Modern Physics Laboratory

Experiment 418

Measurement of velocity of light

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Student should be familiar with the following theoretical concepts:

1. Maxwell equations, electromagnetic waves. [?] and [?].
2. Velocity of light and methods of its measurement. [?] or [?].

The aim of the experiment

The aim of the experiment is to determine the velocity of light using the method of modulation of intensity of light beam.

Description of the phenomenon

Light is an electromagnetic wave which, in material medium propagates with velocity *v* defined by the formula:

$$v = \frac{1}{\sqrt{\varepsilon\varepsilon_0\mu\mu_0}}$$

where $\varepsilon_0 = 8.854\cdot10^{-12}$ F/m is the electric permittivity of vacuum, $\mu_0 = 1.257\cdot10^{-6}$ H/m is the magnetic permittivity of vacuum, ε is relative electric permittivity of the medium and μ is its relative magnetic permittivity. The light velocity in vacuum, conventionally denoted by *c*, is given by:

$$v = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

Thus the refraction index *n* of a medium is given by:

$$n = \frac{c}{v} = \sqrt{\varepsilon\mu}$$

As for magnetic fields of frequencies similar as the visible light frequency we have $\mu = 1$, we may state that for transparent media *n* is given by:

$$n = \sqrt{\varepsilon}$$

Velocity of light is a physical constant of fundamental importance. According to the theory of relativity it is the maximum velocity of interactions and its value is identical in every frame of reference.

Measurement method

The principle of the measurement consists in determination of time needed by light to pass through some defined path *L* (of approximately 3 m). As this time is extremely short it is not measured directly. Instead the following method is used.

The light source is a diode with modulated light intensity (with frequency *f* appr. 50 MHz). The light beam reflects from mirrors and hits detector (fig. 1). There is a phase difference between the modulated and detected signal – it depends on the delay caused by passing the optical path. This time may be determined if we succeed to measure the phase difference. It may be done by connecting both signals to X and Y connectors of an oscilloscope and examining the Lissajous curves. In general the are of elliptical shape, but in some special cases they are circles or straight lines. Straight lines may appear when the phase shift equals 0 or multiplicity of π. They are inclined at an angle α or –α to horizontal. The inclination angle depends on amplifications of both channels of the oscilloscope. The phase shifts corresponding to such two neighboring inclinations differ by π. Phase difference between two subsequent straight lines with the same inclination equals to 2π.

Straight lines with the same inclination may be produced by using two mirror positions differing by path L long enough to cause phase shift of 2π. It corresponds to delay equal to the period of modulation – $T = 1/f$. As during the time T the beam passes the path L twice, the light velocity may be computed as

$$c = \frac{2L}{T} = 2Lf$$

Similarly, the straight lines inclined oppositely appear when the mirror positions differ by L/2. This also makes it possible to compute the light velocity.

Description of the experiment setup

The experimental setup is presented in figs 1 and 2. Its main part is the measurement tool consisting of a light source (a red light emitting diode with its power supply) and light detector. The diode is fed with current of 50 MHz frequency.

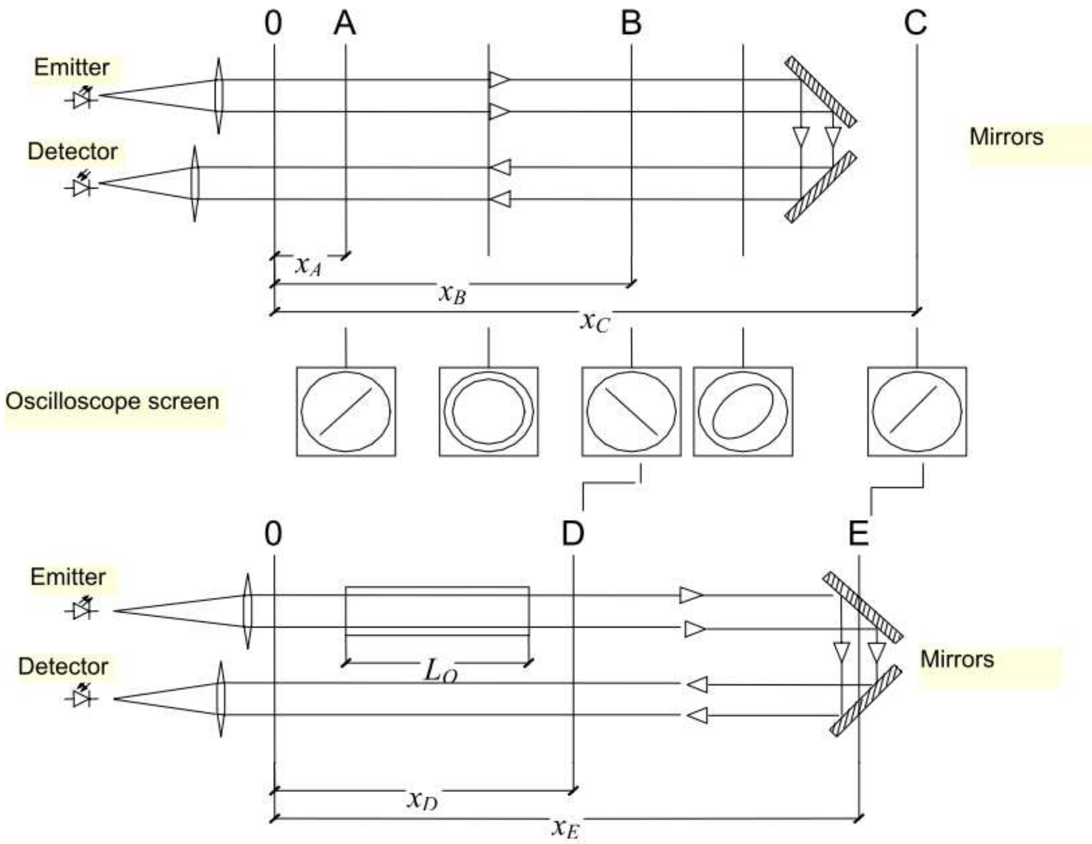

Fig. 1. Measurement setup. Top: measurement of light velocity in air. Bottom: measurement of light velocity in medium in container of L_0 length.

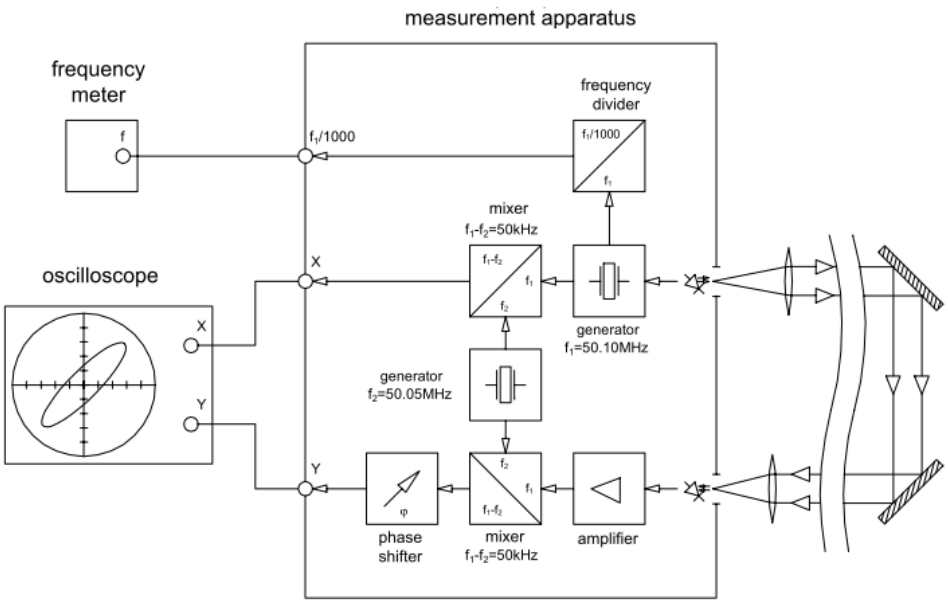

Fig. 2. Details of the measurement system (power supply and detection).

Diode emits light pulses with just this frequency. The pulses, having passed some path are directed to the photodiode detector. Electric signal from the photodiode has identical shape as the signal causing the LED to emit light, but is delayed in relation to the driving signal. The delay time depends on the length of the path of the light beam.

The measurement by this method, when distances of few meters, needs light modulated to some 50 MHz frequency. Direct measurement of the delay time would demand very high quality electronic components. It's much simpler to apply to both driving and detected signals a technique of mixing frequencies, called heterodyne action (fig. 2). It makes it possible to measure signals of differential frequency, much lower than the modulation frequency, and preserve the phase shifts between the measured signals. It's possible to use a standard oscilloscope to observe the Lissajous curves.

In the measurement setup there's also a frequency meter, showing a frequency being one thousandth of the modulation frequency f.

Using this system one can measure the velocity of light in air as well as the velocity of light and refraction coefficient of some medium, filling at least partly the space between the light source and the detector. In this experiment we measure the velocity of light in water. The measurement setup contains a cuvette in the form of a pipe of length L_0 closed on both ends with transparent lids.

It's worth noting that when we change the phase using the knob of the phase shifter or by moving the mirrors, the straight line seen on the oscilloscope screen seems not to change, in spite of the small phase changes of X and Y signals. This effect, caused by finite width of the line drawn on the screen, may influence the precision of the measurement. This influence should be assessed.

Sequence of actions

The apparata (measurement setup, oscilloscope and frequency meter) should be turned on several minutes before the measurement starts.

The measurement apparatus has two outputs, designated as X and Y and additional output of the frequency divider. The X and Y outputs should be connected to X and Y channels inputs of the oscilloscope. The oscilloscope should be set to the X-Y regime. Amplifications of both X and Y channels should be set is such a way that the picture on the screen is fairly big. If the picture is not sharp enough the sharpness should be set correctly, it's most convenient to do it when the picture is not very thin ellipse.

In order to prepare the apparatus for measurement the mirrors should be placed in their farthest position and adjust the mirrors and lenses to obtain maximum illumination of the detector diode. Then a cuvette with water should be put on its supports, the adjustments should be corrected in such a way to assure that removing and introducing the cuvette will not greatly influence the illumination of the detector. Then the cuvette should be removed.

Measurement of light velocity in air

1. Set the mirrors in position A (fig. 1).
2. Using the phase shifter obtain on the oscilloscope screen a picture of straight line inclined by some angle α (about 45°), which means that there's no phase shift between the emitted and detected impulses.
3. Move the mirrors to some other position B, where the picture will be a straight line inclined by –α and farther on, to position C, where the picture will be identical as that obtained in position A. Measure distances x_A, x_B and x_C.
4. Repeat the measurements 8–10 times.

Perform calculations using the following reasoning:
The distance between the positions A and B is:

$$L_{AB} = 2(x_B - x_A)$$

The distance was traversed in time:

$$t_{AB} = \frac{T}{2} = \frac{1}{2f}$$

Thus the velocity of light in air is:

$$c_{AB} = \frac{L_{AB}}{t_{AB}} = 4f(x_B - x_A)$$

Similarly the path between positions A and C is:

$$L_{AC} = 2(x_C - x_A)$$

time:

$$t_{AC} = T = \frac{1}{f}$$

and:

$$c_{AC} = \frac{L_{AC}}{t_{AC}} = 4f(x_C - x_A)$$

The averages of the determined quantities should be used as the result.

Measurement of light velocity in fluid

1. The mirrors should be placed in distance greater than the length of cuvette with fluid under consideration in such a position that the picture on oscilloscope screen presents a straight line inclined by angle α, which proves that the emitted and detected light pulses are in phase.
2. The cuvette with fluid should be placed in the light path, the picture on the oscilloscope screen will become ellipse.
3. Moving the mirrors toward the light source find such position D that the picture on screen becomes straight line again as in point B. Measure positions x_B and x_D.
4. Repeat measurements 8–10 times.

Perform computation according to the following reasoning:

The pulses reflected from mirrors in position D come to the detector in the same time as those reflected from mirrors in position B. The times are given by formulas:

$$t_D = \frac{2x_D - L_0}{c} + \frac{L_0}{c/n} + t_0$$

and

$$t_B = \frac{2x_B}{c} + t_0$$

where n is the refraction coefficient of the fluid and t_0 is time necessary to pass the not measured parts of path from the source to the plane 0 and from it to the detector (fig. 1). The c/n quantity is the velocity of light in the fluid, further on denoted by v. From the equality of times:

$$t_D = t_B$$

we get the formula for the refraction coefficient:

$$n = 2\frac{x_B - x_D}{L_0} + 1$$

and using it we can express v as:

$$v = \frac{L_0 c}{2(x_B - x_D) + L_0}$$

Similarly we can use the equality of times t_C and t_E necessary for light when mirrors are in position C and E, when the lines on oscilloscope screen are identically inclined. From the measurements of x_C and x_E we get:

$$n = 2\frac{x_C - x_E}{L_0} + 1$$

and:

$$v = \frac{L_0 c}{2(x_C - x_E) + L_0}$$

The averages of the determined quantities should be used as the result.

It's worth noting that the light passes through not only the fluid, but also through the material the windows of the cuvette are made of. This causes a constant error. It should be assessed and a method for avoiding it should be proposed.

The report

The report should contain:

1. The average values of the velocity of light c and the average refraction coefficient n.
2. Assessment of errors of the results obtained.
3. Compare the results obtained with the table data.
4. Discuss the reasons of errors.

Questions

1. Describe the nature of the light waves.
2. Formulate the law of refraction.
3. The Lissajous curves.
4. Explain the measurement method.

Literature

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