Revision 10/22/2009

OPTICS 380A
Lab 9: Michelson Interferometer

This lab is an introduction to interference of light waves by division of amplitude. Division of amplitude refers to a beam that is divided at one or more partially-reflecting surfaces. At each surface, part of the light is reflected and part is transmitted, to produce two (or more) beams. Each of the wavefronts maintains the same original size (width) but has a reduced amplitude. After the beams are recombined an interference pattern of fringes is obtained. This lab demonstrates interference by division of amplitude using the Michelson interferometer.

A small bit of the history of Michelson is in order. The following quote is from Fundamentals of Optics, (Jenkins and White, 1976, p. 271):

> "A.A. Michelson (1852-1931). American physicist of genius. He early became interested in the velocity of light and began experiments while an instructor in physics and chemistry at the Naval Academy, from which he graduated in 1873. It is related that the superintendent of the Academy asked young Michelson why he wasted his time on such useless experiments. Years later Michelson was awarded the Nobel prize (1907) for his work on light. Much of his work on the speed of light was done during 10 years spent at the Case Institute of Technology. During the latter part of his life he was professor of physics at the University of Chicago, where many of his famous experiments of the interference of light were done."

To this day, the Michelson interferometer is one of the most fundamental and most useful optical instruments. It can be used for the determination of the wavelength of light, the width and fine structure of spectral lines, measuring lengths or displacements on the order of the wavelength of light, and the measurement of refractive indices. In this lab, we will learn how to properly align the Michelson interferometer: In the next lab, we will use it to measure the wavelengths of light, the spectral separation of the yellow sodium doublet line, and the refractive index of air.

THEORY OF THE MICHELSON INTERFEROMETER

The Michelson interferometer is shown pictorially in Figures 9.l and 9.2. Please refer to these figures for the following discussion of the instrument.

The interferometer consists of two mirrors—M1, which can move along the optical axis, and M2, which is stationary. Both have tip-tilt adjustments to adjust their angular positions. Each mirror is planar and highly reflective. Many interferometers use aluminized mirrors, but ours has dielectric coatings (multiple thin-film layers of different kinds of glass). These have been designed to be highly reflective at the He-Ne laser wavelength of 633 nm. You will note that they appear nearly transparent when looking directly through them. At the same time, they look like a highly reflective gold mirror when looking at them at glancing angles.

The source of light for a Michelson is a large-area, monochromatic source, such as a sodium (Na) lamp, a (filtered) mercury (Hg) lamp, or an expanded laser beam. In order to reduce the effects of non-uniform bulbs, the source is placed behind an opal glass diffuser (labeled D in Figure 9.1). This piece of glass, in turn, becomes the source for the interferometer.

In addition to the mirrors, the interferometer contains two other pieces of glass—a beamsplitter BS and a compensating plate CP. Both of these pieces of glass have highly polished, very flat surfaces. The compensating plate typically has no coatings, and is bare glass. The beamsplitter has a coating on one side of it, making it partially reflective and partially transmissive. This coating is sometimes a thin, partially transparent layer of aluminum, but in our instrument this is a dielectric layer, much like those on the mirrors. Additionally, the thickness of the compensating plate is made to exactly match the thickness of the beamsplitter.

Refer to Figure 9.1 to study the optical paths through the interferometer. An infinite number of rays of light leave the diffuse source at all angles (only an on-axis ray is shown in Figure 9.1). The ray first strikes the front of the beamsplitter, and is partially reflected. This partial reflection isn't shown in the figure, as only a small fraction (≈ 4%) of the light is reflected. The light is refracted into the beamsplitter, and is split into two beams by reflection at the rear surface of the beamsplitter. The optical design of the beamsplitter coating is such that 50% of the light is reflected and 50% transmitted. This gives two output beams of equal amplitude (and therefore highest fringe contrast, or visibility).

The reflected beam travels back through the beamsplitter, toward mirror M1, where it is reflected back through the beamsplitter. <u>Note that this beam has now passed through the beamsplitter three times</u>. At the beamsplitter's rear surface, just as before, 50% is reflected back towards the source (which is ignored) and 50% is transmitted through the coating into the output space of the interferometer. It is this transmitted beam that will interfere with the other beam to form fringes.

The beam originally transmitted by the beamsplitter's rear surface travels towards mirror M2, first passing through the compensating plate. Upon reflection from M2, it once again passes through the compensating plate and strikes the rear surface of the beamsplitter. Again, 50% of the energy is transmitted (ignored) and 50% is reflected. The reflected beam now overlaps the beam that passed through the other arm of the interferometer, to form fringes.

Note two things. First, <u>both beams have passed through the equivalent of 3 thicknesses of glass, thereby traveling the same optical path.</u> Second, <u>only 50% of the total source energy makes it through the interferometer to form fringes in the</u>

output space. The other half of the energy is sent back towards the source. Fringes are, in fact, formed by this energy, but are not available for viewing, as the source is in the way. This is wasted energy, in effect.

Refer to Figure 9.3 for the following discussion. In this figure, the mirrors are labeled M_1 and M_2' (note that M_1 is an actual mirror, and M_2' is the virtual image of M_2 as reflected in the beamsplitter). The source is labeled L, and the two virtual images of the source (as seen in reflection by the two mirrors) are labeled L_l and L_2. The mirrors are separated by a distance d, which typically has values of 0 to a few millimeters. One ray is shown, at a point P on the extended source (which is assumed to be monochromatic). When looking at the two images of the source, this point appears as two point sources, P' and P", separated by a distance 2d. Note that the actual optical path difference (OPD) between these two point sources is $2d\cdot\cos\theta$.

Interference occurs between light coming from each of these two point sources, contributing to one point of light seen in the output fringe pattern. For each source point P, there is a unique corresponding pair of virtual point sources that interfere with each other, contributing to the overall output pattern of interference fringes. If the OPD between these two point sources equals an integer number of wavelengths, constructive interference results (at that particular point in the output fringe pattern). If the OPD between these two point sources equals an integer number of half-wavelengths, destructive interference results (at that particular point in the output fringe pattern).

The equation describing the output pattern for bright fringes is therefore given by:

$$2d\cdot\cos\theta = m\lambda \qquad (5\text{-}1)$$

Taken as a whole, the entire extended source produces the complete output interference pattern (on a point-by-point basis). This occurs because at each source point P, the corresponding pair of virtual point sources is perfectly coherent (their wavefronts are exactly in phase with each other). This is true, even though different points P on the extended source may be very incoherent (emitting wavefronts that are randomly out of phase with each other).

Different types of fringes can be produced, depending on how the mirrors M_1 and M_2' are oriented. Circular fringes are produced when mirror M1 and M_2' are perfectly parallel, but displaced from each other (as shown in Figure 9.3). These circular fringes are the ones used in most kinds of measurements with the Michelson interferometer. These are called fringes of equal inclination. Equation 9-1 shows that, for a given wavelength and mirror separation, θ is constant for the locus of points that make up a single fringe. Constant θ implies a circular fringe.

Straight-line fringes are produced when mirror M_1 and M_2' are tilted with respect to each other and have a small (≈ zero) path difference between them. When this path difference is made to be exactly zero, white light fringes may be produced. In practice, this is a difficult condition to achieve. Extremely stable and high-quality components are required to achieve and maintain a zero OPD.

ALIGNMENT OF THE INTERFEROMETER

CAUTION: In the following alignment steps, it is important that you don't touch the surfaces of the mirrors or beamsplitter. This will ensure that we maintain the highest quality optical surfaces possible in the interferometer. Note also that the interferometer is a precision instrument, and is to be treated with care and caution.

Part A: CIRCULAR FRINGES

(1) Position the extended mercury source in front of the interferometer, in such a manner that the beamsplitter will divide the beam to the two mirrors. The source is eye-safe.

(2) Carefully measure the distances between the two mirrors and the reflective surface of the beamsplitter (WITHOUT TOUCHING THE SURFACES). Loosen the hold-down screw on mirror M1 and adjust it so the distance to the beamsplitter is about 3mm larger than in the other arm of the interferometer. Gently tighten the hold-down screw on mirror M1.

(3) Look into the interferometer at mirror M2. Hold a sharp pencil point in front of the source. Two images of the point should be seen, one coming from the first surface of the beamsplitter, and the other from the reflection at its back surface.

(4) Adjust the tip and tilt screws on mirror M2 until the two images coincide. At this point, interference fringes should appear, although they may be faint and close together. When they first appear, the fringes will not be clear unless your eye is focused on or near the back mirror M2.

(5) When fringes have been found, continue fine-adjusting the screws on M2 to continually increase the width of the fringes (to increase their spacing). With proper adjustment at this point, a set of circular fringes should appear centered in the field of view. At this point, M_2' is exactly parallel to M_1 but displaced axially.

(6) Place the telescope at the output of the interferometer. With the telescope focused at infinity, center the fringe pattern in the field of view.

(A) ***Each person should individually align the interferometer to produce circular fringes.*** Show the fringe pattern to your lab instructor for credit.

(B) What are these circular fringes called? Explain your answer.

(C) Rotate the micrometer from small to larger numbers. (This moves mirror M1). Describe the motion of the fringes. Is M1 moving towards or away from M2? Explain your answer.

(D) Rotate the micrometer from large to smaller numbers. Describe the motion of the fringes. Is M1 moving towards or away from M2? Explain your answer.

Part B: STRAIGHT-LINE FRINGES

(1) Carefully measure the distances between the two mirrors and the reflective surface of the beamsplitter (WITHOUT TOUCHING THE SURFACES). Loosen the hold-down screw on mirror M1 and adjust it so the distance to the beamsplitter is the same as distance to mirror M2. Gently tighten the hold-down screw on mirror M1.

(2) Place the compensator plate in the interferometer in the appropriate arm.

(3) Look into the interferometer at mirror M2. Hold a sharp pencil point in front of the source. Two images of the point should be seen.

(4) Adjust the tip and tilt screws on mirror M2 until the two images coincide. At this point, interference fringes should appear, although they may be faint and close together. When they first appear, the fringes will not be clear unless your eye is focused on or near the back mirror M2.

(5) When fringes have been found, continue fine-adjusting the screws on M2 until a series of straight-line fringes appear, centered in the field of view. At this point, M_2' is in the exact same axial location as M_1 but is tilted.

(E) What are these straight-line fringes called? Explain your answer.

(F) Rotate the micrometer from small to larger numbers. Describe the motion of the fringes.

(G) Rotate the micrometer from large to smaller numbers. Describe the motion of the fringes.

Part C: WHITE-LIGHT FRINGES (optional 10 points extra-credit)

(1) Replace the extended mercury source with a white light source, and a ground glass screen.

(2) Position a narrow spectral filter in front of the ground glass.

(3) Slowly adjust the micrometer until you see fringes (you may "pass through" about 50-100 fringes, and then they will disappear).

(4) Position the micrometer at the center of this fringe pattern, and remove the spectral filter. IF THE OPD =0 (really and truly equals exactly 0), you will see white light fringes!! If not, work harder to (really and truly) achieve an OPD of zero.

Show the white-light fringes to your lab instructor.

(H) Fully describe the pattern of white light fringes that you see. Include a drawing and a complete description of why the center fringes are black and white, why they quickly disappear into a rainbow of color and then just white light.

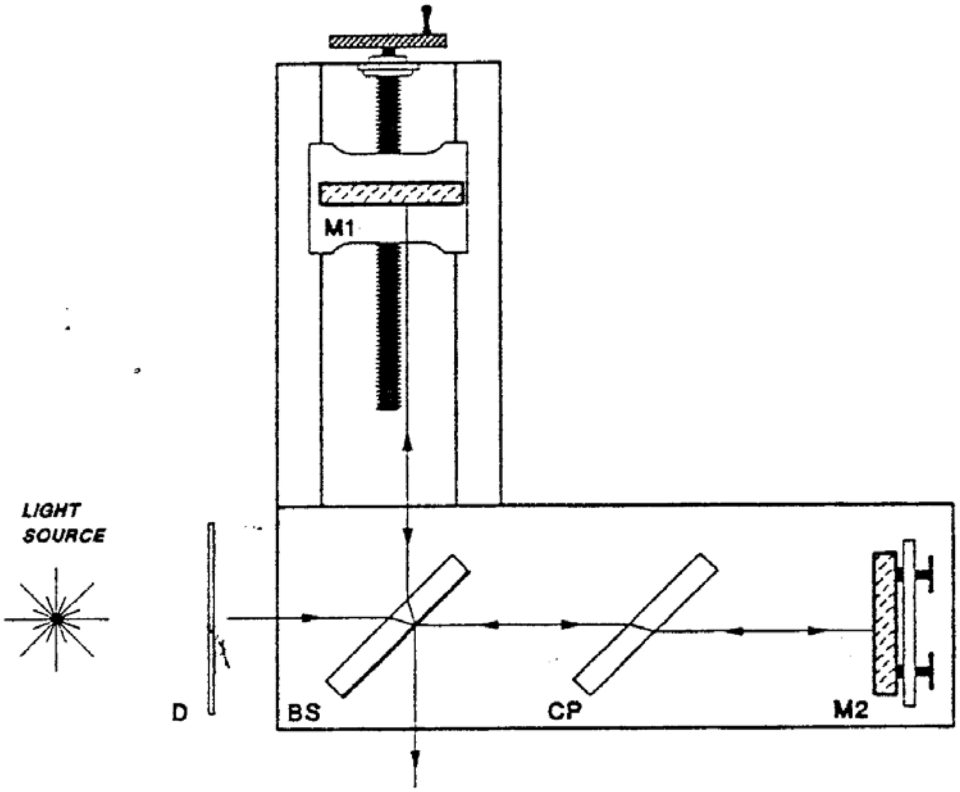

Figure 9.1. Diagram of a Michelson interferometer.

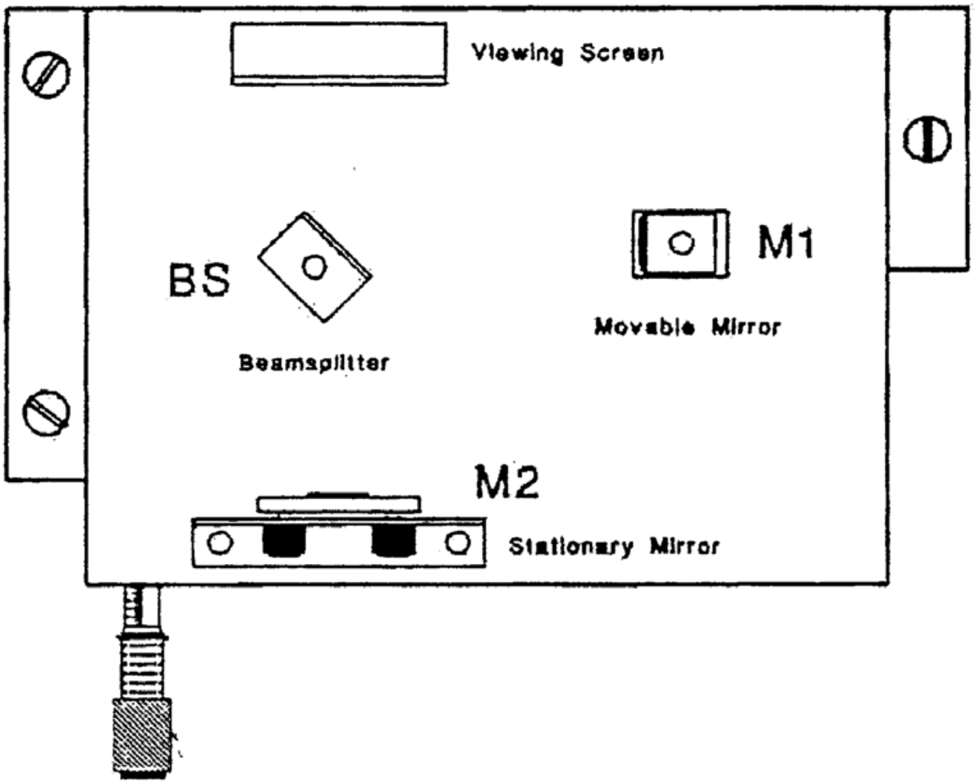

Figure 9.2. Optical layout of the Michelson interferometer used in lab.

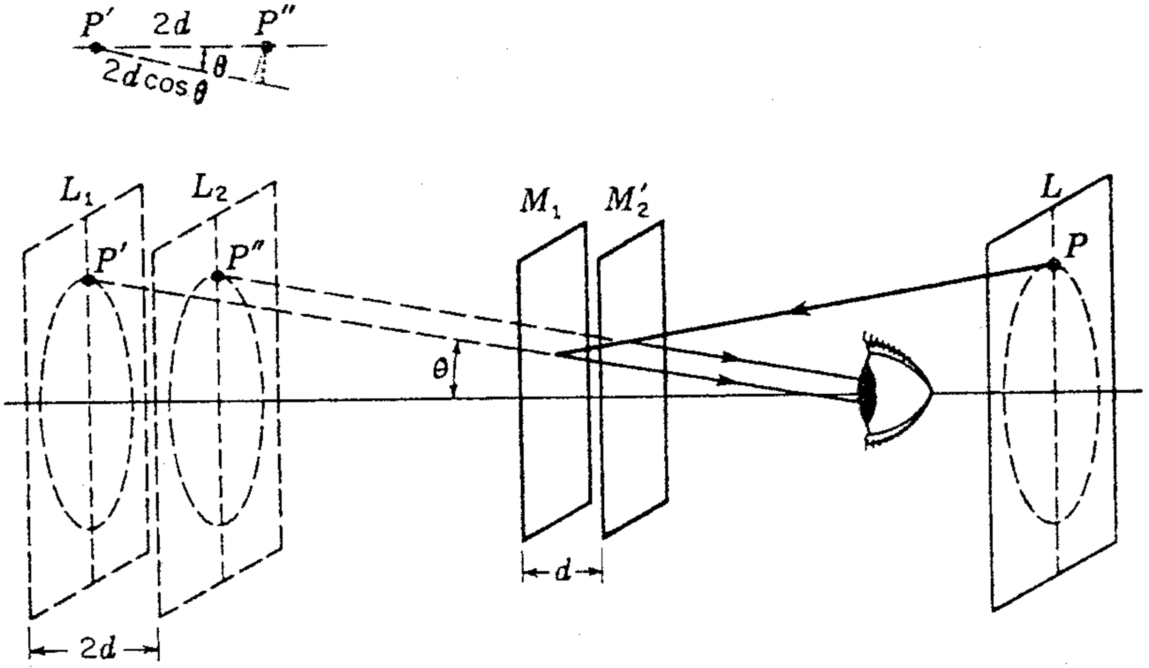

Figure 9.3. Formation of circular fringes in the Michelson interferometer.

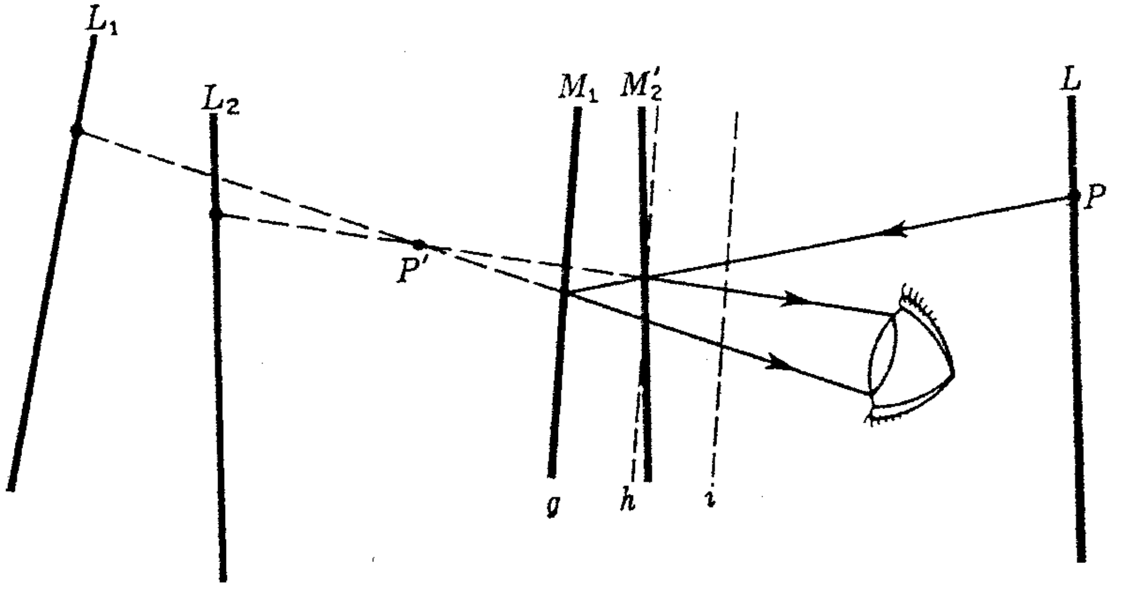

Figure 9.4. Formation of straight-line fringes in the Michelson interferometer.