Experiment 10: Speed of Light (*c*) v1.1

10.1 Introduction

In this experiment you will measure the speed of light (*c*), which is a fundamental constant of physics. By using short pulses of laser light, a high speed detector, and a high bandwidth oscilloscope, it is possible to determine *c* with an accuracy of a few percent. This experiment is an example of a direct time-of-flight (TOF) measurement over a distance of the order of a meter. You will also estimate the speed of light inside a medium of refractive index *n* and the index itself.

10.2 Equipment

A schematic of the experimental setup is shown below. It uses a passively Q-switched solid state laser (Nd:YAG) that produces pulses of ~ 1-ns duration and an infrared (invisible) wavelength $\lambda = 1.064\ \mu m$. The output of the laser has been strongly attenuated to emit an average power < 1 mW, but the peak power of individual pulses is still very high.

DANGER: Although there is not enough average laser power to burn clothing, skin, or equipment, the peak power in a short pulse can permanently damage the retina. The laser used in this experiment is not eye-safe, which requires that **PROTECTIVE EYEWEAR MUST BE WORN** whenever the laser is on. Only approved, specially marked laser safety glasses available in the lab are acceptable. An added complication is that the beam is infrared and thus not visible. Under no circumstances should the laser enclosure be removed. It is the responsibility of the experimenters to secure the lab and control access to it.

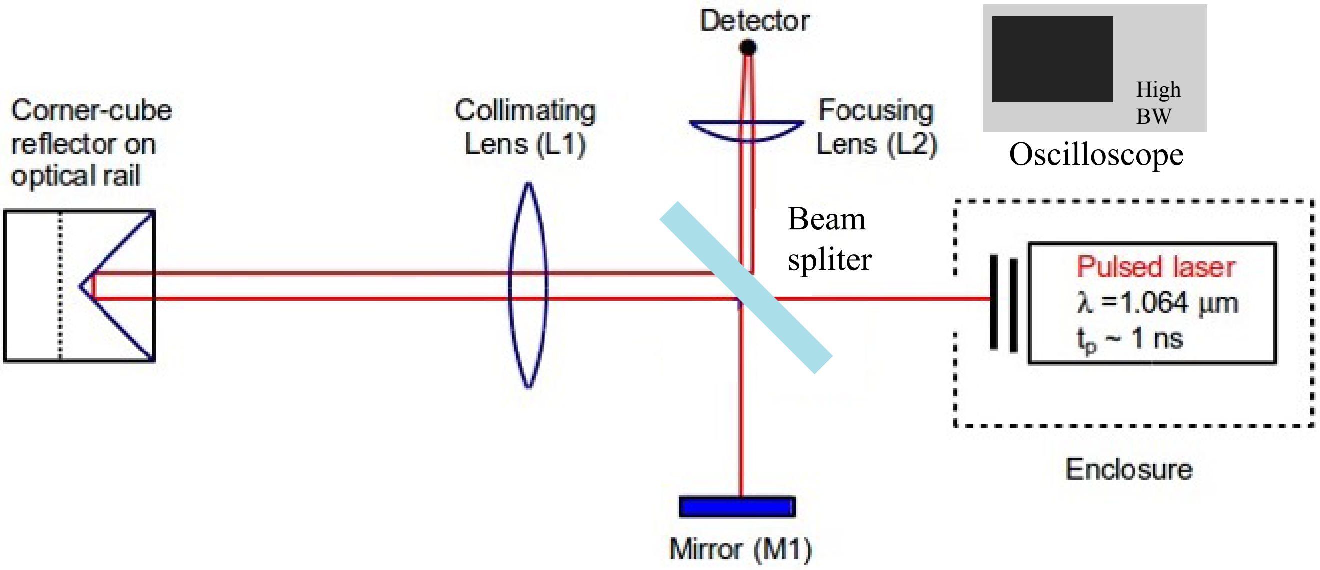

Fig. 1 Experimental setup for time-of-flight measurement

The optical layout in Fig. 1 forms a Michelson-like interferometer. It has the same essential geometry as was used by Michelson and Morley in 1887 to prove that *c* is independent of inertial reference frame. Their original experiment used a continuous white-light source, equal arm lengths, and studied interference fringes at the detector plane. In the present experiment, the light source is pulsed with one arm many times longer than the other. The laser pulses in the two arms of the interferometer arrive at the detector at distinctly different times and thus do not interfere. The temporal separation can be resolved with a high-bandwidth (> 300 MHz) oscilloscope. The linear relation between time and distance can then be used to determine *c*.

The experiment can be done, in principle, by carefully measuring the path lengths of each arm, calculating the path difference, and using the measured time delay between pulses to estimate *c*. It is simpler, however, to vary the path length of only one arm and measure the *change* of delay time observed on the oscilloscope. This is accomplished with a corner cube reflector mounted on an optical rail. Its position on the rail can be changed to be relatively close or far from the beamsplitter. The corner cube reflector is ideal for this application because it can maintain reasonably good reflection alignment when it is moved or translated, i.e. it is much less sensitive to misalignment than a flat mirror.

A 25 cm focal-length lens L1 is used to collimate the laser beam over the extended path length defined by the optical rail. All laser beams diverge depending on how they are designed; the divergence of this small laser must be corrected with the lens. A second, short focal length lens L2 immediately in front of the detector increases the intensity (power/area) and corresponding signal levels.

10.3 Procedure

All participants in this experiment **must wear the designated laser safety glasses**. Turn on the laser key-switch. The laser has a short (10 second) warmup time. Place a power meter immediately in front of the laser, measure and record the continuous power. Even though the laser generates a periodic sequence of pulses, it will produce a cw power reading.

Question: Explain why the oscilloscope time-resolves individual pulses while the power meter temporally integrates them.

You will need to complete the interferometer-like setup used for TOF measurements by aligning a flat mirror M1 that directs the light pulse from the long path to the detector (refer to Fig. 1). The short (reference) path is already aligned, so do not adjust the beamsplitter. With the room lights off, you can verify the presence of an invisible laser beam in the two paths with an infrared photo-card.

Turn on the oscilloscope and the detector (it is powered by a small internal battery). You should see a pulse on the scope that is reflecting from the corner cube. Be sure that the full bandwidth of the scope is enabled and that proper input termination is present. A pulse must be visible on the scope as the corner cube translates the full length of the optical rail.

Question: Explain the difference between using 1-MΩ or 50-Ω termination on the oscilloscope input.

Question: Explain how the corner cube works, how does it ensure that the reflected beam is parallel to the incident beam? (show it using geometric optics)

Align only the reference mirror M1 in the short path (reference arm) to produce a second pulse on the scope. Do not adjust the beamsplitter. Verify that pulses from both arms are being detected by alternately blocking the two arms. Two pulses – one from each arm – must be resolved when translating the corner cube along the entire length of the rail. Setup the scope to trigger on the pulse in the reference arm.

Measure and record the laser repetition rate.

Next, measure the pulse duration. It is conveniently estimated as full-width, half-maximum (FWHM) and is found as follows: Determine the peak voltage of the pulse with the oscilloscope. Then measure the temporal separation between the two points on the pulse envelope that are at half the peak voltage. Record the FWHM value.

Now use the setup to measure the speed of light. Establish a reference point with the corner cube placed at either end of the rail. Using the scope vertical cursors, record the temporal separation between the two pulse peaks. Next, begin a systematic translation of the corner cube along the rail, recording the time delay and displacement from the reference point or about **10** different positions of the retroreflector. Because this is a relative measurement, any convenient physical reference mark will suffice, but it must be consistent at each step. Repeat this measurement at least **four** times to acquire independent data sets.

Question: What are the sources of error in your measurement? Consider systematic and random sources.

Insert an acrylic rod into the long path of the interferometer-like setup used for TOF measurements. The rod will absorb some laser light and the signal levels on the scope will drop. You will have to carefully adjust its position to get a signal. For a fixed corner cube position, measure the separation time of the two pulses with and without the rod. Repeat the alignment and measurement at least four times. This information can be used to estimate the index of refraction of acrylic.

10.4 Analysis

Radiometry Use your recorded data to estimate the i) energy and ii) power in each pulse as the beam exits the enclosure. Estimate iii) the number of photons in each pulse. Calculate iv) the fluence (energy/area) and v) the intensity or irradiance (power/area) of each pulse assuming the beam area is 4 mm^2.

Speed of light Determine c using your collected data for relative time as a function of relative displacement (Note that the displacement is taken as the independent variable). Fit this data with a single straight line and calculate the measurement error/accuracy from the uncertainties in the line fitting parameters. Make sure that the variable with the largest error is plotted on the y-axis. There are two primary sources of measurement error: i) uncertainty in relative displacement and ii) uncertainty in time delay. Estimate values for each (i.e. how well can you resolve distance? Time separation of the pulses?) and determine which one makes the major contribution to the experimental error. That is, what is the quantity (x or t) that contributes the most to the uncertainty in c Hint, use error propagation to show this. Note that different data points will have different error bars and account for this in your analysis and line fit. Estimate the *combined* error introduced by the uncertainties. (Hint: These errors are not additive) How does this compare with the uncertainty in the value of c that you determined with the fit? Refractive index of acrylic Derive an equation that accounts for the time it takes light to propagate through a medium of refractive index n, where the velocity of light is given by c/n. Use this equation to estimate the index of refraction of acrylic based on your data. Let $\Delta t = t_1 - t_2$, where t_1 and t_2 are the pulse separations without and with the acrylic rod present, respectively. Assume that $n = 1$ for air. Estimate the uncertainty in your measurement of n by accounting for the propagation of uncertainties when measuring the rod length and Δt.