9A - MEASURING THE SPEED OF LIGHT

OBJECTIVES

- Measuring the speed of light in air and calculating the refractive index.
- Measuring the speed of light in water and synthetic resin.
- Determining the refractive indices of water and synthetic resin.

EQUIPMENTS

- **Oscilloscope.**
- **Speed of light calculation unit.**
- **Synthetic resin block.**

GENERAL INFORMATION

What are the refractive index, wavelength, frequency, phase, modulation, permittivity constant, and permeability constant?

- ### Speed of light

The speed of light and other electromagnetic waves in a vacuum is given by Maxwell's equations:

$$c = \frac{1}{\sqrt{(\varepsilon_0 \mu_0)}} \qquad (1)$$

and its value in a vacuum is 299,792,458 m/s.

The value of μ will vary depending on the material (water, glass, resin, etc.). In Latin, speed is written as 'celeritas,' which is why it is represented by the letter *c*. Here, the permittivity constant of the vacuum is $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m; the permeability constant of the vacuum is $\mu_0 = 1.257 \times 10^{-6}$ H/m. If the speed of light in a material medium is v, it is described by:

$$v = \frac{1}{\sqrt{(\varepsilon \mu)}} \qquad (2)$$

Here, ε is the permittivity constant of the material medium, and μ is the permeability constant of the material medium. The refractive index of the medium is equal to the ratio of the speed of light in a vacuum to the speed of light in the medium:

$$n = \frac{c}{c'} = \sqrt{\varepsilon_b \mu_b} \qquad (3)$$

- **Measuring the speed of light**

The speed of light is calculated based on the relations between phase, modulation frequency, and changes along the path of light.

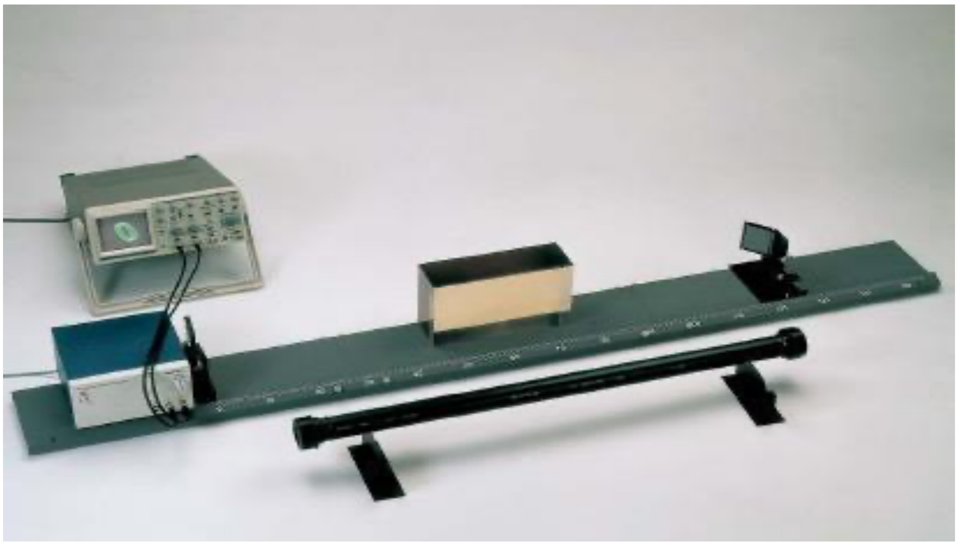

Figure 1: Setup for calculating the speed of light.

With the experimental setup shown in Figure 1, the speed of light in air or different mediums can be measured. This setup consists of a light speed measurement unit placed on an optical plane with a ruler, an oscilloscope, a movable mirror, and lenses. The light speed measurement unit includes a light-emitting diode (LED) and a light-receiving diode (photodiode).

Through the use of a movable mirror and lenses, the light rays emitted from the light-emitting diode are directed to fall onto the photodiode after traveling a certain path. The phase difference between the emitted signal and the received signal depends on the path traveled by the light. By measuring this path, the speed of light can be calculated. Using an oscilloscope, the resulting phase difference can be observed as a Lissajous figure. When the figure is a straight line, the phase difference is 0 (zero) for a positively sloped line and π for a negatively sloped line.

To calculate the speed of light in air, the path taken by the light in increased by an amount:

$$\Delta l = 2\Delta x \qquad (4)$$

The amount of time taken by the light to travel the path difference given in the equation above to create a path difference of π is:

$$\Delta t = \frac{1}{2f} \qquad (5)$$

Hence, the speed of light in air can be calculated using:

$$c_{air} = \frac{\Delta l}{\Delta t} = 4f\Delta x \qquad (6)$$

Here, f is the modulation frequency of the light source used. The actual calculated value of the speed of light in air is 3 x 10^8 m/s.

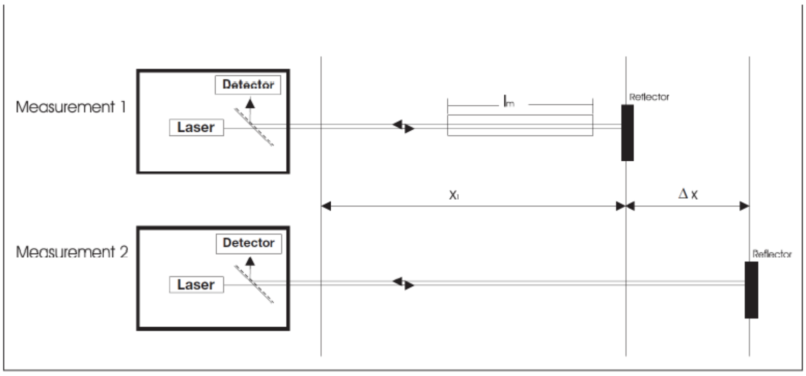

Figure 2: Setup for measuring the speed of light in air or in a different medium.

The speed of light in water and synthetic resin can be determined by comparing it with its speed in air. In the first measurement, the amount of time it takes for the light to travel the distance of $l_1 = 2x_1$ is given as:

$$t_1 = \frac{l_1 - l_m}{c_{air}} + \frac{l_m}{c_m} \qquad (7)$$

In the second measurement, the amount of time it takes for the light to travel the distance of $l_2 = l_1 + 2\Delta x$ is given as:

$$t_2 = \frac{l_1 + 2\Delta x}{c_{air}} \qquad (8)$$

For both cases, the phase difference between the signal emitter and receiver is the same:

$$t_1 = t_2 + \frac{k}{f}\ ;\ k = 0,1,2... \qquad (9)$$

Thus, the index of refraction can be found as the following:

$$n = \frac{c_{air}}{c_m} = \frac{2\Delta x}{l_m} + 1 + \frac{kc_{air}}{fl_m} \qquad (10)$$

The speed of light in water and synthetic resin is known to be 2.248×10^8 m/s and 1.87×10^8 m/s, respectively. Additionally, the refractive index of water is 1.333, and the refractive index of synthetic resin is 1.597.

EXPERIMENTAL PROCEDURES

1. The experimental setup shown in Figure 1 is arranged for measuring the speed of light in air. Using a movable mirror and lenses, the incoming and reflected light beams are adjusted to be parallel to the horizontal plane, ensuring that the maximum signal reaches the photodiode.

2. The speed of light measurement unit has a red light-emitting diode (LED). To make the receiver and transmitter signals observable on the oscilloscope, the modulation frequency of the lamp is reduced from approximately 50.1 MHz to around 50 kHz.

3. The movable mirror is placed as close as possible to the light speed measurement unit (at the 0 point of the optical plane).

4. The phase difference between the light-emitting signal and the receiving signal is observed on the oscilloscope in XY mode as a Lissajous figure.

5. The phase adjustment knob of the light speed measurement unit is used to make the Lissajous figure appear as a straight line.

6.The movable mirror is slid along the optical plane until the phase difference reaches π, and the displacement Δx of the mirror is measured (see Figure 2). The measurements are repeated, and Δx is recorded in Table 1.

7. The speed of light in air is calculated. For red light, the modulation frequency is $f = 50.1$ MHz.

8. The relative error is calculated using the actual value of the speed of light in air and recorded in Table 1.

9. To determine the speed of light in water, a 1-meter-long cylindrical tube filled with water is placed horizontally in the path of the reflected light beams. This ensures that the light passes parallel through the tube, which has glass windows at both ends.

10. The movable mirror is placed right behind the cylindrical tube.

11. Using the phase adjustment knob of the light speed measurement unit, a straight line is again obtained on the oscilloscope screen.

12. The tube placed in the path of the light is removed, and the mirror is shifted until the Lissajous figure again shows the same phase difference.

13. The displacement Δx of the mirror is measured several times, and the results are recorded in Table 2.

14. The speed of light in water and the refractive index of water are calculated for the case where k=0.

15. The relative error is calculated, and the results are recorded in Table 2

16. To determine the speed of light in synthetic resin, a 30 cm long piece of synthetic resin with its effective surfaces perpendicular to the path is placed.

17. Steps 10-15 of the experiment are repeated. The speed of light in the resin and the refractive index of the resin are calculated, and the results are recorded in Table 3.

Question 1: What factors affect the speed of light? Please explain.
Question 2: How is a Lissajous figure formed? Please explain.
Question 3: Draw the Lissajous figure for phase differences of 0 (zero), π, and any other case.
Question 4: How can the speed of light be changed? Please explain.

Table 1

Δx *(air) (cm)*	c_{air} *(m/s)*	Relative error ($\lvert\Delta c\rvert / c_{real}$)
$\Delta x_{average}$ =		

Table 2

Δx *(cm)* *(water)*	c_{water} *(m/s)*	Relative error $(\lvert\Delta c\rvert / c_{real})$	n_{water}	Relative error $(\lvert\Delta n\rvert / n_{real})$
$\Delta x_{average}$ =				

Table 3

Δx *(cm)* *(resin)*	c_{resin} *(m/s)*	Relative error $(\lvert\Delta c\rvert / c_{real})$	n_{resin}	Relative error $(\lvert\Delta n\rvert / n_{real})$
$\Delta x_{average}$ =				

9B - ABSORPTION

OBJECTIVES

- Determine the absorption coefficient of semi-permeable plates and examine the absorption phenomenon.
- Determine the permeability value.

EQUIPMENT

- **Luxmeter.**
- **Light source.**
- **Semi-permeable plates of various thicknesses.**
- **Ampermeter**

GENERAL INFORMATION

As a light beam passes through a semipermeable plate with a thickness of *d*, it's intensity decreases according to the relation:

$$I = I_0 10^{-kx} \qquad (1)$$

Here, I_0 is the intensity of the incoming light, *I* is the intensity of the light exiting the plate, *d* is the thickness of the plate, and *k* is the absorption coefficient of the plate. The coefficient *k* is a constant that depends on the type of medium and the wavelength of the incoming light.

The permeability of the medium, *T*, is defined as the ratio of the intensity of the transmitted light to the intensity of the incoming light. It can be found using the relation:

$$T = \frac{I}{I_0} = 10^{-kx} \qquad (2)$$

By taking the logarithm of both sides:

$$logT = -kx$$

The slope of the graph plotted between *logT* and *x* gives us *k*.

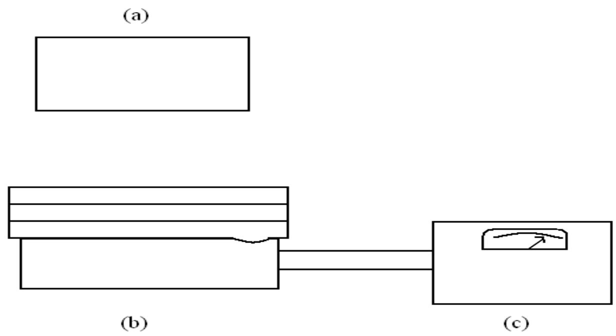

Figure 1: Setup for the experiment. (a) Light source. (b) Luxmeter. (c) Ammeter.

EXPERIMENTAL PROCEDURES

1. The luxmeter is placed directly under the light source so that it reaches full scale deflection, and it is kept stationary there.

2. First, with no plate in front of the source, the maximum intensity value is read from the light meter (I_0) and recorded in the table.

3. By placing a plate of known thickness on the light meter, the transmitted light intensity, I, is read and recorded in the table. Then, other plates of known thickness are sequentially stacked on top of each other, and the intensity is measured for the total thickness.

(We want to draw attention to one point: equation (1) is derived for a continuous medium made of the same material. However, in the experiment, plates of different thicknesses are stacked to perform the measurements. We assume that the error caused by the air layer between the plates remains within the acceptable error limits of the experiment.)

4. The permeability values *T* are calculated, and their logarithms are taken and recorded in the table provided below.

5. A graph of permeability as a function of thickness, i.e., the change in permeability *T* with respect to thickness *d*, is plotted.

6. A graph of *logT* versus thickness *d* is plotted, and the absorption coefficient *k* is determined from the slope of the line.

$$k = tg\alpha = \ldots mm^{-1}$$

$d(mm)$	I_0 (lux)	I (lux)	$T = I / I_0$	$\log T$