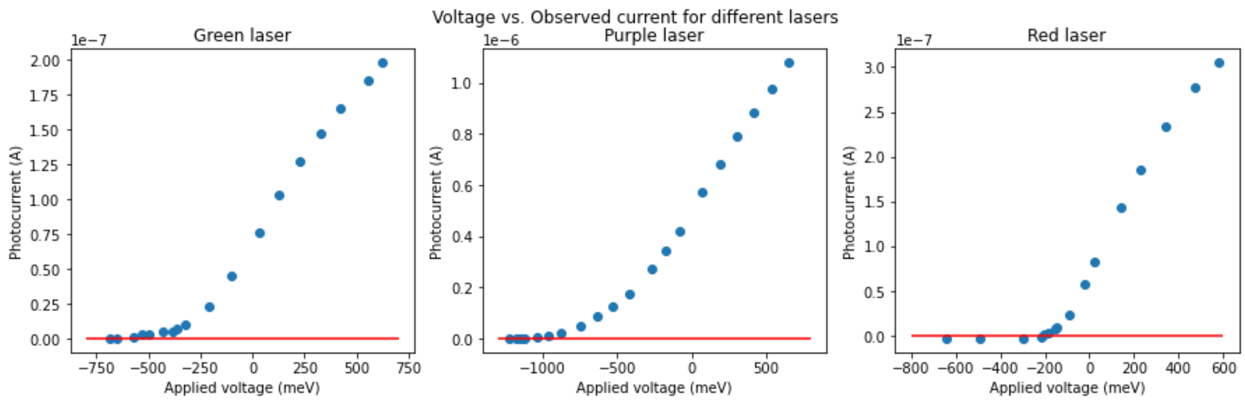
-1180	0
-1230	0

RED

Voltage (mV, ±1 mV)	Photocurrent (nA)
576	305
470	278
343	233
229	185
139	143
23	83
-21	58
-91	23
-148	10
–156	7
-187	3
-206	1
-215	-1
-294	-3
-488	-3
-644	-3

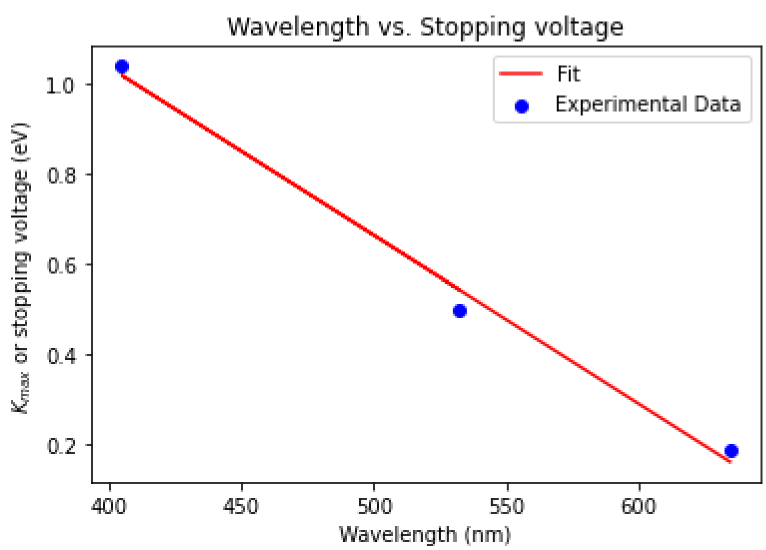
Data Analysis

Plotting these voltage vs. photocurrent values we obtain:



The red line denotes y = 0, which is particularly useful in order to determine where the stopping voltage lies. To determine the stopping voltage, we select the maximum voltage where a current of 5 nA or less was observed. This is to account for any parasitic current, as well as the fact that while we were collecting our data, we often saw the current to fluctuate rapidly and unpredictably around 0-5nA.

Therefore, using this method, we find that the stopping voltage for the green laser is around -498 meV, -1040 meV for the purple laser and -187 meV for the red laser. Next, we can now plot these stopping voltages against the theoretical wavelengths given to us, and also perform a linear fit to find the cutoff wavelength, which will also give us the cutoff frequency.



To find the critical wavelength, we can instead plot wavelength on the y-axis, then perform a linear fit and use the y-intercept (which is determined by our fit algorithm automatically) to determine the wavelength along with its uncertainty. Doing so, we obtain a wavelength of 684.59 ± 15.29 nm. This in turn gives a cutoff frequency of $4.38 \times 10^{14} \pm 9 \times 10^{12}$ Hz. Now, we can calculate Planck's constant. We have three different lasers, so we use

$$h = \frac{eV_{stop}}{f - f_0}$$

to determine three different values of h, with errors calculated using the following relation from error propagation:

$$\alpha_h = \sqrt{\left(\frac{\alpha_{eV}}{f - f_0}\right)^2 + \left(\frac{V}{(f - f_0)^2}\alpha_f\right)^2 + \left(\frac{V}{(f - f_0)^2}\alpha_{f_0}\right)^2}$$

Doing so, we obtain:

Laser	Planck's constant (eV * s)
Green	$4.13 \times 10^{-15} \pm 3 \times 10^{-16}$
Purple	$3.49 \times 10^{-15} \pm 1 \times 10^{-16}$
Red	$6.40 \times 10^{-15} \pm 2 \times 10^{-15}$

Now that we have these values for Planck's constant, we can now calculate the work function, by using the fact that $\phi = hf_0$, with the uncertainties calculated using the relation:

$$\alpha_\phi = \sqrt{\alpha_h^2 f_0^2 + h^2 \alpha_{f_0}^2}$$

Laser	Work Function
Green	1.83 ± 0.17
Purple	1.55 ± 0.07
Red	2.89 ± 1.08

Conclusion and Discussion of Error

We know that the theoretical value for Planck's constant is $4.13 \times 10^{-15}\ eV \cdot s$, meaning that performing a standard agreement test, we can see that only the green laser passes the agreement test. There are a couple of reasons this could have happened. Firstly, one of the primary reasons the violet laser did not pass the agreement test is likely due to the fact that because it is such a high-powered laser, its stopping voltage is naturally extremely high (as we found in our experiment, to be over 1V) and as a result in order to reach the stopping voltage it would have caused the circuit to overheat, resulting in non-ohmic behavior from the circuit heating up that could not be accounted for. Secondly, the reason the red laser resulted in a drastically different value compared to the purple and green lasers was likely because of the fact that we did not use the lens for the red laser, since we believed the light emitted by the red laser to be dispersed enough that it did not require the lens. If the lens had been used, we could have gotten a significantly more uniform light distribution onto the photodiode, and would have produced a more accurate reading for its stopping voltage. This conclusion is also supported by the fact that there is a large discrepancy between the stopping voltage of the red LED compared to the red laser, whereas the difference was not so drastic for the green LED and the green laser.

We also believe these same set of issues can explain the discrepancy in the value of the work function as well. From the lab manual, the work function is theoretically equal to 1.91, and similar to Planck's constant we see that only the green laser passes the agreement test. Finally, and perhaps most importantly, we were not completely consistent in pressing the "zero offset" button on the control panel after every measurement. While we did make sure to offset after switching lasers, we did not repeatedly offset in between measurements for the same laser. Had this been done, we believe that we could have obtained significantly more accurate readings for the stopping voltage, and by consequence we likely would have then had more reliable values for Planck's constant and the work function.

Overall, our attempts at verifying the work function and Planck's constant are a partial success. While our data for the work function and Planck's constant were in agreement with the theoretical values for the green laser, they were not for the other two lasers. As a result, there are a couple of glaring aspects about our experimental setup that could be improved. For instance, the light from the red laser should pass through the lens first so that it could be dispersed more uniformly, which would likely result in a more accurate theoretical value. More importantly, a more consistent usage of the "zero offset" button would eliminate any parasitic current introduced into our system, which would lead to significantly more accurate results.

Experiment 5 – Photocurrent vs. Intensity

Objective

The objective of this experiment was to determine the relationship between photocurrent and intensity of incident light.

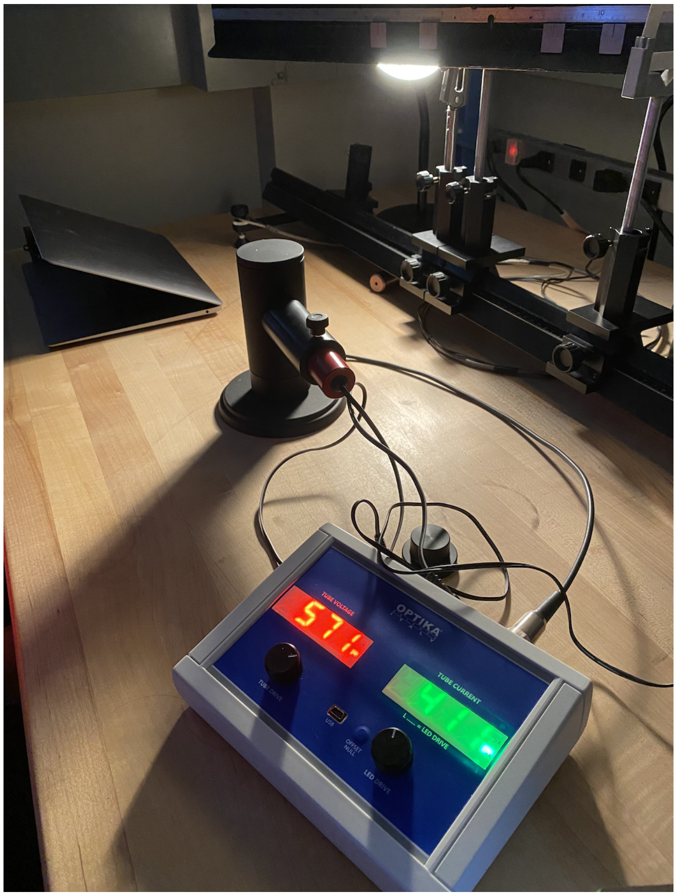
Theory

It has been observed that at any given frequency, the magnitude of the photocurrent is directly proportional to the intensity of light and independent of frequency. This is because they are both dependent only on the number of photons multiplied by some factor, which makes them directly proportional to each other.

Experimental Design

We used a similar setup to experiment 3, where we used the Optika Photoelectric Effect apparatus. However, instead of changing the voltage for this experiment, we changed the intensity of the LED using the knob on the right of the apparatus. We started the power level at L005 (where we observed 0 photocurrent) and increased it in increments of 10 because we wanted to get a wide, evenly distributed range of measurements. When taking measurements, we observed that the reading for the photocurrent tended to fluctuate. We simply chose one of the values that showed up within the first few seconds of changing the power level because we saw that the photocurrent generally continued increasing if we let it sit.

Image of setup:



<u>Data</u>

We choose ± 10 nA for the uncertainty in photocurrent to account for the fluctuations that we saw in the readings. We take the uncertainty in intensity to be 0 because we made sure we set the intensity to the proper value for each reading.

BLUE

Intensity (L___)	Photocurrent (nA)
5	0
15	3
25	2593
35	4428
45	5590
55	6512
65	7284

75	7874
85	8390
95	8810
100	9000

RED

Intensity (L___)	Photocurrent (nA)
5	0
15	0
25	76
35	178
45	258
55	320
65	375
75	411
85	437
95	455
100	469

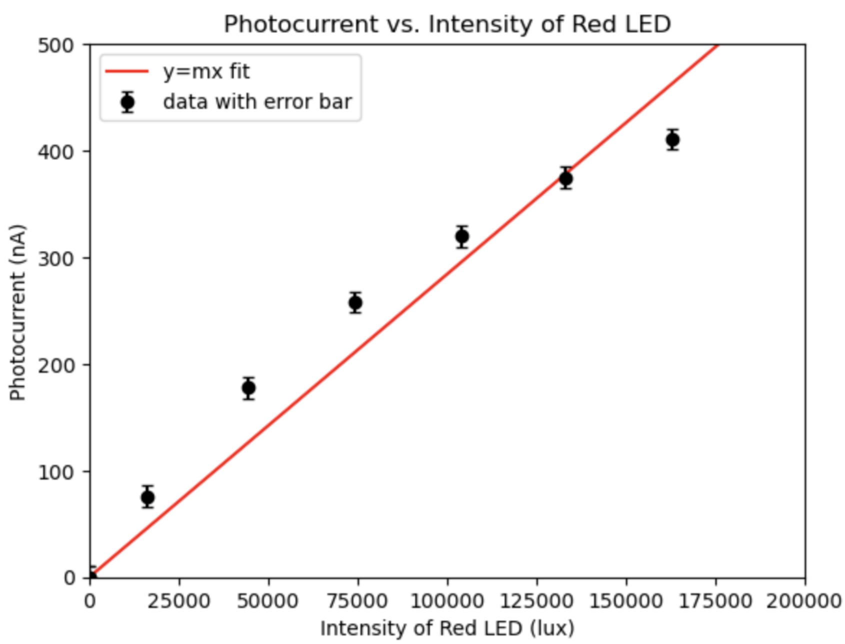
GREEN

Intensity (L___)	Photocurrent (nA)
5	0
15	3
25	961
35	1569
45	1966
55	2243
65	2465
75	2673

85	2826
95	2957
100	3026

Data Analysis

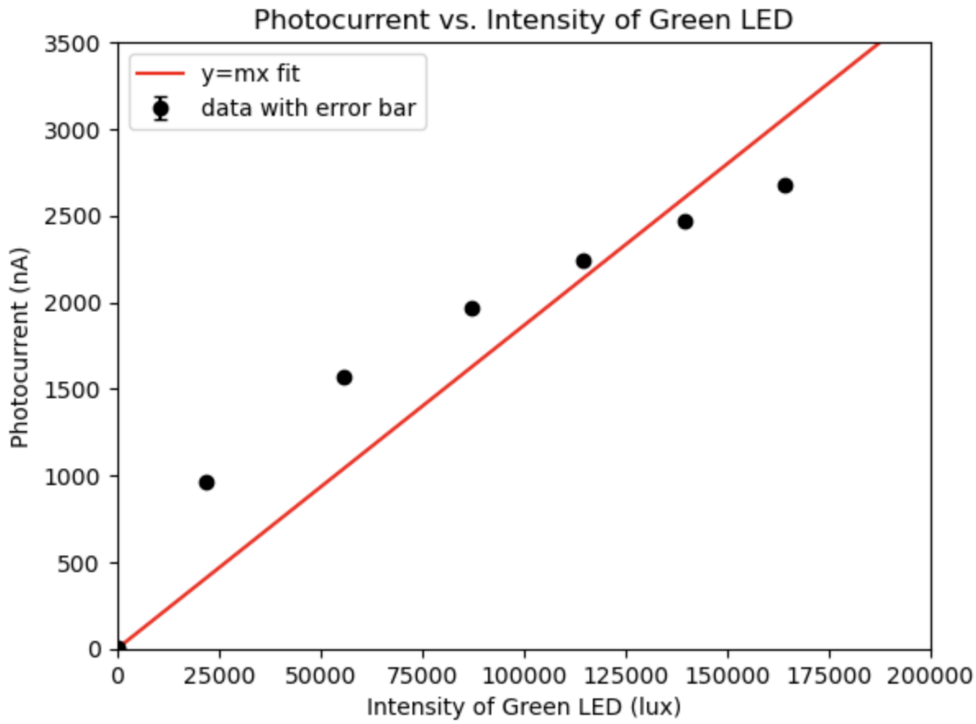
We convert the power levels into intensities using the conversion table given in the lab manual. Because the lab manual does not have the intensities for very high power levels, we discard 3 data points for the green and red LEDs and 6 data points for the blue LED. We then plot photocurrent vs. intensity for all three colors.




```
slope: 2.84e-03 nA/lux
uncertainty in slope: 3.99e-05 nA/lux
Coefficient of linear correlation: 0.9832671790191723
```

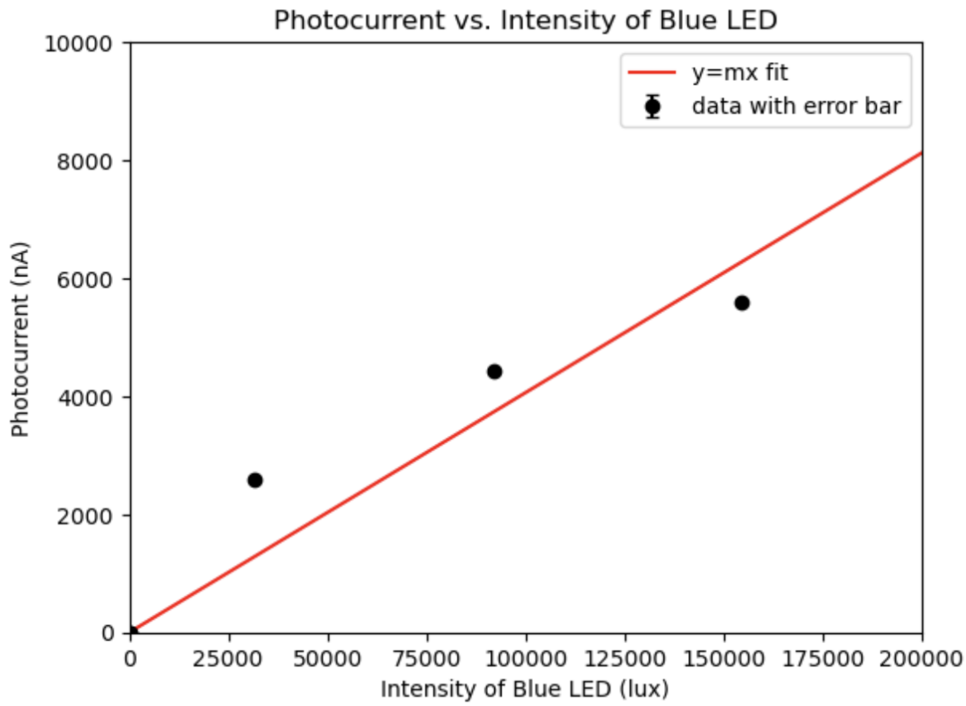
```
χ2 = 90.651
reduced χ2 = 12.950
```

For the green and blue LEDs, the error bars are not visible on the graphs. All data points have an error of ± 10 nA due to the fluctuations on the readings of the photocurrent.




```
slope: 1.86e-02 nA/lux
uncertainty in slope: 3.76e-05 nA/lux
Coefficient of linear correlation: 0.9631066151588161
```

```
χ2 = 8831.587
reduced χ2 = 1261.655
```




```
slope: 4.06e-02 nA/lux
uncertainty in slope: 5.48e-05 nA/lux
Coefficient of linear correlation: 0.9604661642987896
```

$\chi 2$ = 26463.400
reduced $\chi 2$ = 6615.850

The photocurrent vs. intensity graphs of all three colors have a coefficient of linear correlation that is greater than 0.95, which supports the hypothesis that the magnitude of the photocurrent is directly proportional to the intensity of light. However, because we have chi squared values that are much larger than 1, especially for the green and blue LEDs, our data is suspect and lies outside the expected uncertainty range. Thus, we cannot reasonably conclude that our data supports the hypothesis. In addition, we can also see that there is a pattern with the residuals for every color. The residuals start out positive and then become negative after around an intensity of 125000 lux. This is likely due to the imperfection of the LEDs. We know that the wavelengths of LEDs are dependent on temperature, and at higher intensities, the LED heats up and its wavelength shifts. Therefore, we are not completely confident that a direct proportional relationship is ideal for our data.

Conclusion and Discussion of Error

Our coefficients of linear correlation for all three LEDs were close to 1, indicating a strong linear relationship between the magnitude of photocurrent and the intensity of light. However, we cannot come to the conclusion that our data reasonably supports the hypothesis because there were too many uncertainties present in our data, especially for the green and blue LEDs which had very high chi squared values.

One potential source of error was that we turned the power level of the LED too high. The lab manual recommended that we do not exceed L040, but we decided to go above it because we wanted to collect a wider range of data. However, we found that we got a lot of fluctuations in our readings of the photocurrent, and we also had to discard some of our data points for higher power levels because there was no appropriate conversion to light intensity provided. This contributed to uncertainty in our data because of the LED being influenced by changes in temperature. As mentioned previously, another source of error was that there was never one fixed photocurrent reading, except when it was a very low number. We had to pick one of the readings that showed up on the screen and use that as our photocurrent for that power level. This contributed to uncertainty because we were not sure which value to take; we saw that the photocurrent tended to increase even if we kept the power level constant, which was likely due to the LED heating up. In future experiments if there were no limitations, it would be ideal if we had equipment that did not produce as many fluctuations, and it would also be ideal if LEDs did not vary with temperature so that we could get a wider range of measurements.

Appendix

Jupyter notebook for labs 2 and 5: Lab 4.pdf