University of Tasmania

Second-year laboratory work

KYA212

Applications of the Michelson Interferometer

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Contributors to this experiment, its documentation, and support materials include A. J. McCulloch and G. S. C. Stewart.

Safety

General information regarding lab safety can be found on POLUS, the lab website, whereas experiment-specific safety considerations are listed here.

Hazards

This experiment utilises laser radiation. The light source used is classified as a Class 2 laser, meaning it is safe to use without eye protection as the blink reflex will suitably limit the energy deposited by the laser light to the eye in the case of accidental exposure. Prolonged exposure to the beam can be harmful, so not stare directly into the beam.

A risk assessment for this activity has been undertaken and approved by the relevant university authority; it can be accessed here.

Summary

The wave nature of light is explored through the observation of interference, and mechanical systems are systematically used to manipulate the observed interference, from which we can infer information either about the light source or the mechanical system, and ultimately make extremely accurate and precise measurements.

Experiment objectives and learning outcomes

> The primary objective of this experiment is to measure the wavelength of a green laser, measure the refractive index of SOMETHING, and determine the thermal expansion coefficient for aluminium.

Following this experiment, it is expected that you will:

- Be familiar with interferometry and the use of a Michelson Interferometer as a sensitive measuring device.
- Develop an intuition for non-linear sensor calibration and polynomial data fitting

Introduction

Understanding light has always held a special interest to humankind: our world is bathed in the stuff, so much so that light receptors evolved in animals which reside in all types of biome[1]. Human eyesight not only allows us to safely navigate our environment, its existence has also facilitated the development of our brain's ability to visualise, and effectively simulate the world, all from the comfort of our consciousness. It is therefore unsurprising that a preoccupation has existed to understand what is light and how it functions (well, at least since the writings of Empedocles in the fifth century BCE). It wasn't until the 17$^{\text{th}}$ century when the likes of Hooke, Huygens, and Euler started advocating for understanding light as a wave that the our understanding started to well match reality. But it was only once Young with his famous "double-slit" experiment in the early 19$^{\text{th}}$ century demonstrated the interference of light that we started to really get a handle on what we were seeing: *light*.

Interference is the phenomenon whereby the waves at the same location will *superimpose* atop one another. This property ultimately arises when a physical stimulus drives a linear response, as multiple stimuli will individually drive linear responses, which by their nature, can be directly summed and the overall system response is the combination of the individual stimuli. When one gets lost in the weeds, it turns out that few systems are truly linear and thus the superposition principle is not strictly correct, employing interference remains one of the most powerful tools we have for making both accurate and precise measurements. Applications for "interpreting interference" range from non-invasive medical imaging, materials science and engineering, navigation and inertial sensing, astronomy, and much more. In the case of the interferometer that we shall study in this experiment - the Michelson interferometer - it has recently been used to directly detect gravitational waves, an effort which was rewarded with the Nobel Prize in Physics in 2017 .

Background

Pre-lab exercises

Pre-lab questions can be found sprinkled through the introductory section. These are to be completed and submitted *before* you commence a new experiment. The information needed to complete the exercises is

[1]Consequently, the evolution of eyes are often cited as an example of convergent evolution

contained in the experiment background section, your course notes, or in the appendices; however, your own independent research is highly encouraged. Make sure to include references where material has been foraged from elsewhere; this is not only "good form", but making notes of this kind - where to find useful information - is essential should you need to return to the origin of some information.

Context

The wave nature of light was proven by interferometric experiments at the beginning of the 19th century. Because all known mechanical waves require a medium in which to propagate, physicists undertook an intensive search for the medium (the "luminiferous aether") that permitted the transition of electromagnetic waves through air, water, glass, interplanetary space, etc. Albert Michelson invented an optical interferometer that uses a half-silvered mirror to split a single light source across multiple paths, and his use of the interferometer with Edward Morley to disprove the existence of the aether won them the 1907 Nobel Prize in physics.

Interferometers come in many shapes and sizes. A question that you might have is: "Why? Isn't one interferometer enough?" To answer this question, let us pose another question: when I want to build a bridge to cross a river, what type of bridge should I build? The answer of course depends on a number of factors, such as the span, geology, loading, and many other considerations. It is no different for different interferometer designs, with each presenting unique features. Which interferometer design is appropriate depends on practical considerations, for example, what exactly are you trying to measure with it, and what tools do you have to make the measurement. In this experiment, we focus solely on *double-path* interferometers, in which an incoming wave is split into two parts that travel along different paths before being recombined. The resulting interference pattern reveals information about the difference(s) between these paths.

Prelab 1 *Fringe science*

Your first task is to explain what quantities interferometers can measure with high precision. To direct your explanation, imagine that you want to measure the width of a human hair, and all that you have at your disposal is a laser. How could you determine the width of the hair with the highest degree of accuracy, what parameters could you adjust to get the most accurate result, and what limits the accuracy of the measurement?

Prelab 2 *More fringe science*

Consider our experiment from the previous question, but now let us imagine that you additionally had a small rectangular aperture, roughly 10 times the diameter of the human hair. You also posses a deft hand and can place a strand of hair anywhere in this aperture with total control over its orientation. How would this change your ability to determine the width of the hair, and explain any relevant physics.

Hint: What is *fringe visibility*?

The above questions (hopefully) cover familiar territory: namely, interference arising due to diffraction. We are now going to explore other systems which give rise to interference.

Interferometers

In short, and interferometer is a device which uses interference to measure something, and fundamentally this means there must be some component of the device which facilitates interference. This means that there must be two (or more) waves which combine, superimpose and form a meaningful interference pattern. Conceptually, the simplest of these involves taking a single wave, splitting it into two waves which traverse different paths and are subsequently recombined. At the recombination point, they interfere with each other in the usual way: if the waves are in phase, they combine constructively (creating bright regions); if they're out of phase, they interfere destructively (creating dark regions). The resulting pattern observed at the detector is called an interference pattern, and it depends sensitively on the difference in the paths travelled by the waves.

The Mach-Zehnder Interferometer

Normally, physical apparatus and concepts are presented chronologically, that is, in the order that they were developed or discovered; however depart from this well-trodden path to consider the conceptually simpler (simplest?) interferometer as depicted in figure 1. In this setup, a (collimated) beam is incident on a beamsplitter, which splits the wave into two, and these beams travel separate paths and are subsequently recombined, and the resultant wave is observed.

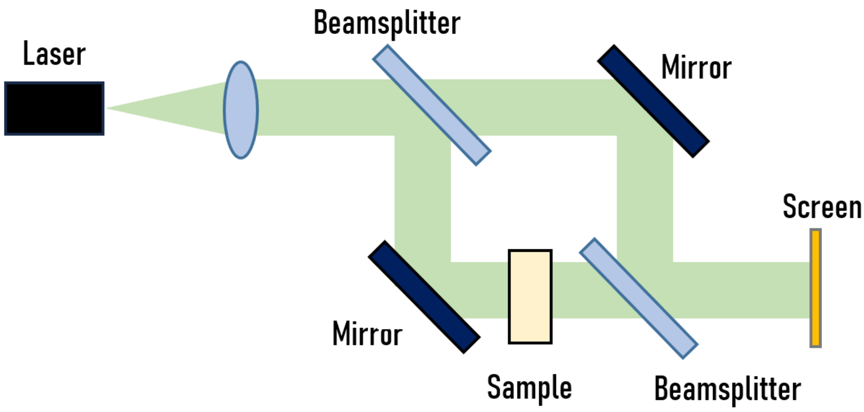

Figure 1: A schematic of a Mach-Zehnder interferometer, adapted from *Building a Mach-Zehnder Interferometer*.

Prelab 3 *Mach 1*

Let us perform a thought experiment: imagine that we have the interferometer as depicted in figure 1, except there is no sample, and the path lengths of each of the interferometer arms are identical. What would you expect to observe on the screen?

Now imagine that we insert a sample that changes the phase of the wave by $\lambda/2$[a]. What would you expect to observe on the screen?

[a] Such a sample is called a half-wave plate

The Michelson Interferometer

A variation of the Mach-Zehnder interferometer is to split the beam in two, allow it to propagate, but with a two-way propagation (an "out-and-back" configuration) rather than a one-way system, which means the beams are recombined on the beamsplitter which initially split the wave. A basic schematic of this is shown in Fig. 2.

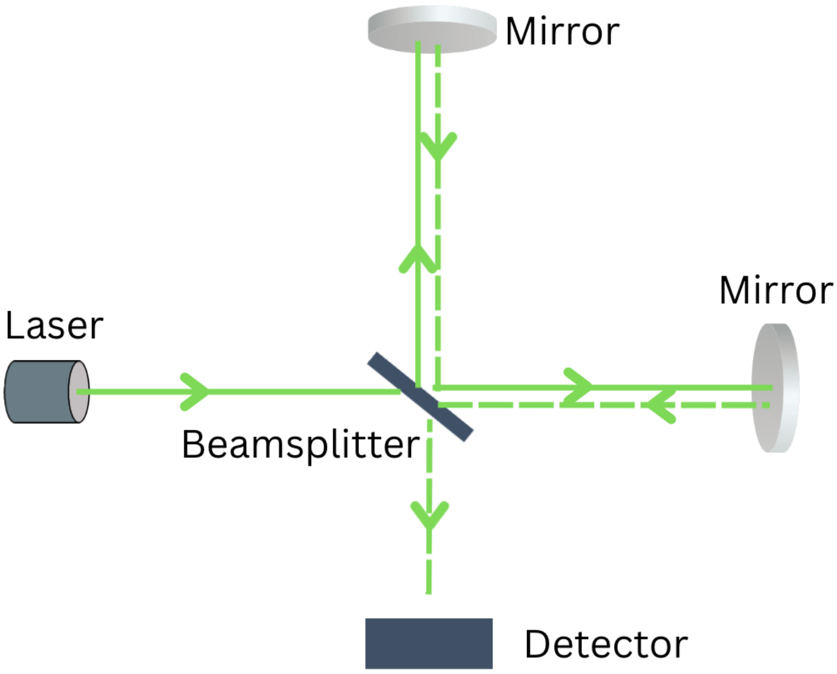

Figure 2: A basic schematic of the operation of a Michelson interferometer.

The Michelson Interferometer has many practical applications, some of which you will explore in this experiment. These include precision length measurement and calibration, refractive index measurement, spectroscopy, and gravitational wave detection. In the case of the latter, experiments were performed at The Laser Interferometer Gravitational-Wave Observatory (LIGO), which is the largest and most sensitive Michelson interferometer ever built.

Prelab 4 *A sensitive question*

Interferometers are sensitive to any differences in the interferometer arms, with differences arising from a variety of sources. In the case of LIGO, a gravitational wave will stretch space in one direction and compresses it in the perpendicular direction (imagine something like the compressions and rarefactions in pressure waves), thus there will be a difference between the interferometer arms and an interference pattern will be produced. Given that the scale of this *ripple in the space-time continuum* is roughly a few attometers (1 attometer = 10^{-18} meters) estimate how large the interferometer should be to detect the gravitational wave?

Phase and path length differences

When one first encounters waves and interference, the key quantity which determines what interference is observed is usually the *path length difference* between waves. Whilst this is a valid quantity, it is neither the most general nor most useful quantity, rather talking about a *phase difference* is much more meaningful, since there are many ways a wave can accumulate phase, and at the end of the day, when we visualise waves interfering to produce light and dark bands, we normally think of peaks aligning with peaks or peaks aligning with troughs.

Prelab 5 *An illustrative exercise*

What is wavenumber? How does it relate to the wavelength, and the phase accumulated by a propagating wave? Explicitly, express the the phase difference between two waves in interferometer arms of different lengths in terms of the wavenumber.

Prelab 6 *An illustrative exercise*

In an interferometer, a wave is split into two partial waves which each travel along an arm of the interferometer before being recombined at the beamsplitter. Consider an incident wave travelling along one arm of the interferometer with the form

$$\mathbf{E_i} = \mathbf{E_o} \cos(\omega t - kx)$$

where ω is the angular frequency, t is time, k is the wavenumber $(2\pi/\lambda)$ and x is the position of the wave along the direction of propagation. The amplitude of *one* of the partial waves (after passing through the beamsplitter) at the detector/screen is

$$|\mathbf{E_1}| = \sqrt{RT} E_o \cos(\omega t + \phi_1)$$

Where T and R are the transmission coefficient and reflection coefficient of the beamsplitter, respectively. We can safely assume that the value of R and T is 0.5.

Show that the average intensity $\overline{I}$ on the screen from *both* partial waves is given by

$$\overline{I} = \frac{1}{4} c\epsilon_0 E_0^2 (1 + \cos \Delta\phi) \tag{1}$$

Measuring Laser Wavelength

Determining the wavelength of a light source is reasonably straight forward if that light source emits only one wavelength. Fortunately, in this experiment you have a green laser with a known wavelength of 532 nm. As per Equation 1, a change in path-length will result in changes to the locations of bright and dark fringes in the interference pattern. Importantly, a transition from light to dark and back to light fringes (as shown below in Fig. 3) corresponds to a path length difference of λ. Since light travels up *and* down the shifted arm of the interferometer, the change in length of the arm $\Delta x = \frac{\Delta s}{2} = \frac{\lambda}{2}$. By counting the number of transitions (number of maximums or minimums that are cycled through), N, that appear as the interferometer arm is adjusted by an amount Δx, the wavelength of the light can be determined:

$$\lambda = \frac{2\Delta x}{N} \tag{2}$$

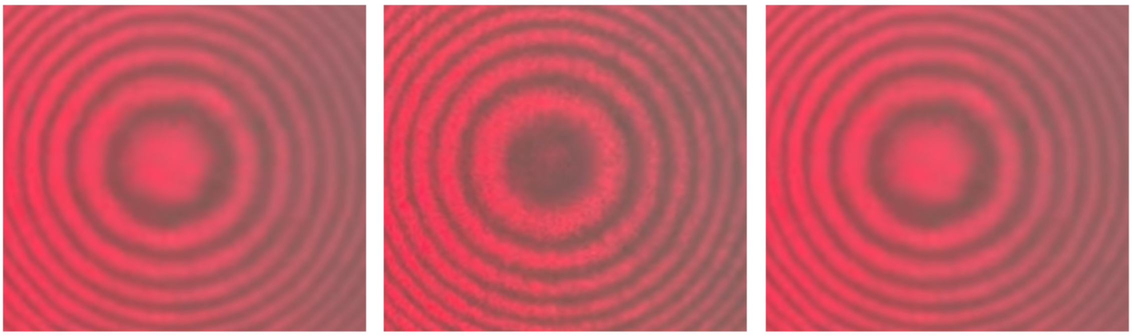

Figure 3: A light, to dark, to light transition as a result of changing the path-length difference by λ.

The Refractive Index

Interferometers can be used to measure the refractive index of solid (ideally transparent) materials to high precision. Consider the case where a transparent solid is placed in the path of an interferometer. If the solid is rotated, the optical path length changes, resulting in a change in the interference pattern. This is illustrated below in Fig. 4.

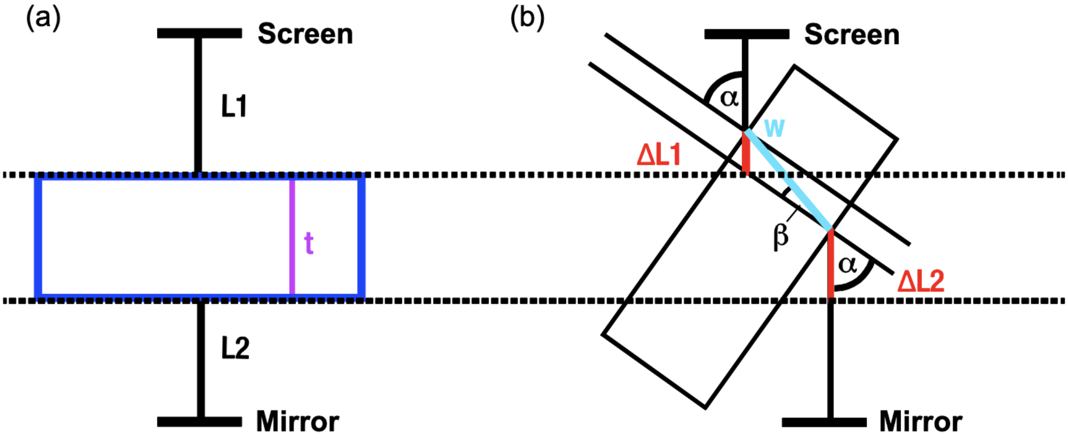

Figure 4: A solid of thickness t is placed in the path of an interferometer. In (a), the solid is perpendicular to the path of the light. In (b), the solid has been rotated, changing the optical path length.

In the case where the solid is not rotated, the optical path length of the light travelling from the mirror to the screen is $L_1 + nt + L_2$ where n is the refractive index of the material and t is the thickness of the material. If the solid is now rotated by some angle α, we get $L_1 - \Delta L_1 + nw + \Delta L_2 + L_2$. The difference in the optical path length (OPL) can be derived from the non-rotated and rotated optical pathlength equations,

$$\Delta\text{OPL} = 2(-\Delta L_1 + nw + \Delta L_2 - nt)$$

The factor of 2 appears in the equation because the light passes along the path twice. The path length difference is derived from the light-dark-light transitions via

$$N\lambda = \Delta\text{OPL}$$

where N denotes the number of light and dark transitions.

The final equation of interest that allows us to determine the refractive index is,

$$n = \frac{\left(\frac{N\lambda}{2t} + \cos\alpha - 1\right)^2 + \sin^2\alpha}{2\left(-\frac{N\lambda}{2t} - \cos\alpha + 1\right)} \tag{3}$$

The Thermal Expansion Coefficient

When the temperature of a solid increases, it typically expands, although the extent of expansion can depend on the material and its environment. This behaviour is characterised by the thermal expansion coefficient, denoted by α, which quantifies the proportional relationship between the relative change in length and the change in temperature:

$$\alpha = \frac{1}{L}\frac{dL}{dT} \tag{4}$$

The solution to this equation describes an exponential process, where the length of the solid is given as:

$$L = L_0 \exp(\alpha \Delta T) \tag{5}$$

where ΔT is the change in temperature of the solid, L_0 is the original length and L is the length after expansion. To an approximation, the change in length of the solid is related to the thermal expansion coefficient by

$$\Delta L \approx \alpha L_0 \Delta T \tag{6}$$

Apparatus

To do this experiment, you will need the following components. A labelled diagram of the setup is shown in figure 5.

Figure 5: Michelson Interferometer Components

1. A **movable mirror** with micrometer
2. A collimated **laser**[2], 532 nm.
3. **Thermal expansion unit** including mirror, 9 cm aluminium rod, foil heater and tape.
4. **Viewing screen**
5. **Beamsplitter cube**
6. **Mirror**
7. **Optical bench**
8. **Bi-Convex Lens**[3], $f = 50.0\,\text{mm}$
9. **Digital thermometer**

Experiment

With the apparatus described and the relevant physics discussed, it is now time to design and execute an experiment that achieves the Experiment Objectives. We will first work towards setting up the interferometer and verifying the wavelength of the green laser.

Exercise 1 *Wavelength measurement*

From the materials you have, design and construct a simple interferometer that produces a clear interference pattern on the white screen. Your interferometer should be similar to the schematic in Fig. 2. How far apart should the components be? How do you know the interferometer is set-up properly?

Using your interferometer, determine the wavelength of the laser.

Exercise 2 *Coherence and white light fringes*

Exchange the laser for a white light source. You may need to adjust your interference pattern to try and find the interference pattern.

- Is it harder or easier to see the interference pattern for white light?
- Describe the interference pattern. What does it look like? Why is it different from the pattern produced by the laser?

Exercise 3 *Refractive index measurement*

You will now measure the refractive index of a solid material. Using the information given in "the Refractive Index" section of the background theory, think about where we should place the solid in our interferometer so we can measure the refractive index.

- When we have placed the solid in the interferometer, how will we measure the refractive index?
- How many measurements should we take?

[2]Thorlabs model CPS532-C2
[3]Thorlabs model LB1471

Exercise 4 *The Thermal Expansion Coefficient of Aluminium*

You will now measure the thermal expansion coefficient of Aluminium. Fortunately, you have a pre-prepared device that consists of a mirror, aluminium rod, and foil heater which should allow you to carry out this part of the experiment. Plugging this device into power using the banana plug leads should allow you to heat the rod up in a controlled manner. As the rod heats up, it will change in length.

The first thing to consider is where should the Aluminium rod unit go in the interferometer. Should it replace one of the existing components? Discuss with your demonstrator.

Once the Aluminium rod unit is in the right spot, think about how you can measure the thermal expansion coefficient. The information contained in the "Thermal Expansion Coefficient" section of the Background theory will be useful. Discuss your method with your demonstrator.

As before, consider

- What sort of data do you want to take? Do you want to make a plot? If so, what quantity are you looking to plot against what other quantity?
- How many measurements will you want to take?

Analysis

You should now have a whole bunch of data, but it needs to be made meaningful. Recall what is you primary goal of this experiment, and plan out how you are going to get there. Some guidance and prompts for discussion are provided below.

Exercise 5

1. Calculate a value for the thermal expansion coefficient of Aluminium. How does this compare to the accepted value of $23.1 \times 10^{-6}\,\mathrm{K}^{-1}$

References

Appendix