UNIVERSITY OF
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Photonics Laboratory Report: Kinegram

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Contents

1 Abstract

This report is about kinegrams, intricate security labels that utilize diffractive structures for optical effects. The aim of the experiment is to understand the principles behind kinegrams, and it is conducted using a spectrometer and a white Light Emitting Diode (LED) light source. We also focused on analyzing how kinegram patterns influence light. The experiment also involved measuring diffraction angles for blue, green, and red light from a white LED through a reflective diffraction grating. Through analysis, the grating period of the kinegram was determined to be 698.8 nm ± 26.7 nm. Furthermore, the investigation into the band gap energy utilized the blue peak wavelength (λ_{peak}=466.5 nm) to calculate a band gap energy of 2.660 eV. The report concluded with an efficiency calculation (grating efficiency of 39%) by comparing the intensities of the highest peaks in the first-order diffraction spectrum to those of the LED spectrum. This experiment contributed to our understanding of diffractive structures in photonics by pointing out their crucial role in security, reliability, and optical innovation.

2 Theory

Kinegrams, a type of security label, employ intricate patterns to produce challenging-to-replicate optical effects. These patterns, known as diffractive structures, are meticulously crafted using advanced technology. Due to their complexity, kinegrams serve as robust safeguards against counterfeiting for various documents and products. Our primary aim here is to understand the underlying principles of kinegrams through experiments utilizing a spectrometer—a device that disperses light into its constituent wavelengths, detecting and analyzing their intensities—and a white LED light source.

Through our experiment setup, we seek to investigate how kinegram patterns influence light and to quantify specific aspects of these effects. This exploration will enhance our understanding of the efficacy of kinegrams as security features and their diverse potential applications.

2.1 Diffraction Phenomena

Diffraction is a key concept when studying kinegrams and their optical properties. It refers to what happens when light waves encounter an obstacle or a slit that is comparable in size to their wavelength. Instead of just traveling in straight lines, the light waves bend around the edges of the obstacle or pass through the slit and spread out. This spreading leads to a pattern of light and dark areas, known as a diffraction pattern [1].

2.1.1 Diffraction Grating

A key tool in studying diffraction is the diffraction grating, which is essentially a series of closely spaced lines or openings. When light hits this grating, it splits into multiple beams traveling in different directions. This is because parts of the light wave interfere with each other, either reinforcing (constructive interference) or canceling out (destructive interference) [2]. A reflection grating reflects light rather than letting it pass through. Kinegrams often use reflection gratings to create their security patterns, as they can precisely control how light is split and redirected.

2.1.2 Diffraction Orders

When light diffracts through a slit or a series of slits (a grating), it doesn't just bend randomly. Instead, it forms distinct paths or "orders" of light. These orders are basically different directions in which the light waves spread out after passing through the grating. The central bright spot is known as the zeroth order, and the bands or lines of light that form on either side are the first, second, third orders, and so on. Each order corresponds to a specific angle at which the light is diffracted, determined by the spacing of the slits in the grating and the wavelength of the light [2].

2.1.3 Grating Period

The diffracted light from such grating has intensity maxima of order m at diffraction angles θ_m (with respect to the grating normal) as described by the grating equation [3]:

$$d(\sin(\theta_i) - \sin(\theta_m)) = m\lambda \qquad \text{(I)}$$

where d is the spacing between the slits in the grating, θ_i is the angle of incidence, and λ is the wavelength of light.

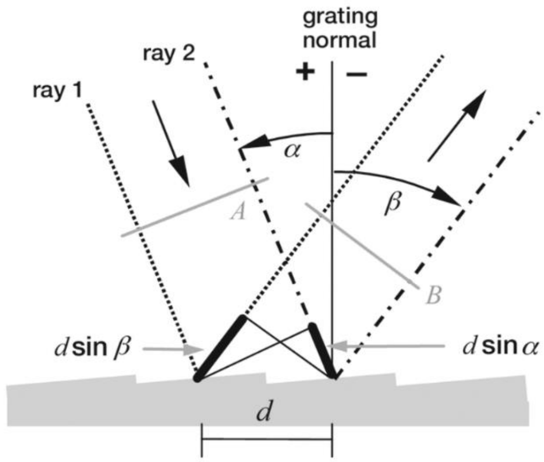


Figure 1: Geometry of diffraction. Two parallel rays are incident on the grating of period d. At wavefront A, these two waves will be in phase. After diffraction, the light rays will be in phase at wavefront B if their optical path difference was equal to a constant time the wavelength of light. Here α represents the angle of the incident angle, and β that of the diffracted angle, θ_i and θ_m respectively *[4, 2]*.

2.1.4 Iridescence

Iridescence is a beautiful optical phenomenon often observed in nature, like in soap bubbles or butterfly wings, and is closely related to diffraction. It describes how some surfaces seem to change color as the angle of viewing or the angle of illumination changes. This happens because diffractive structures, like those in kinegrams, can split white light into its component colors (much like a prism does) at different angles. The change of color with angle is because each color of light is diffracted at a slightly different angle due to its unique wavelength. This results in the colorful, shifting patterns that make kinegrams so visually striking and difficult to replicate accurately [5].

2.2 Light Emitting Diodes

A Light Emitting Diode, (abbreviated as LED), is a semiconductor that emits light when electrical current passes through it. This process, known as electroluminescence, involves electrons moving across the material and releasing energy in the form of light. The specific color of the light depends on the semiconductor material used in the LED [6].

By using LEDs as our light source, we can precisely control the color and intensity of the light shining on the kinegram. This allows us to observe and measure the diffraction effects produced by the grating patterns. In our experiments, we use a white LED, which combines multiple colors to produce a broad spectrum of light. This broad spectrum is essential for observing how the kinegram diffracts different colors of light at different angles.

2.3 Method

The experiment setup is shown in Figure 1, and the apparatus used involved Spectra-1 spectrometer, a reflective diffraction grating, a white LED flashlight for illumination, along with optical components and a rotation table for precise alignment. The setup aimed to direct light from the LED through the grating, where it was then analyzed by the spectrometer to capture the diffracted light spectrum.

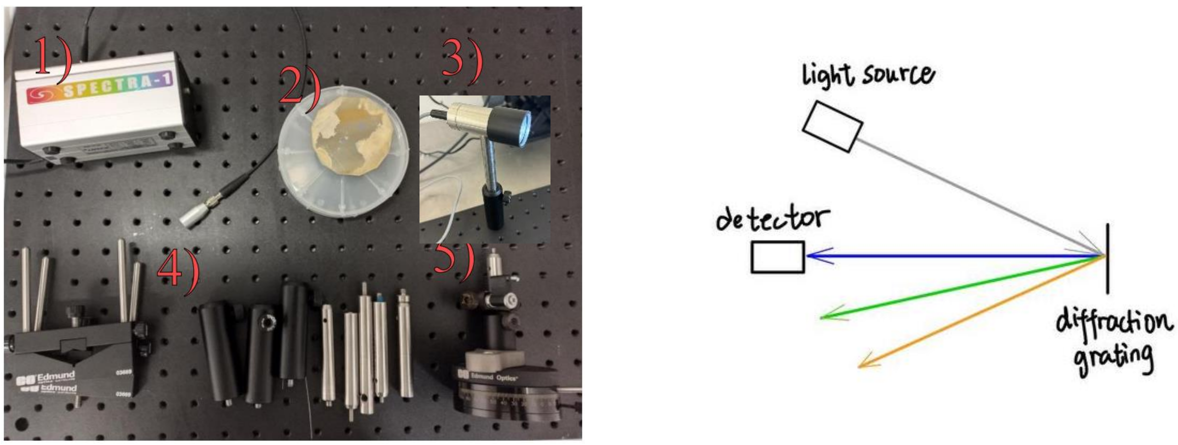


Figure 2: *(on the left)* Apparatus used including (1) Spectra-1 spectrometer, (2) a reflective diffraction grating, (3) a white LED flashlight for illumination, along with (4) optical components and a (5) rotation table for precise alignment, and *(on the right)* simple theoretical experiment setup *[3]*

The core experiment measured the diffraction angles for light wavelengths corresponding to blue, green, and red, chosen based on the LED spectrum. By adjusting the rotation table, we identified the angles where these colors were diffracted, which helped in calculating the grating's period.

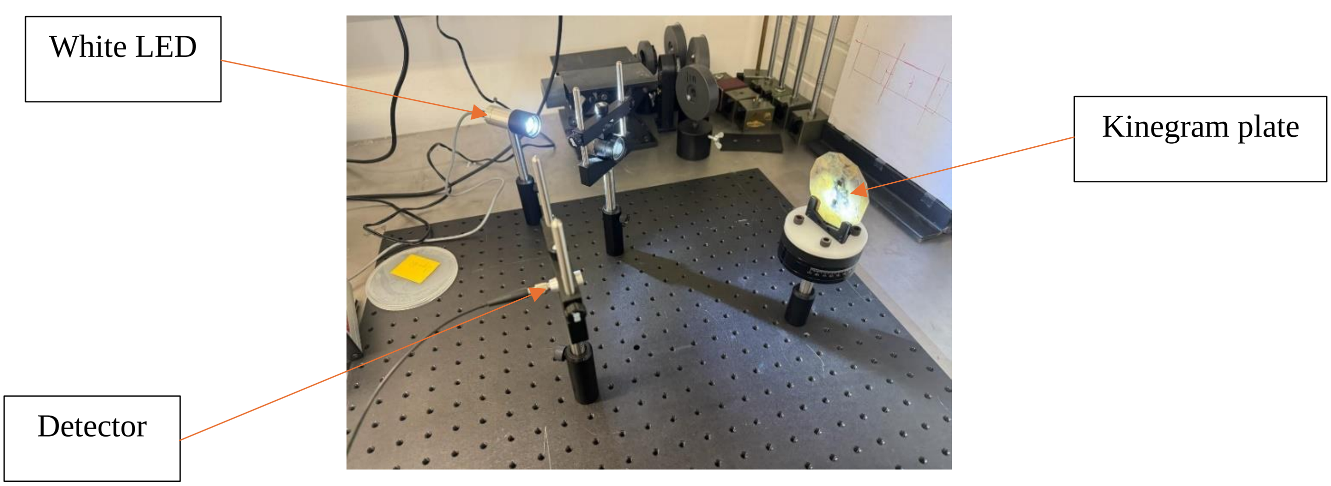


Figure 3: The experiment setup.

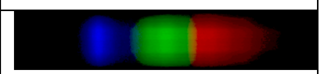
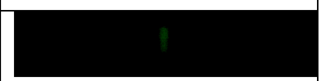
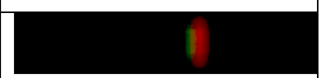
3 Results

In this section, we present the findings from our experiments and discuss their implications.

3.1 Spectral Analysis

The Spectra-1 spectrometer captured the diffracted light spectrum from the kinegram when illuminated by the white LED. We successfully obtained the wavelength corresponding to the maximum intensities of first-order diffraction peaks.

Table 1: Data measurement

Defraction order	**Peak wavelength**	**Rotating table angle**	**Spectrum**
0^{th} order	467.4 nm	25°	
1^{st} order blue	466.5 nm	47°	
1^{st} order green	556.8 nm	51°	
1^{st} order red	603.0 nm	53°	

Shown below in Fig. 2 is the plot of the 0^{th} order spectrum of the white LED obtained from the initial setup, with the rotating table pointed on 25 degrees.

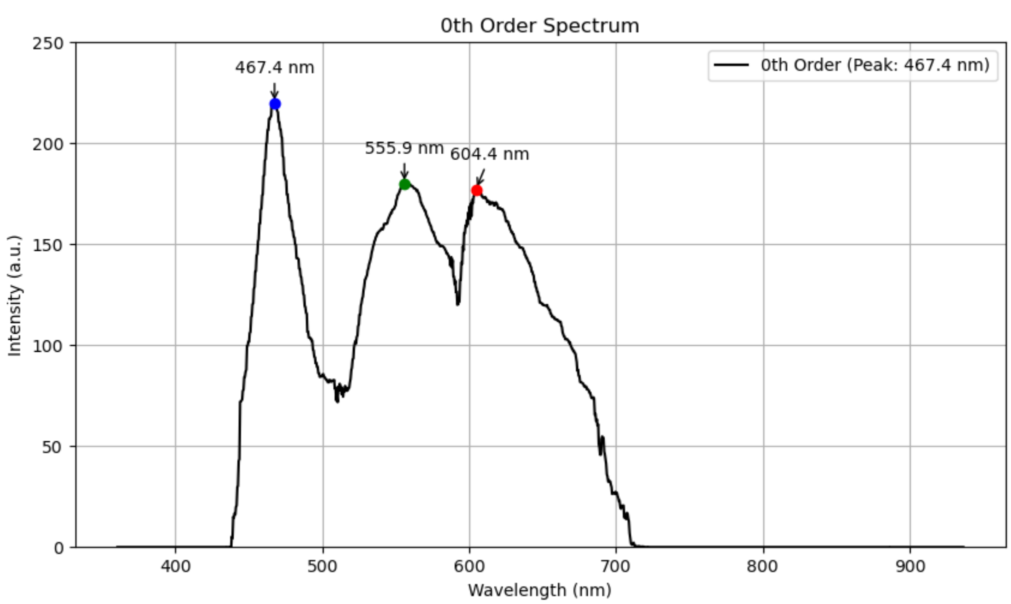


Figure 4: 0^{th} order spectra (peaks from left to right at 467.2 nm, 555.9 nm, and 604.4 nm)

Subsequently we calibrated the rotating table to the angles mentioned in table 1 to obtain the plot of the 1st order for the diffracted blue, green, and red spectra. Then, we plotted the measured spectra and the maximum intensity in a single plot on Fig. 4 for visual convenience.

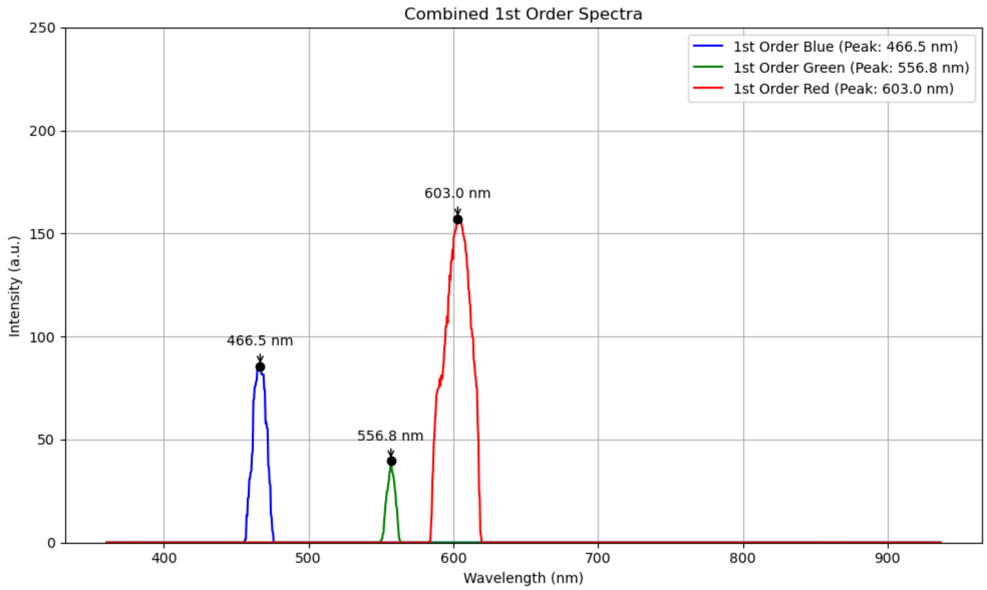


Figure 5: Combined 1st order spectra.

3.2 Grating period calculation

We derived the grating equation from Eq. I and the geometry of our setup, knowing that we get constructive interference (corresponding to maxima) when the geometric path difference is equal to an integer multiple of the wavelength. Therefore, the path difference is $d\sin(\theta_i) + d\sin(\theta_m)$ with θ_m being a negative angle.

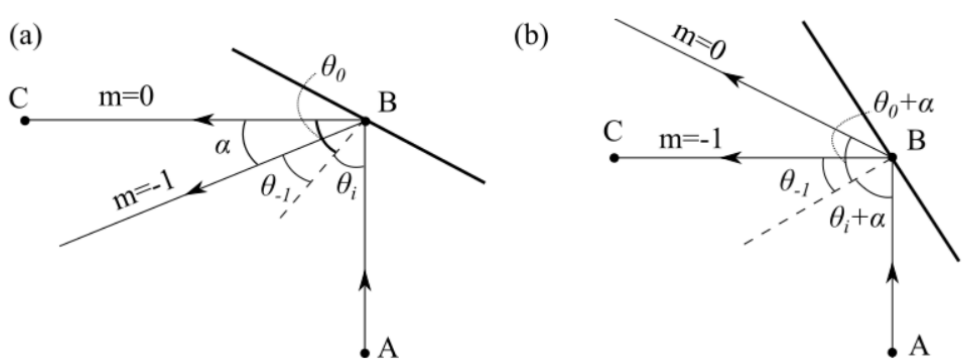


Figure 6: Diffraction from a reflection grating, when (a) the incoming light is incident at an angle θ_i to the grating normal, and when (b) the grating is rotated by angle α that corresponds to the angular separation between diffracted light of orders m = −1 and m = 0 *[7]*.

In our case, we rotated the rotating table with the kinegram plate on top three times (hence obtaining α_{blue}, α_{green}, and α_{red}) to find the peaks of the corresponding 1st orders. For the calculation of the period, the equation above has been modified as follows:

$$d(\sin(\theta_0 + \alpha) - \sin(\theta_0 - \alpha)) = m\lambda \tag{II}$$

$$d = \frac{m\lambda}{(\sin(\theta_0 - \alpha) - \sin(\theta_0 + \alpha))} \tag{III}$$

where θ_0 is the angle of incidence for 0th order maxima, which from table 1 is 25 degrees, and $m = -1$. The overall calculation is summarized in the table below.

Table 2: Summary of the measurement data

Diffracted Angle, θ_m	**Angular separation, α_m**	**Peak wavelength**	**Grating period, d**
47°	22°	466.5 nm	687.0 nm
51°	26°	556.8 nm	700.7 nm
53°	28°	603.0 nm	708.6 nm

The mean value of the grating period, d is 698.8 nm.

3.3 Uncertainty calculation

If correlations between different variables are neglected, the uncertainty can be estimated with the error propagation formula:

$$\Delta f = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \Delta x_i\right)^2}, \tag{IV}$$

where $\frac{\partial f}{\partial x_i}$ is partial derivative of f with respect to x_i, and Δx_i is the uncertainty of x_i.

Given that the grating period equation is a function; $d = f(\lambda, \theta_0, \alpha)$, $\Delta\lambda$ = 0.1 nm, $\Delta\theta_0$ and $\Delta\alpha$ are both $\frac{\pi}{180}$ rad (1 degree), we will then have

$$\Delta d = \sqrt{\left(\frac{\partial d}{\partial \lambda}\Delta\lambda\right)^2 + \left(\frac{\partial d}{\partial \theta_0}\Delta\theta_0\right)^2 + \left(\frac{\partial d}{\partial \alpha}\Delta\alpha\right)^2}. \tag{V}$$

We can simplify the expression of d using trigonometric identities, $\sin(a \pm b) = \sin(a)\cos(b) \pm \sin(b)\cos(a)$. Then we obtained

$$d = \frac{-m\lambda}{2\cos(\theta_0)\sin(\alpha)}. \tag{VI}$$

The partial derivatives of d with respect to λ, θ_0, and α, are

$$\frac{\partial d}{\partial \lambda} = \frac{-m}{2\cos(\theta_0)\sin(\alpha)}, \tag{VII}$$

$$\frac{\partial d}{\partial \lambda} = \frac{-m}{2\cos(\theta_0)\sin(\alpha)}, \tag{VIII}$$

$$\frac{\partial d}{\partial \alpha} = \frac{m\lambda\cos(\theta_0)}{2\cos(\theta_0)\sin^2(\alpha)}. \tag{IX}$$

Substituting Eq. VII, Eq. VIII, and Eq. IX into Eq. V, the uncertainty expression, yields

$$\Delta d = \sqrt{\left(\frac{-m}{2\cos(\theta_0)\sin(\alpha)}\Delta\lambda\right)^2 + \left(\frac{m\lambda\sin(\theta_0)}{2\cos^2(\theta_0)\sin(\alpha)}\Delta\theta_0\right)^2 + \left(\frac{m\lambda\cos(\theta_0)}{2\cos(\theta_0)\sin^2(\alpha)}\Delta\alpha\right)^2}. \tag{X}$$

We substitute the variables into the expression to find three values of Δd from corresponding λ, and α, and tabulated them as follows:

Table 3: Uncertainties from calculation involving corresponding peak wavelength and angular separation.

Peak wavelength λ in nm	**Angular separation, α in degrees**	**Uncertainty, Δd in nm**
466.5	22	29.5443
556.8	26	25.9205
603.0	28	24.5621

The mean value of the uncertainty, Δd is 26.6756 nm. Finally, the grating period and its corresponding uncertainty can be written as:

$$d = 698.8\,nm \pm 26.7\,nm$$

3.4 Full Width at Half Maximum (FWHM)

An important aspect of our results includes the analysis of the Full Width at Half Maximum (FWHM) for the first-order diffraction peak at the highest intensity.

In the combined spectral analysis, a notable observation was made regarding the peak intensities of the different orders. It was expected that the zeroth-order spectrum, corresponding to the blue peak at 466.5 nm with a full width at half maximum (FWHM) of 10.30 nm, would exhibit the highest intensity, as indicated by the source spectrum.

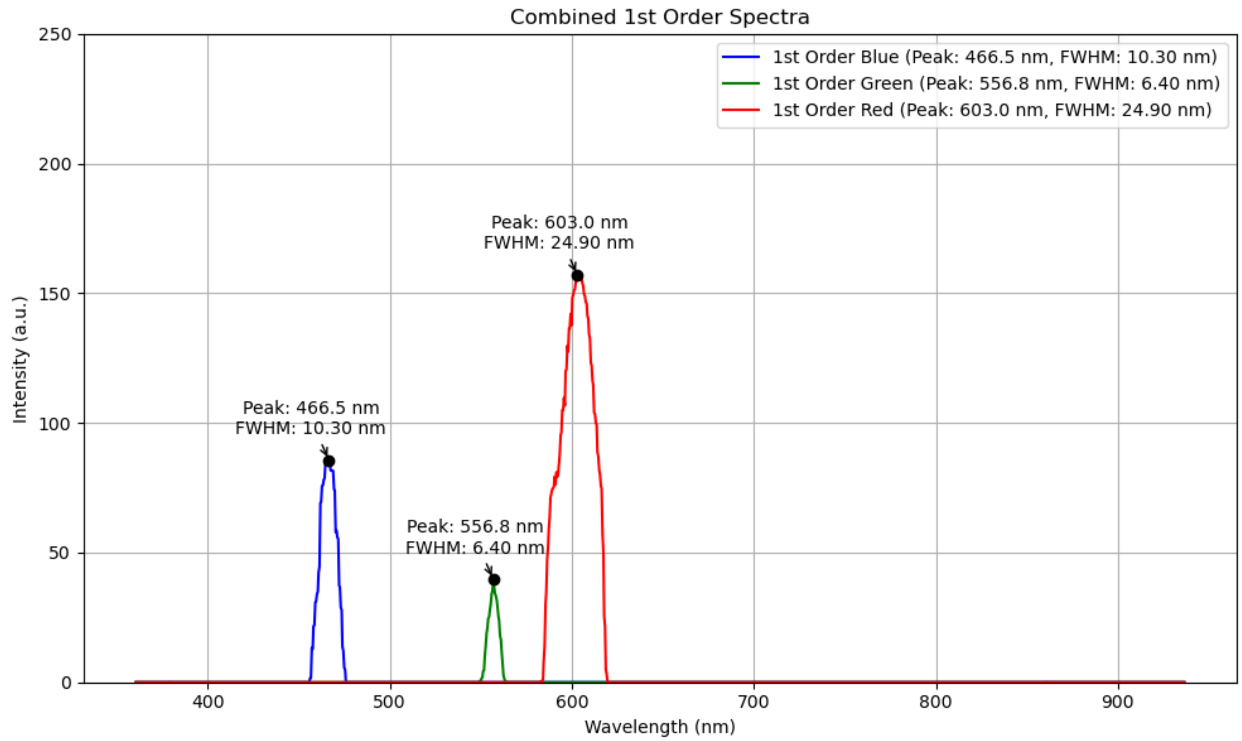


Figure 7: Combined 1st order spectra with FWHM.

However, the composite spectrum revealed higher peak intensities for the first-order spectra. Initially, this raised concerns about the accuracy of the measurements. Upon further investigation, it was determined that the intensity discrepancy was a result of a deliberate adjustment in the power of the LED during the experiment. This modification was necessary to ensure the detectability of the first-order spectra by the spectrometer, which would otherwise be challenging to discern.

3.5 Bandgap Energy and Valence bandwidth

To determine the change of energy between the valence and conduction bands, typically referred to as the band gap energy, we, therefore, used the peak blue wavelength ($\lambda_{peak} = 466.5\, nm$) observed in the spectrum to get the insights into the band gap energy through photon energy equation [8]:

$$E(eV) = \frac{hc}{\lambda \times 1.602 \times 10^{-19}}, \tag{XI}$$

where E is the energy in electron-volts (eV), h is Planck's constant ($6.626 \times 10^{-34}\ m^2 kg/s$), c is the speed of light in a vacuum ($3.0 \times 10^8\ m/s$), and λ is the wavelength in meters.

After substituting the parameters, we get

$$E = 2.660\ eV.$$

To estimate the bandgap, we assume that the conduction and valence bands are equal, therefore the bandwidth is:

$$\Delta E = \frac{E_H - E_L}{2}, \tag{XII}$$

with E_L and E_H being the energies corresponding to the lower and higher frequencies respectively.

Knowing the FWHM, we calculate:

$$\lambda_L = 466.5 - 10.3 = 456.2\ nm,$$

$$\lambda_H = 466.5 + 10.3 = 476.8\ nm.$$

Therefore $E_L = \frac{hc}{\lambda_L} = 2.72\ eV$ and $E_H = \frac{hc}{\lambda_H} = 2.60\ eV$. Thus, we get:

$$\Delta E = 0.06\ eV.$$

3.6 Uncertainty Calculation

The efficiency of the grating at some diffraction order is defined as the ratio of the light diffracted into that order to the total incident light on the grating.

We assume that the higher orders are minimized, and all the light is diffracted into orders 0, +1, and -1, we can assume that the efficiency is mainly determined by these orders. We also assume symmetry, meaning the same amount of light is diffracted into orders +1 and -1.

With these assumptions, we need to calculate the total intensity of light incident on the grating. Since we're considering orders 0, +1, and -1, the incident light intensity is the sum of the intensities of these orders.

Let's denote:

I_0 as the intensity of light diffracted into the zeroth order (central peak),

I_{+1} as the intensity of light diffracted into the first positive order, and

I_{-1} as the intensity of light diffracted into the first negative order.

Given that $I_{-1} = I_{+1}$ due to symmetry, the total incident intensity is:

$$I_{incident} = I_0 + 2I_1 \,. \tag{XIII}$$

We know that $I_0 = 219.7$ a.u. (arbitrary units). We also know the intensity of the highest peak in the first-order diffraction spectrum from the grating, which is $I_{+1} = 85.6$ a.u.

Plugging these values into the equation for total incident intensity, we get:

$$I_{incident} = 390.9 \; a.u.$$

Now, the efficiency of the grating, η, at the first-order diffraction can be calculated as:

$$\eta = \frac{I_{+1}}{I_{\ incident}} \,, \tag{XIV}$$

$$\eta = 0.2188 \,.$$

So, the efficiency of the grating at the first-order diffraction is approximately 21.88%.

4 Conclusion

This report investigated kinegrams, focusing on their diffraction properties under white LED illumination. By conducting experiments and thorough analysis, we successfully determined the grating period of the reflective diffraction grating utilized in the kinegram. This was achieved through the derivation of the grating equation, taking into account the geometry of our experimental setup.

We obtained the diffraction efficiency as well, through analysis of the Full Width at Half Maximum (FWHM) of the highest intensity peak. Furthermore, our results highlight the importance of considering various factors such as LED power adjustment to ensure accurate measurements and reliable results. The deliberate modification in the power of the LED during the experiment was crucial in enhancing the detectability of the first-order spectra by the spectrometer, thus enhancing the accuracy of our measurements.

Moreover, the determination of the band gap energy, utilizing the peak blue wavelength observed in the spectrum, provides additional insights into the optical properties of kinegrams. By understanding the change of energy between the valence and conduction bands, we gain a deeper understanding of the underlying principles governing kinegram optical effects.

As a PSRS student, this experiment significantly contributes to our understanding of the broader field of photonics by highlighting the role of diffractive structures in security, reliability, and optical innovation. By unraveling the intricacies of kinegrams, we pave the way for further advancements in security technologies and optical manipulation techniques and ultimately improving security measures across various applications and industries.

References

[1] K. Golec-Biernat, "Theoritical review of diffractive phenmena.," *Nuclear Physics*, pp. 133-142, 2005.

[2] E. Hecht, Optics, 3rd, Ed., Addison-Wesley, 1998.

[3] Kinegram Measurment: Laboratoy Manual, 2024.

[4] C. Palmer, The Diffraction Grating Handbook, 8th, Ed., New York: Richardson Gratings™ MKS Instruments, Inc, 2020.

[5] K. Kjernsmo, J. R. Hall, C. Doyle, N. Khuzayim, I. C. Cuthill, N. E. Scott-Samuel and H. M. Whitney, "Iridescence impairs object recognition in bumblebees," *Scientific Reports,* 2018.

[6] E. F. Schubert, Light-Emitting Diodes, Cambridge University Press, 2006.

[7] Kinegram Measurment: Laboratoy Manual, 2021.

[8] C. Honsberg and S. Bowden, "Energy of Photon," PVEducation, [Online]. Available: https://www.pveducation.org/pvcdrom/properties-of-sunlight/energy-of-photon. [Accessed 9 May 2024].

Appendix

PHYRA47, "Photonics-Laboratory/1-kinegram/," GitHub, 2024. [Online]. Available: https://github.com/PHYRA47/Photonics-Laboratory/tree/main/1-Kinegram. [Accessed: May 15, 2024].