PHY 108L Optics Lab

EXPERIMENTS: page

APPENDIX:

Mean Free Path (MFP) of A Light Beam through Highly Scattering Media

REFERENCES:

Jenkins and White, *Fundamentals of Physical Optics* (McGraw-Hill)

INTRODUCTION:

Like a molecule in a gas or liquid that repeatedly experiences collisions with other molecules and in turn velocity changes as result of the collisions, a light beam experiences repeated scatterings when traveling through media such as cloud, milk or human tissues where the indices of refraction change rapidly with distance. These media are called turbid media. These media are convenient models for studying light beam propagation through media with finite scattering loss and absorption loss. Detailed understanding of light propagation through human tissues promises hope of new optical imaging techniques for detecting tumors in human tissues.

The objectives of this lab are to learn:

I. Concept of scattering and mean-free path of a light beam through a turbid medium.

II. Setting up a precision measurement of the mean-free-path with a simple experimental arrangement involving only introductory-level optics such as wedge-shaped gap.

III. Computer automation of data acquisition.

IV. AC signal detection methods (soft-ware based spectral analysis).

THEORY:

When you look at a glass of milk, you can see that light passes through it. However, most of the individual photons scatter many times before emerging, and no clear image is formed. Such a medium is said to be turbid. On average, photons travel a distance ℓ between collisions in a turbid medium; ℓ is called the mean free path. In general, the mean free path depends on the medium and on the wavelength of light.

When a monochromatic light beam of intensity I_0 is directed through a layer of turbid medium of thickness *x*, then the emerging intensity is a combination of (i) $I_{diffuse}(x)$, multiply-scattered light which manages to find its way (diffuses) out of the medium in the forward direction and (ii) $I(x)$, unscattered light. In this experiment, we will employ a sample sufficiently thin that the emerging intensity is dominated by unscattered light.

$$I_{diffuse}(x) \approx 0 \tag{1}$$

Every scattering event removes an unscattered photon. The probability that a photon will be scattered as it moves through a distance *dx* is just dx/ℓ. As a result, the intensity at *x* + *dx* is related to the intensity at *x* by

$$I(x + dx) = I(x) - I(x)(dx/\ell) \tag{2}$$

Alternately, Eq. (2) can be written

$$\frac{dI(x)}{dx} = -\frac{I(x)}{\ell} \tag{3}$$

With the initial condition $I(0) = I_0$, Eq. (3) yields

$$I(x) = I_0 \exp(-x/\ell) \tag{4}$$

Ignoring the diffusing photons becomes a bad approximation when $x \gg \ell$. Then $I(x)$ becomes so small that $I_{diffuse}(x)$ is not negligible.

EXPERIMENT:

A He-Ne laser at wavelength 633 nm is used for the light beam. Half-and-half milk is used as a highly scattering medium. Create a wedge shaped sample of milk between two optically flat, circularly shaped glass windows (1 in. diameter) with a spacer of thickness *t* (≈ 100 μm) placed at one end. By using "optically flat" glass windows, when the optical beam passes through the wedge from the end where they touch to the other end where they are spaced by the spacer, the physical distance traversed by the beam, *x*, varies linearly from 0 to *t*.

Use a photodiode to detect the intensity of the transmitted (unscattered) beam at different values of x. To filter out unwanted noise, modulate the beam intensity using a rotary chopper. Use a combination of the photodiode, a data acquisition board on a PC computer, and a LabVIEW software "Mean Free Path" to (i) control a stepper-motor that moves the sample; (ii) measure the photodiode signal at the chopper frequency by Fourier transforming the photodiode signal; (iii) record the detected signal in digital format for subsequent processing and analysis.

Graph $I(x)$ and $\ln(I(x))$ using KaleidaGraph or MathType or Origin or Excel. Analyze the graphs to determine the mean free path of 633 nm photons in half-an-half milk or diluted half-and-half milk.

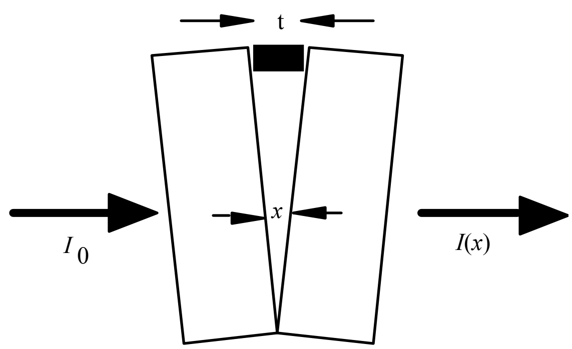

Fig. 1. Assembly for a wedge-shaped sample of highly scattering liquid

Questions:

1. Why does chopping the beam and using an AC detection method improve the signal-to-noise ratio?
2. Why is this important in this experiment (particularly with room light on?
3. What is the physical meaning of the slope and intercept of a plot of $\ln(I(x))$? Explain how the value of the mean free path is effected if *all* of the values for the wedge thickness have a *systematic error* (e.g. in determining the initial distance of the laser beam from the zero-distance end of the wedge), $x_i^{\text{experiment}} = x_i^{\text{actual}} + \Delta x^{\text{systematic}}$, where *i* labels data points.

Michelson Interferometer

REFERENCES:

Frank L. Pedrotti, *Introduction to Optics* (Prentice Hall, 2007), p 193.
Xiangdong Zhu, *Lecture Notes for Physics 108* (UCD).

INTRODUCTION:

Although Michelson invented the interferometer in the late 19th century, it is still widely used today in applications such as Fourier Transform Infrared Spectroscopy (FTIR), Atomic Force Microscopy (AFM), Optical Coherent Tomography (OCT), Optical Metrology in micro-fabrication, and biomolecular sensors.

The objectives of this lab are:

I. Learn to align a Michelson Interferometer.
II. Measure the wavelength of a Helium-Neon laser.
III. Measure the wavelengths of the Sodium doublet.
IV. Observe interference fringes produced by white light (optional).

EXPERIMENTAL PROCEDURE

PART I: *Align a Michelson Interferometer by observing interference patterns*

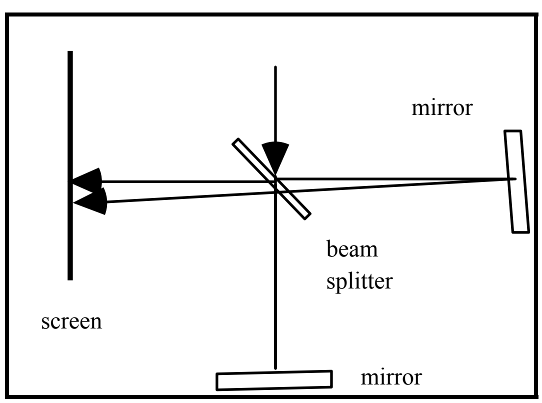

Fig. 1. Michelson Interferometer

Send the laser through the interferometer such that the beams are centered on each mirror. Erect a screen to observe the output spots. Since there are several glass surfaces in the interferometer there will be more than two spots on the screen. Use an index card to determine which spots are the signals you want. Adjust the alignment knob on the adjustable mirror until these two spots overlap.

Place a positive lens in front of the laser so that the beam is diverging and fills the two mirrors of the interferometer. Adjust the alignment knob on the mirror mount until sharply defined interference fringes are observed (each student should do this alone). Continue to adjust the alignment knob on the adjustable mirror until a bull's eye pattern is observed.

Now that you have a bull's eye pattern, slowly turn the micrometer (not the mirror). Note that as you turn the micrometer the fringes appear to move in and out of your field of view.

Questions:

1. Why do you see interference fringes from the He-Ne laser? Why can you project the interference fringes from the diverging He-Ne laser beam onto a screen without any additional lenses?
2. Why do you see a bull's eye pattern? Why does adjusting the mirror in a certain direction produce a bull's eye pattern but moving in other directions do not?
3. Why does the fringe speed depend upon the micrometer? What determines whether the fringes move in or out of the bull's eye?

PART II: *Use the Interferometer to measure the wavelength of a He-Ne laser*

The light arrives at the screen along two paths which differ in *path length* by a distance x. You adjust x by turning the micrometer. However, the distance the micrometer moves is not the distance the mirror moves. There is a 5:1 reduction due to the moment arm attached to the mirror. In addition, the physical path length difference (x) is twice the distance that the mirror moves, so x is 2/5 of the micrometer reading.

After the interferometer, the light intensity on the screen from a monochromatic source varies with the physical path length difference x as

$$I(x) = \frac{I_{inc}}{2}\left[1+\cos\left(\frac{2\pi x}{\lambda}\right)\right]. \qquad (1)$$

Eq. (1) shows that I(x) is a periodic function of x with a periodicity λ.

Now we use the interference fringes to determine the wavelength of the He-Ne laser in air (not in vacuum). First familiarize yourself with how to read the micrometer. Then choose a starting position and record the micrometer reading. Turn the micrometer and count N (say 100) cycles of the interference pattern (bright fringe to bright fringe or dark to dark). Record the final micrometer reading and determine Δx for the N cycles. Calculate the He-Ne wavelength, using the formula $\Delta x = N\lambda$.

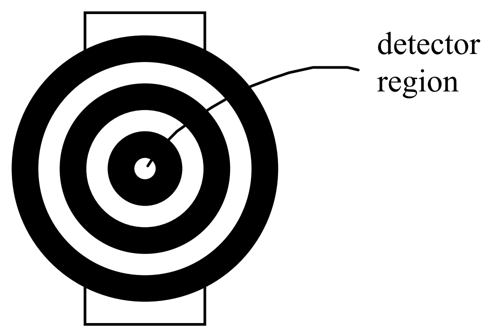

Fig. 2. Bull's eye interference pattern

PART III: *Use the Interferometer to measure the wavelengths of the Sodium doublet*

When an optical beam consists of two monochromatic components with wavelengths λ_1 and λ_2, the interference pattern from such a beam varies with path length difference as

$$I(x) = \frac{I_{inc}(\lambda_1)}{2}\left[1+\cos\left(\frac{2\pi x}{\lambda_1}\right)\right] + \frac{I_{inc}(\lambda_2)}{2}\left[1+\cos\left(\frac{2\pi x}{\lambda_2}\right)\right]. \qquad (2)$$

If the wavelength difference $\Delta\lambda \equiv |\lambda_1 - \lambda_2|$ is small compared to the mean wavelength $\bar{\lambda}$,

$$\bar{\lambda} \equiv \frac{\lambda_1 + \lambda_2}{2} >> \Delta\lambda \equiv |\lambda_1 - \lambda_2|, \qquad (3)$$

and $I_{inc}(\lambda_1) \approx I_{inc}(\lambda_2)$, Eq. (2) is approximated by

$$I(x) \approx I_{inc}(\bar{\lambda})\left\{1+\cos\left(\frac{2\pi x}{\bar{\lambda}}\right)\cos\left[\frac{2\pi(\Delta\lambda)x}{2\bar{\lambda}^2}\right]\right\} \qquad (4)$$

Eq. (4) shows that the interference pattern repeats with period $\bar{\lambda}$, as in the monochromatic case. But now, the contrast changes periodically between the minimum and the maximum with a period of $2\bar{\lambda}^2/\Delta\lambda$.

Align the interferometer as in **Part I**. Turn on a sodium lamp and allow some time for it to "warm up". When it emits a bright yellow-orange glow you may use it. Set up the sodium lamp so that its light goes through the interferometer. Set the lamp as close to the interferometer as possible. Place a piece of ground glass in the slide clamp on the interferometer so that the light from the sodium lamp must pass through the glass before going through the interferometer. Look into the interferometer (with the sodium lamp only!!! NOT WITH THE LASER AS THE SOURCE!!!) to see the interference pattern from the lamp. It may be necessary to make fine adjustments to the mirrors to optimize the appearance of the fringes.

Now *very slowly* turn the micrometer and you will see the interference pattern disappear and reappear. As in **Part II**, determine the change in path difference Δx for n cycles (bright fringe to bright fringe) and calculate $\bar{\lambda}$ using $\Delta x = n\bar{\lambda}$. Additionally, measure the change in path difference Δx for 1 cycle of the envelope function (minimum contrast to minimum contrast to minimum contrast). Using the formula $\Delta x = 2\bar{\lambda}^2 / \Delta\lambda$, with $\bar{\lambda}$ obtained above (or use the known value 589.3 nm), calculate $\Delta\lambda$, the difference of the two sodium frequencies.

Questions:

1. Why is there no cross term in equation (2)?
2. Why does the contrast of the interference pattern change?

PART IV: *Find the zero path length difference position of the interferometer and observe interference fringes from a white light source*

Using either a He-Ne laser or a sodium lamp, find the neighborhood of micrometer positions containing the position of zero path length difference of the interferometer arms. As you turn the micrometer *in one direction*, the fringe motion will reverse upon passage through the zero path length difference point. Use this observation to systematically narrow down the region containing this point.

Now replace the monochromatic source with a white light lamp (use the ground glass plate as with the sodium lamp). Now slowly search through the neighborhood determined previously until you see fringes. The zero path length difference position is identified by the appearance of a few (one or two) white and black fringes in the center of the bull’s eye, surrounded by some colored fringes. It is easy to miss this point if you move too fast; that is why it is helpful to narrow down the possible region using a monochromatic source.

Questions:

1. What happens to the fringe spacing as one approach the neighborhood of zero path length difference?
2. Why does this make it difficult to precisely identify this point with a monochromatic source?
3. Why are fringes only observable near the zero path length difference position with white light? Why are the outer fringes colored?

Measurement of Refractive Indices of Transparent Materials

REFERENCES:

F.L. Pedrotti, *Introduction to Optics* (Prentice Hall, 2007), pp 20-25.
F.L. Pedrotti, *Introduction to Optics* (Prentice Hall, 2007), pp 495-498.

INTRODUCTION:

When a light beam is incident on the interface of two media with different refractive indices, the direction of the transmitted light changes. This effect is described by Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2. \tag{1}$$

There exists a particularly interesting angle for the p-polarized light (linearly polarized in the plane of incidence) when the propagation direction of the transmitted light is normal to the propagation direction of the reflected light. This angle is known as Brewster's angle θ_p.

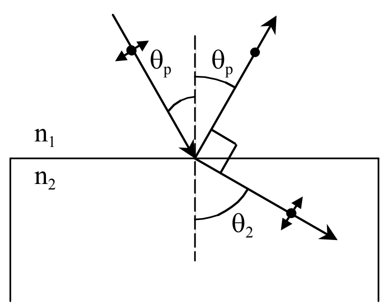

Fig. 1: Light incident on an interface.

The significance of Brewster's angle is that the **p-polarized** light completely transmits through the interface and thus there is no reflected beam. From Figure (1), we can see geometrically that $\theta_p + \theta_2 = 90°$. Using this relation and Eq. (1), one can show that the Brewster's angle is a simple function of refractive indices of the two media,

$$\theta_p = \arctan\left(\frac{n_2}{n_1}\right). \tag{2}$$

If $n_1 > n_2$, one continues to increase the angle of incidence beyond Brewster's angle, one will find another significant angle θ_c at which the refracted angle $\theta_2 = 90°$. θ_c is known as the critical angle. At incident angles greater than the critical angle will result in total reflection so that no light beam propagates far from the interface into the transmission medium. The relationship between the critical angle and the indices of refraction for the two media is,

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right). \tag{3}$$

Question: Why must $n_1 > n_2$ in order to observe total internal reflection?

EXPERIMENT:

For this experiment you will use your knowledge of Brewster's angle to find the index of refraction of a glass microscope slide. First, attach a microscope slide to a rotation stage. Using light from He-Ne laser, rotate the slide so that Brewster's angle can be demonstrated. Start by finding a position where you can reference the incident angle. Remember, the incident light must be p-polarized in order to extinguish the reflected light. Make a detailed drawing of your optical setup and report your method for allowing only p-polarized light from the laser. Once you have found Brewster's angle for your microscope slide, the index of refraction can easily be obtained using Eq. (2). As a final exercise, apply some pressure on the glass microscope slide and observe the effect on the reflected beam intensity at Brewster's angle.

For the next part of the experiment we will use total internal reflection to find the index of refraction of a glass prism. Attach a prism to the same rotation stage you used for the microscope slide and again find a position where you can reference the incident angle from. Now, rotate the stage to find the minimum angle of incidence at which total internal reflection occurs. Once you find the angle, calculate the index of refraction for the glass prism with the aid of Eq. (3). (HINT: You need to account for any refraction that occurs as well!) No prism is perfect; if the prism angles were not exact, explain how this would affect your result.

Laser Safety

Lasers can deliver a lot of power per unit area and therefore can cause burns. Since the eye's lens system increases light intensity by thousands of times, even low intensity lasers can burn the retina. Higher intensity lasers can burn the skin as well. (Some lasers burn holes in metal.)

Injury may be caused by a laser beam directly if it's intensity is great enough. However, specular reflections (i.e. from reflective surfaces) of the beam can be equally hazardous. With very intense laser beams, even diffuse reflections (i.e. from non-reflective surfaces) are potential hazards if focused to the eye with optical instruments.

Lasers are classified as I, II, III, or IV with increasing potential to cause injury.

<u>Class I</u>
Laser output is insufficient to cause injury.

<u>Class II (≤ 0.95 mW), Class IIIA (≤ 5 mW), Class IIIB</u>
Direct exposure or specular reflection of laser light is insufficient to burn skin, but capable of causing retinal damage. Diffuse reflections are not hazardous. Typical classroom and demonstration lasers fall in these categories.

In PHY 108L we will use a 10 mW, Class IIIb, helium-neon laser.

<u>Class IV</u>
Output is capable of causing retinal damage and skin burns. Even diffuse reflections may pose a hazard.

Never look directly into a laser beam or its specular reflection!!