

Experiment 4 — Michelson Interferometer

References: *Optics* by E. Hecht, Section 9.4.2
Fundamentals of Optics by F. Jenkins & H. White,
 Chapter 13, Sections 8 through 15, and Chapter 14, Section 13
An Introduction to Interferometry by S. Tolansky, Chapter 8
Light by R. W. Ditchburn, Section 5.21
The Feynman Lectures on Physics by R. P. Feynman, R. B. Leighton,
 and M. Sands, Volume I, Sections 30.7, 31.1, 31.2, 31.3.

Introduction

In this experiment a Michelson interferometer will be used to observe white light interference fringes (Part I), measure the wavelength of the output beam of a helium-neon laser (Part II), and measure the index of refraction of air (Part III). The Michelson interferometer that will be used is sketched in Fig. 4-1, and a photograph appears in Fig. 4-2. The compensator plate is necessary to observe white light fringes, but it is not an essential component of the interferometer for the measurements in Parts II and III of this experiment.

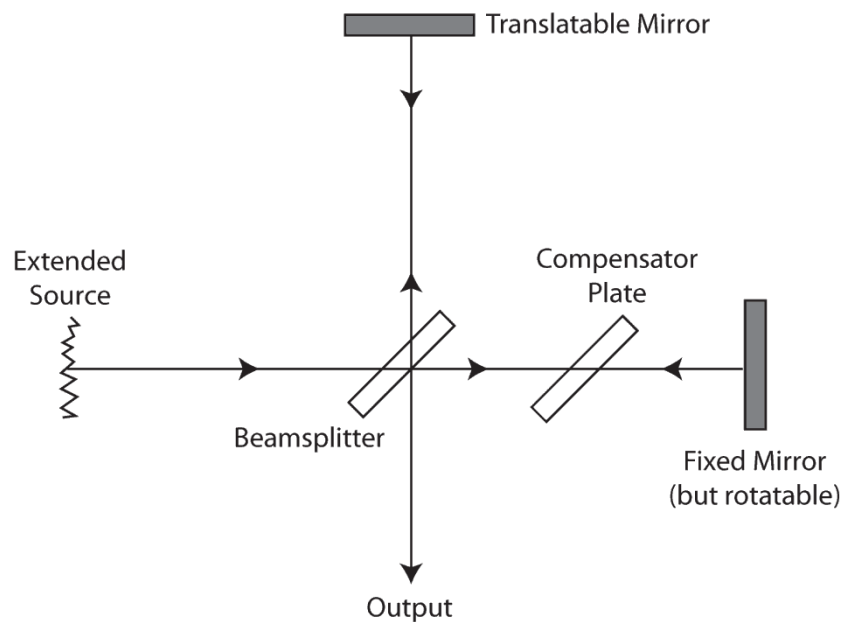


Fig. 4-1. The Michelson interferometer.

Part I - Visual Observation of White Light Fringes

In the first part of this experiment, you will adjust a Michelson interferometer so that white light fringes are seen at the output. The spectral width of light incident upon the interferometer is increased from a narrow spectral line to a broad “white” spectrum in two convenient steps with the help of optical interference filters. These stepwise increases in

the width of the incident spectrum result in a decreasing range of movement of the translatable mirror over which interference fringes can be observed. In other words, the broader the incident spectrum, the narrower the “coherence function.” In effect, the equal path setting of the interferometer is located with increasing precision in two “bite-sized” steps. Without the use of the optical filters, an inexperienced person might require an hour or two to produce white light fringes, but with the aid of the filters, the white light fringes can be located in perhaps fifteen minutes. Part I of the experiment may take an entire laboratory session.

In addition to the interferometer, the laboratory station is supplied with a mercury arc lamp, an optical filter that has a 10 nm bandwidth centered at 546 nm that is used to isolate the green line of the mercury lamp, another optical filter with a 25 nm bandwidth centered at 550 nm, and a white light source.

Caution: The mercury arc lamp is a strong source of ultraviolet light (UV) and must be covered *at all times* by either an optical filter or a glass diffusing screen. Damage to the eyes may result if the bulb is viewed directly!

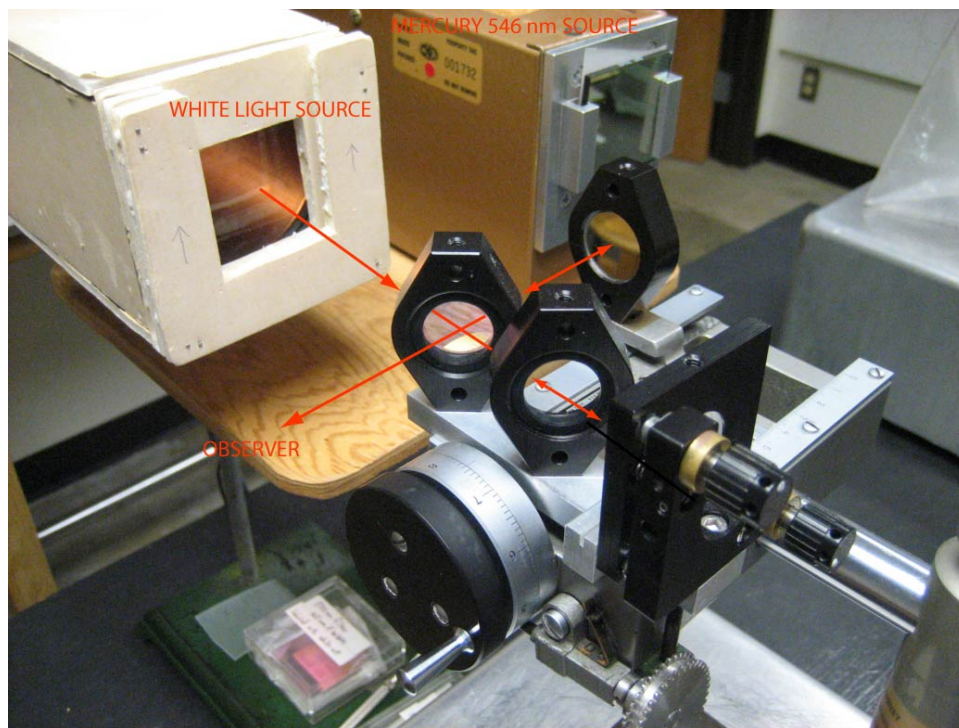


Fig. 4-2 Photograph of the Michelson interferometer. The observer is out of view to the lower left and sites along the emerging beam.

The following six steps comprise a suggested procedure for bringing the interferometer into adjustment for observation of white light fringes. You should not feel obliged to follow this suggested procedure, but rather you should understand the motivation behind

each step and, if desired, you may shortcut the procedure or improvise another. As Mr. Michelson himself once said, “The key to success with the hands is to employ the head.”

1. Your micrometer has a main, coarse translation screw and also a fine motion screw which can be engaged and disengaged by tilting the translation screw assembly. Make certain the fine motion is disengaged and translate the carriage until the distances of each mirror from the beamsplitter are equal. A simple measurement with a ruler is sufficient for this.
2. Place a pointed object at the input of the interferometer. If the instrument is not in good adjustment, you will see two images of the object when looking into the output of the interferometer. Rotate the fixed mirror until the two images coincide.
3. Place the mercury lamp (with 10 nm bandwidth green interference filter mounted on the front) in position to illuminate the field of view. Fringes should be visible when you look into the output of the interferometer. If they are not, repeat the adjustment described in (2). When fringes are seen, rotate the fixed mirror to produce circular fringes in the field. The manipulations required to accomplish this are much better learned by practice than by a long description. However, practice by itself without understanding will be tedious at best, and impossible at worst. Be sure you understand the origin of the interference fringes. See the references listed above.
4. Engage the fine translation screw and turn it (or use the coarse screw and turn slowly) in the direction that will make the fringes disappear into the center of the field. You should understand from your reading that this is the direction toward the equal path length position. Continue until only a few fringes are in the field. It may be necessary to rotate the fixed mirror slightly to keep the circular fringes centered as this operation is carried out.
5. When there are only a few circular fringes in the field, rotate the fixed mirror about a vertical axis so that the center of curvature of the fringes moves off to one side out of the field of view. Rotate until there are from 5 to 10 vertical, slightly curved fringes in the field of view. Continue translating the carriage in the same direction as before until the fringes appear to be straight. For a complete treatment of these “fringes of equal thickness” you’ll need to see Section 5.21 of Ditchburn as well as Section 13.10 of Jenkins & White.
6. Replace the mercury source with the white light source and transfer the 10 nm bandwidth green interference filter to the white light source. Be careful; don’t drop the filter and please handle the filter by its *edges*. Continue translating the carriage in the same direction. If all the steps have been followed correctly, interference fringes should soon appear. Record the range of positions of the translatable mirror over which these fringes are visible (which should be a distance of roughly 20 μm). The range of visible fringes is called the “width of the coherence function.” Never attempt a single measurement that involves translating the carriage back and forth with reversals of direction, as the gears have significant mechanical backlash and in fact may take time to “engage” fully when the direction is reversed.

7. Repeat (6) with the 25 nm bandwidth filter, and notice that fringes are visible over a narrower range—record this range. Finally remove the interference filter and observe white light fringes near the center of this range. Estimate and record the range over which these white light fringes occur. You should see that the broader the incident spectrum, the narrower the coherence function, with a simple inverse relationship.

Looking directly into the interferometer, play with these white light fringes and record your observations in your notebook. The condition for white light fringes is, of course, the condition for equal path lengths. Since no source is completely monochromatic, fringes produced by any source will be strongest near this position. This would, in principle, apply even to a laser, but the helium-neon laser you will use in the second and third weeks of this experiment has a coherence length of about 10 cm, so in practice path differences large enough to wash out the laser fringes are not encountered often. Circular fringes are best for the measurement of wavelength and wavelength difference. When using circular fringes, it is necessary to begin measurement at a point slightly removed from the position of equal path lengths. The fringes are otherwise too broad to be clearly seen. Note the scale reading and direction of approach for the white light fringes before proceeding.

Notice in Fig. 4-1 that, without the compensator plate, the path to and from the translatable mirror would include two traverses through glass (the beamsplitter) which would not be included in the path to and from the fixed mirror. Since the optical path length equals the geometrical path length times the refractive index, and since the refractive index varies with wavelength, it follows that without the compensator plate the position of equal path lengths would not be the same for all wavelengths. If the compensator plate thickness equals the beamsplitter plate thickness, there will be equal optical thicknesses of glass in the two legs for all wavelengths, and white light fringes can be observed. If the thicknesses of the two plates are not equal, the white light fringes are degraded. Calculate the difference in the thicknesses of the two plates if the position of equal lengths for red light (say 650 nm) corresponds to a half-wave difference for blue light (say 450 nm). (The famous Handbook of Optics lists the refractive index of BK7 optical glass as 1.5253 at 450 nm and 1.5145 at 650 nm.) You should now have some appreciation for the importance of the compensator plate.

Measuring the group refractive index and dispersion of glass or water: You may have time at the end of the first lab meeting, or perhaps during the second, to use the Michelson interferometer to measure the group refractive index of either a glass microscope slide or of water placed in a small cuvette. The group refractive index is the ratio of the free-space velocity of light c to the group velocity in the medium (glass or water in our case). It is related to the ordinary or phase refractive index by

$$n_g = n_p - \lambda \frac{dn_p}{d\lambda} \quad (1)$$

where n_g is the group refractive index, n_p is the phase refractive index, and $dn_p/d\lambda$ is called the dispersion of the medium. The method for measuring n_g is a natural extension of our

method for finding the position of the white light fringes, and is described below. If the phase index n_p is known for the material, then a measurement of n_g also provides a value for the dispersion $dn_p/d\lambda$ through the relation expressed in Eqn. (1). For glass and water, the group and phase refractive indexes differ by about 2% for visible wavelengths.

To measure the group refractive index, first find the position of the white light fringes. Next place a microscope slide in the path of the fixed but rotatable mirror using one of the two aluminum holders provided. The slide will cover just the bottom half of the field of view. It will be very difficult, if not impossible, to find white light fringes now because the dispersion of the slide will broaden the coherence function and reduce the visibility of the fringes. (See the paragraph above concerning the importance of the “compensator plate.”) However, if you cover the white light source with an interference filter, e.g., the 546 nm filter with a 10 nm bandwidth, you will be able to find green fringes by moving the translatable mirror, though the contrast or visibility of the fringes will be reduced from that which you observed without the slide in place. The visibility is reduced because the dispersion of the slide, even over the narrow 10 nm bandwidth, will broaden the coherence function and reduce its amplitude, i.e., the visibility of the fringes. If d is the distance that the translatable mirror must be moved in order to observe green fringes, then the group refractive index of the slide for 546 nm is given by

$$2d = 2(n_g - 1)t \quad \text{or} \quad n_g = 1 + \frac{d}{t} \quad (2)$$

where t is the thickness of the microscope slide and can be measured with the micrometer available in the lab. It makes a certain amount of intuitive sense that a measurement of the displacement of fringes due to a group or band of wavelengths is related to the group refractive index, not the ordinary phase index, and this result can be derived rigorously. The wavelength at which you measure n_g can be varied by using the assortment of interference filters available in the lab (435 nm, 546 nm, and 656 nm).

If you don't have time to perform measurements of the group refractive index during the allotted three laboratory sessions, you may want to pursue this path of investigation as a tech report. Adam Pivonka (HMC '05) was the first to perform these measurements, and his tech report from the spring of 2004 is available in the lab. Please note that Adam was not fully aware of the difference between the group and phase refractive indexes, but his tech report has a very nice description of the measurements.

Part II - Measurement of the Wavelength of a He-Ne Laser

The second laboratory session will be spent measuring the wavelength of a helium-neon laser by translating the mirror and recording the movement of fringes at the output of the Michelson interferometer. The mirror may be translated with the motor drive provided. The interferometer should be adjusted to produce circular fringes at the output, and a photodiode should be placed at the center of the fringe pattern (counting fringes by eye can be *very* tedious). The photodiode should be placed sufficiently far from the interferometer so that the central fringe (spot) covers the photodiode. Note that for a given distance from the interferometer to the photodiode, the central spot will increase in diameter as the

translatable mirror approaches the equal path length position. The oscillations of the output of the photodiode amplifier can be counted with the frequency counter and/or the LabView software provided. Instructions for data acquisition in Labview are provided next to the computer in the Michelson interferometry lab.

Use your ingenuity to devise a procedure to measure the wavelength of the laser with a precision of better than 1%. Do not *guesstimate* uncertainties; use a *sample variance technique* to determine them rigorously!

Part III - Measurement of the Index of Refraction of Air

When you have completed Part II, notify your instructor so that the vacuum chamber may be positioned in one leg of the Michelson interferometer. (It's better to let your instructor shatter the glass windows of the chamber and knock the interferometer onto the floor.) The refractive index difference between air and vacuum will be measured by varying the pressure (density) of air in a chamber of constant length while recording the movement of fringes with the photodiode and computer data acquisition system.

A mechanical vacuum pump is used to evacuate the chamber which comprises 2.0165 ± 0.0005 inches of one leg of the interferometer. A mercury manometer is used to measure the air pressure in the chamber. When the chamber has been evacuated, the valve connecting the vacuum pump and the chamber may be closed and the pump turned off. This will eliminate vibrations transmitted from the pump through the vacuum hose to the chamber. These vibrations can lead to jitter in the photodiode record, because there is some light reflected from the chamber windows. If the needle valve connecting the chamber with room pressure is opened slightly (be gentle, it's a delicate needle valve), the chamber pressure will rise slowly and the fringes will move. The incoming air molecules scatter light, and hence they increase the refractive index and increase the optical path length of that leg of the interferometer. See the reference by Feynman for a beautiful discussion of the origin of the index of refraction.

The following technique is suggested for recording and analyzing the pressure change and fringe movement. Each time the chamber pressure increases by, for example, 10 cm of Hg, a mark should be made at the corresponding point on the fringe signal recorded by the computer data acquisition system. (This mark can be made by a brief interruption of the laser beam.)

The particular method you devise for data acquisition and analysis should utilize a sample variance technique to determine the uncertainty in your measured value of $n - 1$. Discuss your proposed method with your instructor *before* taking serious data.

Your technique for data analysis should yield a plot of the number of fringes recorded since the valve was opened versus the change in chamber pressure since the valve was opened. (The pressure change should range from, for example, 10 cm to 70 cm.) The plot should be linear. A least squares fit of the data to a straight line should yield a y intercept of zero (within uncertainty), and the slope of the fit can be used to deduce a value of $n - 1$ for air at atmospheric pressure. Compare your value for $n - 1$ with the value tabulated in, for example, the CRC Handbook. You will have to take into account the difference of the

laboratory temperature from the temperature at which the tabulated value was measured. A thermometer is provided with the laboratory equipment. Convert your measured value of $n - 1$ to a value at the temperature quoted in the literature (e.g., 15°C). (The ideal gas law is adequate for this purpose.)