Lab 22

Michelson Interferometer

A. Purpose

To obtain the wavelength of a laser source and to measure the indexes of refraction of glass and air by the Michelson Interferometer.

B. Introduction

The Michelson interferometer was invented by the American physicist Albert Abraham Michelson, who received the 1907 Nobel prize in physics for disproving the existence of the *aether* in 1887 by this interferometer.[1] The finding eventually opened a new door in physics and is regarded as the revolution in physics at the beginning of the twentieth century. In 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) applied two long-arm Michelson interferometers to make the first direct observation of gravitational waves, which validated the space-time distortion in the cosmic events predicted by Einstein's general relativity. This lab focuses on the Michelson Interferometer, trying to apply this common configuration for optical interferometry to obtain the wavelength of a laser source and further measure the index of refraction of glass and air.

Fig. 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 splits into two: one reflected toward mirror M_1, and the other 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 the beam-splitter reflects half the light from M_2 to the viewing screen.

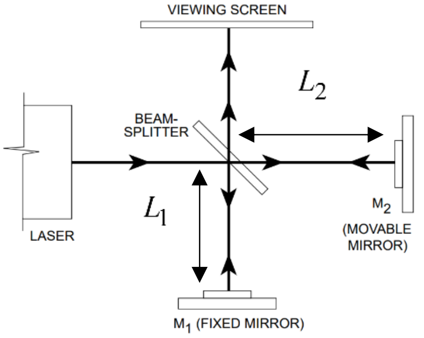

Fig. 1. Michelson Interferometer

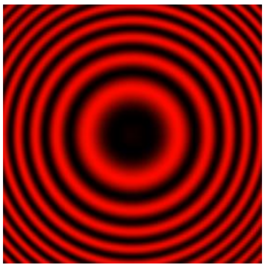

Fig. 2. Interference pattern

Therefore, 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. When a

---

[1] It's worth noting that the experiment of Michelson and Morley was set up to detect the speed of earth relative to the aether. They failed, but this failure earned Michelson a Nobel prize! This is the most famous "failed" experiment in history.

focusing lens is placed between the laser source and the beam-splitter, after the focus, the light ray spreads out, and an interference pattern of dark and bright rings is seen on the viewing screen, as shown in Fig. 2. 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 depends on the difference in the length of their optical paths in reaching that point. Since the beam traverses the path between M_2 and the beam-splitter twice, moving M_2 1/4 wavelength nearer the beam-splitter will reduce the optical path of that beam by 1/2 wavelength. The radii of the maxima of the interference pattern will be reduced to occupy the former minima position. If M_2 is moved an additional 1/4 wavelength closer to the beam-splitter, the radii of the maxima will again be reduced such that maxima and minima trade positions. However, this new arrangement will be indistinguishable from the original pattern.

By slowly moving M_2, the difference in distance $d\left(=L_2-L_1\right)$ changes, and the fringes will move. If a reference point is given, by counting Δm, the number of times the moving fringe pattern restored to its original state, the wavelength λ of the laser source can be determined by

$$\lambda = 2\frac{\Delta d}{\Delta m} \tag{1}$$

Moreover, if λ is known, the same procedure can be used to measure the minute displacement.

C. Apparatus[2]

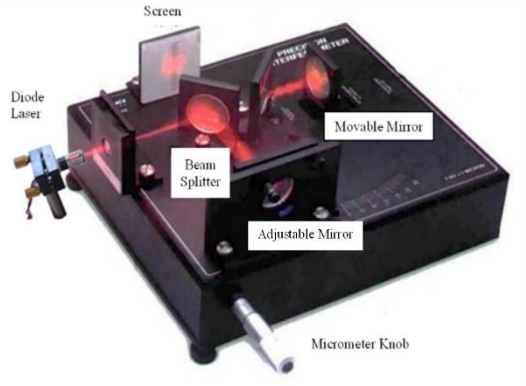

Fig. 3. Setup of Michelson Interferometer

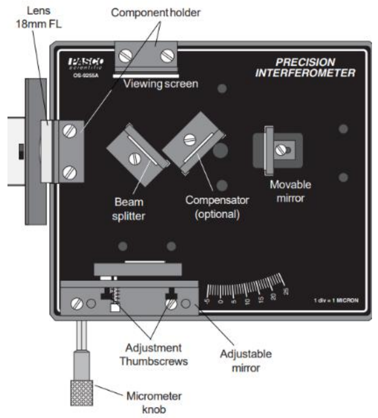

Fig. 4. Schematic of Michelson Interferometer

The wavelength of the diode laser is 657 nm. The movable mirror can be adjusted by using the micrometer knob. A movement of 10 μm on the micrometer knob is equal to a movement of 0.4 μm for the movable mirror.

---

[2] As discussed in Theory section that one beam passes through the glass of the beam-splitter only once, while the other beam passes through it three times. If a highly coherent and monochromatic light source is used, such as laser, this is no problem. However, with other light sources, this is a problem. The difference in the effective path length of the separated beams is increased, thereby decreasing the coherence of the beams at the viewing screen. This will obscure the interference pattern. A compensator is identical to the beam-splitter, but without the reflective coating. By inserting it in the beam path, as shown in Fig. 3 and Fig. 4, both beams pass through the same thickness of glass, eliminating this problem.

D. Procedures

1. Pre-lab assignments (hand in before the experiment)
   (0) See the following link for a brief introduction of this laboratory: https://youtu.be/KGcytB5CXok
   (1) Make a flowchart of this experiment and answer the questions.
   (2) Consider the minimal setup of the Michelson interferometer shown in Fig. 1. Suppose M_2' is a reflected image of mirror M_2 over the beam splitter. The interference fringes (Fig. 2) can be interpreted as the result of the two virtual images S_1' and S_2' behind the mirrors M_1 and M_2'.,

      (i) For the case that M_1 is parallel to M_2', and the two virtual images S_1' and S_2' are in line with the center of the viewing screen as shown in Fig. 5(a), the optical path from the virtual sources to the screen can be viewed as Fig. 5(b). Find the condition of constructive interferences in terms of the angle θ, the wavelength of the laser source λ, and the distance difference of the mirrors $d\left(=\left|L_2-L_1\right|\right)$ from the beam splitter. Assume that the phase differences due to the beam-splitter and the reflective mirrors are zero.

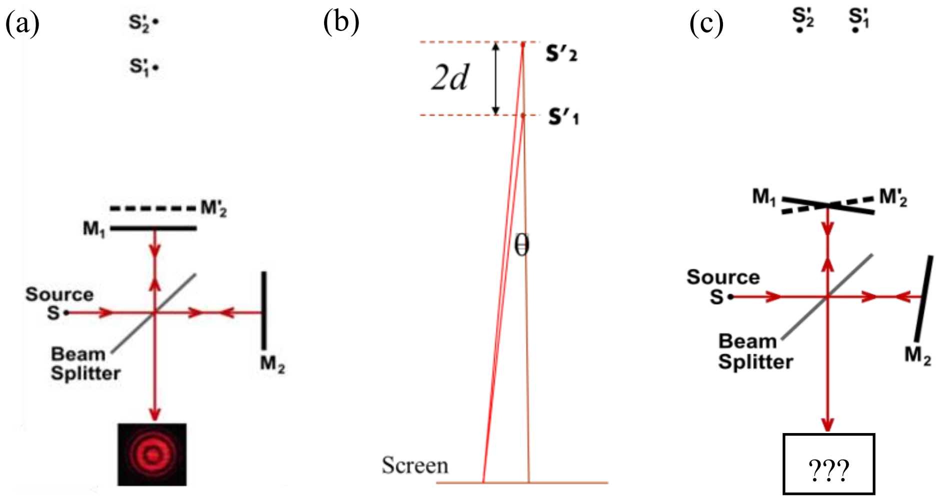

Fig. 5. (a) Schematic of the case that M_1 is parallel to M_2'. (b) Schematic of the optical paths for the virtual sources S_1' and S_2' (c) Schematic of the case that M_1 and M_2' are tilted with respect to each other.

      (ii) Following (i), in the lab, you will adjust M_2 by the micrometer knob, which means d is adjusted. Consider one bright circular fringe that is due to the constructive interference. From the formula you obtain in (i), what would happen to the fringe when you adjust the micrometer knob? (Hint: Moving inwards or outwards)

(iii) If M_1 and M_2' are tilted with respect to each other and also overlap as Fig. 5(c) shows instead of being parallel to each other as discussed above, what would the fringes become? (Hint: Double slit experiment)

It's worth noting that if M_1 and M_2' do not overlap, the interference fringes will generally take the shape of conic sections (hyperbola). However, in the lab, do not worry if your pattern shows irregularities or has fewer fringes. As long as fringes are clearly visible, measurements will be accurate. See Ref. 1 for more discussion on the interference fringes in a Michelson interferometer.

2. In-lab activities

(1) Set up of a Michelson interferometer

(i) To align the laser (Fig. 6)

(a) Screw the holders for the lens and screen.

(b) Place the laser on the bench and secure the movable mirror in the recessed hole in the base within the marks.

(c) Turn on the laser. Adjust the height (~5.5 cm) of the laser and screw the laser on the laser bench. Adjust the direction of the laser beam until it is parallel with the interferometer base.

(d) Adjust the laser until the beam is reflected from the movable mirror right back into the laser aperture.

Fig. 6. Alignment of the laser

(ii) To align the interferometer (Fig. 7)

(a) Attach the viewing screen to the magnetic backing of its holder.

(b) Position the beam-splitter at a 45 degree angle to the laser beam within the marks to reflect the beam toward the screen center.

(c) Position the adjustable mirror and adjust it so that the two bright dots on the screen overlap together. (Fig. 8)

(d) Attach the focusing lens to the magnetic backing of its holder. You should see the interference patterns, as Fig. 9 shows. The difference between the three patterns is the optical path length difference between the two beams arriving at the screen. Either pattern is fine for the following experiment.

(e) Turn the micrometer knob both clockwise and counterclockwise and observe the changes in the fringes.

Fig. 7. Alignment of the interferometer

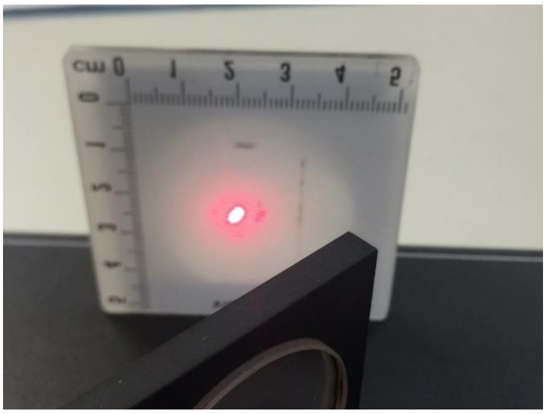

Fig. 8. Use the adjustable mirror to make the two bright dots overlap together

Fig. 9. Interference patterns of different optical path lengths

(2) Interference and Polarization (Fig. 10)

(i) Use a polarizer to determine the polarization axis of the laser beam.

(ii) Place one polarizer between the beam-splitter and the mirror M_1. Adjust its polarization axis to 45 degrees with respect to the polarization axis of the laser beam.

(iii) Place the other polarizer between the beam-splitter and the mirror M_2. Adjust the polarization axis of this polarizer to observe the interference patterns for the two cases: **(a)**Two parallel polarized beams. **(b)**Two orthogonal polarized beams.

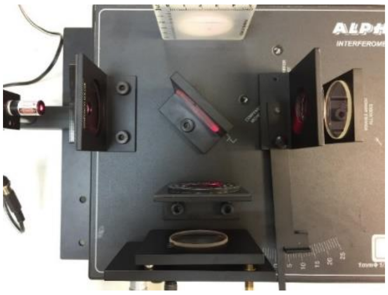

Fig. 10. Effect of Polarization on interference

(3) Measuring the wavelength of the laser

(i) Make a reference mark on the viewing screen. You will find it easier to count the fringes if the reference mark is one or two fringes out from the pattern's center. You can also replace the viewing screen with another white screen at a further distance, as shown in Fig. 11, to make the counting even easier.

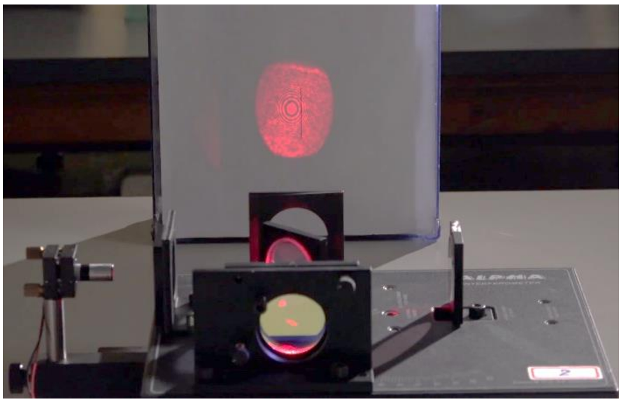

Fig. 11. A white screen as the viewing screen.

(ii) Set the micrometer knob to 10 mm. Turn the micrometer knob one full turn counterclockwise and continue turning it until one bright fringe is overlapped with the reference mark on the screen. Record the position.

Note: When you reverse the direction in which you turn the micrometer knob, there is a small amount of giving before the mirror begins to move. This is called mechanical backlash and is present in any mechanical system involving reversals in the direction of movement. You can eliminate backlash in your measurement by starting with a full counterclockwise and turning only counterclockwise when counting fringes.

(iii) 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 for 20, 40, 60, 80, and 100 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.

(iii) Record the data and use eq(1) to obtain the wavelength of the laser. Compare the result with the reference value.

(4) Measuring the index of refraction for glass (Fig. 12)

(i) Position the rotating pointer on the base and attach the glass to the pointer.

(ii) Starting from the smallest angle (-5 degree), slowly rotate the pointer while observing the changing fringes until the changing fringes act differently. Record the angle as the starting angle θ_0 where the beam is reflected right back into the laser aperture.

(iii) Slowly rotate the pointer counterclockwise. Count the fringes as they pass your reference mark on the screen. Count for 100 fringes five times, and record the angle for each time.

(iv) Use eq(2) to obtain the index of refraction for glass.

$$n = \frac{(2t - N\lambda)(1-\cos\theta)}{2t(1-\cos\theta) - N\lambda} \tag{2}$$

where θ is the rotating angle with respect to the starting angle θ_0, t is the thickness of the glass ($= 6$ mm), λ is the wavelength of the laser, and N is the counting number of the fringes.

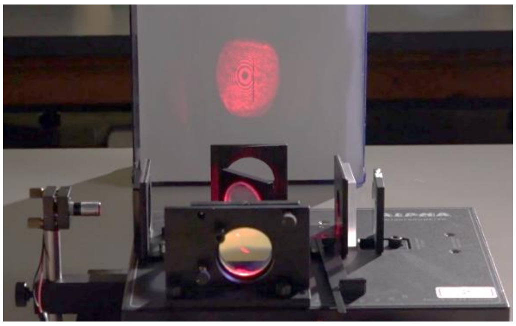

Fig. 12. Measuring the index of refraction for glass

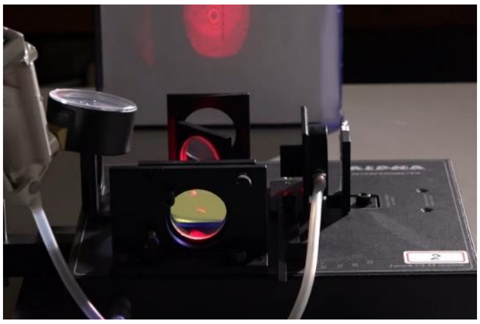

Fig. 13. Measuring the index of refraction for air

(5) Measuring the index of refraction for air (Fig. 13)

(i) Replace the glass with the vacuum chamber.

(ii) Slowly pump out the air in the vacuum chamber to some convenient pressure while counting the number of fringes that pass the reference mark on the screen. Record the counting Δm and the pressure difference ΔP. Eight trials are needed. Note that the reading of the gauge shows the vacuum pressure with respect to atmospheric pressure.

(iii) Use eq(3) to obtain the difference Δn in the index of refraction for the air of different pressure.

$$\Delta n = \frac{\lambda \Delta m}{2h} \tag{3}$$

where h is the length of the vacuum chamber ($= 3$ cm).

(iv) Plot Δn versus ΔP. Analyze their relationship and find the index of refraction for the air of 1 atm. Compare the result with the reference value (~1.0003).

3. Post-lab report

(1) Recopy and organize your data from the in-lab tables in a neat and readable form.

(2) Analyze the data you obtained in the lab and answer the given questions

E. Questions

1. Michelson-Morley's experiment disproved the existence of the aether, which earned Michelson a Nobel prize in 1907. This experiment is viewed as the most successful "failed" experiment, for they initially set this experiment to prove the existence of the aether.
   (1) Explain how to use the Michelson interferometer to conclude that aether doesn't exist.
   (2) The 2017 Nobel prize in physics was half awarded to LIGO for the work of measuring the gravitational waves by the Michelson interferometer. Explain how they can conclude the existence of gravitational waves by the results obtained.
2. Derive equation (2) and equation (3).
3. Can the interference patterns be formed by two polarized lights with perpendicular polarization axes? Explain how to prove your statement by the Michelson interferometer.
4. Find two applications of the Michelson interferometer excluding the experiments mentioned in the lab.

F. References

Fang, Guangyu, et al. "Geometric explanation of conic-section interference fringes in a Michelson interferometer." American Journal of Physics 81.9 (2013): 670-675.

Abbott, Benjamin P., et al. "Observation of gravitational waves from a binary black hole merger." Physical review letters 116.6 (2016): 061102.