

# LAB #6 — The Michelson Interferometer

## OBJECTIVE

To study the capabilities and uses of the Michelson interferometer; to use the interferometer to measure wavelength of the HeNe laser and to measure the refractive index of air and investigate its dependence on pressure.

## MATERIALS

- o Pasco Optical Bench
- o Pasco Interferometer
- o Movable mirror
- o Beam splitter
- o HeNe Laser
- o Vacuum cell with hand vacuum pump
- o Beam Expander Lens with component holder
- o Pasco Component Holders
- o Adjustable Fixed Mirror
- o MS Excel for Plotting

## INTRODUCTION

### INTERFERENCE THEORY

A beam of light can be modelled as a wave of oscillating electric and magnetic fields. When two beams of light meet in space, these fields add according to the principle of superposition. At each point in space, the electric and magnetic fields are determined as the vector sum of the fields of the separate beams.

If the two beams of light originate from separate sources, there is generally no fixed relationship between the electromagnetic oscillations in the beams. If two such light beams meet, at any instant in time there will be points in space where the fields add to produce a maximum field strength.

However, the oscillations of visible light are much faster than the human eye can apprehend. Since there is no fixed relationship between the oscillations, a point at which there is a maximum at one instant may have a minimum at the next instant. The human eye averages these results and perceives a uniform intensity of light. However, if the two beams of light originate from the same source, there is generally some degree of correlation between the frequency and phase of the oscillations of the two beams. At one point in space the light from the beams may be continually in phase. In this case, the combined field will always be a maximum and a bright spot will be seen. At another point the light from the two beams may be continually out of phase and a minima, or dark spot, will be seen.

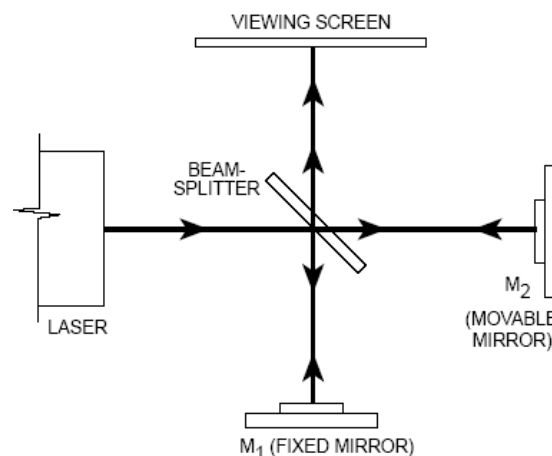
Thomas Young was one of the first to design a method for producing such an interference pattern. He allowed a single, narrow beam of light to fall on two narrow, closely spaced slits. Opposite the slits he placed a viewing screen. Where the light from the two slits struck the screen, a regular pattern of dark and bright bands became visible. When first performed, Young's experiment offered important evidence for the wave nature of light.

Young's slits function as a simple interferometer. If the spacing between the slits is known, the spacing of the maxima and minima can be used to determine the wavelength of the light. Conversely, if the wavelength of the light is known, the spacing of the slits could be determined from the interference patterns.

## THE MICHELSON INTERFEROMETER

In 1881, some 78 years after Young introduced his two-slit experiment, A.A. Michelson designed and built an interferometer using a similar principle. Originally Michelson designed his interferometer as a method to test for the existence of the ether, a hypothesized medium in which light could propagate. Due in part to his efforts, the ether is no longer considered a viable hypothesis. Michelson's interferometer has become a widely used instrument for measuring the wavelength of light, and for using the wavelength of a known light source to measure extremely small distances.

Figure 1 shows a diagram of a Michelson interferometer. A beam of light from the laser source strikes the beam-splitter. The beam-splitter is designed to reflect 50% of the incident light and transmit the other 50%. The incident beam therefore splits into two beams; one beam is reflected toward mirror  $M_1$ , the other is transmitted toward mirror  $M_2$ .  $M_1$  and  $M_2$  reflect the beams back toward the beam-splitter. Half the light from  $M_1$  is transmitted through the beam-splitter to the viewing screen and half the light from  $M_2$  is reflected by the beam-splitter to the viewing screen.



**Figure 1: Michelson Interferometer**

In this way the original beam of light splits, and portions of the resulting beams are brought back together. The beams are from the same source and their phases highly correlate. The HeNe laser beam we use makes a small spot, so the interference is hard to see. To make it bigger we insert a lens between the laser and the beam splitter. When a lens is placed between the laser source and the beam-splitter, the light ray spreads out. An interference pattern of dark and bright rings, or fringes, is seen on the viewing screen, as shown in Figure 2. This spreads out the beam and makes it easier to see the interference. However, this spreading also means that only the central ray of the laser beam is still travelling on a straight line through the interferometer. All the surrounding rays are travelling at some angle, depending on how close to the center of the beam they are. Thus rays at different radii from the center of the laser beam travel a different total distance through the interferometer. This causes the interference pattern we see to look like a bullseye or target shape, with rings of bright and dark fringes instead of just one spot. During the experiment we will be counting bright-dark-bright fringe cycle. To do this you should pay attention to the center spot of the bullseye pattern, not to the outer part.

Since the two interfering beams of light were split from the same initial beam, they were initially in phase. Their relative phase when they meet at any point on the viewing screen, therefore, depends on the difference in the length of their optical paths in reaching that point. By moving mirror  $M_2$ , the path length of one of the beams can be varied. Since the beam traverses the path between  $M_2$  and the beam-splitter twice, moving  $M_2$  one-quarter wavelength nearer the beam-splitter will reduce the optical path of that beam by one-half wavelength. The interference pattern will change; the radii of the maxima will be reduced so they



**Figure 2: Interference Pattern**

now occupy the position of the former minima. If  $M_2$  is moved an additional one-quarter wavelength closer to the beam-splitter, the radii of the maxima will again be reduced so maxima and minima trade positions. However, this new arrangement will be indistinguishable from the original pattern.

By slowly moving  $M_2$  a measured distance  $d_m$ , and counting  $m$ , the number of times the fringe pattern is restored to its original state, the wavelength of the light ( $\lambda$ ) can be calculated as:

$$\lambda = \frac{2d}{m}$$

If the wavelength of the light is known, the same procedure can be used to measure  $d_m$ .

## BASIC OPERATION OF THE INTERFEROMETER

### The Interferometer

The Michelson Interferometer is shown in Figure 3. The alignment of the beamsplitter and the movable mirror,  $M_2$ , is easily adjusted by loosening the thumbscrews that attach them to the interferometer. The fixed mirror,  $M_1$ , is mounted on an alignment bracket. The bracket has two alignment screws to adjust the angle of the mirror. The movement of  $M_2$  toward and away from the beam-splitter is controlled and measured using the micrometer knob. Each division of the knob corresponds to 1 micrometer ( $10^{-6}$  meter) of mirror movement.

### The Movable Mirror

To measure the wavelength of light, the movement of  $M_2$  must be measurable for distances about  $10^{-6}$  meters. Also, as the mirror moves, its reflective surface must remain perpendicular to the axis of the incident light beam.

A taut-band carriage is used to maintain the alignment of the reflective surface of  $M_2$  as it moves. The mirror is mounted in a cradle that is fixed to two semi-rigid aluminum bands. With this set-up the mirror is free to move, but its movement is constrained to a line parallel with the beam axis.

The micrometer mechanism controls and measures the movement of  $M_2$ . The cradle of  $M_2$  is attached to a mylar strip that is attached to a lever arm. The displacement of the lever is controlled with the micrometer knob.

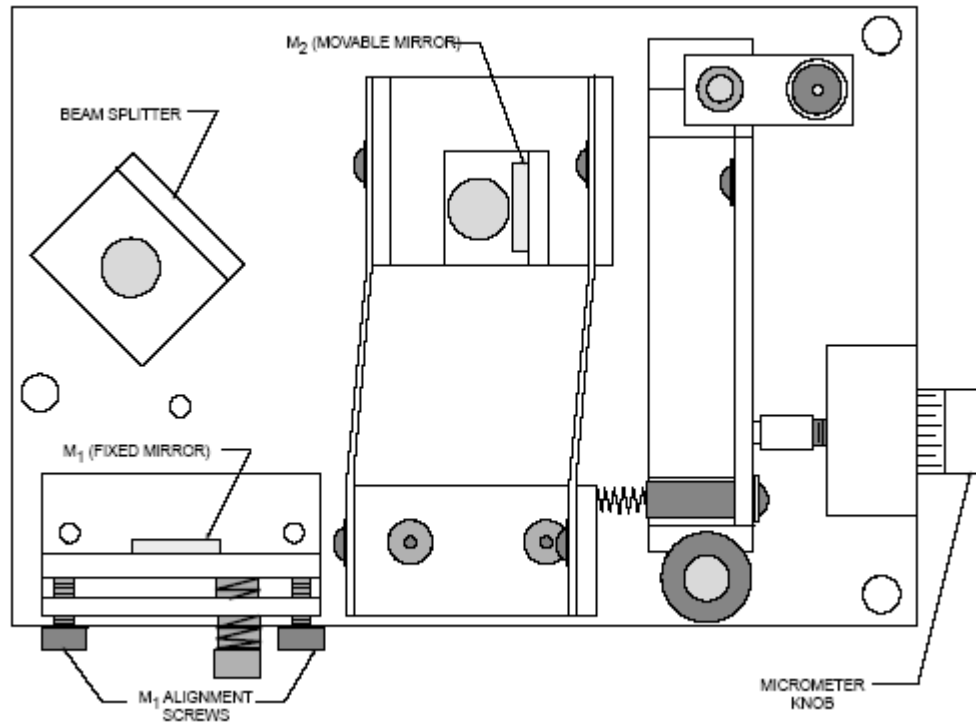


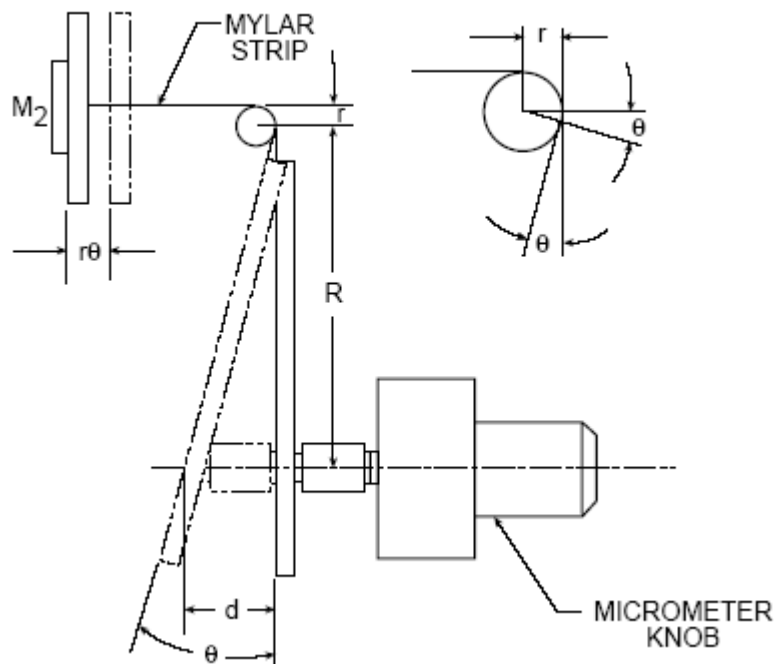
Figure 3: Interferometer

Suppose the micrometer knob is turned so it pushes the lever in by a distance  $d$  (see Figure 4). The angle of the lever arm changes by an amount  $\theta$  such that  $d = R \tan \theta$ , as shown. Since the angle change is always small,  $R \tan \theta = R\theta$ , to a close approximation. This change in the lever arm angle causes the mylar strip to be pulled further around the lever post by an amount  $r\theta$ , where  $r$  is the radius of the lever post. The mirror is therefore pulled away from the beam-splitter by the amount,  $r\theta$ .

In this way, a relatively large displacement of the lever ( $d = R\theta$ ) results in a much smaller displacement of the mirror ( $d_m = r\theta$ ). By selecting appropriate values for  $r$  and  $R$ , the motion of  $M_2$  is controlled so that each division on the micrometer dial corresponds to 1 micron of mirror movement.

### Aligning the Interferometer

1. Place the laser and the interferometer on the Optics Bench, approximately 10 - 20 cm apart (Figure 5). Be sure that the edges of both units are flush against the alignment rail of the bench. Place a viewing screen as shown. Turn on the laser.
2. Loosen the thumbscrew that holds the beam-splitter and rotate the beam-splitter so it is out of the beam path of the laser as shown in Figure 5. Then loosen the thumbscrew that holds  $M_2$ , the movable mirror. Adjust the rotation of  $M_2$  so the laser beam is reflected directly back toward the aperture of the laser. (The reflected beam need not be at the same height as the incident beam, but it should strike the front panel of the laser along a vertical line through the aperture.) Hold  $M_2$  in position and tighten the thumbscrew.
3. Rotate the beam-splitter so its surface is at an angle approximately  $45^\circ$  with the incident beam from the laser (see Figure 6). You will see two sets of laser spots on the viewing screen, corresponding to the two paths that the beam takes in reaching the screen. (Each path results in more than one laser spot because of multiple reflections within the beam-splitter.) Adjust the beam-splitter so



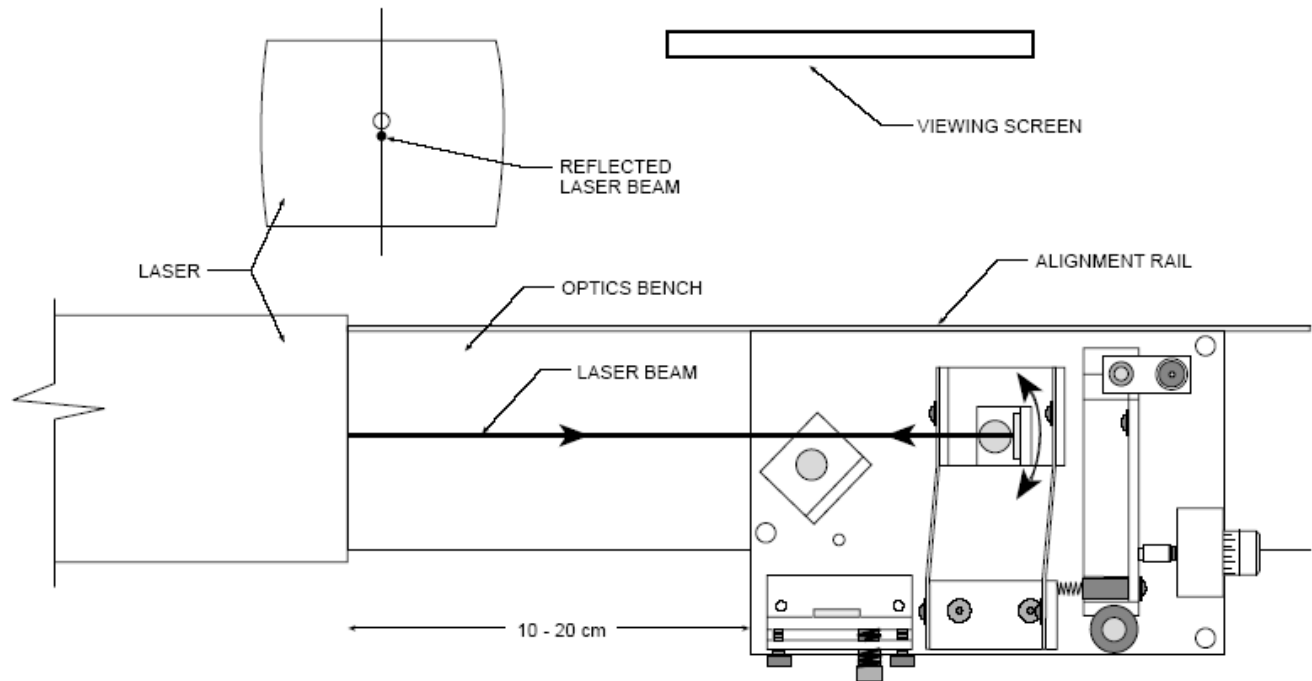
**Figure 4: Mirror Movement Mechanism**

the two sets of laser spots are as close as possible, then tighten the thumbscrew to secure the beam-splitter.

4. Using the alignment screws, adjust the angle of  $M_1$  until the two sets of laser spots are superimposed on the viewing screen (the two brightest spots must be superimposed).
5. Place the lens holder on the optical bench as shown in Figure 7. Be sure its edge is flush against the alignment rail. Then place the 18 mm focal length lens on the lens holder (it attaches magnetically). Adjust the position of the lens on the holder so the light from the laser, now spread out by the lens, strikes the center of the beam-splitter. If you have performed the alignment correctly, you will see an interference pattern of concentric rings on the viewing screen. If the alignment is not just right, the center of the fringe pattern may not be visible on the screen. Adjust the alignment screws on  $M_1$  very slowly as needed to center the pattern.

This step requires patience, and may take you a while. The problem is that the beams along the two arms must be exactly parallel to properly interfere, and if one of the mirrors is tilted differently than the other, the beams won't be parallel. If you can't get the interference pattern, remove the lens and make sure the two brightest beams are still overlapped – by turning the mirror knobs too far you might have moved them apart. If they are not overlapped, fix them, replace the lens, and try again. You may need to move the lens up or down vertically by small amounts, or give the lens a slight twist to get the center part of the interference pattern displayed on the screen.

6. Proceed once you have the interference pattern on the screen. Block the light along one arm. Observe what happens to the interference pattern, and explain.
7. Tap one of the mirrors and observe what happens.

Figure 5: Adjusting  $M_1$ 

## PROCEDURE

### PART A: Measuring the Wavelength of Light

In many scientific and industrial uses of interferometers, a light source of a known wavelength is used to measure incredibly small displacements - about  $10^{-6}$  meters. However, if you know the distance of mirror movement, you can use the interferometer to measure the wavelength of a light source. In this part you will use the interferometer to measure the wavelength of your laser light source.

1. Align the laser and interferometer as described in the previously, so an interference pattern of circular fringes is clearly visible on your viewing screen.
2. Adjust the micrometer knob so the lever arm is approximately parallel with the edge of the interferometer base. In this position the relationship between knob rotation and mirror movement is most nearly linear.
3. Turn the micrometer knob one full turn counterclockwise. Continue turning counterclockwise until the zero on the knob is aligned with the index mark.
4. Tape a blank piece of paper on your viewing screen, make a reference mark on the paper between two of the fringes. You will find it easier to count the fringes if the reference mark is one or two fringes out from the center of the pattern.
5. Rotate the micrometer knob slowly counterclockwise. Count the fringes as they pass your reference mark. Continue until a predetermined number of fringes has passed your reference mark (count at least 20 fringes). As you finish your count, the fringes should be in the same position with respect to your reference mark as they were when you started to count.
6. Record  $d_m$ , the distance that the movable mirror moved toward the beam-splitter as you turned the micrometer knob. Record  $m$ , the number of fringes that crossed your reference mark during the mirror

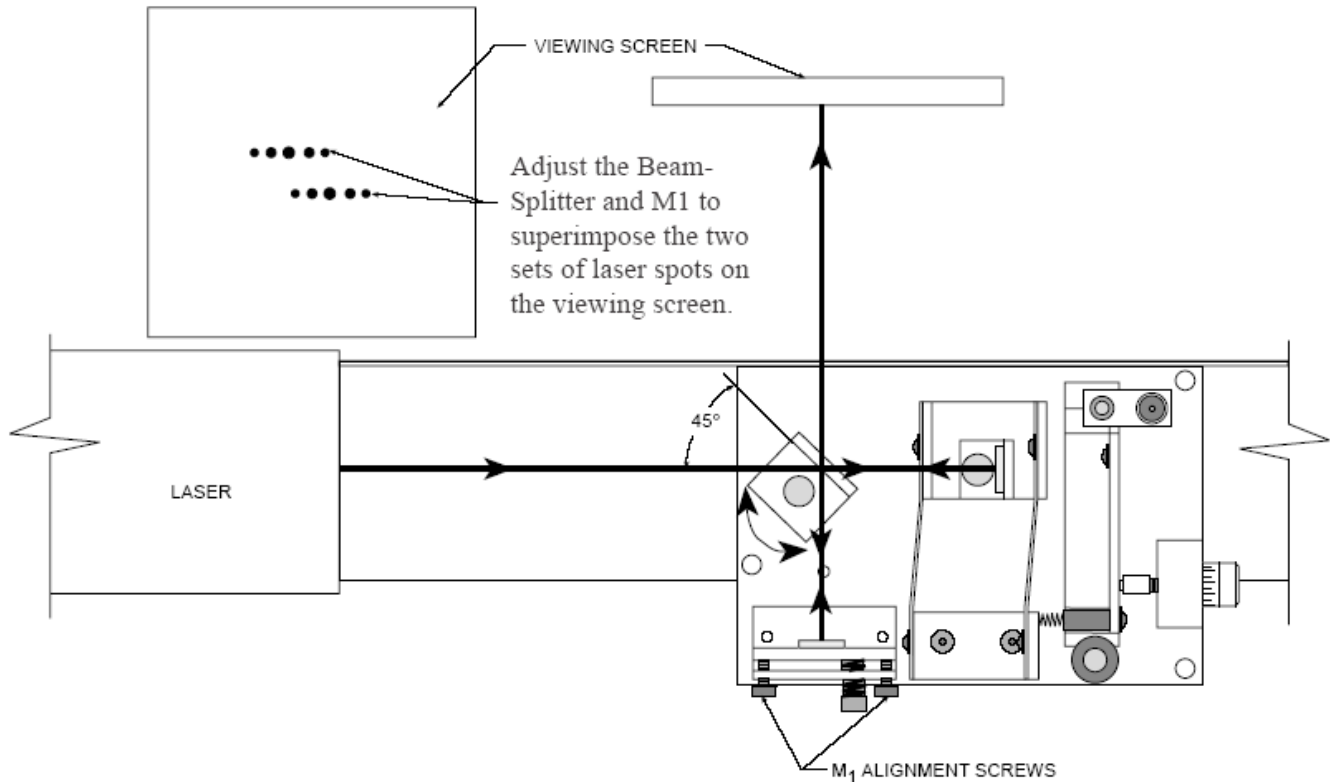


Figure 6: Adjusting  $M_1$

movement. Remember, each division on the micrometer knob corresponds to one micron ( $10^{-6}$  meters) of mirror movement. From these measurements calculate the wavelength of the laser light using

$$\lambda = \frac{2d_m}{m}$$

7. Repeat the previous step measurements at least four more times for a total of five measurements of  $\lambda$ .
8. Find the average measured value for  $\lambda$  and compare it to the accepted value for the HeNe laser wavelength, 632.8 nm. Do your average and the accepted value agree within the expected error?

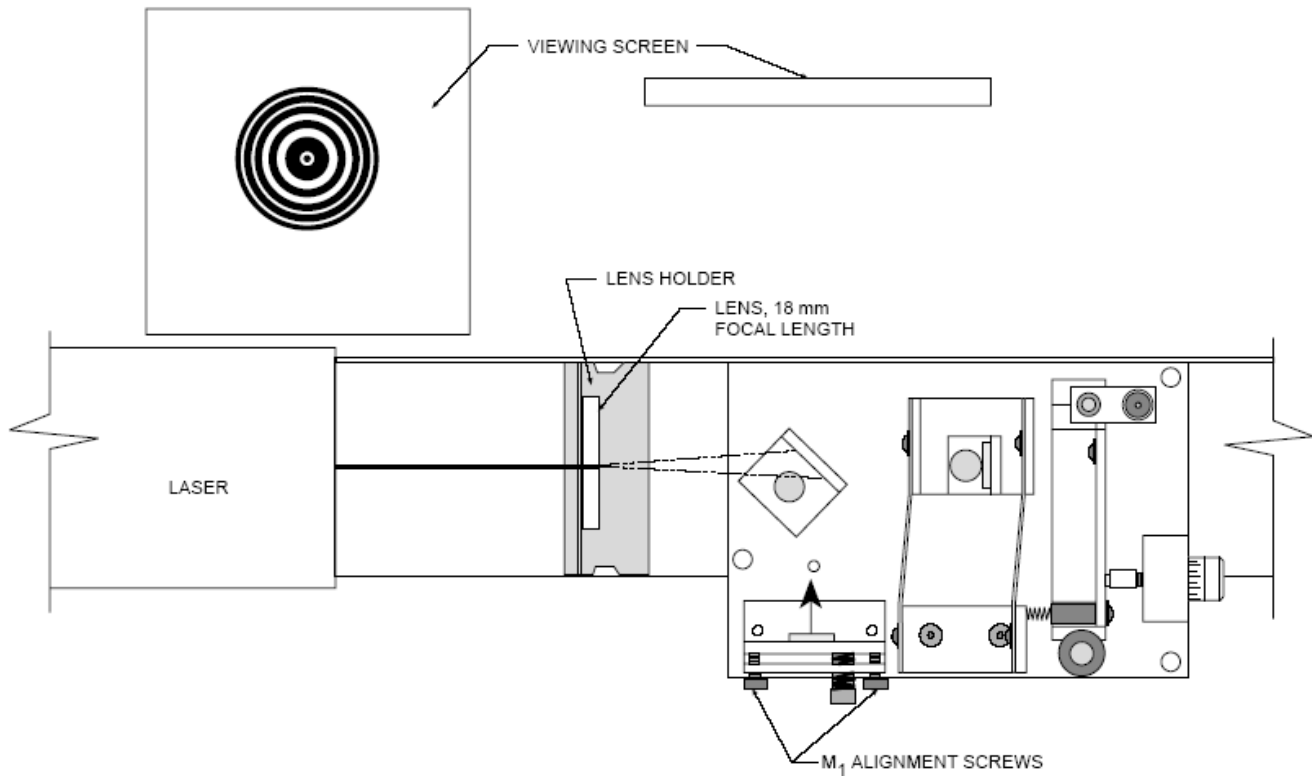
### PART B: Measuring the Index of Refraction for Air

For light of a specific frequency, the wavelength  $\lambda$  varies according to the formula:

$$\lambda = \frac{\lambda_0}{n}$$

where  $\lambda_0$  is the wavelength of the light in a vacuum, and  $n$  is the index of refraction for the material in which the light is propagating. In this experiment, you will use the interferometer to measure the index of refraction for air.

For reasonably low pressures, the index of refraction for a gas varies linearly with the gas pressure. Of course for a vacuum, where the pressure is zero, the index of refraction is exactly 1. A graph for the refraction index versus gas pressure is shown in Figure 8. The measurements you make in this experiment will allow you to calculate the slope of this graph for air. From that, numerical values can be determined for the index of air refraction at various pressures.



**Figure 7: Positioning the Lens**

1. Align the laser and interferometer as described earlier.
2. The experimental set-up is shown in Figure 9. Measure the length of the vacuum chamber. Push the air hose of the vacuum pump over the air outlet hole of the vacuum chamber. Then plug the banana plug of the vacuum chamber into the hole in the interferometer base — between the fixed mirror and the beam-splitter.
3. Adjust the alignment screws of the fixed mirror so the center of the interference pattern is clearly visible on the viewing screen. (The fringe pattern will be somewhat distorted by irregularities in the glass end-plates of the vacuum chamber.)
4. Notice that the banana plug of the vacuum chamber is free to rotate in its hole. For accurate measurements, the end-plates of the vacuum chamber must be perpendicular to the laser beam. Rotate the chamber slowly and observe the effect on the interference fringes. Based on your observations, how can you be sure that the end-plates of the vacuum chamber are properly aligned?
5. Be sure that the air in the vacuum chamber is at atmospheric pressure. This is performed by flipping the vacuum release toggle switch. (Alternatively, many people find it more convenient to begin with the vacuum chamber evacuated — they then let air into the chamber as the fringes are counted. Use whichever method you find to be easier for controlling the air flow.)
6. Record  $P_i$ , the initial reading on the vacuum pump gauge.



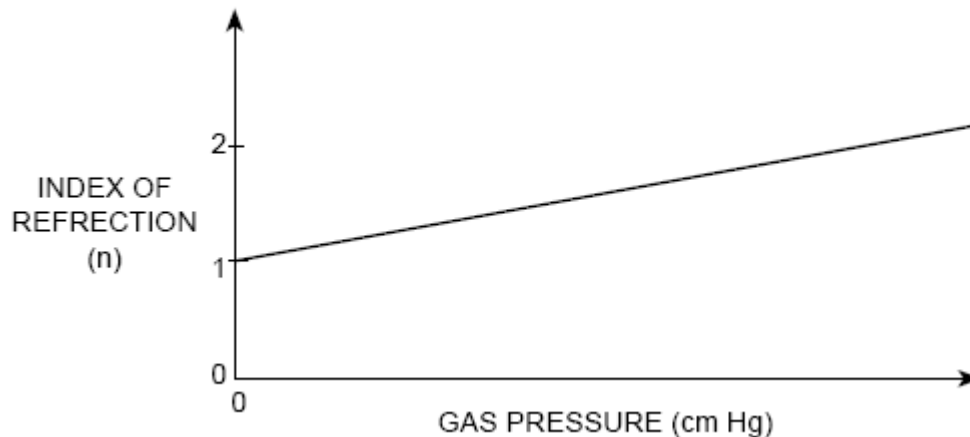


Figure 8: Index of Refraction vs Pressure

**NOTE:**  $P_i$  and  $P_f$  must be absolute pressure readings. Most vacuum gauges measure vacuum pressure with respect to atmospheric pressure (e.g., when the gauge reads 34 cm Hg, it means that the pressure is actually 34 cm Hg BELOW atmospheric pressure). In this case, the absolute pressure reading must be calculated as:

$$P_{\text{absolute}} = 76.0 \text{ cm Hg} - P_{\text{gauge}}.$$

Of course, the room pressure may vary slightly from 76.0 cm Hg. If you have a more accurate way of measuring room pressure, you can use that value to replace 76.0 cm Hg in the above equation.

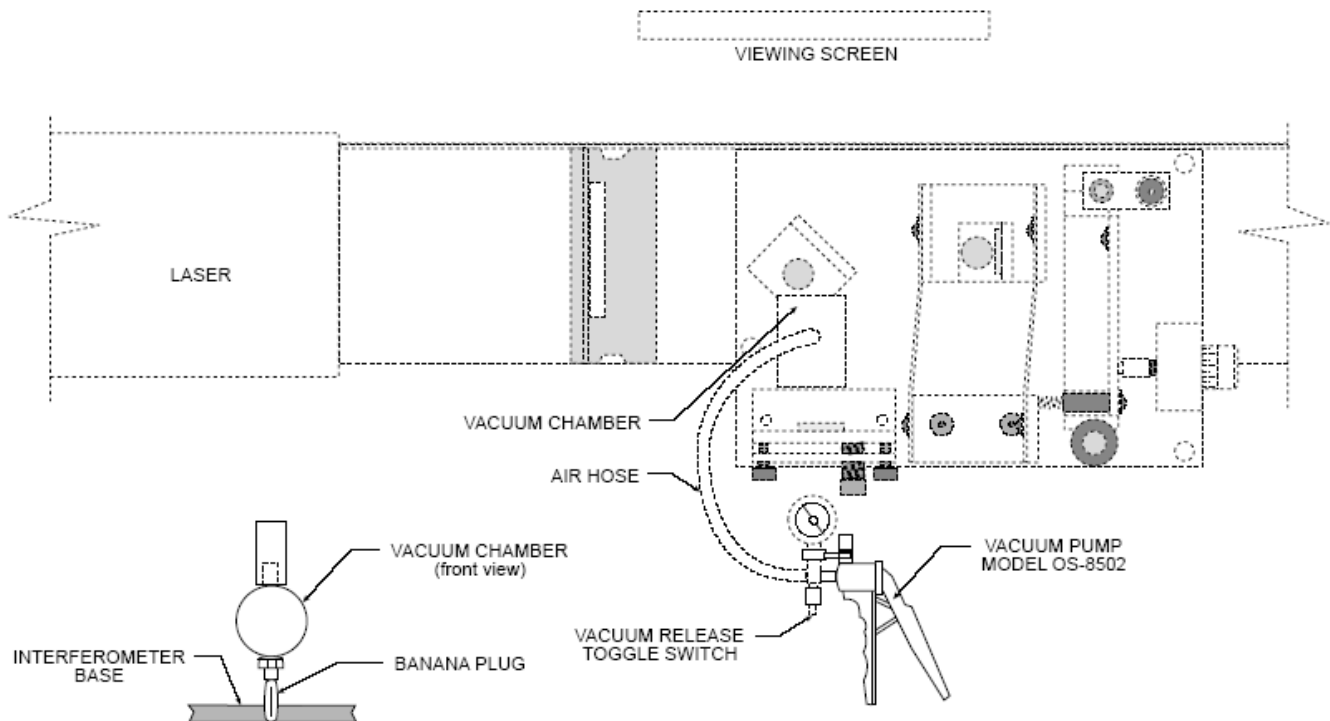
7. Tape a piece of paper onto the view screen and mark a reference point between a pair of fringes on your viewing screen. Slowly pump out the air in the vacuum chamber to some convenient pressure level. As you do this, count  $\Delta m$ , the number of fringes that pass your reference point. Record  $\Delta m$ . Also record  $P_f$ , the final reading on the vacuum gauge.
8. As the laser beam passes back and forth between the beam-splitter and the fixed mirror, it passes twice through the vacuum chamber. Outside the chamber the optical path-lengths of the two interferometer beams do not change throughout the experiment. Inside the chamber, however, the wavelength of the light gets longer as the pressure is reduced.

Suppose that originally the chamber length  $d$  was 10 wavelengths long (it is actually much longer). As you slowly pump out the chamber, the wavelength increases until, at some point, the chamber is only 9-1/2 wavelengths long. Since the laser beam passes twice through the chamber, the light now goes through one less oscillation as it passes through the chamber. This has the same effect on the interference pattern as when the movable mirror is moved toward the beam-splitter by  $\frac{1}{2}$  wavelength. A single fringe will have passed by the reference mark on the viewing screen.

Originally there are  $m_i = \frac{2d}{\lambda_i}$  wavelengths of light within the chamber (counting both passes of the laser beam). At the final pressure there are  $m_f = \frac{2d}{\lambda_f}$  wavelengths within the chamber. The difference between these values,  $\Delta m$ , is the number of fringes you counted as you evacuated the chamber. Therefore:

$$\Delta m = \frac{2d}{\lambda_i} - \frac{2d}{\lambda_f}.$$

However,  $\lambda_i = \frac{\lambda_0}{n_i}$  and  $\lambda_f = \frac{\lambda_0}{n_f}$ ; where  $n_i$  and  $n_f$  are the initial and final values for the refraction index of the air inside the chamber. Therefore  $\Delta m = \frac{2d(n_i - n_f)}{\lambda_0}$ , so that  $n_i - n_f = \frac{\Delta m \lambda_0}{2d}$ . The slope of the  $n$  vs



**Figure 9: Experiment Setup for Index of Refraction of Air Measurement**

pressure graph is therefore calculated as:

$$\frac{n_i - n_f}{P_i - P_f} = \frac{\Delta m \lambda_0 / 2d}{P_i - P_f}$$

where

$P_i$  = the initial air pressure,

$P_f$  = the final air pressure,

$n_i$  = the index of refraction of air at pressure  $P_i$ ,

$n_f$  = the index of refraction of air at pressure  $P_f$ ,

$\Delta m$  = the number of fringes that passed the reference point during evacuation,

$\lambda_0$  = the wavelength of the laser light in a vacuum,

$d$  = the length of the vacuum chamber (3.0 cm).

Calculate the slope of the  $n$  vs pressure graph using the above.

9. Repeat the previous Steps 6 – 8 for a minimum of ten trials and get an average value for the slope of the  $n$  vs pressure graph.
10. Using your average slope, plot  $n$  vs  $P$  (you know that for  $P = 0$ , the index of refraction for the vacuum is  $n \equiv 1$ , so  $n = (\text{slope}) \times P + 1$ ).
11. Using  $n = (\text{slope}) \times P + 1$ , what is  $n_{\text{atm}}$ , the index of refraction of air at a pressure of 1 atmosphere (76.0 mm Hg). For the wavelength of HeNe light and at room temperature, the accepted value for the index of refraction of air is 1.00028. Is your experimentally determined value for  $n_{\text{atm}}$  within the estimated error of the accepted value?