3. Interference Experiments

3.1 Constructing a Michelson Interferometer & Measuring Refractive Index of Air

Objective:

Learn how to assemble a Michelson interferometer, and measure the refractive index of air

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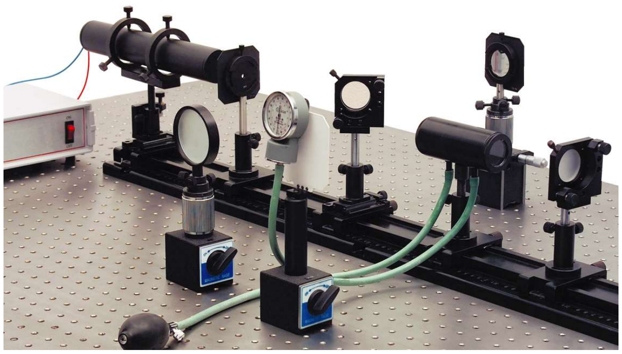

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Figure 3-1-1 Photo of experimental setup

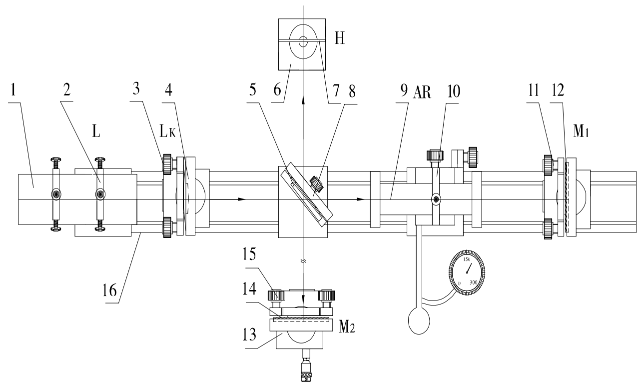


Figure 3-1-2 Configuration of system

1: He-Ne Laser L (LLL-2)
2: Laser Holder (SZ-42)
3: Lens Holder (SZ-08)
4: Beam Expander Lens L_1 (f'=6.2 mm)
5: Beam Splitter *BS* (5:5)
6: Magnetic Base (SZ-04)
7: White Screen *H* (SZ-13)
8: Plate Holder (SZ-12) or Lens Holder (SZ-08)
9: Air Chamber with Pump *AR*
10: Aperture Adjustable Clamp (SZ-19)
11: Two-axis Mirror Holder (SZ-07)
12: Flat Mirror M_1
13: Magnetic Base (SZ-04)
14: Flat Mirror M_2
15: Two-axis Mirror Holder (SZ-07)
16: Optical Rail

Principle

Figure 3-1-3 shows the schematic of a Michelson interferometer, in which a light ray from source *S* strikes a beam-splitter *BS* that reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams; one beam is reflected toward mirror M_1, the other is transmitted toward mirror M_2. The light reflected from M_1 transmits through the beam-splitter to the observer's eye *E*, and the other light reflected from M_2 is reflected by the beam-splitter *BS* to the observer's eye *E*.

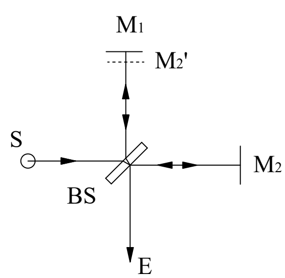


Figure 3-1-3 Schematic of Michelson interferometer

Since the beams are from the same light source, their phases are highly correlated. When a lens is placed between light source and beam-splitter, the light ray spreads out, and an interference pattern of dark and bright rings, or fringes, can be seen by the observer. There are numerous variants of the Michelson interferometer with different features. Two important examples are the Mach-Zehnder and the Sagnac interferometer.

If we place an air chamber in the light path between beam splitter and mirror M_2, and then change the density of the air (by deflating or pumping the air), the length of the light path will change by δ

$$\delta = 2\Delta n l = N\lambda , \quad \text{so } \Delta n = N\lambda / 2l \tag{3-1-1}$$

where l is length of the air chamber λ is the wavelength of the light source, N is the number of the fringes counted, and n is the refractive index of air. The refractive index of air n is dependent upon both temperature and pressure. If n is near unity, then n-1 is directly proportional to the density of the gas, ρ. For an ideal gas:

$$\frac{\rho}{\rho_0} = \frac{n-1}{n_0 - 1} \tag{3-1-2}$$

Therefore,

$$\frac{\rho}{\rho_0} = \frac{PT_0}{P_0 T} \tag{3-1-3}$$

where T is the absolute temperature, P is the ambient pressure. So we get

$$\frac{PT_0}{P_0 T} = \frac{n-1}{n_0 - 1} \tag{3-1-4}$$

When temperature is constant, then

$$\Delta n = \frac{(n_0 - 1)T_0}{P_0 T} \Delta P \tag{3-1-5}$$

Based on equation (3-1), $\Delta n = N\lambda / 2l$, we have

$$\frac{(n_0 - 1)T_0}{P_0 T} \Delta P = N\lambda / 2l \tag{3-1-6}$$

So

$$n = 1 + \frac{N\lambda}{2l} \times \frac{P}{\Delta P} \tag{3-1-7}$$

Experimental Procedures:

1. Refer to Figure 3-1-2, align all components in same height on the rail;

2. Adjust the output direction of the He-Ne laser to make it parallel along the optical rail (beam expander lens should not be inserted at this moment);
3. Put in beam splitter *BS* at an angle of 45° with respect to beam axis, and adjust its tilt to make the two beams (transmission and reflection) parallel to the table;
4. Adjust the tilt of mirrors M_1 and M_2 to make the reflected beams coincide with their incident paths, and the two beam spots on the screen *H* overlap together;
5. Insert beam expander L_1, finely adjust beam splitter, M_1 and M_2, till concentric interference rings can be observed on the screen *H*;
6. Insert an air chamber between beam splitter and M_1, adjust the chamber parallel to optical path, pump air into the air chamber till the maximum permit pressure is reached (40 kPa) and write as ΔP;
7. Slowly release the air valve, count the number of interference rings changed in the center till air pressure falls to zero (using the provided hand tally counter);
8. Repeat steps 6 and 7 several times to obtain averaged data;
9. Calculate the refractive index of air according to equation (3-1-7).

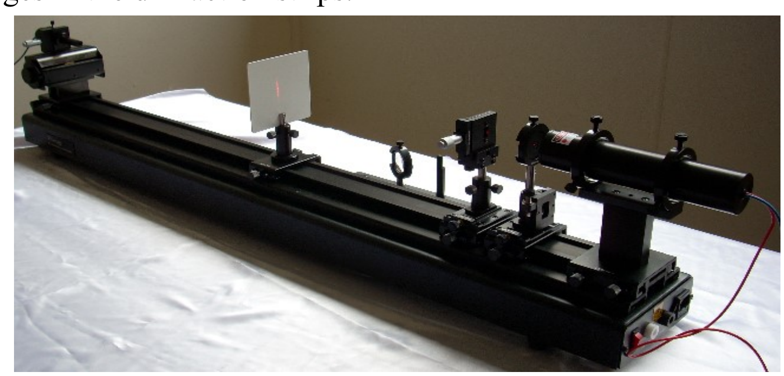
Diffraction pattern of a transmission grating

4.2.5 Fresnel Diffraction through a Single Slit

1) Mount the laser tube in its holder on the carrier. Place it at the end of the optical rail. Install the optical receiver probe onto its carrier and place it at the other end of the optical rail.
2) Turn on the He-Ne laser. Set the transversal measurement stage to its zero point.
3) Carefully adjust laser height and directions (using the 6 adjustable screws on the laser holder) to make the beam parallel to the rail and enter the center of the hole in front of the receiver.
4) Mount the two lenses (f=6.2 and f=150) into lens holders, place them onto carriers, and use them to form a beam expander. The divergent angle of the beam can be controlled by changing the spacing of the two lenses. The carriers provide fine position adjustments. Secure the carriers close to laser tube. Adjust the heights until the laser beam always passes through the centre of the expander when sliding expander backward and forward so that the centre of the expanded beam does not deviate. Now the optical axis of the expanded laser beam will coincide with the laser beam.
4) Place the adjustable slit onto a carrier. Adjust the slit so that the laser beam is incident on the slit.

Note:
The flat plane of the slit should face the incident light. Keep two edges of the slit from contacting each other. This is best viewed in a dark environment.

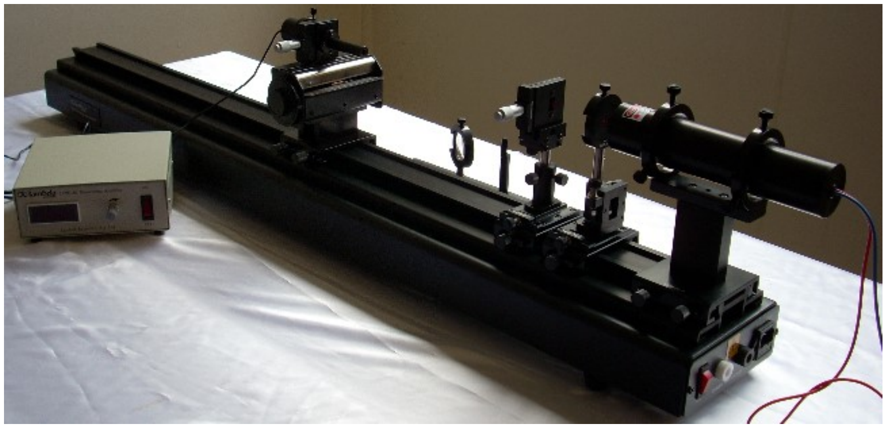
5) Insert white screen into carrier to observe diffraction pattern. Slide white screen and observe diffraction pattern when distance between the screen and the slit varies. Adjust the slit width and observe the changes in the diffraction strips.



Note: Photo may vary from actual parts

6) Remove the white screen and align diffraction strips into the entrance tube of the optical receiver.

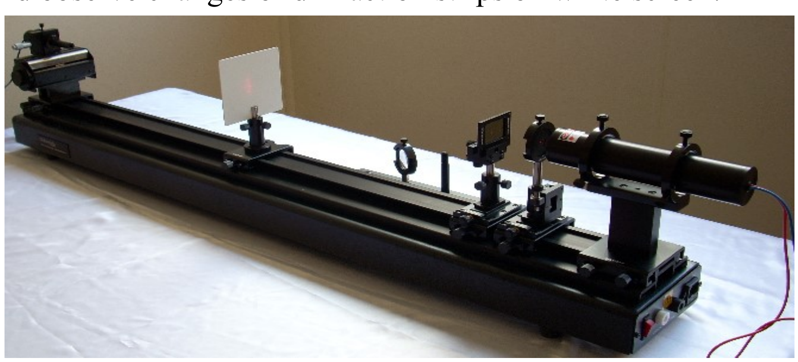
7) Rotate the drum on the optical receiver and record the coordinate readings of the receiver in step of 0.1 mm (10 divisions of the drum). Draw a diffraction intensity distribution curve from the data collected.



Note: Photo may vary from actual parts

4.2.6 Fresnel Diffraction through a Multi-Slit Plate

1) Please refer to the previous experiment and place laser, beam expander on optical rail.
2) Insert multi-slit into plate holder, then mount onto carrier and place the assembly onto the rail. Adjust height of multi-slit plate so that the laser beam strikes one of the slits. Carefully adjust the beam expander until the diffraction pattern is aligned into the entrance tube of the optical receiver.
3) Observe the diffraction strips with a white screen. Slide the white screen and observe changes of diffraction pattern while the distance between the screen and the multi-slit plate varies. Slide multi-slit plate and observe changes of diffraction strips on white screen.



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4) Remove the white screen and align the diffraction strips into the entrance tube of the optical receiver. Rotate the drum of the optical receiver and record the coordinate reading of optical receiver in step of 0.1 mm. Draw a diffraction intensity distribution curve from the data.

5. Polarization Experiments

5.1 Introduction

Along with interference and diffraction, polarization is also an important property of light. Without special equipment, human eyes or even optical detectors cannot identify the polarization of a light wave.

Light is a transverse wave. We define the direction of polarization by the direction of the electric field vector, ***E***. Light from common sources such as light bulbs is unpolarized, meaning that the plane of vibration of the electric field vector changes rapidly in a completely random fashion.

However, when light interacts with matter, the plane of vibration of the electric field vector may become fixed in a particular direction (linear polarization) or the plane of vibration may rotate or otherwise vary in a uniform manner (circular or elliptical polarization).

Polarized light can be described by the two orthogonal components of its electric field, E_y and E_z,

$$\begin{aligned} E_y &= E_{oy}\cos(\omega t - kx) \\ E_z &= E_{oz}\cos(\omega t - kx - \delta) \end{aligned} \tag{5-1}$$

Where E_{oy} and E_{oz} are the amplitudes of the electric field along y and z axes, respectively; and δ is the phase delay between these components. The value of the phase delay determines the type of the polarization of a light wave as

$\delta=0$, linear
$\delta\neq0$, elliptical
$\delta=\delta(t)$ random, unpolarized
$\delta=\pi/2$, $E_{oy}=E_{oz}$, circular
$\delta=\pi/2$, $E_{oy}\neq E_{oz}$, elliptical, major/minor axes aligned along y and z axes.

A polarizer used in this equipment is a special device that selectively passes only the component of the electric field parallel to the optical axis of the polarizer. When unpolarized light passes through a polarizer, it becomes linearly polarized parallel to the direction of the optical axis of the polarizer.

5.2 Experiments on Polarization

5.2.1 Brewster's Angle

When unpolarized light travels from a transparent medium with a refractive index n_1 to another one with a higher refraction index n_2, part of the light is refracted into the second medium while the other part of the light is reflected back into the first medium. If the angles of incidence and refraction are θ_1 and θ_2, respectively, then the following condition exists, known as Snell's law

$$n_1\sin\theta_1=n_2\sin\theta_2 \tag{5-2}$$

According to Sir David Brewster, at a specific angle of incidence, θ_b, called Brewster's angle, the reflected ray and the refracted ray are perpendicular to each other, so the sum of the incident angle and the refractive angle is 90° as

$$\theta_b + \theta_2 = 90°\text{, namely } \theta_2 = 90° - \theta_b \tag{5-3}$$

By substituting equation (3) into equation (2), we get

$$\begin{aligned} n_1 \sin\theta_b &= n_2 \sin(90° - \theta_b) = n_2 \cos\theta_b \\ \tan\theta_b &= \frac{n_2}{n_1} \end{aligned} \tag{5-4}$$

Equation (5-4) is known as Brewster's Law. When the incident beam is travelling in air, $n_1 \approx 1.00$, equation (5-4) becomes $\tan \theta_b = n_2$. The Brewster's angle of a material is sometimes referred to as the polarizing angle of the material.

Note: Using Brewster's Law, one can determine the refractive index of a black glass. This can be achieved by substituting the value of the Brewster's angle into Eq. (5-4) to obtain n_2.

Note: Photo may vary from actual parts

Figure 5-1 Experimental setup for measurement of Brewster's angle

Experimental Procedure:

1) Mount the laser tube in its holder on the carrier. Place it at the end of the optical rail.
2) Turn on the He-Ne laser. Carefully adjust laser directions (using the 6 adjustable screws on the laser holder) to make the beam parallel to the rail.
3) Insert the goniometer into the post holder an on carrier and secure the carrier on the other end of the optical rail. Unpack the black glass and secure it on the center of the dial using the clamping arm. Make sure one edge of the glass just overlaps the 90º axis of the dial as shown in Figure 5-2. Adjust tilt and direction of the black glass to let the reflected laser beam return to the aperture of the laser tube (i.e. return along the incident path). Secure the black glass.

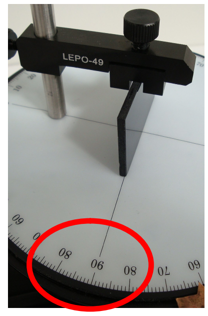

Figure 5-2 Black glass mounted on goniometer

Note:
Handle the black glass with care. Keep the two reflective surfaces from fingerprints and dirt.

4) Mount a polarizer into a lens holder, place it onto one carrier, and locate the carrier next to the laser tube. Rotate the polarizer to set its axis along horizontal direction so that the transmitted light is horizontally polarized. Insert the post of detector on the hole next to the dial of the goniometer and connect the detector to the amplifier. Make sure the detector area faces the point where two axes of the dial intersect.

5) Set the pointer of goniometer at 56°~57° and rotate the dial to allow the reflected laser beam to hit the center of the active area of the detector. Read the light intensity on the digital display of the photocurrent amplifier.

6) Carefully turn the rotating arm and the dial to achieve the minimum readout. Record the reading on the dial. This is the Brewster's angle.

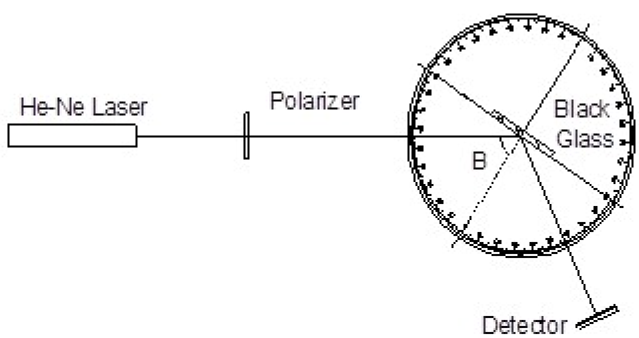

Figure 5-3 Schematic of experimental configuration

5.2.2 Verification of Malus's Law

Malus's law defines the transmitted intensity of light through two polarizers with an angle of θ between the transmission directions of the polarizers, as

$$I = I_{\max} \cos^2 \theta \tag{5-5}$$