

THE INDEX OF REFRACTION OF GASSES
using a Michelson Interferometer

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INTRODUCTION

An electromagnetic wave (light) propagating past an atom or molecule will induce an oscillating electric polarization of the particle at the same frequency as that of the light. This electric dipole oscillation will in turn generate electromagnetic radiation which modifies the original wave. If the light is propagating through a gas of atoms or molecules, then the induced radiation by these particles will manifest itself as a slight reduction in the phase velocity of the wave as it passes through the gas. This effect is the origin of the *index of refraction* of a transparent material medium.

In this experiment you will use a very sensitive instrument, the *Michelson Interferometer*, to measure the small change in phase velocity of light passing through various gasses. The index of refraction depends not only on the composition of the gas but also on the frequency of the light, so you will perform measurements using both a red laser and a green laser. You will use your data to investigate the reasonableness of a simple theory of the atomic origin of the index of refraction, and your lab work will give you a bit of experience with modern optical components and techniques of interferometry.

THEORY: ORIGIN OF THE INDEX OF REFRACTION OF A MATERIAL MEDIUM

An isolated atom will arrange its electron charge distribution so that the nucleus experiences no net electric field (otherwise the nucleus would experience a net electrostatic force, causing it change its position relative to the electron distribution), and the total energy of the system is minimized. In the presence of an external electric field, however, the original configuration of nucleus and electrons is no longer the equilibrium state, since the electrons and the nucleus are subject to externally-generated electrostatic forces in opposite directions. Thus the nucleus and the electron charge distribution must shift position relative to each other to find a new equilibrium configuration, and the electron charge distribution changes shape, because the outer electrons feel less Coulomb attraction by the nucleus than do the inner electrons.

As a result of the shift to a new equilibrium configuration in the presence of the applied field, the atom experiences a slight separation of its positive and negative charges, so that it acquires an electric dipole moment. For relatively small fields applied to a thin gas of atoms, the induced dipole moment per atom is proportional to the field strength:

$$\langle \vec{p}_{atom} \rangle = \gamma_{atom} \vec{E} \quad (19.1)$$

In (19.1) $\langle \vec{p}_{atom} \rangle$ is the average dipole moment induced by the field \vec{E} , averaged over the various possible relative orientations of the field and atom, and γ_{atom} is very nearly constant for small external fields. A similar relationship would hold for the average polarization of a simple molecule subject to a weak external electric field.

Because the electrons are so much lighter than the nucleus, they are the ones that mainly change position as a result of the field, not the nucleus. In fact, because they are much more weakly bound by the nuclear Coulomb force, it is reasonable to assume that the displacements of a few outer (valence) electrons make the dominant contribution to the induced dipole moment (19.1), so that

$$\langle \vec{p}_{atom} \rangle = -n_e e \bar{x} \quad (19.2)$$

where n_e is the number of electrons in the atom or molecule mainly contributing to the generation of the dipole moment, and \bar{x} is their average displacement relative to the nucleus, which is opposite to the direction of \vec{E} since they are negatively charged. The restoring force from the Coulomb attraction of the nucleus grows with an electron's small displacement, and this force is very nearly proportional to it, leading to the linear relationship (19.1). This implies that if the external field were to suddenly vanish, the electrons' displacement \bar{x} could oscillate with simple harmonic motion at some resonant frequency ω_0 and with some quality factor Q .

In the presence of a passing light wave with frequency ω , the electrons will experience an oscillating electric field \vec{E} which will drive their average displacement \bar{x} at that same frequency (since the wavelengths of visible light are 1000's of times larger than the size of an atom or simple molecule, the electrons' experience is that of an oscillating field and not a passing wave). Thus we have a situation analogous to the driven harmonic oscillator (the series RLC circuit) of Experiment 2, and the displacement $\bar{x}(t)$ can be written as the real part of $x(\omega) \hat{E} e^{j\omega t}$, where the complex phasor $x(\omega)$ is given by:

$$x(\omega) = \left(\frac{-e E}{m \omega_0^2} \right) / \left[\left(1 - \frac{\omega^2}{\omega_0^2} \right) + j \frac{1}{Q} \frac{\omega}{\omega_0} \right] \quad (19.3)$$

You should compare this expression to equation (11) of Experiment 2 (page 2–6). As we know from that experiment or a careful examination of (19.3), if $\omega < (1 - n/Q)\omega_0$, for large Q and $n \gtrsim 3$, then $x(\omega)$ is very nearly real. This happens to be the case for visible light and the gasses used in this experiment, where ω_0 is in the ultraviolet and Q is very large. Thus, from (19.2), $\langle \vec{p}_{atom} \rangle$ oscillates in phase with $\vec{E}(t)$ and with an amplitude $\propto 1/(\omega_0^2 - \omega^2)$.

Assume that a plane wave traveling in a direction normal to a thin, tenuous sheet of molecules passes through it. The oscillating electric field $\vec{E}(t)$ of the wave at the position of the sheet will be in the plane of the sheet and will induce oscillations of the electrons in the molecules of the

sheet according to (19.3). These oscillating charges will radiate another plane electromagnetic wave of the same frequency and in the same direction as the wave (as well as in the opposite direction). Feynman's *Lectures on Physics*, Volume I, section 30–7 gives an excellent derivation of the radiation from such a sheet of oscillating charge: if we have electrons oscillating with the phasor $\vec{x}(\omega)$, the electric field phasor of the induced wave will be (*cf.* Feynman eqn. 30.18)

$$\vec{E}_{ind}(\omega, z) = \sigma_e \frac{e}{2\epsilon_0 c} j\omega \vec{x}(\omega) e^{-jz\omega/c} \quad (19.4)$$

where z is the distance from the sheet, and σ_e is the surface number density of the oscillating electrons in the sheet. Using (19.3) in the limit that $Q \rightarrow \infty$, the sum of the original and induced wave phasors leaving the sheet is

$$\vec{E}(\omega, z) + \vec{E}_{ind}(\omega, z) = \vec{E}(\omega, z) \left[1 - j \frac{\omega}{c} \frac{\sigma_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)} \right] \quad (19.5)$$

Since the electron surface density in the thin sheet is small, we know that $\vec{E}_{ind} \ll \vec{E}$. Thus the expression in the brackets in (19.5) represents a *small phase delay in the wave after passing through the sheet*:

$$1 - j \frac{\omega}{c} \frac{\sigma_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)} = 1 - jd\phi = e^{-jd\phi} \quad , \text{ since } d\phi \ll 1 \quad (19.6)$$

If the sheet thickness is dz , the surface density of the electrons in the sheet is given by the volume number density of the molecules, N , and the number of oscillating electrons/molecule, n_e , so $\sigma_e = Nn_e dz$. If another sheet of molecules is added immediately following the first, the wave will be further delayed, and so on for additional sheets. The phase delay per thickness of the combined, finite volume of molecules is therefore $d\phi/dz$, and after traveling a finite distance z through such a medium the wave's phasor will be

$$\begin{aligned} \vec{E}(\omega, z) &= \vec{E}(\omega, 0) \exp \left[-jz \left(\frac{\omega}{c} + \frac{d\phi}{dz} \right) \right] \\ &= \vec{E}(\omega, 0) \exp \left[-jz \frac{\omega}{c} \left(1 + \frac{Nn_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)} \right) \right] \end{aligned} \quad (19.7)$$

Note that the spatial phase variation of the plane wave described by (19.7) is that of a wave traveling with a *reduced phase velocity* $c' = c/n$. The factor n is called *the index of refraction* of the medium, and for a tenuous gas and our simple theory it is given by the formula

$$\boxed{n - 1 = \frac{N n_e e^2}{2 \epsilon_0 m (\omega_0^2 - \omega^2)}} \quad (19.8)$$

An excellent, much more thorough derivation of (19.8) is given in Feynman chapter 31. Let's express (19.8) in terms of vacuum wavelengths and the *classical electron radius*:

$$\omega = \frac{2\pi c}{\lambda} \quad ; \quad r_e = \frac{e^2}{4\pi\epsilon_0 mc^2} = 2.82 \times 10^{-15} \text{ m} \quad (19.9)$$

$$\boxed{n - 1 = \frac{N n_e r_e}{2\pi} \left(\frac{1}{\lambda_0^2} - \frac{1}{\lambda^2} \right)^{-1}}$$

THE APPARATUS

The Michelson interferometer

Let's use (19.9) to estimate the order of magnitude of $n - 1$ for air near standard density. The number density of the molecules in this case would be 1 mole/22.4 liter = $2.7 \times 10^{25} / \text{m}^3$. Thus,

$$\lambda_0 \sim 80 \text{ nm (in the ultraviolet)}, \quad \lambda \approx 630 \text{ nm (red light)}, \quad n_e \sim 4$$

$$\left(\frac{1}{\lambda_0^2} - \frac{1}{\lambda^2} \right)^{-1} \sim 6.5 \times 10^{-15} \text{ m}^2$$

$$\therefore n - 1 = \frac{N n_e r_e}{2\pi} \left(\frac{1}{\lambda_0^2} - \frac{1}{\lambda^2} \right)^{-1} \sim \frac{2.7 \times 10^{25} \times 4 \times 2.8 \times 10^{-15}}{6.3} \times 6.5 \times 10^{-15} \approx \boxed{3 \times 10^{-4}}$$

So the speed of light should be decreased by only about 0.03% in air vs. vacuum, a small change indeed. Even worse, the difference in the index of refraction for green light (543nm) vs. that for red light is only about 2×10^{-6} . Accurately measuring such small changes in the speed of light could be a daunting task were we not able to take advantage of the fact that light is a wave. A change in phase velocity means that light of a given frequency has a slightly different wavelength, and we can very accurately measure this wavelength shift by monitoring the change in the interference pattern between a signal wave (whose wavelength is changing) and a reference wave (whose wavelength remains constant). The *Michelson Interferometer* accomplishes this task.

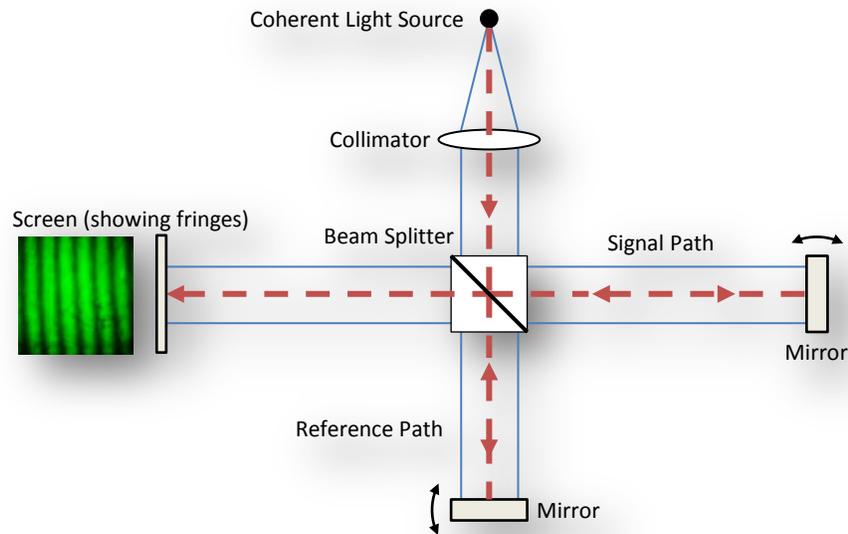


Figure 1: A modern version of the Michelson Interferometer. A plane wave with a well-defined wavelength is produced by the source and collimator. It is split and sent down two orthogonal paths by the beam splitter. The mirrors reflect the light back toward the beam splitter, where it is recombined and sent toward the screen (as well as back toward the source). Interference fringes are displayed on the screen.

A schematic representation of the interferometer is shown in Figure 1. This design was invented by Albert Michelson in about 1880. He, with Edward Morley, used an improved design in 1887 to conduct the famous *Michelson-Morley* experiment, which, along with other evidence, inspired Albert Einstein to develop the theory of *special relativity* 25 years later. Michelson was the first American to win the Nobel Prize in physics, and was also the Ph.D. research advisor of Robert Millikan at U. Chicago.

Michelson's interferometer (as we implement it here) works as follows:

- (1) The coherent source emits light of a well-defined wavelength. The light is focused into a plane wave beam (i.e., the source image is at ∞) by the collimator.
- (2) The beam enters the beam splitter so that half of its energy passes through to the *reference path*, and the other half is reflected into the *signal path*.
- (3) The *reference path* and *signal path* beams are each reflected by their respective mirrors and returned to the beam splitter.
- (4) The beam splitter sends half of the energy from each returning beam toward a viewing screen, and the rest of the energy is sent back toward the light source.
- (5) The waves returning from each path *interfere*, causing the viewing screen to be bright or dark, depending on the relative phases of the two waves at the screen.

If one or both of the mirrors is not quite normal to its incoming beam, then the path length of the light from the beam splitter to the mirror and back will vary depending on the lateral position of the ray away from the beam centerline. Thus, a slight tilt of one mirror will produce an interference pattern at the screen of bright and dark fringes, as shown in Figure 2.

As the length of one of the two paths (or “arms”) of the interferometer changes, the relative phase of the light from the two returning beams will change, causing the interference pattern to shift. If the fringes shift by one fringe-spacing, *then the round-trip path length difference between the two arms has changed by one wavelength of the light.*

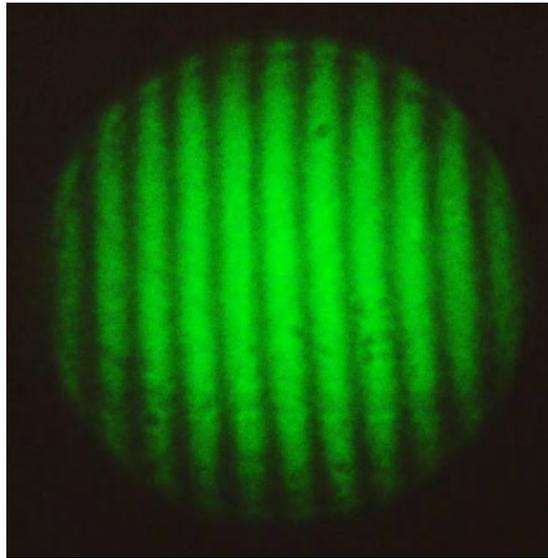


Figure 2: A typical interference fringe pattern from the Michelson interferometer. The source is a helium-neon (HeNe) laser tuned to emit 543 nm light. If the fringe pattern shifts left or right by a distance equal to the fringe spacing, then the difference in the *round-trip* path lengths between the signal and reference beams has changed by one wavelength.

In this experiment, the two arms of the Michelson interferometer are each approximately 10 inches long. The signal path of the interferometer contains a chamber which can be filled with various gasses or pumped to vacuum (the “gas cell” referred to in Figure 3 and Figure 4). The changing index of refraction of the medium in the cylinder will change the total number of wavelengths of light in the beam traveling along the signal path, thus causing the fringe pattern to shift. The total shift of the pattern as a gas is evacuated from or released into the cell will allow you to accurately determine the gas’s index of refraction. Two lasers (red and green) are available, so that the index may be determined at two different wavelengths.

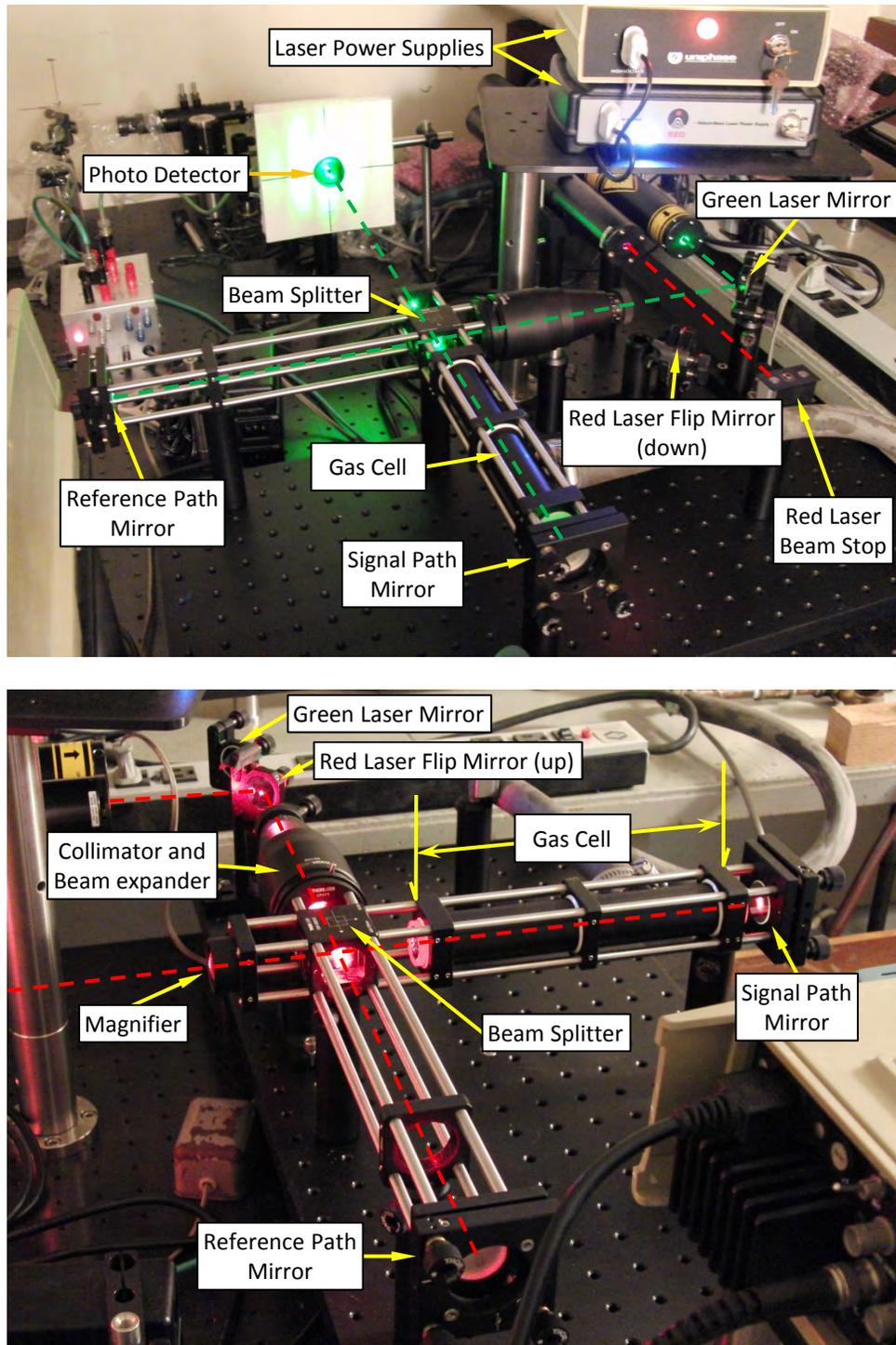


Figure 3: Two views of the interferometer used in the experiment. The two HeNe laser wavelengths are 543nm (green) and 633nm (red). The mirror used to inject the red laser light into the apparatus flips up or down to select the laser color. The paths of a central ray are indicated by the dashed lines. As the gas cell is filled or emptied, the phase length of the signal path changes, causing the fringe pattern to shift. The lower photo shows where the length of the gas cell should be measured.

Gas-handling system

The gasses you will use in this experiment are ambient room air, carbon dioxide, and helium. Figure 4 shows the arrangement of the major components of the gas-handling system.

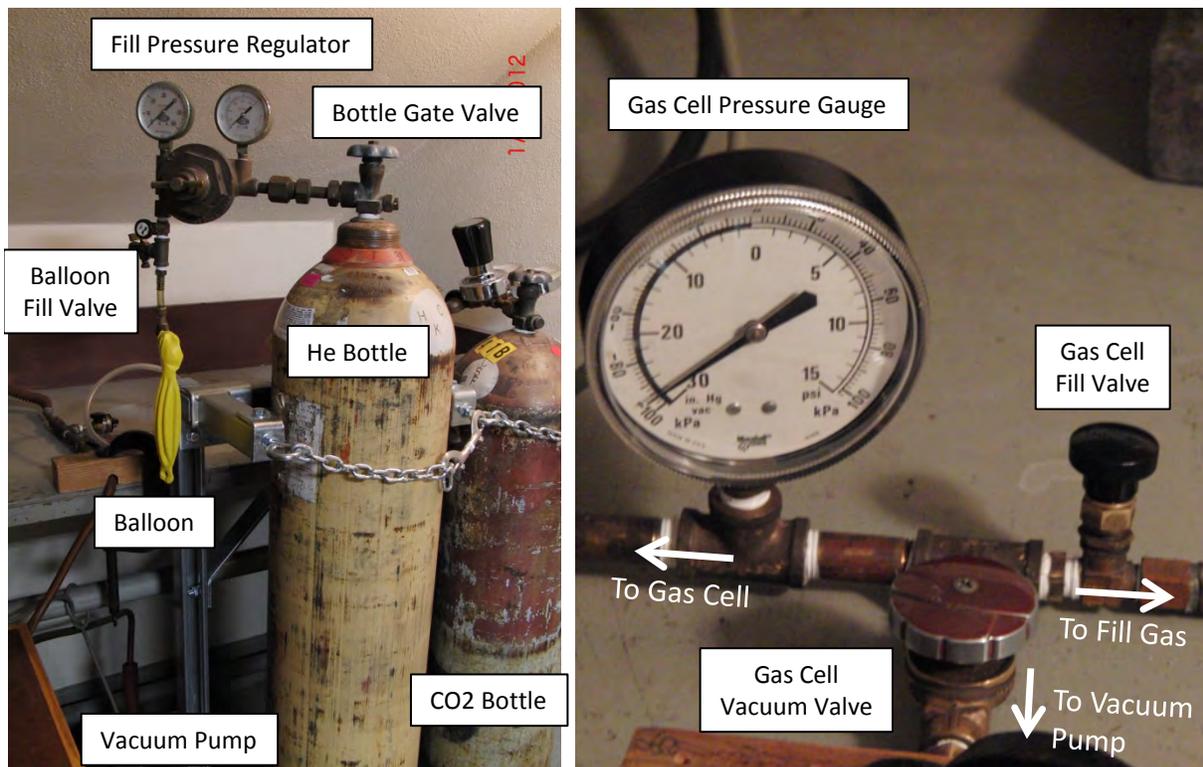


Figure 4: The gas-handling components. The vacuum pump is on the floor underneath the bench; it should be left running for the duration of the experiment. The balloon serves as a gas reservoir and also ensures that the gas cell pressure (when filled) is the same as the ambient air pressure in the room. Air (from the room's atmosphere), carbon dioxide, and helium are the available gasses. The He and CO₂ bottles' positions may be interchanged from those shown in the photo. The right-hand photo shows the valves used to control gas flow into and out of the interferometer gas cell.

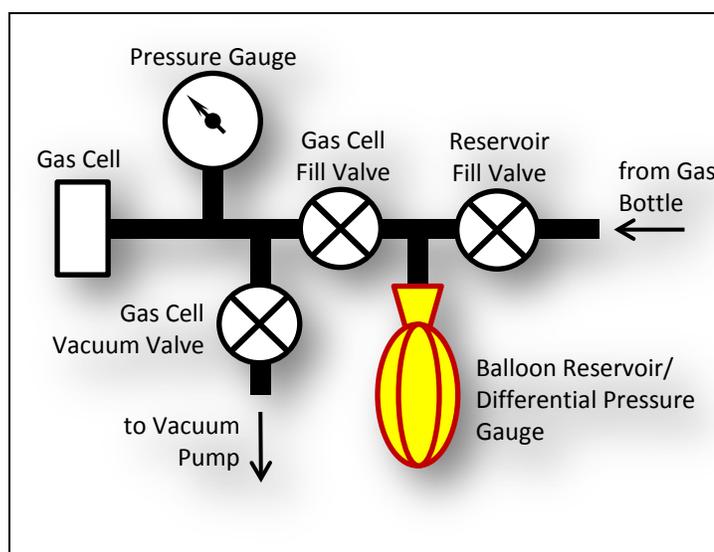
A small vacuum pump on the floor behind the gas bottles is used to evacuate the interferometer gas cell. The pump should be turned on at the beginning of the experiment and remain active throughout the data collection. By opening and closing the vacuum valve shown in the right-hand photo in Figure 4 you can control the connection of the gas cell to the pump. The fill valve shown in the same photo is used to control the release of gas into the cell. The pressure gauge displays the gas cell's pressure relative to ambient atmospheric pressure (called the cell's *gauge pressure*). In the photo it shows that the gas cell is near vacuum, which would be at about -29.25 inch Hg on the gauge, since ambient air pressure in the lab is usually about 743 Torr (mm Hg).

A flexible hose connects the fill valve to the source of gas for the cell. It is left open to the room air when air is the desired gas; otherwise it is connected to the outlet of the balloon fill valve

connected to the desired gas bottle's pressure regulator. The flexible hose has a tee-fitting which connects a balloon gas reservoir to the fill system. The balloon has folds in its rubber fabric, so if the folds are not pulled tight by the volume of gas within it, then the rubber is relaxed and does not support a pressure difference between the gas in the balloon and the ambient room air surrounding it.¹

Thus, when the balloon's rubber fabric is relaxed and folds in the fabric are evident, then the gas pressure within the balloon is equal to the ambient room air pressure. This will also apply to the gas within the interferometer gas cell if the gas fill valve is open and the vacuum valve is closed.

Figure 5: Diagram of the gas-handling system controls used to introduce one of the bottled gases, CO₂ or helium, to the gas cell of the interferometer. The reservoir fill valve is used to slightly inflate the balloon. After exhausting the gas cell's contents using the vacuum pump, gas from the balloon is expanded through the gas cell fill valve to slowly bring the gas cell up to atmospheric pressure. If some small amount of excess gas remains in the balloon after the fill valve is opened, then the pressure in the cell will equal the ambient room air pressure.



Fringe-counting electronics

Because the relative difference in $(n - 1)$ for green and red light is typically less than 1%, the number of fringes which must be counted as the interferometer's gas cell is emptied or filled must be fairly large to obtain a reasonable estimate of this difference. Thus the gas cell's length is several inches so that a typical fringe count is well over 100 (except for helium). It can be tedious to count so many fringes, especially since the count data should be repeated a few times to improve the accuracy of the measurement. A photodetector and associated counting electronics are therefore added to the apparatus to help the experimenter accurately obtain count data. The following figures (Figure 6 to Figure 8 on page 10 – 11) briefly describe the electronics and how to properly set up and use the system for accurate fringe counting.

¹This clever design is due to Don Skelton, the long-time Caltech undergraduate physics laboratory manager who retired in 2001.

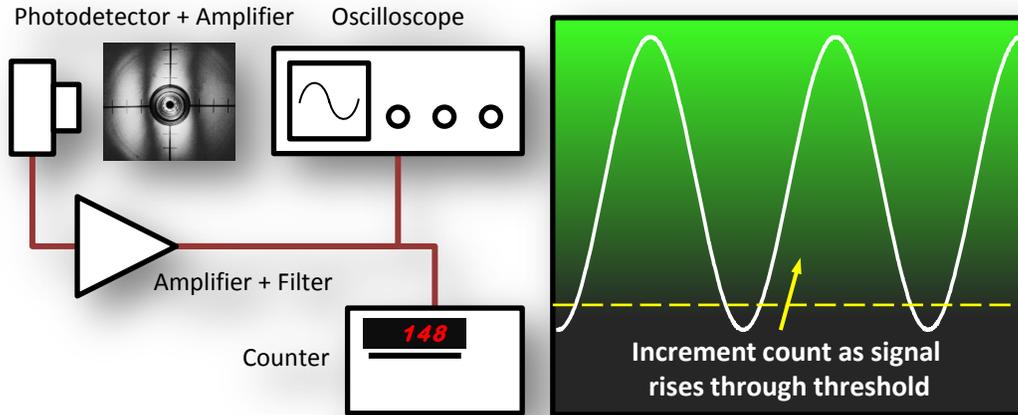


Figure 6: (left): fringe counting electronics. The detector is constructed from a silicon photodiode whose output is amplified and filtered to remove noise before input to the oscilloscope and counter. (right): the light intensity from the interferometer causes the photodiode signal to vary sinusoidally as fringes pass across the detector. The counter's trigger threshold should be set so that the fringe count is incremented whenever the intensity has begun rising following the passage of a dark fringe, as illustrated by the dashed line and the arrow in the right-hand graphic.

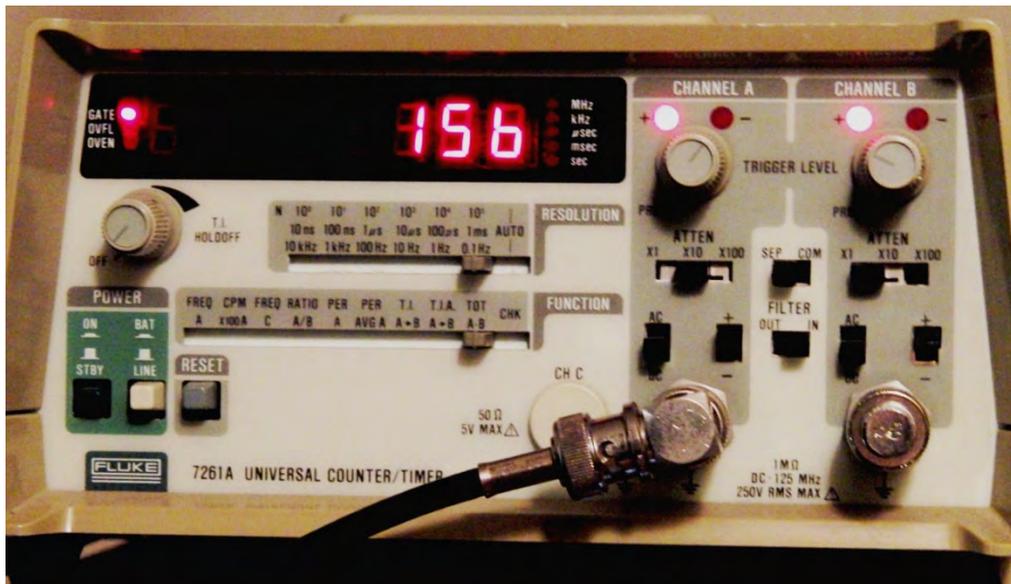


Figure 7: The *Fluke 7261A* Counter/Timer used to count the number of dark fringes passing the photodetector. The proper settings of its controls are shown in this photo; its user manual is available here:

http://www.sophphx.caltech.edu/Lab_Equipment/Fluke_7261a_manual.pdf

The *Channel A* input is used for the signal from the photodetector, whereas the *Channel B* input is terminated to ground. The *Reset* button (lower left) is used to zero the count between measurements. A voltmeter is attached to a rear-panel monitor port of the counter which shows the trigger level voltage. With the *Channel A Atten* set to X10 (as shown), the actual trigger level is 10 times greater than the monitor voltage.

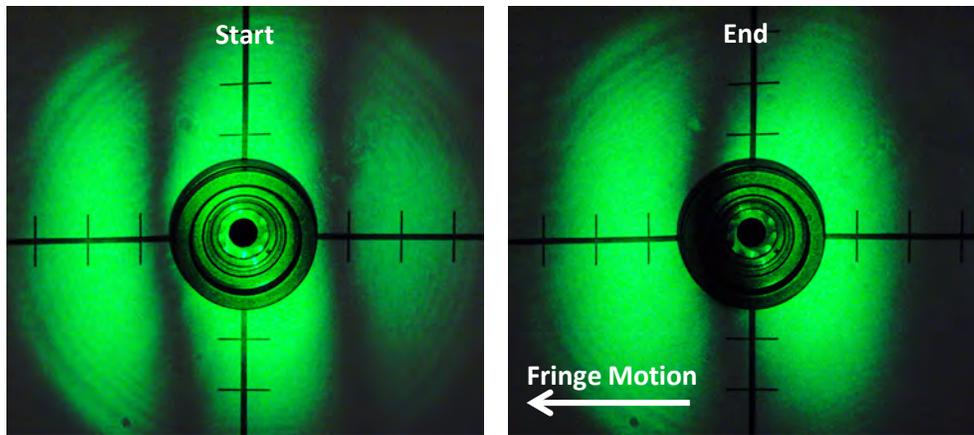


Figure 8: Accurately determining the actual wavelength shift starting from the photodetector electronics count data demands some experimenter savvy and thoughtfulness. The goal should be to determine a wavelength count with a resolution of ~ 0.1 wavelength. The left photo shows a desirable starting fringe pattern with the photodetector centered between dark fringes. The right photo shows a possible ending fringe pattern. In this case the counting electronics, by counting the passage of dark fringes, will give a count which is effectively rounded to the nearest whole number. For the situation shown in the photo, with the fringe motion past the detector having been from right to left, the fringes stopped moving before the detector quite reached the center between two dark fringes. Therefore a count of N from the electronics should be correctly interpolated to $(N - 1) + 0.7$, with an uncertainty of approximately ± 0.1 fringe.

PRELAB PROBLEMS

1. If the length of the gas cell is L , the index of refraction of the gas is n , and the laser vacuum wavelength is λ_{vac} , then what is the difference in the number of wavelengths of a light ray passing through the cell when it is evacuated and when it is filled with the gas? What then is the difference in wavelengths for a round-trip along the signal path of the interferometer? How will this difference relate to the number of interference fringes which pass the photodetector when the gas cell is evacuated or filled with the gas?
2. If the interference fringe count for the green laser ($\lambda_{vac} = 543.52$ nm) is 181.4 as air slowly fills the gas cell from vacuum to room pressure, and the length of the cell is 7.354 inches, then what is the measured $(n-1)$? If the ambient air temperature and pressure are 22.2°C and 740 Torr for this data, then what would be the expected $(n-1)$ of air at 0°C and 760 Torr?
3. Equation (19.9) may be expressed in the form:

$$a \times (x - c) = y, \quad \text{where } x = \frac{1}{\lambda_0^2}; \quad y = n_e$$

$$\text{and } a = \frac{2\pi}{Nr_e}(n-1); \quad c = \frac{1}{\lambda^2}$$

For each gas, you would have two such equations, one for each laser wavelength, with unknowns x (from which we get λ_0) and y (from which we get n_e), and coefficients a_1 , c_1 , a_2 , and c_2 . Show that the solutions for x and y of this system of equations is:

$$x = \frac{a_1 c_1 - a_2 c_2}{a_1 - a_2}; \quad y = \frac{a_1 a_2 (c_1 - c_2)}{a_1 - a_2} \quad (19.10)$$

Assuming the uncertainties in λ and $r_e = 2.82 \times 10^{-15}$ m may be neglected, then the only remaining uncertainties would be in the $(n-1)$ values at the two laser wavelengths and the air density determination $N = P/k_B T$. Note further that the solution for $\lambda_0 = \sqrt{1/x}$ does not depend on $2\pi/Nr_e$, but only on the laser wavelengths and the values of n_1 and n_2 .

4. Should $(n-1)$ of a dilute gas be additive, that is, should $(n-1)$ for air be given by a weighted sum of the values of $(n-1)$ for N_2 and O_2 (neglecting the trace gasses in air)?

PROCEDURE

Initial Setup

Don't touch or blow on any of the optical surfaces!

Activate both lasers by turning the keys on their power supplies. It may take a few minutes for the green laser to turn on; the red laser should turn on after a few seconds. If one of the lasers is not emitting light even after several minutes, ask your TA for assistance. Check for spots of stray laser light on the walls of the room.

Don't let a laser beam hit you in the eyes!

Make sure you record the temperature and pressure of the air in the room so that you may accurately calculate the number density of the molecules in the gas cell when filled. Use calipers to accurately measure the length of the metal gas cell (don't include the thicknesses of the end windows – measure just the metal bit: see Figure 3 on page 7).

Review Figure 4 and Figure 5. The gas cell fill tube should be open to the ambient room air; if necessary, disconnect it from any compressed gas bottle. Ensure that the gas cell vacuum valve is fully closed (clockwise) and that the gas cell fill valve is open (counterclockwise), and then plug in the power to the vacuum pump. You should leave the vacuum pump on for the remainder of the experiment.

**Don't let any part of your body or your clothing get near the vacuum pump!
The drive belt and pulleys can easily remove your fingers or other body parts that you probably want to keep!**

If something falls on the floor near the pump, unplug the power to the pump before reaching down to retrieve it.

Don't completely close the door to the lab room! Let fresh air enter the room so that you have oxygen to breathe, not just the fumes from the vacuum pump and the CO₂ gas you will exhaust into the room.

Ensure that the fringe counting electronics is activated and operating properly. Your TA can help you get everything turned on. If necessary, adjust the kinematic mounts of the signal path and

reference path mirrors until the interference fringes are clearly visible and are conveniently spaced and aligned with the reference lines on the projection screen (Figure 8).

Conduct a few trial runs by evacuating and filling the gas cell while checking that the electronics system is properly counting fringes. Familiarize yourself with:

1. the operation of the valves (Figure 4),
2. the initial placement and orientation of the fringes around the photodetector using the interferometer mirror adjustments (Figure 8),
3. the operation of the counter and the correct setting of the counter trigger threshold (Figure 6 and Figure 7),
4. the red laser flip mirror to change between laser colors (Figure 3).

Data Collection

A data point consists of a count of the number of fringes through which the interference pattern shifts as you slowly fill or evacuate the gas cell. You repeatedly fill and evacuate the cell with one gas (use air at first, save helium for last) recording fringe counts. You repeat this process for both the red and green lasers and for each of the gasses available. It is important that you accurately interpolate each fringe count value (Figure 8); the fringe count is not an integer! Get sufficient data for each gas and each color to get a good measurement (with uncertainty) of the mean fringe count.

When using gas from a cylinder, slowly fill the balloon to the proper volume using the reservoir fill valve attached to the gas cylinder pressure regulator. With this valve closed, slightly opening the gas cell fill valve will slowly transfer the gas into the cell. At equilibrium, there should still be some gas in the balloon, but its material should be limp and have clearly visible folds, so that you know that the pressure in the cell is exactly the same as the ambient room air pressure.

Whenever you change gasses, completely purge the previous gas from the system by flushing the gas cell several times with the new gas. You will know that the old gas has been completely removed when your fringe counts converge to some small range of values.

When you are finished collecting data: unplug the vacuum pump, fill the gas cell with air, close the gate valves on top of the two gas bottles, and turn off the lasers. Check the temperature of the room again.

DATA ANALYSIS

The two Helium-Neon laser *vacuum* wavelengths are 543.52 nm (green) and 632.99 nm (red), and they correspond to transitions in Neon out of a state 20.66 eV above its ground state to a state 18.38 eV or 18.70 eV above the ground state (respectively). Neon atoms are excited to the 20.66 eV state by collisions with excited Helium atoms; the He atoms are excited by an electric discharge through the gas.

From your measured fringe count data determine the index of refraction at both laser wavelengths for each of the gasses you tested (see prelab problem 1). Use the ideal gas law,

$$P = Nk_B T \rightarrow N \propto P/T$$

(where N is the number density of particles in the gas) to calculate the indices of refraction (with uncertainties) at 0° C and 760 Torr. Present your results as a table of values for $n - 1$.

Use your results and your consideration of prelab problem 3 to calculate the average number of oscillation electrons n_e and the wavelength corresponding to the oscillator resonant frequency λ_0 for each of the gasses you tested. Your helium data may not be precise enough to see an index of refraction difference between the two laser wavelengths, but you should be able to see an effect for both air and CO₂. Does n_e seem to be related to the total number of electrons in the molecule? Does the energy $E_0 = hc/\lambda_0$ seem to be related to the ionization energy of the molecule (N₂: 15.6 eV; O₂: 12.1 eV; CO₂: 13.8 eV; He: 24.6 eV)?