

The Michelson Interferometer and a Study of Optical Interference Effects

PHYSICS 143 Modern Physics

1 General Description of the Experiment

Visible light is often referred to as the 4000 to 7000 Å region of the electromagnetic spectrum. This means that you would have to be able to measure one one-thousandth of a millimeter to get even a crude idea of the size of a crest of a wave. This is not easy. How do we measure the behavior and properties of such little bitty stuff?

Likewise, how do we measure the interaction of light with matter? This may not seem important to most people, but if you use a telephone (fiber-optic cables), a computer, or a window, you need to know things like index of refraction. It is surprisingly easy to measure such things- if you are clever.

A humble device to measure and work with such principles is the Michelson interferometer. Its original use, to prove or disprove the existence of ether, is not its only application. We will be using it to observe the interference property of light waves (that two superimposed beams of coherent light produce an interference pattern) and in turn using this property to measure wavelengths and indices of refraction.

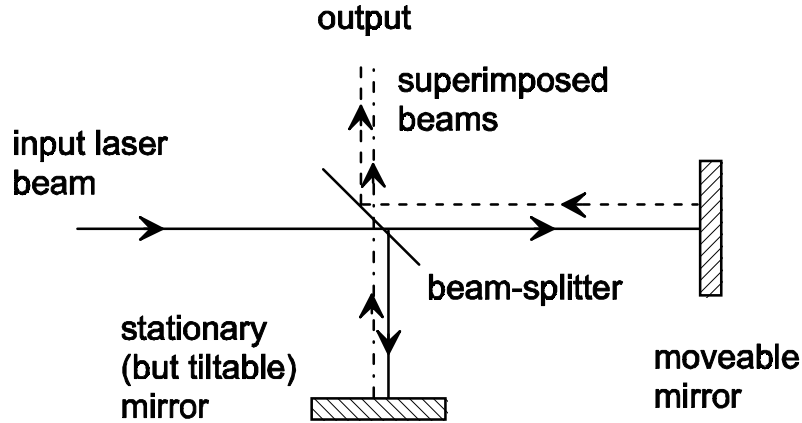
2 The Michelson Interferometer

CAUTION: DO NOT LOOK INTO THE LASER BEAM OR ITS REFLECTION DO NOT TOUCH THE FRONT SILVERED MIRRORS

2.1 Principle of Operation

The interferometer divides an incident beam of light into two parts via a partially reflecting mirror called a beam-splitter. The two resulting beams are coherent and travel two separate, but nearly equal, paths. Both beams are reflected by mirrors in such a manner that they recombine (see Figure 1). If the mirrors are perfectly parallel, the interference pattern, when viewed on a screen, will be a set of straight lines called fringes. One of the mirrors can be moved in very small increments using a micrometer driven device attached to the mirror's stage. Convince yourself that a movement of $\lambda/2$ will cause one complete cycle of the interference fringes.

To get a really good pattern of interference fringes (it will look like a red and black straight lines if you aim it at a white piece of paper or other screen), you have to tweak the mirrors and laser with some patience and skill. To make small adjustments to large objects, lightly brush the object rather than grabbing.



Note: beams have been displaced for clarity

Figure 1: Tracing rays in the interferometer.

2.1.1 Alignment Procedure

(Refer to Figure 2)

1. Swing the beam-splitter out of the way of the laser beam. Adjust the laser's position until the beam reflected from the moveable mirror re-enters the laser. That is, the mirror reflects the light perfectly back into the barrel of the laser. You will have to figure out how to adjust the level of the laser with respect to the interferometer, and how to make the laser and interferometer level with the table. (For this and all other steps, it's a good idea to have the laser dot in the center of the mirror rather than near an edge.) Put some kind of screen behind the moveable mirror, and you should see several red dots surrounding a brighter red dot. (The moveable mirror is actually a 90% silvered mirror- that is, 10% of the intensity which hits it will penetrate.) Turn these several dots into one dot by adjusting the three screws which are the feet of the interferometer. Now the moveable mirror is exactly perpendicular to the laser beam. (Make sure the beam still exactly re-enters the laser, and there you are still hitting the center of the moveable mirror.)

2. Swing the beam-splitter into the laser's beam so that part of the beam is reflected onto the stationary mirror. Put a screen at the 'output' of the interferometer. (Think of the laser as the 'input' and the moveable mirror and the stationary mirror as the two 'arms.' The laser beam will leave the interferometer through the remaining side.) There should be two sets of bright dots on the screen. Adjust the beam-splitter slightly until the two sets of dots are as close together as possible. Fasten down the beam-splitter with its little screw. Finally, use the two adjusting knobs on the back of the stationary mirror to make the two sets of dots coincide.

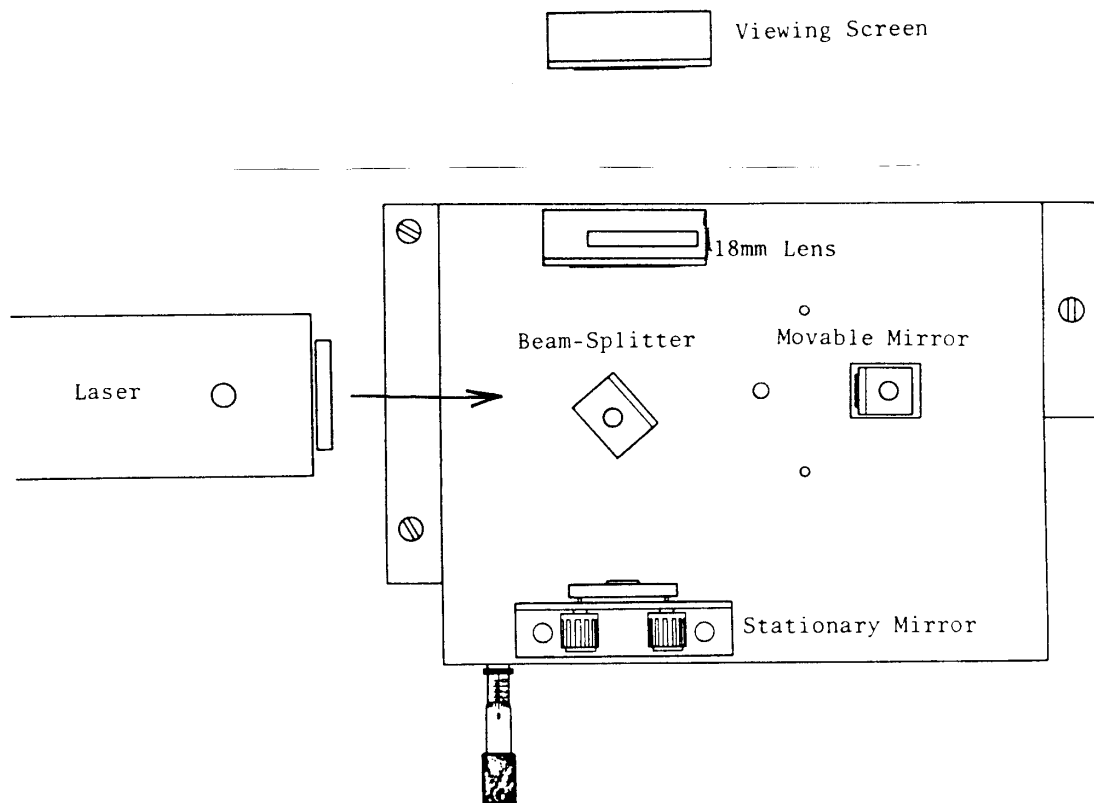


Figure 2: Interferometer setup.

3. Diverge the exiting laser beam by placing the 18mm focal length lens in the path of the output of the interferometer (about 20 cm before the screen). You should now see interference fringes on the screen. Carefully fine tune the tilt and position of the stationary mirror until the interference pattern becomes straight. See how you can change the spatial frequency of the fringes in either the horizontal or vertical direction by fine tilting the stationary mirror. Try to 'fluff out' the fringes (try to make them go away so the pattern on the screen is spatially uniform). You can also use the two knobs on the stationary mirror for this. This can be tedious, but it is important. Make sure no part of the laser beam is going around any mirror or lens instead of through it- if you centered the beam on each optical element in turn, this shouldn't be a problem.

4. Confused? Ask for help! This is tricky. For some people it's intuitive; for some, it makes no sense at all.

3 Measurement of the Wavelength of the Laser's Light

Learn to use and read a micrometer by practicing with one. They look like a 'C' clamp with a ruler printed on the handle. Be careful, these things are kind of expensive. Measure a few objects roughly with a ruler and then see if you can duplicate the measurement with a micrometer. Some micrometers are in centimeters, some are in inches. A thousandth of an inch is called a 'mil.' This is good to know when talking to machinists, designers, or other physicists. You have to figure out the units on each of the micrometers used in this lab.

In the interferometer you will be using, the handle of a micrometer drives a fine gear apparatus. The gear-ratio is about 27:1. Supposedly, a motion of one division of the micrometer handle corresponds to $1\ \mu\text{m}$ of mirror motion. Do you agree with this? **Sometime during the experiment (easiest if you do it either at the beginning or end of the lab), carefully tilt the interferometer on its side, remove the bottom panel using a screwdriver, and measure the gear ratio.** You will want to move the handle in one direction only during the course of any one experimental 'run' because, if you go backwards, 'backlash' can occur- a small space between the gear teeth can cause the handle to turn for a while before the mirror actually moves. There are ways around this- figure them out if you want, or just be careful to only go one direction.

As you move the handle, thus moving the moveable mirror, you change the length of one of the 'arms.' The other arm does not change its length. Thus the beam of light which was split between the two arms by the beam splitter (also referred to as a 'half-silvered mirror') is recombined and sent to the 'output' in a slightly different combination of phases. (Huh? What? This is the entire key to the experiment- see an Introductory Physics textbook, Section 1-4 and Chapter 2 in Bernstein, or ask for help if you still have trouble visualizing this.) Thus the interference pattern will change its appearance. Try to figure out the relationship between phase changes and the amount the mirror moves - this is how you will measure the wavelength of light. Figure out how to get a measurement of the wavelength of light to a one or two percent precision. Compare this to the known value of $6328\ \text{\AA}$.

4 Measuring the Index of Refraction of Air

In the previous section, we literally varied the path length of one arm of the interferometer. In these next parts, we will effectively vary the path length of one arm by introducing obstacles into the path of the light - slowing it down by making it travel through glass or whatnot. We will then determine - very accurately and easily - the index of refraction of air. One method for finding the index of refraction of various kinds of glass or crystal will also be shown.

Examine the gas cell and learn how to pump it down to a vacuum. One of the needle valves introduces a slow leak of air back into the cell and gradually brings it up to atmospheric pressure. (A rule of thumb for valves of all kind is that when the handle points along the flow, the valve is open. If the handle is perpendicular to the flow, the valve is closed.) For some reason, the gauge reads backwards. A mechanical pump can generally get air pressure down to 1% or so of atmospheric pressure; for higher vacuums, more technology is needed. Does this matter here?

Carefully mount the air cell on the interferometer in between the moveable mirror and the

beam splitter. Realign the interferometer to obtain a fringe pattern. Pump the cell down, and then crack the air back in slowly. The number of wavelengths of light spanning the cell depends on the index of refraction of the gas. Therefore the optical interference pattern will change as the pressure of the gas is changed. By counting the number of interference fringes shifted, you can measure the index of refraction of air at atmospheric pressure. Tricky...

You should think of what fringe pattern you should use to reduce errors.

Derive the following equation in an appendix to your report

$$n_{air} = \frac{1}{1 - (M\lambda_{air}/2\ell)} \approx 1 + (M\lambda_{air}/2\ell),$$

where ℓ is the length of the gas cell (see label on top of the cell), and M is the number of shifted fringes as you go from vacuum back to atmospheric pressure.

Measure the index of refraction of air and assign an error to your measurement. Compare your result to the known value of 1.000273 (15 °C, atmospheric pressure).

5 Measuring the Index of Refraction of Glass

The optical path length of one of the light paths will change if a glass plate is inserted into it. As the plate is rotated, the length of glass in the path will increase and therefore the number of wavelengths in that path will increase. This will, of course, change the interference pattern. The index of refraction of the glass plate can be calculated from the number of interference fringes shifted during the rotation of the glass plate through some angle θ . (See Figure 3). The angle scale is slightly offset, and the zero does not indicate the angle at which the light strikes the plate perpendicularly. Rotate the plate until it is exactly perpendicular to the laser beam (how will you know it's perpendicular? mess around and figure out a way) and note the scale correction that must be applied to measure θ .

The following equation can be used to calculate the index of refraction of the plate (see Monk, Light, Principles and Experiments, McGraw-Hill [Physics Library: 535, M747L]:

$$n = \frac{(2t - M\lambda_{air})(1 - \cos \theta)}{2t(1 - \cos \theta) - M\lambda_{air}},$$

where M is the number of shifted fringes, θ is the angle of rotation, and t is the thickness of the glass plate. *Measure the index of refraction of a few of the glass and plastic plates provided.* The index of refraction of some common materials are listed below.

Material	n (at $\lambda \approx 6200\text{\AA}$)
dense flint glass	1.66
light flint glass	1.58
crown glass	1.52
Lucite	1.5
polystyrene	1.6

Discuss the systematic and statistical errors that effect your determination of the refractive index of the materials and attempt to identify the materials.

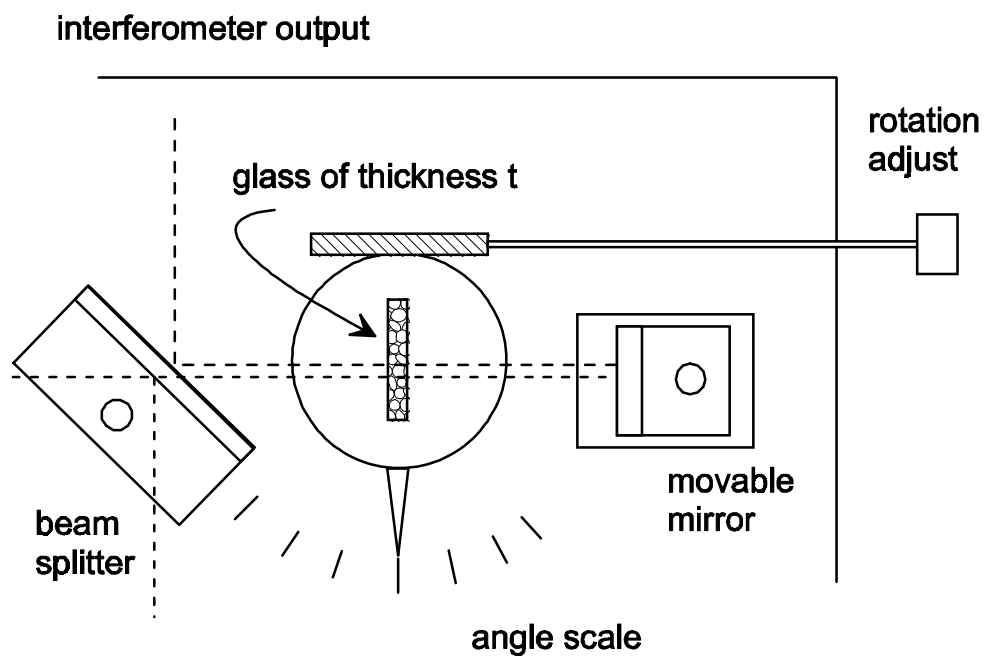


Figure 3: Measurement of the index of refraction of transparent materials.