## Experiment #5: Optical properties

**Overview.** In this experiment you will build two kinds of *spectrometers* – one using a diffraction grating and one using a prism – and use them to observe how materials interact with light. You will study how grating density affects spectral resolution, record the full emission spectrum of an LED light source, use the grating equation to calculate unknown wavelengths from geometric measurements, and determine the index of refraction of an optical glass prism.

### Background: Index of refraction and Snell's Law

When light is transmitted through a material, it interacts with the electron clouds that surround atomic nuclei. This interaction creates a slight "drag" that slows light from its vacuum speed ($c$) to a lower speed ($v$) inside the material. The **index of refraction ($n$)** quantifies this:

$$\boldsymbol{n = c/v > 1}$$

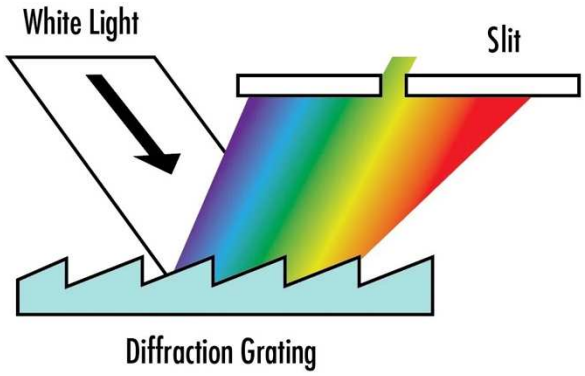
When a light beam crosses the interface between two materials with different indices $n_1$ and $n_2$, the beam changes direction. This bending is described by **Snell's Law:**

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where $\theta_1$ and $\theta_2$ are the angles measured from the surface normal in each medium. Importantly, the **index of refraction ($n$) varies with wavelength – a phenomenon called *dispersion*.** Shorter wavelengths (blue) are slowed more and therefore refracted more than longer wavelengths (red). This is the principle behind a prism: white light enters and each color exits at a slightly different angle, spreading into a rainbow.

### Background: Diffraction gratings

A diffraction grating is a surface etched with thousands of parallel, equally spaced grooves. When light hits the grating, each groove acts as a new source of waves. These waves overlap, and whether they add up (constructive interference) or cancel (destructive interference) depends on the path length difference between adjacent grooves.



For grooves spaced a distance $d$ apart, with light incident at angle $\theta_i$ and diffracted at angle $\theta_d$, constructive interference (a bright spot) occurs when:

$$d(\sin\theta_i + \sin\theta_d) = n\lambda$$

Where $n = 0, \pm1, \pm2, \ldots$ is the diffraction order and $\lambda$ is the wavelength. Because the equation depends on $\lambda$, different wavelengths (colors) reach constructive interference at different angles – this is how the grating separates white light into a spectrum.

In the experiment you'll run today, the grating is aligned to **normal incidence** ($\theta_i = 0°$), which simplifies the equation to:

$$\boldsymbol{d \sin\theta_d = n\lambda}$$

A grating with more lines (per mm) has a smaller $d$ and therefore diffracts each wavelength to a larger angle, providing better angular separation between colors (higher dispersion).

**Experiment 1: Influence of grating density**

The purpose of this first experiment is to compare how gratings with 600 *vs.* 1200 lines/mm affect the angular spread and resolution of the diffracted spectrum. You'll observe the trade-off between slit width (which affects brightness) and spectral resolution (which affects sharpness).

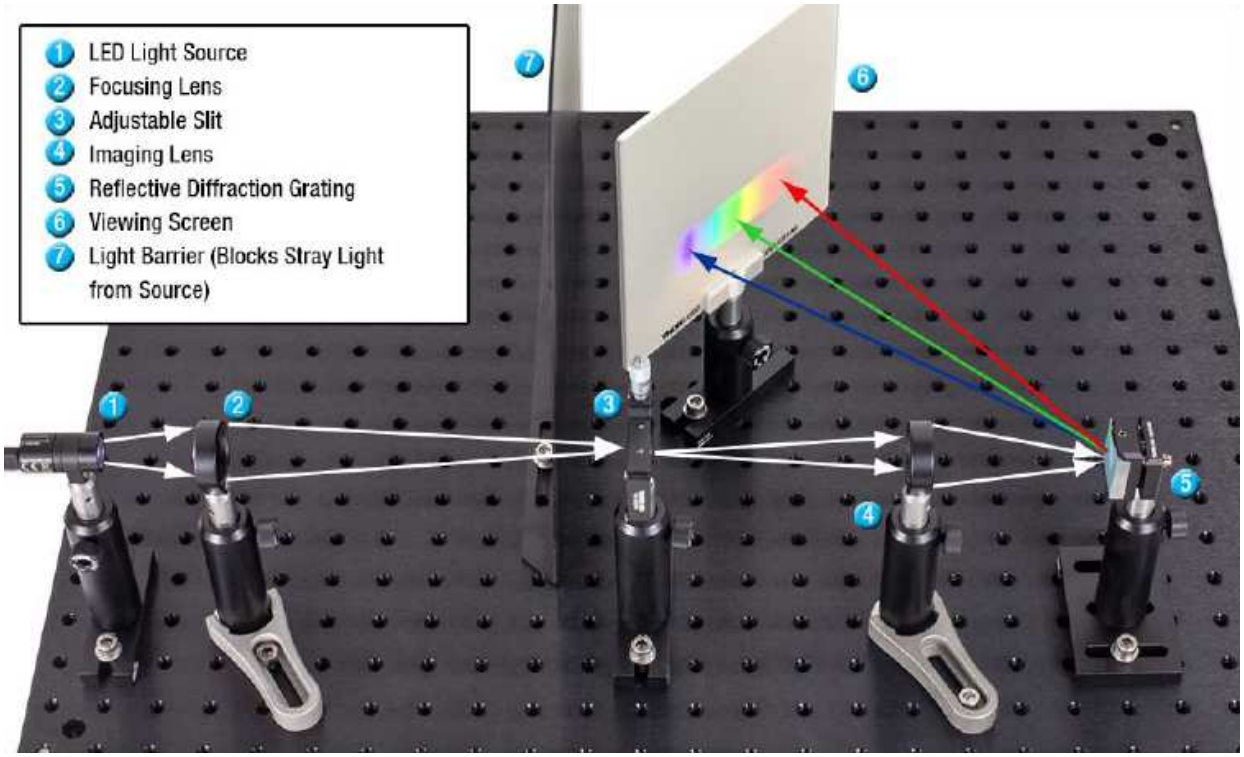



**Figure 1:** An overview of the diffraction grating-based spectrometer setup for Experiment 1.

| # | Component | Notes |
|---|---|---|
| ① | **LED Light Source** | Broadband white LED. Bandpass filters thread directly onto the front of the housing. |
| ② | **Focusing Lens (f = 50 mm)** | Images the LED chip onto the entry slit so that a sharp, bright line enters the optical path. |
| ③ | **Adjustable Entry Slit** | Controls the width of light entering the spectrometer. Narrower slit → sharper spectral lines but less intensity. |
| ④ | **Imaging Lens (f = 100 mm)** | Re-images the slit onto the viewing screen after the light has been dispersed by the grating or prism. |
| ⑤ | **Diffraction Grating** | Reflective grating available in 600 or 1200 lines/mm. Separates wavelengths *via* interference. |
| ⑥ | **Viewing Screen** | White screen on which the dispersed spectrum is projected for observation and measurement. |
| ⑦ | **Light Barrier** | Black screen that blocks stray, undispersed light from the LED from reaching the viewing screen directly. |

**Setup**

1. **Place the LED light source** ① at the far left of the breadboard, close to the front edge. Then turn it on.
2. **Place the adjustable slit** ③ 24 cm to the right of the LED and fix its position.
3. **Place the 50 mm focusing lens** ② halfway between the LED and the slit. Slide it toward the LED until you see a sharp image of the LED chip projected onto the slit. You should see two small dark dots on a bright rectangle (see **Figure 2**, left). Then fix the lens.



**Figure 2:** (Left) Image of LED chip on slit, and (Right) zero-order reflection from the grating centered on the back of the entry slit.

4. **Mount the 1200 lines/mm grating** ⑤ in its holder 20–25 cm behind the slit and then fix the position.
5. **Place the 100 mm imaging lens** ④ halfway between the slit ③ and the grating ⑤, centered on the beam.
6. **Set the grating to normal incidence:** rotate the grating until the undispersed zero-order reflection is centered on the back face of the entry slit (see **Figure 2**, right). This ensures $\theta_i = 0°$. If the zero-order beam is too high or too low, adjust the pitch angle using the lower kinematic setscrew on the grating holder.
7. **Attach a bandpass filter to the LED ①.** Place the viewing screen ⑥ and the black light barrier ⑦ as shown in **Figure 1**, then fix their positions.
8. **Adjust the 100 mm lens** ④ along the optical axis until a sharp image of the entry slit appears on the viewing screen ⑥. If the image is too dim, open the slit ③ slightly. Fix the lens when the image is sharp.

**Observation: <u>You are encouraged to take photos for your presentations!</u>**

9. **With the slit nearly closed:** observe the narrow, bright line on the screen. At this point the image width is governed by diffraction broadening from the grating – not by the slit.
10. **Slowly open the slit** and observe that the image at first grows brighter without growing wider. This is because the grating's diffraction broadening still dominates. The bandpass filter has a spectral bandwidth of only ~3 nm, so the narrowness of the spectral line is not limited by the light source at this stage (details in *Note* below).
11. **Continue opening the slit** until you notice a transition: the image begins to widen. At this point, the geometric width of the slit image has become larger than the diffraction-limited width. This is the resolution limit of the spectrometer for a given slit width.
12. **Swap in the 600 lines/mm grating** and repeat. Compare the two gratings by noting:
    - Which grating spreads the spectrum across a wider angle?
    - With which grating can you open the slit further before the image begins to widen? What does this tell you about its resolving power?
    - How does grating density $g$ (lines/mm) relate to groove spacing $d$ and the diffraction angle? (Hint: $d = 1/g$)

*Note:* The 3 nm spectral bandwidth of the bandpass filter sets a lower bound on how narrow the spectral image can appear. In the regime where the slit is very narrow, diffraction broadening from the grating (not slit width) controls image width.

**Experiment 2: Observing the Spectrum of the LED**

In this experiment, you will observe the full emission spectrum of a white LED and compare it with the spectra produced by individual bandpass filters and with a calibrated digital spectrometer.

**Procedure**

1. **Remove the bandpass filter** from the LED ①.
2. **Re-optimize the 100 mm lens ④** until the slit image on the viewing screen is sharp. Widen the slit ③ if the image is too dim.
3. **Observe the full LED spectrum** on the viewing screen ⑥ (see **Figure 3**). Make note of the colors present, the relative brightness of each color, and where in the spectrum the LED emits most intensely. Again, **photos are encouraged!**




**Figure 3:** Full spectrum of the LED on the viewing screen.

4. **Compare your observation** to the reference spectrum from the Ocean Insight digital spectrometer at the bench. The Ocean Insight gives a quantitative plot of intensity *vs.* wavelength. Consider:
    - Do the colors you see on the screen match the peak wavelengths reported by the Ocean Insight spectrometer?
    - Are any features visible in the digital spectrum that you cannot resolve by eye on the screen?
5. **Repeat with each available bandpass filter (see Figure 4)**: screw each one onto the LED in turn and record what you observe on the screen.
    - What color(s) pass through each filter?
    - Does the filtered image appear as a single narrow line or a broad band? What does this tell you about the filter's spectral width?

    Be sure to discuss these questions (and your answers to them) in the final presentations!

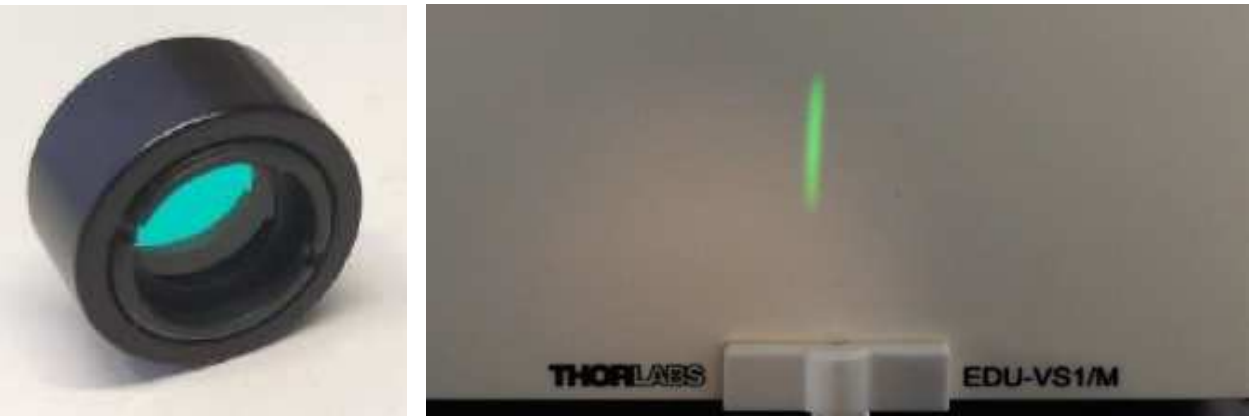



**Figure 4:** Photographs of (left) the bandpass filter component, and (right) the viewing screen after the entry slit and bandpass filter.

**Experiment 3: Wavelength Measurement Using the Grating Equation**

Here you'll use the geometry of the grating spectrometer to calculate the wavelength of a known spectral line (532 nm green) and verify the result. Then apply the same method to determine the wavelength of the violet line in the unfiltered LED spectrum.

Recall that with normal incidence ($\theta_i = 0°$), the grating equation is:

$$d \sin \theta_d = n\lambda$$

You cannot easily measure $\theta_d$ directly, but you can derive it from two distances measured on the breadboard (**Figure 5**): the perpendicular distance $x$ from the entry slit ③ to the grating ⑤, and the lateral displacement $y$ from the zero-order position to the first-order diffracted spot on the viewing screen. From these:

$$\theta_d = \arctan(y/x)$$

For first-order diffraction ($n$ = 1):

$$\lambda = d \sin \theta_d$$

where the grating spacing is:

$d$ = 1/1200 mm ≈ 0.000833 mm ≈ 833 **nm**

(for the 1200 lines/mm grating)

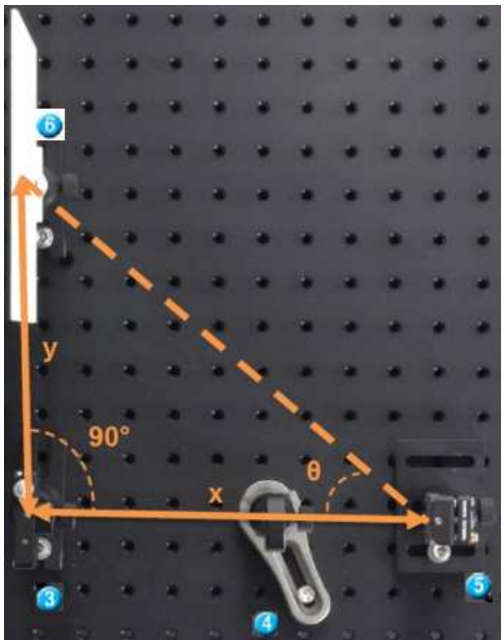



**Figure 5:** Schematic guide to find $\theta_d$.

**Procedure**

1. **Attach the 532 nm bandpass filter** to the LED ①.
2. **Reposition the viewing screen** ⑥ to the same lateral line as the entry slit ③, perpendicular to the slit-to-grating axis (as shown in **Figure 5**). The *y*-value will be measured on the screen from the slit's lateral position to the diffracted spot.
3. **Measure** *x*: the distance along the optical axis from the entry slit ③ to the grating ⑤.
4. **Measure** *y*: the distance on the screen from the zero-order (straight-through) position to the center of the first-order green spot.
5. **Calculate the diffraction angle:**
$$\theta_d = \arctan(y/x)$$
6. **Calculate the wavelength:**
$$\lambda = d \sin \theta_d$$
Compare your result to the known value of 532 nm. **Report the percent error.**
7. **Remove the bandpass filter.** Identify the violet spectral line in the full LED spectrum on the screen. Measure its lateral displacement *y* from the zero-order position and calculate its wavelength. **Take a picture and record your results!**

**Experiment 4: Measuring the Index of Refraction of a Prism**

In this experiment, you'll replace the diffraction grating with a glass prism. Then use the angle of minimum deviation to determine the index of refraction of the prism, and compare it to known values for common optical glasses (see *Note* on next page).

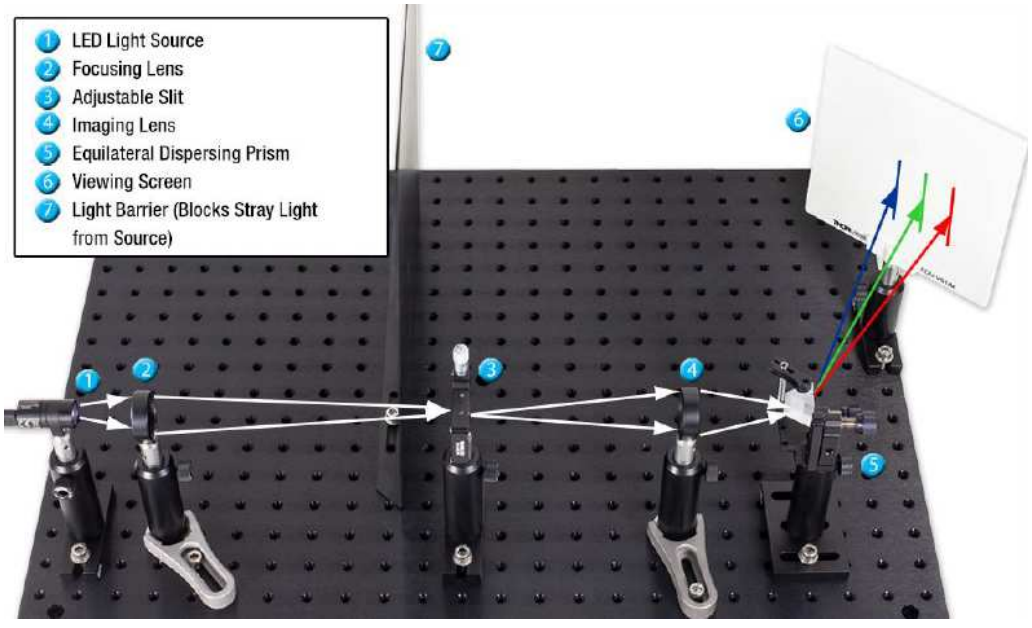



**Figure 6:** Overview of the prism-based setup for Experiment 4.

A prism separates white light because the index of refraction ($n$) varies with wavelength. Light entering the prism is refracted at the first face, travels through the glass, and is refracted again at the second face. The total angular deflection of the beam from its original direction is called the **angle of deviation**, $\boldsymbol{\delta}$.

As you rotate the prism, $\delta$ passes through a minimum value ($\delta_{\text{min}}$), which is called the **angle of minimum deviation**. At this orientation the ray passes symmetrically through the prism, and it can be shown that for an equilateral prism with apex angle $A = 60°$:

$$n = \frac{\sin[(A + \delta_{\text{min}})/2]}{\sin(A/2)}$$

In this experiment $\delta_{\text{min}}$ is obtained from the measured distances $x$ and $y$ shown in **Figure 7**:

$$\delta_{\text{min}} = \arctan(y/x)$$

*Note.* Some reference values for common optical glass indices are:

- Silica glass $n \approx 1.46$; borosilicate (Pyrex) $n \approx 1.47$; soda-lime glass $n \approx 1.51$; dense flint glass $n \approx 1.65$.

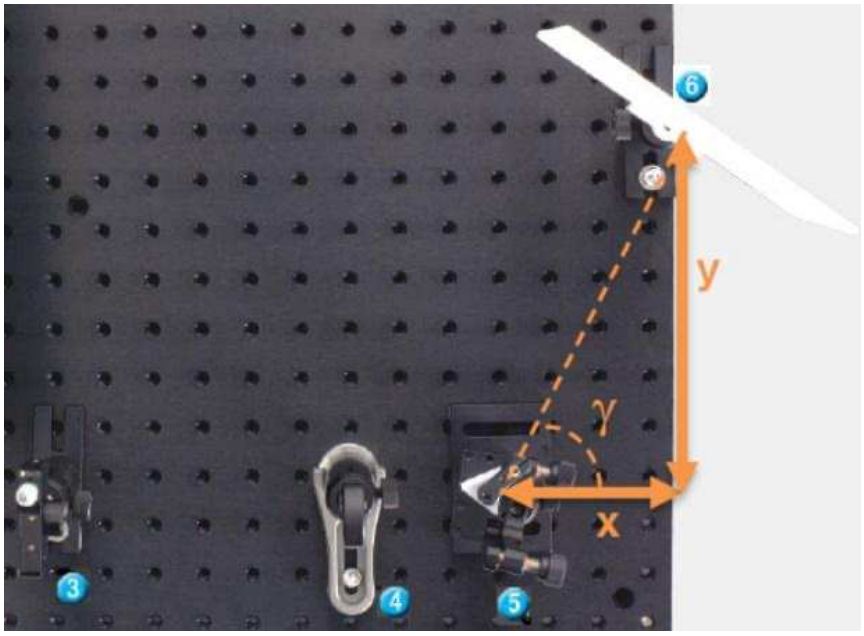



**Figure 7:** Schematic guide to find the angle of minimum deviation.

Here $\gamma$ is used to describe the angle of deviation ($\delta$).

**Setup**

1. **Remove the grating** ⑤ from its holder.
2. **Mount the equilateral dispersing prism** ⑤ in the prism holder 20–25 cm behind the entry slit ③. Then fix the holder.
3. **Rotate the prism** by turning the post until a dispersed spectrum appears on the viewing screen ⑥. The matte (frosted) side of the prism should face toward the viewing screen and the light barrier.
4. **Optimize the image sharpness:** adjust the position of the 100 mm lens ④ and the viewing screen ⑥ until the slit image on the screen is sharp. Widen the slit ③ if needed for brightness. If you cannot obtain a sharp image, adjust the lens position and then try rotating the prism slightly; repeat until sharp. The complete setup is shown in **Figure 6**.
5. **Find the angle of minimum deviation:** slowly rotate the prism and watch the spectral line(s) on the screen move. The angle of minimum deviation corresponds to the orientation at which the spectral line momentarily stops and reverses direction as you continue rotating the prism. Fix the prism at this orientation.

**Measurement**

6. **Attach the 532 nm bandpass filter** to the LED ①.
7. **Confirm the image is still sharp** after attaching the filter; re-optimize the lens or screen position if needed.
8. **Measure the distances** *x* and *y* from the geometry in **Figure 7**:
    - *x*: the horizontal distance from the prism to the viewing screen (along the zero-order beam direction)
    - *y*: the perpendicular displacement of the refracted green spot from the straight-through (zero-order) position on the screen
9. **Calculate the angle of minimum deviation:**
$$\delta_{\min} = \arctan(y/x)$$
10. **Calculate the index of refraction:**
$$n = \frac{\sin[(60° + \delta_{\min})/2]}{\sin 30°}$$
11. **Compare your result** to the reference values listed above. Which type of glass is the prism most likely made from? Report the percent error relative to the closest reference value. Discuss this in your final presentation.