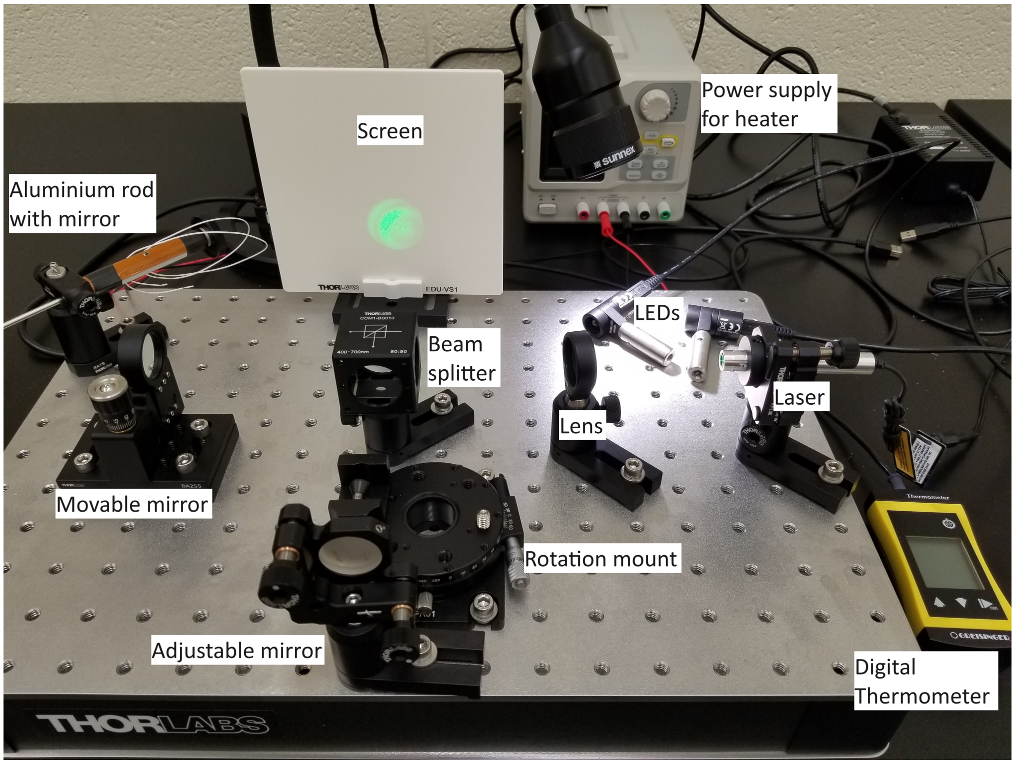
Physics
UNIVERSITY OF TORONTO

Interferometry



Revisions

2025	C Lee
2024	Brian Wilson
2014	P. Albanelli and S. Fomichev
1982	Joe Vise

current revision: 39a6584
date: July 21, 2025

Introduction

Interferometers are devices employed in the study of interference patterns produced by various light sources. They are conveniently divided into two main classes: those based on *division of wavefront*, and those based on *division of amplitude.* They can be used to measure differences in distances with precision better than a micron (micrometre). You will be using a Michelson interferometer, which employs a division of amplitude scheme.

You will use the interferometer to measure the wavelength of the green laser and the red LED, the coherence length of the red LED, the index of refraction of a plastic square prism, and the thermal expansion coefficient of aluminum.

NOTE: Most mirrors in the apparatus are front surface aluminized. Do not touch the surfaces, nor wipe them. They can easily be permanently damaged.

Michelson interferometer: theory

Light from the laser passes through a lens before being split by a beam splitter. Half the light goes straight through to the movable mirror while the other half is reflected toward the aiming mirror. Light from both paths return to the beam splitter and gets split again. Half of the light from each path is directed to the screen, and the remaining light is directed toward the lens and effectively leaves the system. If the beams are aligned and the path length of the light through both paths are nearly identical then you get a circular interference pattern as pictured in Figure 1 on the left. The other two images show the pattern for unequal path lengths (middle) and incorrect alignment (right). As you get farther from the central bright spot, the lines get less curved (large radius of curvature) and the lines get smaller and closer together, and tend to blur. If you are too far off-center, you will not be able to see any pattern.

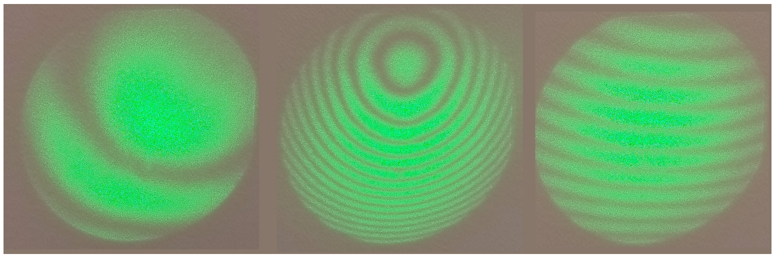


Figure 1: A schematic diagram of the Michelson interferometer. Left: the path lengths are nearly identical, and the alignment is almost centred. Middle: the path lengths differ by hundreds of wavelengths, but the alignment is almost centred. Right: the alignment is off (the center is above the image).

The aiming mirror has two knobs. One will move the pattern horizontally, the other will move it vertically. If your alignment is off by a small amount, you can use these to correct it. If your alignment is off by a large amount, you should remove the lens. You will then have two dots. Use the knobs on the aiming mirror to align the two dots at the same location. If you do this well enough, you will see the interference pattern in the dots. However, as long as you are close, you should see a pattern similar to the one on the right side of Figure 1 when you put the lens back.

> Most of your data will be obtained by slowly changing the path length of one of the two beams. When you do so, fringes will either appear or disappear in the center circular fringe. When one fringe completely disappears and the image looks nearly identical to what it was before you changed the pathlength you will know that the path length changed by **exactly half of one wavelength** of light. It's half a wavelength because the light travelled from the beam splitter to the mirror and back, and that round trip has changed by a full wavelength when one fringe appears or disappears. Your tasks primarily consist of doing something while counting how many fringes **appear or disappear**. You will want to count up to 100 fringes, so try not to lose track of your count.

In general, having exactly equal path length differences makes the interference pattern too large to be useful and may increase the mistakes you make when counting fringes. Except for the part where you're using the red LED, you don't want the two path lengths to be identical. Try to keep them equal to within a millimetre or so when using the laser. As you will discover, LED light has a much smaller coherence length than lasers. As a result, the path lengths need to be nearly identical before you can see the interference pattern for the LED.

A note about blurriness: the laser is not a single wavelength; it has multiple peaks separated by less than a nanometer. These peaks cause multiple interference patterns with slightly different radii. When the path lengths are identical, this does not matter, and you will get a sharp image as all the rings are in the same locations. As you change the path lengths using the adjustable mirror, the bright rings of some of the peaks will overlap the dark rings of the others; the image will become blurry. If you keep moving, the image will come into focus again. You could use this feature to measure the spectral separation of the peaks, but that is not necessary. If you ever find that your image is too blurry, adjust the adjustable mirror until it becomes sharper.

Apparatus

When everything is set up and aligned, you will have three main things to change and measure while counting fringes: the movable mirror, the rotation mount, and the temperature of the aluminum rod.

The movable has a screw on the front. Turning the screw moves the mirror forward and backward. There's a slight lag when you go from moving forward to moving backward, which in general means you should be wary of adjusting it back and forth. It is better to move it in one direction continuously. **One scale division on the screw corresponds to one micrometre of movement of the mirror.** Twenty complete rotations of the screw corresponds to one millimetre of movement. The mirror can move several millimetres.

The rotation mount must be turned manually (most easily by using the screw that protrudes near the micrometre), but it does not exhibit the same forward-to-backward problems as the screw. It features a micrometre that measures angles in degrees and minutes. The zero line on the right in Figure 2 gives the degrees. The line on the right, which most closely aligns with the line on the left (the disk), indicates the minutes. There are 60 minutes in 1 degree. In Figure 2 the zero lines up between 67 and 68, so the angle is about 67.5 degrees. The top line of 35 and the bottom line of 25 best line up with the disk lines. This means it is 35 minutes above 67 degrees and 25 minutes below 68 degrees (which is the same value). The final value is 67°35′. You will need to convert the angles to radians.

Figure 2: A close-up of the micrometre for the rotation mount. The reading is 67°35′.

The temperature is determined by reading the yellow digital thermometer. Changing the temperature of the aluminum rod is done by turning on the power supply, changing the voltage setting, and then waiting for thermal equilibrium. When you start this part of the experiment, you will need to swap the aluminum rod with the movable mirror and then adjust the distances and alignment.

Experiment and Procedure

> The important measurement for most experiments here is the number of fringes that appear or disappear. This is a measure of how far you move the mirror. The number of fringes currently on the screen is *not* usually important unless you are trying to find the exact point where the mirrors are equidistant from the screen. For that experiment, the fewer fringes that cover the screen, the closer you are to that equidistant point.

Wavelengths and Coherence Lengths

Set up the system with the movable mirror and the green. Do not put the plastic square in the rotation mount. Adjust the movable mirror so that the path lengths are nearly equal (as measured with a ruler), and then align the beams with the lens removed. Replace the lens and adjust the settings as needed to center the interference pattern on the screen.

Record the reading on the screw of the movable mirror. Slowly turn the screw while counting fringes which **appear or disappear** on the screen. You want between ten and twenty measurements over as many fringes as you can reliably track (though not more than 100 fringes). Convert the readings to distances (one scale division is one micrometre). Plot the data; it should be a linear function. The slope is a measure of the wavelength (λ) of the laser. Remember that moving the mirror by a distance equal to half the wavelength should cause one fringe to disappear, meaning that N fringes should disappear when you move the mirror a distance of Δx as

$$N\lambda = 2\Delta x. \tag{1}$$

When you have taken this data, look for any features that may indicate you missed a fringe. This might be most noticeable in your residuals plot. You may want to restrict your linear fitting to the largest interval that you are confident you did not miss any fringes. Note that you will have an uncertainty of your fringe count based on your inability to exactly replicate the initial and final fringe locations. This uncertainty is smaller than 1 fringe, but presumably bigger than 0.01 fringes.

You will use this measured wavelength for the remainder of this experiment whenever you use the green laser.

Index of Refraction

Measure the thickness of the plastic square with a Vernier caliper (ask the lab technicians to borrow one). Call this thickness t. Place the plastic square in the holder of the rotation mount. Rotate the mount until the beam is perpendicular to the plastic. You will know you have this correct when you find the local minimum/maximum of fringe count with respect to further rotations. Record that angle; this is your reference angle, which corresponds to zero degrees.

Rotate the mount by various small angles θ while counting the number of fringes that **appear or disappear** N. Using the wavelength λ which you previously determined, you can find that the index of refraction n is

$$n = \frac{(\frac{N\lambda}{2t} + \cos\theta - 1)^2 + \sin^2\theta}{2(1 - \cos\theta - \frac{N\lambda}{2t})}. \tag{2}$$

Instead of finding n for various angles and averaging them, you can rearrange the equation and employ the small angle approximation for θ (in radians, not degrees) to find

$$N \simeq \frac{t}{\lambda}\theta^2(1 - \frac{1}{n}). \tag{3}$$

Fit your data to this function and find the index of refraction of the plastic square. Again, check your data to see if there is evidence that you missed a count.

Thermal Expansion of Aluminium

Replace the movable mirror with the aluminum rod. You will need to remove the lens to align the mirror at the end of the rod correctly. Remember to get the two path distances approximately the same, within a millimetre is probably fine. Put the lens back in when you have everything ready. You should obtain the usual interference pattern, although it may be distorted (not circular). Fortunately, you only need to count fringes; the shape of the pattern is irrelevant.

Turn on the digital thermometer and record the temperature. This is your zero point. Next, turn on the power supply. You will want to increase the voltage in small increments and count fringes. The power supply heats the aluminum rod, causing it to expand and thereby decrease the path length. Thermal expansion is exponential,

$$L = L_0 \mathrm{e}^{\alpha \Delta T} \tag{4}$$

where L is the current length of the rod, L_0 is the length at your base temperature (approximately 9 cm at room temperature, measure this with a vernier caliper), α is the thermal expansion coefficient, and ΔT is the temperature difference from the base temperature. The thermal expansion of aluminum is sufficiently small that your data should be linear unless you reach temperatures hot enough to risk melting things (please don't melt anything). This means you can use the simpler equation

$$N \simeq \frac{2L_0}{\lambda} \alpha \Delta T \tag{5}$$

where N is the usual fringe count and λ is the wavelength of the laser. Measure the fringe count at various temperatures, fit your data, and find the coefficient of thermal expansion for aluminum.

Red LED interference

Set up the interferometer with the fixed mirror and movable mirror in place, and use the green laser to find the point where the mirrors are equidistant. You will find this point when only one or two fringes are visible on the screen. Once you are close to the equidistant point, replace the laser with a red LED and a collimator lens. Use the interferometer to measure the wavelength of the red LED, using the information from the micrometre and the green laser wavelength.

> If you are too far from the equidistant point (also known as the 'zero path difference' (ZPD) point), the red LED interference pattern will be weak or invisible. The red LED has a larger spread of frequencies than the laser, each with its own interference pattern, and these patterns eventually overlap, destroying the visible pattern. The closer you are to ZPD, the cleaner the image will be.

Once you have the wavelength of the LED, return to the ZPD point and measure the distance in fringes and microns that the mirror moves before the interference pattern disappears. This distance (with a factor of two to account for the path travelled) is the coherence length of the light and is proportional to the spectral bandwidth($\Delta\lambda$) of the LED

$$L = \frac{\lambda^2}{\Delta\lambda}. \tag{6}$$

> ⚠ For a laser diode, this coherence length can be multiple centimetres, but for LEDs, it can be as small as fractions of a millimetre. You will need to be close to ZPD to observe this effect.

Calculate the spectral bandwidth of the LED.

References

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