8 Michelson Interferometer

8.1 Summary

The wave nature of light at visible wavelengths is demonstrated by use of a dual-beam interferometer of the sort pioneered by Michelson. By altering the optical path length of one beam relative to the other, interference effects are used to measure the index of refraction of mica and of air over a range of pressures.

Objectives

1. To verify the wave nature of monochromatic and white light and gain experience with optical bench equipment.
2. To use monochromatic light of known wavelength to verify the calibration of a micrometer gauge.
3. To use moving interference patterns (fringe-tracking) to measure the index of refraction of mica, and of air over a range of pressures.

Equipment

Beck interferometer mounted on a small optical bench, with removable glass compensating plates and pressure cell; light source box with mercury discharge tube (green monochromatic light) with removable green filter (Please note, the white light in the box does not work and the switch should always be off). A white light lamp, Sodium discharge tube (yellow monochromatic light source) and power supply; thin slices of mica (muscovite) in slide holders; vacuum pump and pressure gauge.

Principal Data Taken

1. Visual inspection and recording of interference patterns
2. Interferometer micrometer dial readings, and dimensions of mica sheet, pressure cell and compensating plates
3. Air pressure readings

Things to Watch Out For

• Do not stare at the mercury (green) light source with no filter in place because some ultraviolet light is produced; this is not highly dangerous in the amounts that are present, but long-term exposure can damage your eyes. The green glass filter will eliminate this risk entirely.

• Make sure that the switch for white light (the white light bulb is not working) on the light source box is switched off.

• Eye strain and fatigue may occur when searching for interference patterns during the initial attempts to find interference fringes in the device. Trade places with your lab partner if your eyes are getting tired.

• **DO NOT TOUCH OPTICAL SURFACES** (mirrors and glass compensating plates). These components are manufactured to be optically flat to a precision of better than one tenth of the wavelength of optical light and any scratches or dust transferred to the surface can degrade your results. Fingerprints are particularly insidious because skin oils are difficult to remove and over time can etch the surface coatings. The same general principle applies to any optical surface (although some, such as the mica sheets used here, are more tolerant than others).

8.2 Theoretical Background

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 could transmit 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 Morley to disprove the existence of the aether won them the 1907 Nobel Prize in physics.

The interferometer here is not nearly large enough nor isolated enough from thermal or vibrational effects to replicate Michelson's work, but it can be used to demonstrate the concept of optical path length (length measured in units of waves instead of mm or nm), to measure distances extremely precisely, and to determine indices of refraction. The concept of a preferred reference frame that was addressed by Michelson and his contemporaries has theoretical relevance today in attempts to unify general relativity and quantum mechanics. In a practical context interferometry is widely used in astronomy, gravitational wave detection, and meteorology.

Review the physics of interference between light waves from your KYA102 or KYA211 physics notes, a suitable online reference such as *hyperphysics*, or a textbook (see reference list below). The observable effect of interference will be a pattern of alternating light and dark bands corresponding to the constructive and destructive interference between light from different sources. These bands are known as "fringes". The Michelson interferometer uses a single source of light with a beam splitter rather than two independent light sources in order that the relative phase of the light at the observing screen is controlled purely by the different paths taken and not by variation in phase between light sources.

Since the path length difference determines the appearance of interference fringes, think carefully about the relationship between physical distance travelled and the distance travelled as counted by peaks or troughs of waves. Consider the geometric conditions that would lead to the observation of interference "fringes" of various patterns (e.g., straight line or circular). Consult the grey binder with the experimental notes for help visualising the geometry.

Discuss and answer the following questions in your report:

1. Under what conditions are straight line fringes and circular fringes observed, and where

are they formed?

2. What condition on the optical path length *must* hold true in order to observe fringes in white light (as distinct from monochromatic light), and why? Relate this to the need for compensating glass plates in the interferometer path.

3. Show that if the path length in one arm of the interferometer changes, the size of the change can be related to the number of bright fringes that move across the field of view, assuming the wavelength of monochromatic light is known. That is, starting from the condition for constructive or destructive interference, derive the expression:

$$d_1 - d_2 = \frac{(m_1 - m_2)\,\lambda}{2}, \tag{8.1}$$

where $(\mathrm{d}_1 - \mathrm{d}_2)$ is the change in path length and $(\mathrm{m}_1 - \mathrm{m}_2)$ is the number of fringes that appear from the centre of the field (or from the edge of the field) during the movement.

8.3 Procedure

Alignment

1. The interferometer may require alignment before any fringes can be observed. This is achieved by making small adjustments to the mirror set screws, following the instructions in the interferometer handbook.

Observation of Monochromatic and White Light Fringes

2. With the interferometer tuned up appropriately, use the light source with the mercury lamp and the green filter to observe both straight and circular interference fringes. The mercury lamp produces several highly monochromatic emission lines; the strongest one is in the green part of the spectrum at $\lambda = 546.1$ nm. The green filter screens out the other, weaker lines (especially the potentially harmful UV). Turn the micrometer dial to observe the motion of fringes across the field of view. Document your attempts to observe the fringes and their appearance; be as detailed as possible.

3. With the mirrors adjusted so that straight line fringes are visible, remove the mercury lamp and switch to the incandescent (white light) source. Unless you are extremely lucky, the interference pattern will be destroyed. Why is this? (Consider Equation 8.1 for the case where many values of λ are present). Use the micrometer to adjust the position of the interferometer mirror until you recover the fringe pattern (you may see "technicolor" fringes when you are quite close to the correct position). Record the reading on the micrometer dial so you can recover this position if necessary when you are making your measurements! Describe and/or sketch your observations of white light fringes.

Calibration of Micrometer Scale

4. The manufacturer of the instrument claims that there is a 5:1 reduction between the micrometer scale and the motion of the attached beam. By using Equation 8.1 and the sodium discharge tube (yellow monochromatic light, $\lambda = 589.3 \pm 0.3$ nm), make and record enough measurements of fringe motion to confirm or reject the manufacturer's claim. This can be carried out by beginning near the position for white light fringes and

measuring the mirror movement for every ten fringes up to about 200. Tabulate and graph your results.

Refractive Index of Mica

5. Change the optical path length in one arm of the interferometer by inserting one of the thin sheets of mica into the path. These are sheets of insulation used in small transistors, less than half a millimetre thick. Measure their thickness precisely using the calipers provided; don't forget to make an estimate of the uncertainty in your thickness measurement!

6. There are at least two different possible ways to use the change in fringe pattern and the change in path length to derive the index of refraction of the mica. We will leave it to you to think about what you can measure and what you can change in the system to obtain the data you need. Consult with your demonstrator if you are unsure. Mathematically, you will need to relate the wavelength in a material with index of refraction n ($\lambda' = \lambda/n$) to the condition for constructive interference and Equation 8.1. Use your fringe observations and the calibrated micrometer measurements to derive n for mica. Describe your procedure and show your calculations. Compare your results to the accepted value for the index of refraction (give your references in full).

Refractive Index vs. Pressure for Air

7. Take out the mica and put the pressure cell into one arm of the interferometer, and the glass compensating plates into the other. Measure the length of the pressure cell and the thickness of the compensating plates. Connect up the hoses to the vacuum pump.

8. As with the mica experiment, there are a couple of different ways to proceed with measuring the variation in refractive index as a function of pressure in the cell. Devise a method to accomplish this using fringe tracking and your observations. Calculate the refractive index as a function of pressure for at least 10 different pressures in the range from $0 \leq \mathrm{P} \leq \mathrm{P}_{atm}$. Graphically or algebraically derive an equation that shows the dependence of index of refraction on pressure; it may be helpful to work with the quantity $(n-1)$ instead of n because the changes will be quite small.

8.4 Calculations

Your report should include the calculations described above in enough detail to follow your derivations of the micrometer reduction ratio, the index of refraction of air, and the variation of index of refraction with pressure. All quantities should be accompanied by properly derived uncertainty estimates.

References

Beck Interferometer handbook (in manilla folder; not to be removed from the lab)
Watson, R.D. 1998, *"Grey Binder": Michelson Interferometer* (not to be removed from the lab)
Hecht, E. 1987, *Optics, 2nd ed.* (Addison-Wesley: Reading)
Jenkins, F.A. & White, H.E. 2001, *Fundamentals of Optics, 4th ed.*, (McGraw-Hill: New York)