

Lab 3: Coherence and Interferometry

6.2370 Modern Optics Project Laboratory
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I. INTRODUCTION

This lab aims to explore the constructive and destructive interference behavior between coherent light waves. When light is coherent, its phase is independent of time. In this state, phase differences between light sources can be determined by examining path length differences between rays. By manipulating paths of travel, one is able to determine whether a "sharp" or "null" point in the wave is formed. In the lab, these concepts are used to determine physical properties of dielectrics, such as their dimensions and flatness. They are also used to analyze the structures of interference patterns.

II. APPROACH

The approaches for each experiment will be separated into sections.

A. 3.2 Flatness Measurements

In this experiment, we are given four glass samples with unknown curvatures. To determine the relative flatness of the glass samples, we utilize a sodium lamp and reference flat. Fig 1 demonstrates a schematic of this setup. First, the optical flat is selected. The flats are designed with extraordinary care so as to be nanometers off from perfect flatness. They also provide little noise to the interference fringe observations. After this, a lens cleaning paper is placed on the flat. Next, the sample's curved side is placed facing the flat. This allows light hitting the sample to travel different path lengths, thus creating interference patterns. Following this, the cleaning paper is slowly slid off the flat. This allows the paper to clean any dust on the flat, which could massively alter the fringe results. Finally, a sodium vapor lamp emitting green light is shone at an angle relative to the glass sample. The lamp is used to isolate the interference patterns into a single color and thus make interpreting results easier. Had we used white light/ceiling light, we would have observed colorful and faint interference patterns.

B. 3.3 Parallelism Measurements

In this experiment, we are given five glass slides with unknown parallel plane features. To determine the relative parallel plane features of each slide, we utilized a sodium lamp and the concept of Haidinger fringes. Fig 2 demonstrates the working principles of our approach. First, the slides are placed on a clean, flat surface. There is no need for an optical flat since the parallel plane features will be pronounced enough for our observations. Next, a sodium lamp emitting green light

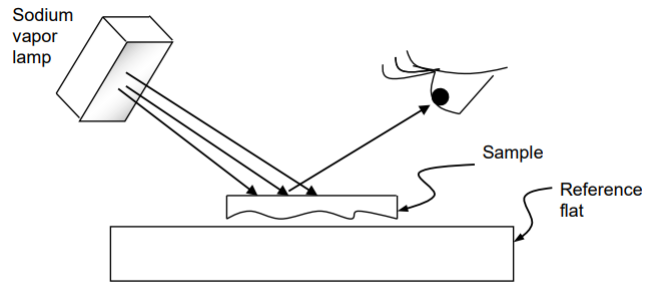


Fig. 1: Working Principle of Flatness Measurements

is shone above the slides. Inside the sample, the light rays consecutively bounce in the slide, transmitting parallel rays as a result. These transmitted rays generate the observed fringes.

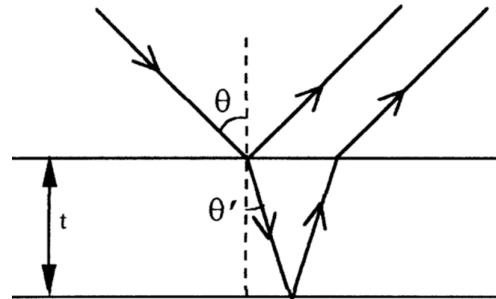


Fig. 2: Working Principle of Haidinger Fringes

C. 3.4 Multiple Beam Interferometry with a Thin Glass Plate

In this experiment, we are asked to determine fringe patterns produced by a thin glass slide based on the incident angle of TE-polarized light. Fringe patterns are observed at incident angles equal to around 0 degrees (incident wave normal), around 45 degrees, and around 90 degrees (incident wave grazing surface). Fig 3 demonstrates a schematic of the setup. A polarizer is set up such that its polarizing axis is perpendicular to the incident plane of the setup. This allows for TE-polarized light. After this, a beam expander followed by a lens is set in front of the polarizer. By moving the third lens, it is possible to control the light concentration incident on the glass. Next, the glass slide is set on a rotary table and set in front of the third lens. Two screens are then set up to determine the locations of the produced fringes.

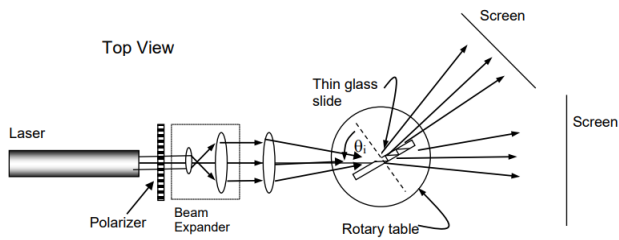


Fig. 3: Multiple Beam Interference Setup Schematic

D. 3.6 Fabry-Perot Interferometer

The objective of this lab is to understand the optical workings of a Fabry-Perot interferometer. Fig 4 demonstrates a schematic of the setup. A lens is set in front of a collimated laser source, allowing the light to converge and then diverge. A diffuser is then set in front of the diverging light, spreading the light radially outwards from the optical axis. The light then encounters a cavity with highly reflecting mirrors. Light bounces around in this cavity, with some light transmitting out of the area and towards a lens. The lens then provides a sharp image of the fringe patterns on a screen.

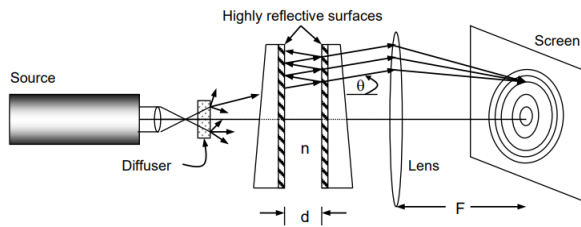


Fig. 4: Fabry-Perot Interferometer Setup Schematic

E. 3.7 Lummer-Gehrcke Interferometer

The objective of this exercise was to understand the optical workings of a Lummer-Gehrcke interferometer. Fig 5 demonstrates a schematic of the setup. A light-coupling prism is attached to a thin glass plate. The prism is specifically designed to allow light incident to its flat face reflect in the glass slide near critical angle. When light is incident to a surface near its critical angle, the transmitted light grazes the surface of the medium. The light then hits a screen, where an interference pattern is visible.

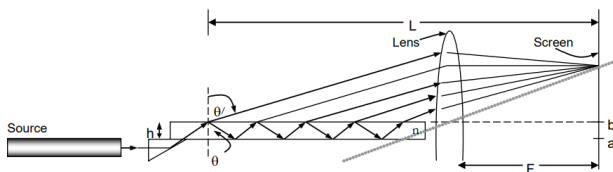


Fig. 5: Lummer-Gehrcke Interferometer Setup Schematic

III. RESULTS

The results for each experiment will be separated into sections.

A. 3.2 Flatness Measurements



Fig. 6: Green Light Incident to Glass Samples of Various Curvatures

B. 3.3 Parallelism Measurements

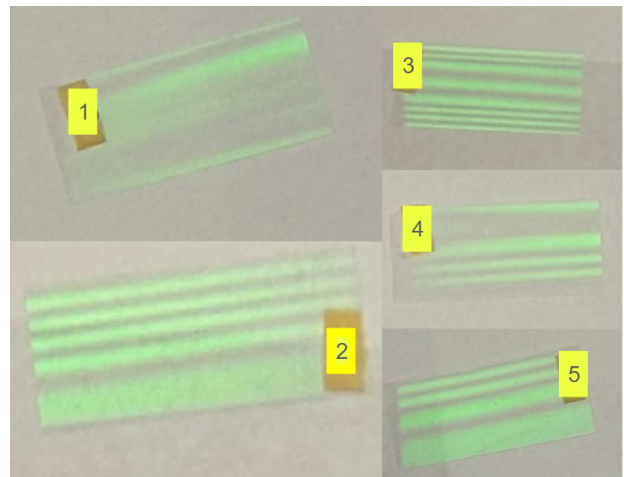


Fig. 7: Green light Incident to Glass Slides of Various Curvatures

C. 3.4 Multiple Beam Interferometry with a Thin Glass Plate (Fig 8, Fig 9, Fig 10)

D. 3.6 Fabry-Perot Interferometer (Fig 11)

E. 3.7 Lummer-Gehrcke Interferometer (Fig 12)

IV. DISCUSSION

The discussions for each experiment will be separated into sections.

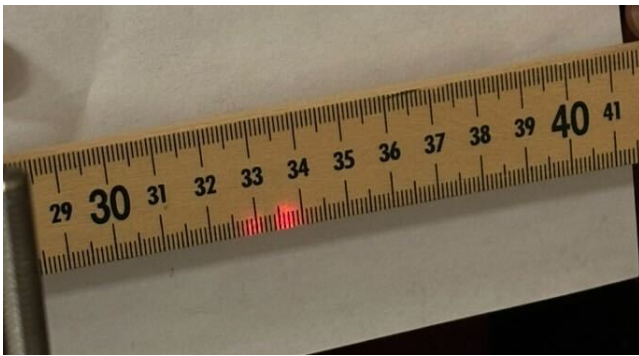


Fig. 8: Angle of Incidence around Normal

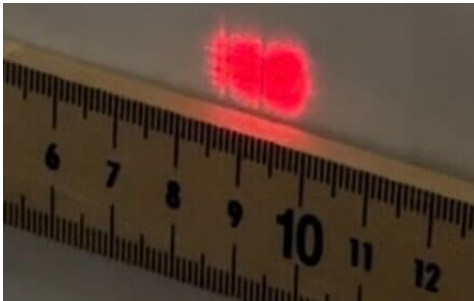


Fig. 9: Angle of Incidence around 45 Degrees

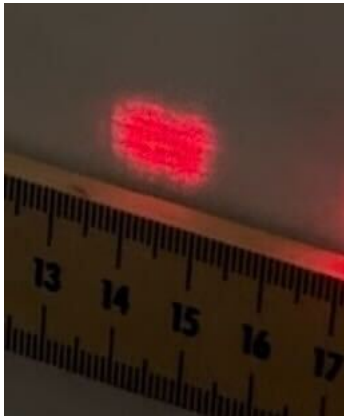


Fig. 10: Angle of Incidence around 90 Degrees (Grazing)

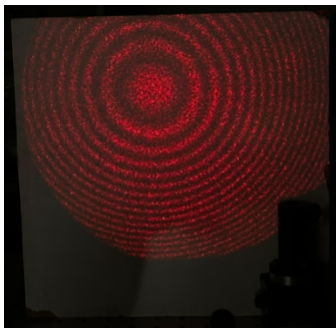


Fig. 11: Interference Pattern for Fabry-Perot Interferometer

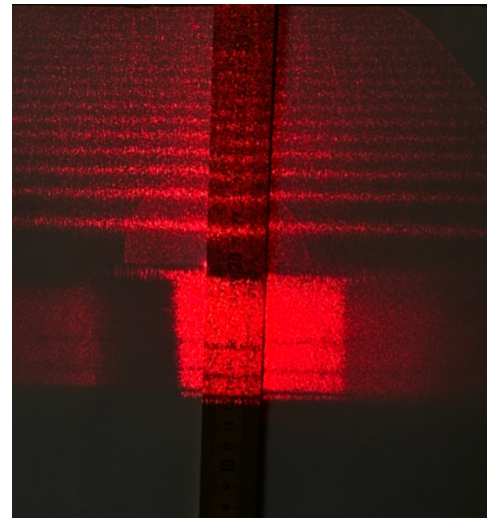


Fig. 12: Interference Pattern for Fabry-Perot Interferometer

A. 3.2 Flatness Measurements

To determine the general flatness of each sample, we look at how parallel each fringe is. In the ideal flat case, we know that the fringes will be uniformly-spaced and parallel with each other. I will analyze each sample from Fig 6.

Sample A: Sample A appears to have concentric rings with uniform, parallel fringes to the left and right. This implies that there is some air gap in the center and flatness to the edges.

Sample B: Sample B appears to be flat to on its left side and curves on its right side. This implies that the left area is flat, while the right area seems to have an air gap. It is not as intense as A's curvature, however, since there are no concentric circles, implying an air gap that began but did not fully develop.

Sample C: Sample C has around four areas with concentric circles, implying numerous air gaps and, thus, a curvature more intense than A and B.

Sample D: Sample D appears to be very flat, as the fringes are parallel.

With this analysis, my ranking of the glass samples (from most to least flat) is:

D, B, A, C

B. 3.3 Parallelism Measurements

Upon viewing the results of this experiment (Fig 7), all samples have parallel lines as fringes, meaning a more sophisticated strategy from the optical flat exercise is necessary. One observation to use is the spacing between fringes. In an ideal slide, the spacing between fringes should

be uniform. Another important consideration is the sharpness of the fringes. A sharper fringe implies greater interference, which implies a much flatter surface. I will analyze each sample from Fig 7 to determine a ranking of the slides from most to least plane parallel.

Slide 1: The sample has very abrupt and inconsistent changes in fringe spacing. The fringes are also rather dull.

Slide 2: The sample has much better spacing consistency than sample 1. There is an interruption to uniform fringe spacings at the bottom portion. The fringes are somewhat sharp.

Slide 3: The sample overall has better fringe spacing than 1 and 2. The fringes are quite sharp at the top and bottom and less so in the middle.

Slide 4: The sample has consistent fringe spacing at the bottom, but begins to increase near the top. The sharpness is somewhat good.

Slide 5: The sample has about the same spacing consistency as sample four, but with uniform spacing near the top rather than the bottom. The sharpness of the fringes seems to be slightly better than slide 4.

Based on these observations, this is my ranking of most to least plane parallel slide samples:

3, 2, 5, 4, 1

C. 3.4 Multiple Beam Interferometry with a Thin Glass Plate

In analyzing my results for this section, I will refer to the post-lab questions.

(a) For the experiment above, explain your observed results (from a theoretical point of view) for the smallest fringe separation [Hint: consider $d\delta/d\theta$].

The smallest fringe separation distance was when we arranged the rotary table such that the angle of incidence was about 45 degrees. The formula for phase difference is as follows:

$$\delta = \frac{4\pi h}{\lambda} \left(\frac{1}{2} \right) (n_1^2 - \sin^2(\theta_i))^{1/2}$$

The derivative with respect to incident angle, $\frac{d\delta}{d\theta_i}$, is proportional to:

$$\frac{d\delta}{d\theta_i} \propto \frac{-2\sin(\theta_i)\cos(\theta_i)}{(n_1^2 - \sin^2(\theta_i))^{1/2}}$$

Plotting these formulas on Desmos and approximating n_1 to 1.5, we get the following relations in Fig 13. As seen, at $\theta_i = \frac{\pi}{4}$, $d\delta/d\theta_i$ reaches a minimum, implying that the region around

$\frac{\pi}{4}$ is where phase changes the greatest, meaning destructive interference happens at a greater frequency, thus giving smaller fringe spacings.

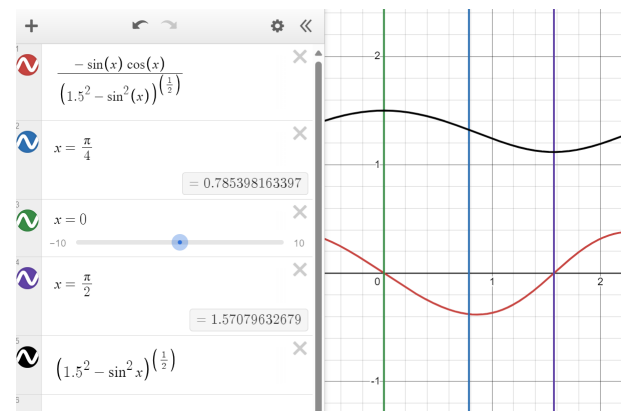


Fig. 13: Graphs of Phase (δ) with x-axis as θ_i [Black: δ] [Red: $d\delta/d\theta_i$]

(b) Explain why near grazing incidence the reflected interference pattern consists of dark fringes on a bright background, while near normal incidence the pattern could be interpreted as either dark fringes on a bright background or vice versa.

Near grazing incidence, most of the laser power is reflected, leaving only a few laser sources to bounce in the glass and transmit interfering waves. Near normal incidence, a fairly equal amount of the power either transmits through the glass repeatedly reflects in the medium. Thus, based on very minute angle changes, you could observe either dark fringes on a bright background or bright fringes on a dark background.

(c) What important statements can you make concerning the complementarities of the reflected and transmitted beams? Justify your statements.

By the conservation of energy, the reflectivity of the glass surface is inversely proportional to the transmissivity of the glass. This is supported by the formula:

$$R + T = 1$$

where R is the percent of reflected power from a boundary and T is the percent of transmitted power from a boundary. This formula makes physical sense since, assuming the boundary material does not absorb the laser energy, any reflected or transmitted rays should sum up to the power of the incident beam.

D. 3.6 Fabry-Perot Interferometer

I will refer to the post-lab questions on this section of the lab to analyze this interferometer.

(1) Write the condition for a bright maximum

The bright maximum condition can be given as:

$$m\lambda = 2nd\cos(\theta_t)$$

Since the cavity with the reflective mirrors is air, $n = 1$, so this equation can be further simplified to:

$$m\lambda = 2d\cos(\theta_t)$$

(2) Explain why circular fringes are obtained.

Circular fringes are obtained because of the diffuser material. By spreading the waves radially outwards from the optical axis, there are numerous waves in all directions. These waves can go on to interact with the mirror cavity and image onto the sheet, thus making a circular pattern.

(3) From the data in (a) determine the order of interference of the innermost bright ring and the thickness d of the air gap

To determine the height of of the dielectric, we can use the given formulas in the lab handout:

$$m_1\lambda = 2nd\cos(\theta_t)$$

$$m_2\lambda = (m_1 - \Delta m)\lambda = 2nd\cos(\theta_t)$$

we can approximate the angles of transmission by measuring the distance between fringes and knowing the distance between the lens and screen. The length between the lens and screen was set to be the focal length of the lens, which is 45 cm. "m" refers to the order of light, which is defined here as the integer locations where a bright maximum is obtained. The lens is also removed to remove magnification effects from the lens. Using measurements, the fringe length between the center of the ring and the 1th order is about 2.5cm, while the distance between the center of the ring and the 4th order is about 5cm. Using $\tan(\theta) = \frac{\text{opposite}}{\text{adjacent}}$.

$$\tan(\theta_1) = \frac{2.5}{45} \approx \theta_1 = \frac{1}{18}$$

$$\tan(\theta_4) = \frac{5}{45} \approx \theta_4 = \frac{1}{9}$$

$$\Delta m\lambda = 2d(\theta_4^2 - \theta_1^2)/2$$

$$d = \frac{\Delta m\lambda}{\theta_4^2 - \theta_1^2} \approx 0.2[\text{mm}]$$

The order of the innermost bright ring is thus:

$$m_1 = \frac{2d\cos(\theta_1)}{\lambda} \approx 647$$

E. 3.7 Lummer-Gehrcke Interferometer

For this section analysis, I will discuss the features visible on from the interference pattern based on the post lab questions.

To determine the order of interference of the slide used in the Lummer Gehrcke interferometer, we can use the following measured values:

$$d = 150[\mu\text{m}]$$

$$\theta \approx \frac{2.5[\text{cm}]}{100[\text{cm}]}$$

$$\lambda = 633[\text{nm}]$$

And some known values/formulas:

$$n_{\text{glass}} = 1.5$$

$$m = \frac{2nd\cos(\theta)}{\lambda}$$

$$m \approx \frac{(2)(1.5)(150 * 10^{-6})\cos(\frac{2.5}{100})}{633 * 10^{-9}} \approx 710$$

Using this value to find the refractive index of the glass slide:

$$n = \frac{m\lambda}{2d\cos(\theta)} = \frac{(710)(633 * 10^{-9})}{(2)(150 * 10^{-6})(\cos(\frac{2.5}{100}))} = 1.49 \approx n_{\text{glass}}$$

Although the input laser beam is well collimated, the Lummer-Gehrcke interferometer still outputs numerous fringes at various transmission angles. This can be explained by the numerous reflections light experiences inside of the glass. The numerous reflections allow for waves of the same transmission angle to escape the medium at different locations, allowing for a wide spread of interference patterns on the screen.

V. CONCLUSION

Overall, interferometry is a powerful tool for measuring the general flatness of objects. By using fundamental coherence properties, one is able to calculate properties of small objects that are otherwise impossible to determine, such as their heights and slight slants.