October 23, 2023

MEASURING THE SPEED OF LIGHT

Objective: To measure the speed of light in air.[1]

Preparation: To be done *before* starting the lab.

1. Read section *1.6 The Postulates of Relativity* in the course textbook.
2. The speed of light *in a vacuum* is $299\,792\,458\,\mathrm{m\,s^{-1}}$. In some medium like air or glass the speed of light $v_{\text{light}} = c/n$ where n is the refractive index for the medium. For air at standard temperature and pressure (STP), $n_{\text{air}} = 1.000293$. What is the speed of light in air at STP?

The speed of light is one of the fundamental constants of physics. The idea that it is finite and is the same in all reference frames had profound implications on the development of physics. Its size determines the relative influence of classical, relativistic, and quantum physics, and so is essential to our understanding of the structure of the universe. Attempts to measure its very large value have been made by many different physicists in many different ways throughout history.

In this experiment you measure the speed of light by measuring the time it takes for light to traverse a known distance. The apparatus is shown in Figure 1. It consists of a laser diode (labeled A in Figure 1) that emits light pulses. The pulses are received at the end of a fiber optic cable B and directed to a detector C. The time it takes the light pulse to travel from the laser diode to the fiber optics cable is related to the distance x between the diode and fiber optics,

$$\Delta x = c(t_B - t_A) = c\Delta t,$$

where t_A is the time that the pulse leaves the diode, t_B is the time when it arrives at the detector, and $\Delta t = t_B - t_A$.

The output voltage of the detector and the voltage on the laser diode are displayed on an oscilloscope (Figure 2). A rising diode voltage indicates

[1] The speed of light in a vacuum is actually a defined value in SI units. It is defined to be precisely $299\,792\,458\,\mathrm{m\,s^{-1}}$. The meter is then defined as the distance light travels in $1/299\,792\,458\,\mathrm{s}$. In this lab we used a calibrated measuring tape to measure the speed of light in air. See the video at https://www.youtube.com/watch?v=IZjyAn3ma4 for a nice introduction to the base SI units.

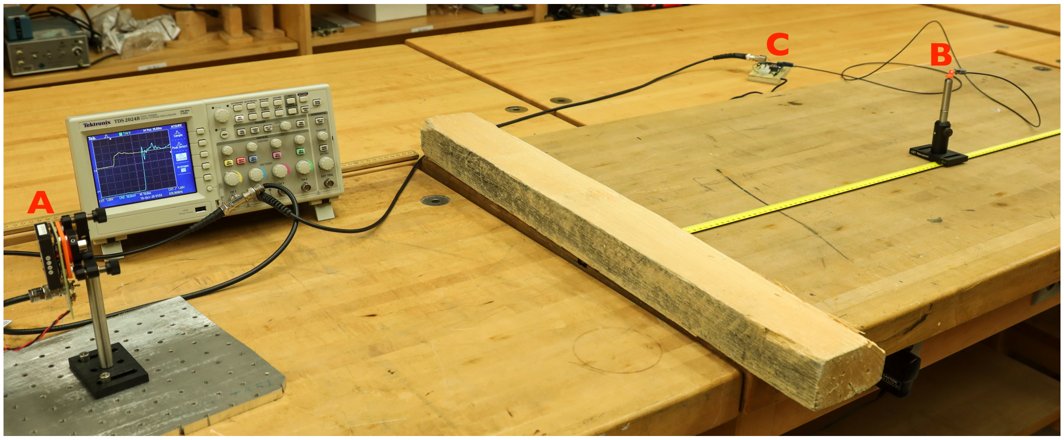

Figure 1: Apparatus for measuring the speed of light. A indicates the laser diode, B the end of the fiber optic cable that directs the light to the detector C.

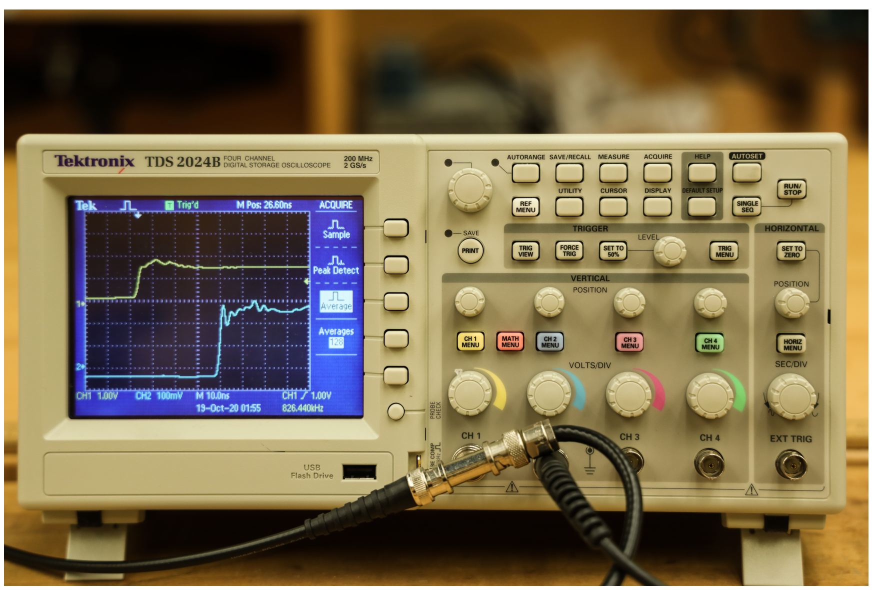

Figure 2: The oscilloscope trace showing the rising portion of the diode and detector voltages.

laser turning on and a rising voltage from the detector indicates the light was detected. The time of rising diode signal t_d doesn't happen exactly when the diode turns on because of delays in the electronics and the time it takes the signal to travel in the cable to the oscilloscope. Hence, $t_d = t_A + \tau_d$ where τ_d is the delay time. The same is true of the rising detector signal t_s. There is a delay in this signal because of the time it takes the light to travel through the fiber optics, the time for the detector to respond, and the time it takes the signal to travel through the cable to the oscilloscope. Again, we can write $t_s = t_B + \tau_s$ where τ_s is the signal delay time. If we define the *measured* time difference $t_s - t_d = \Delta t_m$ it isn't too hard to show that (do the derivation yourself!)

$$\Delta x = c\Delta t_m - c\Delta\tau, \tag{1}$$

where $\Delta\tau$ is the difference in the delay times.

The value of $\Delta x = x - x_0$, where x is the reading from the measuring tape and x_0 is the distance from the end of the measuring tape to the point where the light leaves the laser. Hence,

$$x = c\Delta t_m - (c\Delta\tau + x_0). \tag{2}$$

This means that if you plot x vs Δt_m it should be linear with a slope equal to the speed of light and intercept equal to $c\Delta\tau + x_0$.

Procedure: Before you turn anything on examine the apparatus and make sure you understand how it works. Ask your lab instructor for a quick check-out before you begin to take data.

1. Move the stand holding the fiber optic entrance aperture to the position you wish to use for the measurement.

2. Align the laser diode beam so that the detector picks up a reasonable signal.

3. Adjust the oscilloscope to show both the laser diode and the detector signals. Use the the oscilloscope to measure the time difference between the two signals at the point of zero voltage crossing for both signals. This time is the Δt_m in Equation 2.

4. Repeat the process to get at least five measurements at different distances.

Analysis: Plot the distance x vs. Δt_m. According to Equation 2 the slope of this line should be the speed of light. Do a linear-least-squares fit to the data. Don't forget to determine the uncertainty in your measurement.

Interpretation and Summary: Answer the following questions.

1. How does your result compare to the accepted value for speed of light in air? If they don't agree, try to explain some possible sources of error. For each hypothesis try to use your data to test it.

2. The intercept of your fit gives $c\Delta\tau + x_0$. Determine the difference in the time delay $\Delta\tau$ from your data. Is it a significant fraction of the light travel times Δt?

3. What might be done to improve the accuracy of your result?