Experiment 322: The Michelson Interferometer

Aim

To investigate the theory of the Michelson interferometer, gain experience in its setup and adjustment, and use it to measure the wavelength of sodium light and the thickness of a microscope cover slip.

References

1. Jenkins and White, "Fundamentals of Optics", McGraw Hill
2. Hecht, "Optics", Addison Wesley
3. Francon, Krauzman, Mathieu, and May "Experiments in Physical Optics", Gordon and Breach

Introduction

The Michelson interferometer is one of the most elegant of all optical instruments. It was invented by Albert A. Michelson in the late 1800s, as an instrument to try and detect the "ether drift". At that time, light was thought to travel in an all-pervading medium known as the "luminiferous ether". Scientists of the time expected that the apparent velocity of light would change depending on the relative directions of motion of ether and light. The Michelson interferometer precisely measures the relative travel times of two light beams travelling at right angles to each other, and so the output of the instrument was expected to change as the earth orbited and rotated in the ether. Despite great effort, Michelson was unable to detect any change and so unknowingly confirmed Einstein's key hypothesis that the speed of light is independent of the motion of the observer – one of the cornerstones for the theory of relativity. This is a classic example where a null experimental result has far-reaching consequences!

We now know that light requires no supporting medium in which to travel, but although the instrument gave (naturally!) a null result in the ether-drift experiment, it has found a myriad of applications in precision measurement.

Optical System

The optical system of the instrument is shown in Fig. 1. Light from the source is split into two weaker beams by a semi-reflecting mirror (the *beam splitter*). The two beams proceed off at right angles – one of them passing through a piece of glass identical to that on which the beam splitter semi-reflecting coating is deposited. This is known as the *compensator*, and compensates for the dispersive effects of the beam splitter substrate. The beams are reflected by mirrors at the ends of the interferometer arms and recombined at the beam splitter again to produce two outputs – one of which goes back to the source, the other of which goes to the observer.

Interference occurs between the two beams in each output to produce a pattern of light and dark bands in the output beam known as *interference fringes*. Bright fringes occur in the output field where the phase difference between the two beams (introduced by differences in the interferometer arm lengths) is an integral multiple of 2π, and dark fringes occur where it is an odd integer multiple of π (the two beams are out of phase). Fig. 2 is an 'unwrapped' diagram of the optical system of the interferometer showing what an observer looking into the instrument sees when looking at an extended source with the distances between the mirrors and beam splitter unequal and the mirrors adjusted to be parallel to each other as seen via the beam splitter.

All points of the ground glass source emit rays in all directions. From each source point, the eye collects rays whose mean angle to the optic axis depends on the distance of the source point from the optic axis

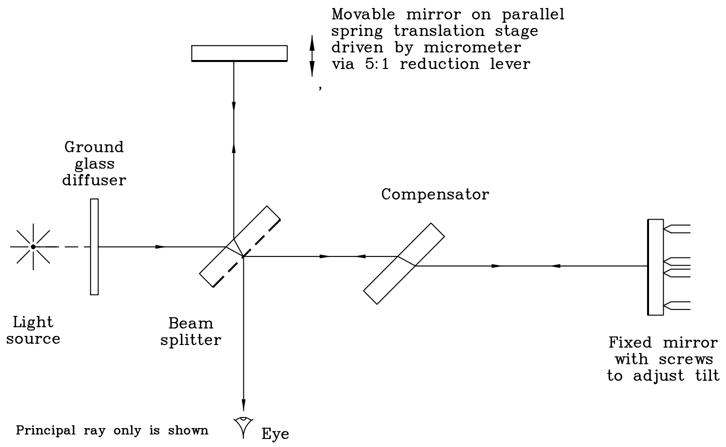

Figure 1: The Michelson Interferometer

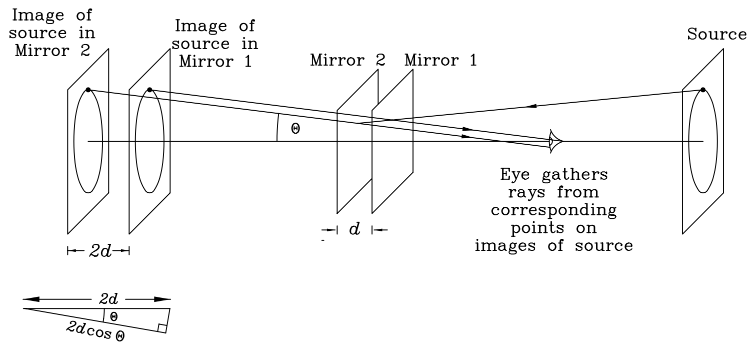

Figure 2: Unwrapped Michelson Interferometer

and the distances between the source, mirrors, and eye. The eye actually sees two images of each point on the source, one via each arm of the interferometer. The path difference between the images of the point determines whether it lies in a light or dark fringe. For example, in Fig. 2 the path difference, p, to the eye between the images of the point shown is $p = 2d\cos\theta$. The loci of light fringes seen by the eye will be therefore be given by:

$$n\lambda = 2d\cos\theta$$

Note that this equation depends on $\cos\theta$ and is symmetric about the optic axis. The fringe loci are therefore circles. Looking through the instrument you will see the source crossed by circular light and dark bands which get closer together as you look further away from the optic axis. Note also, that the fringes will be more widely spaced (the change in viewing angle θ required to move from one light fringe to another is larger) when d is smaller, ie. when the interferometer path difference is close to zero. These fringes are known as "Haidinger Fringes".

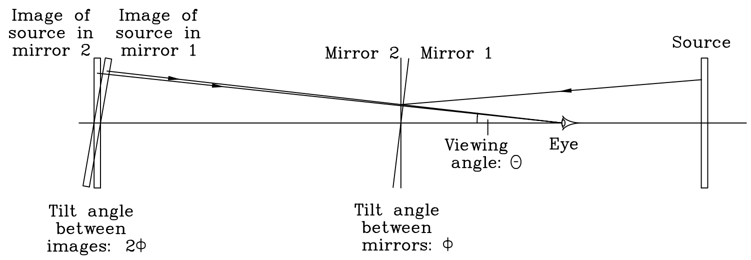

Figure 3: Effects of tilting a mirror by ϕ

If you adjust the interferometer path difference to be zero and tilt one of the mirrors, you will now get the situation (in a plane perpendicular to the tilt axis) shown in Fig. 3. As you can see in the diagram, the path difference varies very nearly linearly with the off-axis viewing angle in the plane of the diagram (provided that the viewing angle is small). A little thought should soon convince you that the path difference is approximately independent of viewing angle perpendicular to the plane of the diagram so the fringes will be straight lines. The path difference and therefore the fringe loci in (off-axis viewing angle) are given by:

$$p = n\lambda = 2\phi l\theta$$

These fringes are known as "Fringes of equal thickness" because of their even spacing. A very good description of the interferometer is given in Ref.1. **Read it before you do the experiment!**

Caution

The interferometer you will use is made by the Ealing Corporation in England and is unsurpassed for it's simplicity and ease of operation in a teaching environment. Before you begin, just a few words of caution:

(a) **DON'T TOUCH ANY OF THE OPTICAL SURFACES IN THE INTERFEROMETER!**
To do so will damage them beyond repair and bring the wrath of the Physics Department upon your head.

(b) The light source has an in-built glass window. If this breaks accidentally, don't use the source without it. You will suffer severe eye damage from UV rays which are usually filtered out by the glass.

(c) When adjusting the instrument, ADJUST SLOWLY AND GENTLY. You will get it right MUCH quicker if you do. Adjusting too quickly usually results in overshoot, loss of alignment, and frustration.

Practical Setup and Operation

(1) Having taken note of these cautions, look at the interferometer. You should be able to see the beam splitter and compensator (in the rhomboid-shaped block), and the two mirrors. One mirror is fixed, and has two thumbscrews for adjusting it's tilt, and the other is mounted on a precision carriage which uses a beautiful parallel spring strip mechanism to obtain precise linear movement along the optic axis without introducing unwanted tilt. The carriage is driven by a micrometer operating through a 5:1 reduction lever, which pushes the carriage via a wobble pin. Just take a few moments to examine this most elegant mechanism and admire the skill of the designer and manufacturer. This mechanism is the KEY to successful mechanical operation of the interferometer as it has to move the mirror precisely back and forth to an accuracy of better than 0.1 μm. Amazingly, it does!

You are provided with three light sources for the interferometer. Two of them (the mercury and white light sources) are mounted in a small black box on a bracket which clips to the side of the interferometer, and illuminates it through a ground glass diffuser and (optional, depending on the experiment) green filter. A power supply with two switches is provided for this box. The third source is a sodium lamp which has it's own supply, and is mounted on a stand.

Experiments

Initial setup

(2) Clip the box with the mercury source onto the side of the interferometer. Take the green filter from its plastic box and insert it into the holder provided on the lamp housing. The ground glass screen should be in the holder on the interferometer. Take the pointer and clip it on to the side of the ground glass screen so that you can see it poking into the field of view when you look into the interferometer. Set the micrometer to the value indicated on the interferometer. Switch the mercury source on.

(3) Looking into the interferometer, you should see two images of the clip – one from each mirror. Adjust the screws on the fixed mirror to exactly superimpose the two images of the clip, and you should see fine fringes crossing the field of view. Adjust the mirror tilt to make them as big as possible and they should resolve into rather large (and slightly distorted) circles. These are Haidinger fringes.

Measurement of the wavelength of the Mercury source

(4) Wind the micrometer slowly in the direction that makes the fringes collapse towards the middle of the circle. The circles should gradually get bigger until one fringe fills the whole of the field of view. Why does this happen?

(5) Now, tilt the fixed mirror about a horizontal axis (by adjusting the upper thumbscrew) until you see about 5 horizontal fringes across the field of view. These are fringes of equal inclination. Measure the wavelength of the Mercury green line by moving the micrometer and counting fringes going by the pointer. Move the micrometer so ≈ 100 fringes move by the pointer. Calculate the wavelength from the change in micrometer reading, remembering the 5 : 1 reduction ratio in the micrometer lever arm and the double pass of the light in each interferometer due to reflection at the mirrors. Repeat this experiment 3 times to help estimate your uncertainty. You are reminded that the results of *all* measurements should include an estimation of uncertainty and comparison with accepted standards (where possible).

Measurement of the mean wavelength, and wavelength separation of the Sodium doublet.

(6) Remove the box with the mercury source and position the sodium lamp so that it illuminates the ground glass. You should see yellow fringes. Now scan the micrometer over a distance of $\sim 2\,\mathrm{mm}$, stopping at a number of positions along the way to observe the fringes. At some positions you will find that the dark fringes are essentially black in comparison to the bright fringes (maximum contrast). At other positions you will find that the bright and dark fringes are almost equal in intensity (minimum contrast); the fringes might even become very difficult to see. This occurs because the bright yellow light from the sodium lamp is made up of two components of near equal intensity and slightly different wavelength (see Experiment 242, *Optical Spectrum of Sodium using the Diffraction Grating*). When the bright fringes for one wavelength (λ_1) coincide with the bright fringes for the second wavelength (λ_2), the result is maximum contrast. When the bright fringes from λ_1 coincide with the dark fringes from λ_2, the result is minimum contrast.

(7) Adjust the micrometer to a position which gives approximately maximum contrast. Measure $\lambda \simeq \lambda_1 \simeq \lambda_2$ by counting fringes, as you did for the mercury light.

(8) Now determine some positions of the micrometer which correspond to minimum fringe visibility. In your report, show that:

$$\frac{1}{\lambda_1} - \frac{1}{\lambda_2} = \frac{1}{2t}$$

where t is the distance moved by the mirror between positions of minimum contrast. This can be rearranged to:

$$\lambda_2 - \lambda_1 = \frac{\lambda_1 \lambda_2}{2t} \simeq \frac{\lambda^2}{2t}.$$

Use this, together with your measurements to determine $\lambda_2 - \lambda_1$.

White light fringes

(9) Go back to using the lamp housing containing the mercury and white light sources. Remove the green filter and return it to its plastic box. White light fringes can only be observed if the separations between each mirror and beam splitter are equal to within a few wavelengths of visible light. In other words, the micrometer must be adjusted to lie within a very narrow range of values. The first task

is to identify candidate ranges. Two pieces of information can act as a guide. Firstly, the spacing between the circular fringes increases as you approach zero path difference (see page 322-2). Near zero path difference, the central fringe is expected to expand and occupy the entire field of view. This is assuming the mirrors are perfectly flat. In a real instrument, the mirrors are often slightly curved. The position at which the central fringe has maximum diameter is then somewhat displaced from zero path difference. Hence, this first piece of information can only be used to localize zero path difference within a few millimetres. The second piece of information is the positions of minimum contrast obtained with the sodium lamp (and hence, by extrapolation, the positions of maximum contrast; it is left to you to try and deduce if zero path difference will coincide with a point of maximum contrast, minimum contrast, or some other alternative).

(10) Once you have identified candidate ranges, use the mercury light to adjust the tilt of the fixed mirror until you are looking near the centre of the circular fringe pattern. Then change to the white light and *slowly* scan the moveable mirror. Sufficiently close to zero path difference, the white illumination will abruptly transform into vivid colours. These are white light fringes. Set the micrometer to the position where the colours are the most saturated, and tilt the fixed mirror again to get about 10 horizontal fringes across the field. You may have to make small adjustments to the micrometer to centre these in the field.

(11) Examine the fringes closely. Notice how they are black and white in the middle, then get edges of saturated colour as you move out, finally becoming more and more pastel-coloured, until they disappear into the white background. Explain these phenomena in your report.

Measurement of the thickness of a glass cover slip

(12) The glass cover slip is delicate - please treat it gently.

Place the glass cover slip in one of the interferometer arms so that it covers half the beam. You should see white light fringes in the uncovered part of the field, but nothing where the glass is. Note the micrometer reading, and then move the micrometer to restore white light fringes in the part of the field covered by the glass. Derive an equation from which you can calculate its thickness from the micrometer readings. Assume that the glass is standard Borosilicate glass, (you will need to look up its properties in the data books provided in the lab) and calculate its thickness. Be sure to show your derivation, assumptions, and calculation steps clearly in your report. The lab technician may have spare slips that you can measure with a micrometer as a comparison. See your demonstrator.

Note any differences between the original white light fringes, and the fringes after you have restored them in the part of the field covered by the glass. Explain these in your report.

List of Equipment

1. Ealing Michelson interferometer with diffuser and green filter
2. Mercury, white light, and sodium sources
3. Clip-on pointer
4. Glass cover slip

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