Experiment 8

Interferometers

Equipment Needed

- Interferometer base.
- Adjustable mirror.
- Movable mirror.
- Beam splitter
- Component holder (2)
- Viewing screen
- 18 mm FL lens
- Diffuser
- Laser(OS-9171)
- Laser Bench (OS-9172)
- Rotating pointer
- Vacuum cell.
- Polarizer (2)
- Vacuum Pump with gauge.

Introduction

Interference Theory

A beam of light can be modeled as a wave of oscillating electric and magnetic fields. When two or more beams of light meet in space, these fields add according to the principle of superposition. That is, at each point in space, the electric and magnetic fields are determined as the vector sum of the fields of the separate beams.

If each beam of light originates from a separate source, there is generally no fixed relationship between the electromagnetic oscillations in the beams. At any instant in time there will be points in space where the fields add to produce a maximum field strength. However, the oscillations of visible light are far faster than the human eye can discern. Since there is no fixed relationship between the oscillations, a point at which there is a maximum at one instant may have a minimum at the next instant. Your eye averages these results and perceives a uniform intensity of light.

If the beams of light originate from the same source, there is generally some degree of correlation between the frequency and phase of the oscillations. At one point in space the light from the beams may be continually in phase. In this case, the combin the light from the beams may be continually out of phase and a minima, or dark spot, will be seen.

Thomas Young was one of the first to design a method for producing such an interference pattern. He allowed a single, narrow beam of light to fall on two narrow, closely space slits. Opposite the slits he place a viewing screen. Where the light from the two slits struck the screen, a regular pattern of dark and bright bands appeared. When first performed, Young's experiment offered importand evidence for the wave nature of light.

Young's slits can be used as a simple interferometer. If the spacing between the slits is known, the spacing of the maxima and minima can be used to determine the wavelength of the light. Conversely, if the wavelength of the light is known, the spacing of the slits could be determined from the interference patterns.

Michelson Interferometer

In 1881, 78 years after Young introduced his two slit experiment, A. A. Michelson designed and built an interferometer using a similar principle. Originally Michelson designed his interferometer as a means to test for the existence of the ether, a hypothesized medium in which light propogated. Due in part to his efforts, the ether is no longer considered a viable hypothesis. But beyond this, Michelson's interferometer has become a widely used instrument for measuring the wavelength of light, for using the wavelength of a known light source to measure extremely small distances, and for investigating optical media.

Figure 8 shows a diagram of a Michelson interferometer. The beam of light from the laser strikes the beam-splitter, which reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams; one beam is transmitted toward the movable mirror (M_1),

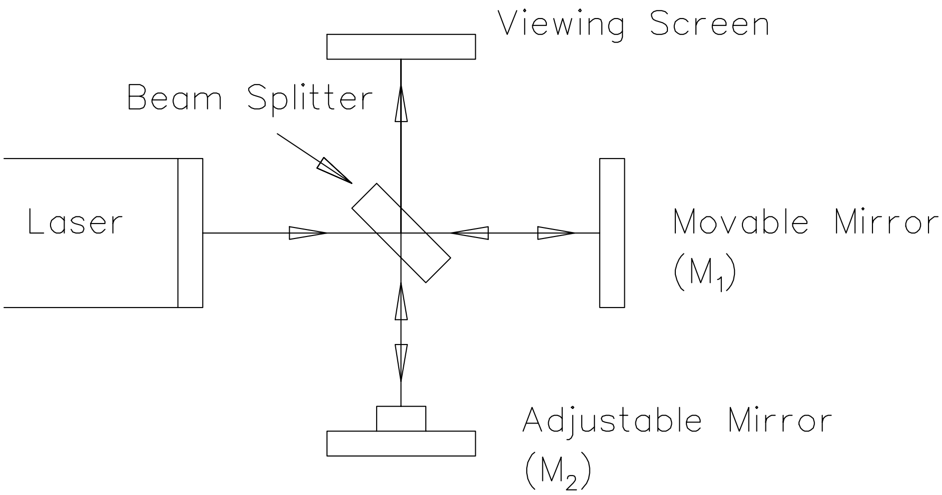

Figure 8.1 – Michelson interferometer.

the other is reflected toward the fixed mirror (M_2). Both mirrors reflect the light directly back toward the beam splitter. Half the light from M_1 is reflected from the beam splitter to the viewing screen and half the light from M_2 is transmitted through the beam splitter to the viewing screen.

In this way the original beam light is split and portions of the resulting beams are brought back together. Since the beams are from the same source, their phases are highly correlated. When a lens is placed between the laser source and the beams splitter, the light ray spreads out and an interference pattern of dark and bright rings, or fringes, is seen on the viewing screen.

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 therefore depends on the difference in the length of their optical paths in reaching that point.

By moving M_1, the path length of one of the beams can be varied. Since the beam traverses the path between M_1 and the beam splitter twice, moving M_1 1/4 wavelength nearer the beam splitter will reduce the optical path of that beam by 1/2 wavelength. The interference pattern will change; the radii of the maxima will be reduced so that they occupy the position of the forma minima. If M_1 is moved an additional 1/4 wavelength closer to the beam splitter, the radii of the maxima will again be reduced so maxima and minima trade positions, but this new arrangement will be indistinguishable from the original pattern.

By slowly moving the mirror a measured distance d_m, and counting m, the number of times the fringe pattern is restored to its original state, the wavelength of the light λ can be calculated as:

$$\lambda = \frac{2d_m}{m} \tag{1}$$

If the wavelength of the light is known, the same procedure can be used to measure d_m.

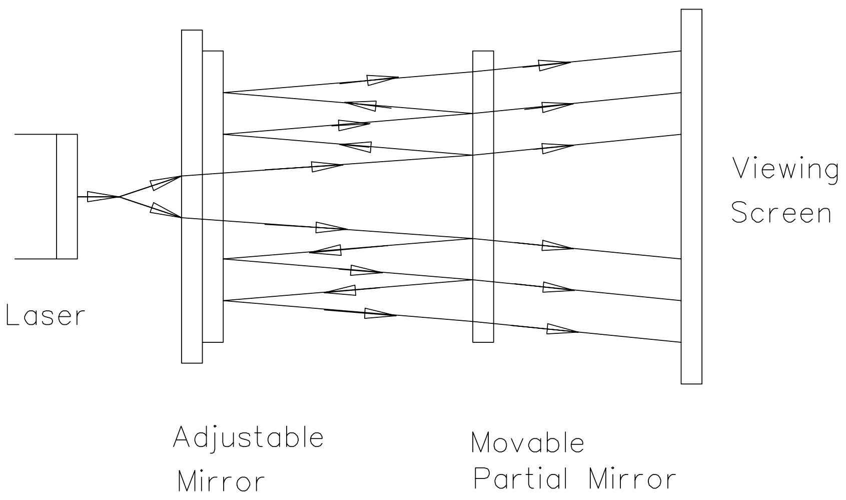

Figure 8.2 – Fabry-Perot interferometer.

The Fabry-Perot Interferometer

In the Fabry-Perot Interferometer, two partial mirrors are aligned parallel to one another, forming a reflective cavity. Figure 8 shows two rays of light entering such a cavity and reflecting back and forth inside. At each reflection, part of the beam is transmitted, splitting each incident ray into a series of rays. Since the transmitted rays are all split from a single incident ray, they have a constant phase relationship (assuming a sufficiently coherent light source is used).

The phase relationship between the transmitted rays depends on the angle at which each ray enters the cavity and on the distance between the two mirrors. The result is a circular fringe pattern, similar to the Michelson pattern, but with fringes that are thinner, brighter, and more widely spaced. The sharpness of the Fabry-Perot fringes makes it a valuable tool in high resolution spectrometry. As with the Michelson Interferometer, as the movable mirror is moved toward or away from the fixed mirror, the fringe pattern shifts. When the mirror movement is equal to 1/2 of the wavelength of the light source, the new fringe pattern is identical to the original.

8.1 Setup and Operation

8.1.1 Laser

A. Set the interferometer base on a lab table with the micrometer knob pointing toward you.

B. Position the laser alignment bench to the left of the base approximately perpendicular to the interferometer base and place the laser on the bench.

C. Secure the movable mirror in the recessed hole in the interferometer base.

D. Turn the laser on. Using the leveling screws on the laser bench, adjust its height until the laser beam is approximately parallel with the top of the interferometer base and strikes the movable mirror in the center. To check that the beam is parallel with the base, place a piece of paper in the beam path, with the edge of the paper flush against the base. Mark the height of the beam on the paper. Using the piece of paper, check that the beam height is the same at both ends of the bench.

E. Adjust the X–Y position of the laser until the beam is reflected from the movable mirror right back into the laser aperture. This is most easily done by gently sliding the rear end of the laser transverse to the axis of the alignment bench.

You are now ready to set up the interferometer in any of its modes of operation.

Michelson Mode

A. Align the laser and interferometer as described above.

B. Mount the adjustable mirror on the interferometer base. Position one component holder in front of the laser. Place the other component holder opposite the adjustable mirror and attach the viewing screen to its magnetic backing.

C. Position the beam splitter at a 45 degree angle to the laser beam, within the crop marks, so that the beam is reflected to the fixed mirror. Adjust the angle of the beam splitter as needed so that the reflected beam hits the fixed mirror near its center.

D. There should now be two sets of bright dots on the viewing screen; one set comes from the fixed mirror and the other comes from the movable mirror. Each set of dots should include a bright dot with two more more dots of lesser brightness (due to multiple reflections). Adjust the angle of the beam splitter again until the two sets of dots are as close together as possible, then tighten the thumbscrew to secure the beam spli

E. Using the thumbscrews on the back of the adjustable mirror, adjust the mirror's tilt until the two sets of dots on the viewing screen coincide.

F. Attach the 18 mm FL lens to the magnetic backing of the component holder in front of the laser as shown, and adjust its position until the diverging beam is centered on the beam splitter. You should now see circular fringes on the viewing screen. If not, carefully adjust the tilt of the adjustable mirror until the fringes appear.

8.1.2 Fabry-Perot Mode

A. Align the laser and interferometer base as described in the *Laser* section above.

B. Mound the adjustable mirror where indicated on the interferometer base and one component holder in front of the movable mirror. See Figure 8.

C. Place the other component holder behind the movable mirror and attach the viewing screen to its magnetic backing. You should see several images of the laser beam on the viewing screen.

D. Using the thumbscrews, adjust the tilt of the adjustable mirror until there is only one bright dot on the screen.

E. Now mount the 18 mm FL lens on the front component holder. A clear sharp interference patter should be visible on the viewing screen.

8.1.3 Accurate Fringe Counting

The following techniques can help you make accurate measurements.

A. It's not necessary that your interference pattern be perfectly symmetrical or sharp. As long as you can clearly distinguish the maxima and minima, you can make accurate measurements.

B. It's easy to lose track when counting fringes. The following technique can help. Center the interference patter on the viewing screen using the thumbscrews on the back of the fixed mirror. Select a reference line on the millimeter scale and line it up with the boundary between a maximum and a minimum. Move the micrometer dial until the boundary between the next maximum and minimum reaches the same position as the origina boundary. The fringe pattern should look the same as in the original position. One fringe has gone by.

C. When turning the micrometer dial to count fringes, always turn it one complete revolution before you start counting, then continue turning it in the same direction while counting. This will almost entirely eliminate errors due to backlash in the micrometer movement. Backlash is a slight slippage that always occurs when you reverse the direction of motion in a mechanical system. (Turning the micrometer dial clockwise moves the movable mirror toward the right.)

D. Always take several readings and average them for greater accuracy.

E. The slip ring at the base of the micrometer knob adjusts the tension in the dial. Before making a measurement, be sure the tension is adjusted to give you the best possible control over the mirror movement.

F. Warm up the laser. Many lasers vary in intensity and/or polarization as they warm up. To eliminate any possible fringe or intensity variations, allow the laser to warm up for at least an hour, if possible, before setting up an experiment.

8.2 Determining Laser Wavelength

8.2.1 Fabry-Perot

A. Align the laser and interferometer in Fabry-Perot mode.

B. Adjust the micrometer knob to a medium reading (approximately 50 μm). In this position, the relationship between the micrometer reading and the mirror movement is most nearly linear.

C. Turn the micrometer knob one full turn counterclockwise. Continue turning counterclockwise until the zero on the knob is aligned with the index mark. Record the micrometer reading.

D. Adjust the position of the viewing screen so that one of the marks on the millimeter scale is aligned with one of the fringes in your interference pattern. You will find it easier to count the fringes if the reference mark is one or two fringes out from the center of the pattern.

E. Rotate the micrometer knob slowly counterclockwise. Count the fringes as they pass your reference mark. Continue until some predetermined number of fringes have passed your mark. Count **at least** 20 fringes. As you finish your count, the fringes should be in the same position with respect to your reference mark as they were when to count. Record the final reading of the micrometer dial.

F. Record d_m, the distance that the movable mirror moved toward the beam splitter according to your readings of the micrometer knob. Remember, each small division on the micrometer knob corresponds to 1 μm (10^{-6} m) of mirror movement.

G. Record m, the number of fringe transitions that you counted.

H. Repeat the above steps several steps, recording your results several times.

I. For each trial, calculate the wavelength of the light, then average your results.

8.2.2 Michelson

A. Align the laser and interferometer in the Michelson mode, so an interference pattern is clearly visible on the viewing screen.

B. Adjust the micrometer knob to a medium reading (approximately 50 μm). In this position, the relationship between the micrometer reading and the mirror movement is most nearly linear.

C. Turn the micrometer knob one full turn counterclockwise. Continue turning counterclockwise until the zero on the knob is aligned with the index mark. Record the micrometer reading.

D. Adjust the position of the viewing screen so that one of the marks on the millimeter scale is aligned with one of the fringes in your interference pattern. You will find it easier to count the fringes if the reference mark is one or two fringes out from the center of the pattern.

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G. Record m, the number of fringe transitions that you counted.

H. Repeat the above steps several steps, recording your results several times.

I. For each trial, calculate the wavelength of the light, then average your results.

J. Place a polarizer between the laser and the beam splitter. Try several polarization angles. How does this affect the brightness and clarity of the fringe pattern.

K. Remove that polarizer and place in front of the fixed or movable mirror. Try several polarization angles. How does this affect the fringe pattern?

L. Now try two polarizers, one in front of the fixed mirror and one in front of the movable mirror. First rotate one polarizer, then the other. Again, note the effects. Do cross-polarized beams interfere?

M. Remove the polarizers.

8.3 The Index of Refraction of Air

In the Michelson interferometer, the characteristics of the fringe pattern depend on the phase relationship between the two interfering beams. There are two ways to change this phase relationship: one way is to change the distance travelled by one or both beams (by moving the movable mirror, for example), another is to change the medium through which one or both of the beams pass. In this part of the experiment, you will use the second method to measure the index of refraction of air.

For light of a specific frequency, the wavelength λ varies according to the formula:

$$\lambda = \lambda_0/n \tag{2}$$

where λ_0 is the wavelength of the light in a vacuum and n is the index of refraction for the material in which the light is propogating. For reasonably low pressures, the index of refraction for a gas varies linearly with the gas pressure. Of course, for a vacuum, where the pressure is zero, the index of refractin is exactly 1. By experimentally determing the slope, the index of refraction of air can be determined at various pressures.

A. Align the laser and interferometer in Michelson mode.

B. Place the rotational pointer between the movable mirror and the beam splitter. Attach the vacuum cell to its magnetic backing and push the air hose of the vacuum pump over the air outlet hole of the cell. Adjust the alignment of the fixed mirror as needed so the center of the interference patternis clearly visible on the viewing screen. The fringe pattern will be somewhat distorted by irregularities in the glass end-plates of the vacuum cell, but this is not a problem.

C. For accurate measurements, the end-plates of the vacuum cell must be perpendicular to the laser beam. Rotate the cell and observe the fringes. Based on your observations, how can you be sure that the vacuum cell is properly aligned?

D. Evacuate the vacuum cell and record the initial pressure in the cell P_i.

E. Slowly let air back into the cell by flipping the vacuum release toggle switch. Record m, the number of fringe transitions that occur, and P_f, the final cell pressure.

As the laser beam passes back and forth between the beam splitter and the movable mirror, it passes twice through the vacuum cell. Outside the cell the optical path lengths of the two interferometer beams do not change throughout the experiment. Inside the cell, however, the wavelength of the light gets longer as the pressure is reduced.

Suppose that originally the cell length d was 10 wavelengths long (of course, it's much longer). As you pump out the cell, the wavelength increases until, at some point, the cell is only 9.5 wavelengths long. Since the laser beam passes twice through the cell, the light now goes though one less oscillation within the cell. This has the same effect on the interference pattern as when the movable mirror is moved toward the beam splitter by 1/2 wavelength. A single fringe transition will have occured.

Originally there are $N_i = 2d/\lambda_i$ wavelengths of light within the cell (counting both passes of the laser beam). At the final pressure there are $N_f = 2d/\lambda_f$ wavelengths within the cell. The difference between these values: $N_i - N_f$ is just m, the number of fringes you counted as you evacuated the cell. Therefore $m = 2d(n_i - n_f)/\lambda_0$; so that $n_i - n_f = m\lambda_0/2d$. The slope of the n *vs.* pressure graph is therefore:

$$\frac{n_i - n_f}{P_i - P_f} = \frac{m\lambda_0}{2d(P_i - P_f)} \tag{3}$$

where $P_i(P_f)$ is the initial (final) air pressure, $n_i(n_f)$ is the index of refraction of air at pressure $P_i(P_f)$, m is the number of fringe transitions counted, λ_0 is the wavelength of the laser light in vacuum (see the lab T.A. or use the value measured in the first part of the experiment for the laser wavelength in air.), and d is the length of the vacuum cell (3.0 cm).

A. Graph the index of refraction n *vs.* pressure for air and calculate the slope of the graph.

B. Find the index of refraction of air at a pressure of 1 atmosphere.

8.4 Index of Refraction of Glass

In the above section the index of refraction of air was measured by slowly varying the density of air along a fixed length of one beam path in the Michelson Interferometer. That method obviously won't work with a solid substance, such as glass. Therefore, in order to measure the index of refraction of glass, it's necessary to slowly vary the length of glass through which the interferometer beam passes. This experiment introduces a technique for making such a measurement.

A. Align the laser and interferometer in the Michelson mode.

B. Place the rotating talbe between the beam splitter and movable mirror, perpendicular to the optical path.

C. Mount the glass plate on the magnetic backing of the rotational pointer.

D. Position the pointer so that its "0" edge on the Vernier scale is lined up with the zero on the degree scale on the interferometer base.

E. Remove the lens from in front of the laser. Hold the viewing screen between the glass plate and the movable mirror. If there is one bright dot and some secondary dots on the viewing screen, adjust the angle of the rotating table until there is one

F. Replace the viewing screen and the lens and make any minor adjustments that are necessary to get a clear set of fringes on the viewing screen.

G. Slowly rotate the table by moving the lever arm. Count the number of fringe transitions that occur as you rotate the table from 0 degrees to an angle θ (where θ is at least 10 degrees).

In principle, the method for calculating the index of refraction is relatively simple. The light passes through a greater length of glass as the plate is rotated. The general steps for measureing the index of refraction is as follows:

A. Determine the change in the path length of the light beam as the glass plate is rotated. Determine how much of the change in path length is through glass $d_g(\theta)$, and how much is through air, $d_a(\theta)$.

B. Relate the change in path length to your measured fringe transitions with the following equation:

$$\frac{2n_a d_a(\theta) + 2n_g d_g(\theta)}{\lambda_0} = N \tag{4}$$

where n_a is the index of refraction of air (measured above), n_g is the index of refraction of glass (as yet unknown), λ_0 is the wavelength of the laser in vacuum and N is the number of fringe transitions that you counted.

Carrying out this analysis (a bonus point for those who work this out before the lab and show the T.A. the analysis), gives the following result for the index of refraction in glass:

$$n_g = \frac{(2t - n\lambda) + (1 - \cos\theta)}{2t(1-\theta) - N\lambda_0} \tag{5}$$

where t is the thickness of the glass plate.