



## Michelson Interferometry

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The goal of the current experiment is to familiarize students with the concept of the interference of light using a Michelson interferometer. It introduces optical components like beam splitters, translation and rotational stages, and lenses and highlights important concepts in wave interference. A Michelson interferometer is used for measuring the laser wavelength and finding the refractive index of glass.

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### PreLab activity

Visit the Michelson Interferometry web page on our course website (<https://physlab.org/lab-ii-phy-300/> and <https://www.astrolab.ac/>) to review the background material for the experiment.

## 1 Introduction

This experiment is part of a series of experiments available in the optics stream (*Ibn Sahl Corner* for Optics) and in the astronomy stream (*Astrolab*). The Michelson interferometer

is a remarkable instrument with significant applications in both optics and astrophysics. For instance, in optics, the setup can be used to study interference phenomena and measure the wavelength of light with precision. In astrophysics, interferometry is used to enhance the resolution of telescopes. The Very Large Telescope Interferometer (VLTI) and the Event Horizon Telescope (EHT) are examples of large-scale interferometric projects used in astrophysical research.

Michelson interferometry has historical significance too. Albert A. Michelson designed the interferometer to verify the effect of Earth's motion on the propagation of light. In 1887, the famous Michelson-Morley experiment used a similar interferometer to measure Earth's velocity relative to the hypothetical "ether," which was believed to be the medium through which light traveled [1, 2]. LIGO, a colossal Michelson interferometer, confirmed Einstein's gravitational wave prediction in 2015. The 2017 Nobel Prize honored the pioneers behind this groundbreaking project (<https://www.nobelprize.org/prizes/physics/2017/press-release/>).

## 1.1 Interference

The wave superposition principle states that when multiple waves intersect in a given space, the total amplitude at any point is the combined sum of the individual wave amplitudes. When two waves have the same frequency and are in phase so that their crests and troughs coincide, they create constructive interference. Conversely, if two waves have the same frequency but are entirely out of phase—where the crest of one wave aligns with the trough of another, and vice versa—destructive interference takes place.

Consider two waves represented by  $E_1 e^{i(\phi_1 - \omega t)}$  and  $E_2 e^{i(\phi_2 - \omega t)}$ , where  $E_1$  and  $E_2$  are real numbers and denote the magnitudes of their respective fields,  $\phi$  represents the phase,  $\omega$  is the angular frequency, and  $t$  denotes time. Combining these waves results in the expression:

$$E_T = E_1 e^{i(\phi_1 - \omega t)} + E_2 e^{i(\phi_2 - \omega t)}. \quad (1)$$

When  $\phi_1 - \phi_2$  equals  $2n\pi$ , with  $n$  being a non-negative integer ( $n = 0, 1, 2, \dots$ ), the waves are in perfect phase alignment, and if  $E_1 = E_2$ , we observe complete constructive interference. Conversely, if  $\phi_1 - \phi_2$  equals  $(2n + 1)\pi$ , the two waves are out of phase, and if  $E_1 = E_2$ , we observe complete destructive interference. In common practice, one measures the intensity of the field rather than the field itself. The intensity is directly proportional to the square of the field. The intensity of the interference pattern produced by two waves is then given by the expression:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi_1 - \phi_2). \quad (2)$$

For the two waves to interfere, it is required for the two waves to be coherent. Coherence can be in space as well as time. Mathematically, it is measured using a cross-correlation function. Physically, coherence reflects the degree to which the relative phase of the two waves remains constant. In this experiment, our focus will be on temporal coherence, specifically examining the correlation between the wave and a version of itself delayed in time. Essentially, temporal coherence provides insights into the monochromatic nature of a wave.

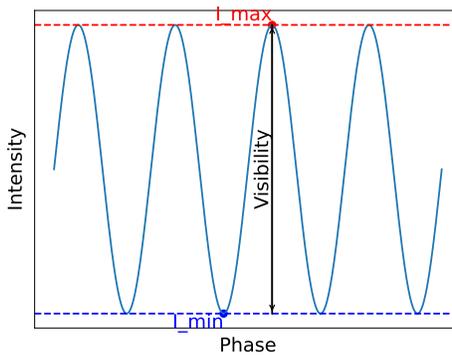


Figure 1: Illustration depicting interferometric visibility.

The interferometric visibility (often denoted as  $V$ ), also known as contrast or modulation depth, measures the contrast of the interference pattern (Figure 1). It is defined as:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (3)$$

where  $I_{\max}$  is the maximum intensity (bright fringe) and  $I_{\min}$  is the minimum intensity (dark fringe). When the waves are highly coherent, the interference fringes have high contrast (large  $V$ ).

**Q 1.** Derive the expression for intensity in Equation 2.

## 1.2 Michelson Interferometer

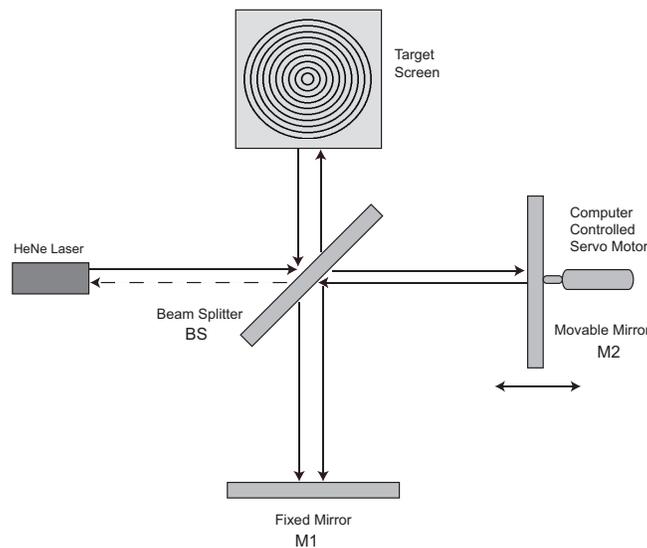


Figure 2: Working principle of the Michelson interferometer.

An interferometer exploits the interference of light. The Michelson interferometer uses interference to measure the optical path difference between the two paths [3, 4]. Figure 2 shows the schematic of the Michelson interferometer. The Michelson Interferometer is an amplitude-splitting interferometer. It splits the beam into two perpendicular paths using a 50 % beam splitter. The beams then reflect from the mirrors placed on each arm and return

to the beam splitter. The light beams from the two paths are aligned to hit the same spot on the photodetector or screen where they interfere, forming the interference pattern. Figure 3 shows the interference pattern observed on the screen.

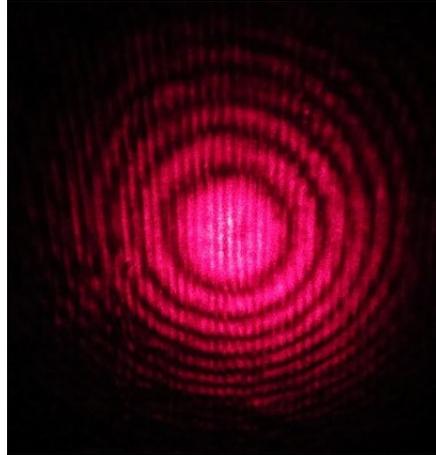


Figure 3: Bright and dark fringes resulting from the interference of the two paths. This is a typical pattern seen on the screen.

The expression for the interference at the screen is given by:

$$I \propto \frac{E_0^2}{2} [1 - \cos(2k(l_1 - l_2))]. \quad (4)$$

**Q 2.** Derive the expression for intensity in Equation 4.

**Q 3.** Discuss the phase shift added to the field that is transmitted through the beam splitter and the field that is reflected by a beam splitter.

## 2 Procedure

**CAUTION:** Handle optical components with care, avoiding direct contact with mirrors, lenses, or other surfaces, as the oils from fingertips can degrade their performance and compromise data quality. **WARNING:** Exercise caution when

**activating lasers to prevent potential harm to the eyes. Take necessary precautions to ensure that laser beams remain contained within the experimental area, avoiding unintended exposure to yourself, colleagues, or others.**

## **2.1 Optical Alignment**

Start by setting up the experiment according to the illustration in Figure 2. Perform the following procedure to align the interferometer.

1. Place the HeNe laser into the laser mount, which is bolted to the optical breadboard. Align the laser parallel to the breadboard.
2. Now mount the beam splitter (BS) on the breadboard in front of the laser.
3. Place a fixed mirror (M1) in the mirror mount assembly. Align the mirror such that the reflected beam from BS falls in the middle of it.
4. Now mount the other mirror (M2) on the translation stage, which is being operated by the computer-controlled servo motor. Align M2 such that the transmitted beam from BS falls in the middle of it. Remember to keep the length of each arm of the interferometer approximately the same length.
5. Turn on the laser, and you will see the two small dots on the screen. Using the screws of the mirrors, overlap the dots. Now the two beams will be aligned.
6. Place the plano-convex lens of focal length 35 mm (L1) in between the laser and BS.
7. On the opposite side of M1, place another plano-convex lens of focal length 25.4 mm before the target screen to enlarge the image.
8. Carefully adjust M1 and M2 using their screws so that the beams overlap on the target.
9. Perform alignment until you see concentric circular fringes.

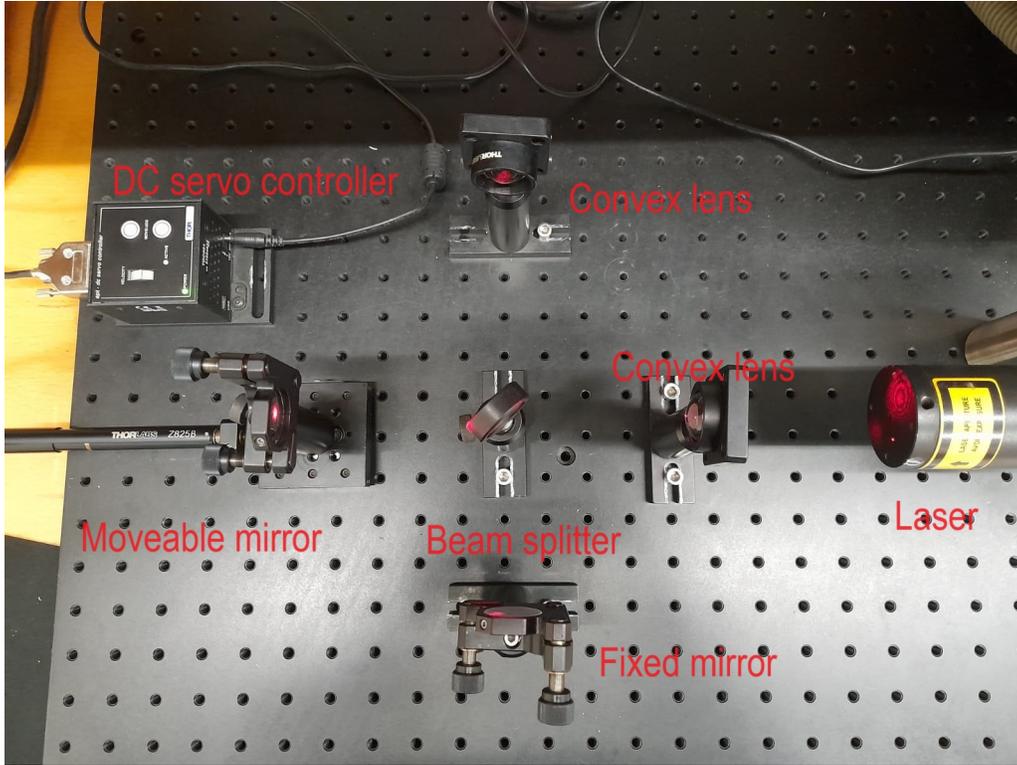


Figure 4: Laboratory setup for measuring the wavelength of the light source.

## 2.2 Measuring the wavelength of a laser

Your first task is to measure the wavelength of the laser source (Figure 4). If we move the movable mirror, we see the fringes entering or exiting the center of the fringe pattern, depending on the direction in which the mirror moves. The following equation relates the distance moved by the mirror to the number of fringes passed by [5]:

$$\lambda = \frac{2\Delta d}{N}, \quad (5)$$

where,  $\lambda$  is the laser wavelength,  $N$  is number of fringes passed by and  $\Delta d$  is the distance moved by M2. Use the computer software to move M2 using the servo-controlled motor with a fixed distance of around 10  $\mu\text{m}$ . Count the number of fringes that pass by a fixed point. Repeat the same procedure at least five times and take the average to minimize the errors. Use Equation 5 to measure the laser wavelength.

**Q 4.** Derive Equation (5).

**Q 5.** What is your uncertainty in the wavelength?

### 2.3 Measuring the refractive index of glass

Your second task is to measure the refractive index of glass. A glass slide is mounted on the rotational stage and placed between BS and M1. If we rotate the glass slide, we see the fringes entering or exiting the center of the fringe pattern, depending on the direction in which the rotation takes place. Rotate the glass slide by a certain number of degrees and count the number of fringes that pass by a fixed point. The refractive index is [6, 7]:

$$n_g = \frac{(2t - N\lambda)(1 - \cos\theta)}{2t(1 - \cos\theta) - N\lambda}, \quad (6)$$

where,  $n_g$  is the refractive index of glass,  $\lambda$  is the laser wavelength,  $t$  is the thickness of glass slide,  $N$  is number of fringes passed by and  $\theta$  is the angle rotated in radians. Use equation (6) to compute the refractive index of glass. Repeat the same procedure at least 5 times and take the average result to minimize the error. Remember that the relationship (6) between  $N$  and  $\theta$  is nonlinear.

**Q 6.** Draw a figure showing the path of the light beam as it passes through the glass slide at an arbitrary angle  $\theta$  to the light ray. What is the optical path length difference in this case?

**Q 7.** Derive Equation (6).

**Q 8.** Plot  $N$  versus  $\theta$  as using Equation (6).

**Q 9.** Calculate the uncertainty in  $n_g$  arising from the uncertainties in  $N$  and  $\theta$ .

### 3 Idea Experiments

1. Find the thermal expansivity of a solid using an interferometer [8].
2. Demonstrate an experiment that simulates gravitational-wave interferometry using sound waves [9].
3. Determining Young's Modulus through Michelson Interferometry [10].
4. Implement a Michelson laser interferometer to demonstrate remarkable picometer sensitivity in distance measurement[11].

### References

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## 4 Appendix A: Moving mirror using a linear actuator

The motor controller we are using to move the mirror is DC Servo Motor Controller, Z825B with specifications:

1. Travel range = 25 mm
2. Lead Screw Pitch = 1 mm
3. Resolution = 29 nm

We have two software that we can use to drive the DC Servo Actuator:

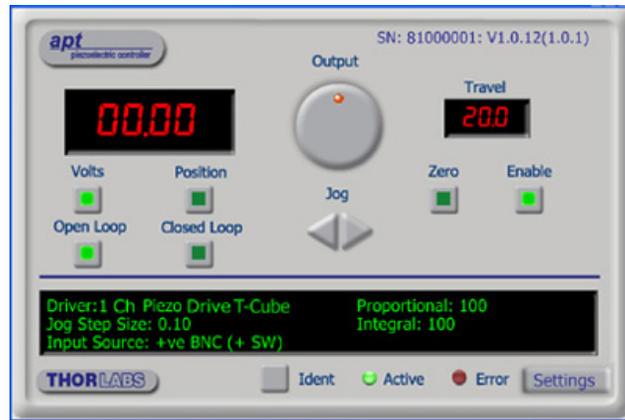
1. Thorlabs' Kinesis®
2. Thorlabs' APT™

### 4.1 Software Instructions

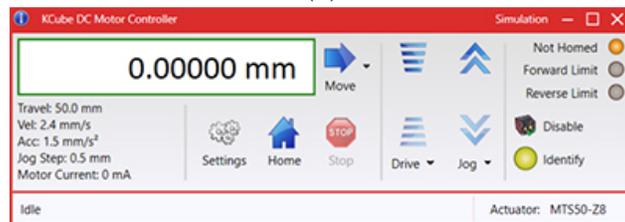
Both programs are already installed on the computer.

1. Open **APT Configuration Utility**, and select the following Motor and Stage options:
  - (a) Motor **83843713**
  - (b) Channel **1**
  - (c) Stage **Z825**
2. After configuration, close this window and run **APT User Utility**.

**Note:** Instead of APT User utility you can run the Kinesis software. The GUI of each software is shown in Figure 5.



(a)



(b)

Figure 5: GUIs of (a) APT User Utility, and (b) Kinesis®.

3. Select the **Motor driver Settings** tab and enter the following parameters,

(a) In **Moves-Velocity Profile**:

Max. Vel. = 0.0003 mm/sec

Acc./Dev. = 0.03 mm/sec/sec

(b) Step distance = 0.001 mm. We must advance the mirror  $M_2$  through some distance and simultaneously count the number of fringes that pass through a reference point. Remember to count the fringes *during* translation.