Physics 80 Lab Manual

March 2, 2019

Chapter 1

The Speed of Light

1.1 Pre-lab Calculations

1) What is the definition of the meter ? What is the exact value of the speed of light in vacuum?

2) How long does it take a light to travel a length of 1m? Using the time you just calculated and assuming that the uncertainty in the length measurement is 1 cm, calculate the uncertainty in the speed of light you would obtain if you were to use this measurement. Using again the time you just calculated and assuming that the uncertainty in time measurement is 0.2 ns, calculate the uncertainty in the speed of light you would obtain if you were to use this measurement. Which uncertainty is larger?

3) Light is slowed down in transparent media such as air, water and glass. The ratio by which it is slowed is called the refractive index of the medium. Calculate this speed of light in air if the index of refraction is 1.0003. Calculate (in %) how far off is speed of light in the air from the speed of light in vacuum? Assuming that in our setup we are aiming at few % accuracy is this correction relevant for us?

1.2 Safety

The laser used in this lab is of low power. Even so, avoid pointing the laser directly into anyone's eye.

1.3 Introduction

In this lab, you will measure the speed of light in air by measuring the time between sending and receiving a flash of light over a known distance.

The light signal is provided by a laser diode. Like an LED, the photons in the laser diode are the result of electrons and holes recombining. The laser diode produces simulated emission of photons from population inversion of holes and electrons injected from p-type and n-type semiconductors into an intermediate layer of un-doped intrinsic semiconductor.

If laser light is produced continuously, we'll have no way to measure a time difference between sending and receiving the pulse. Instead, we'll produce a brief pulse of laser light and a reference

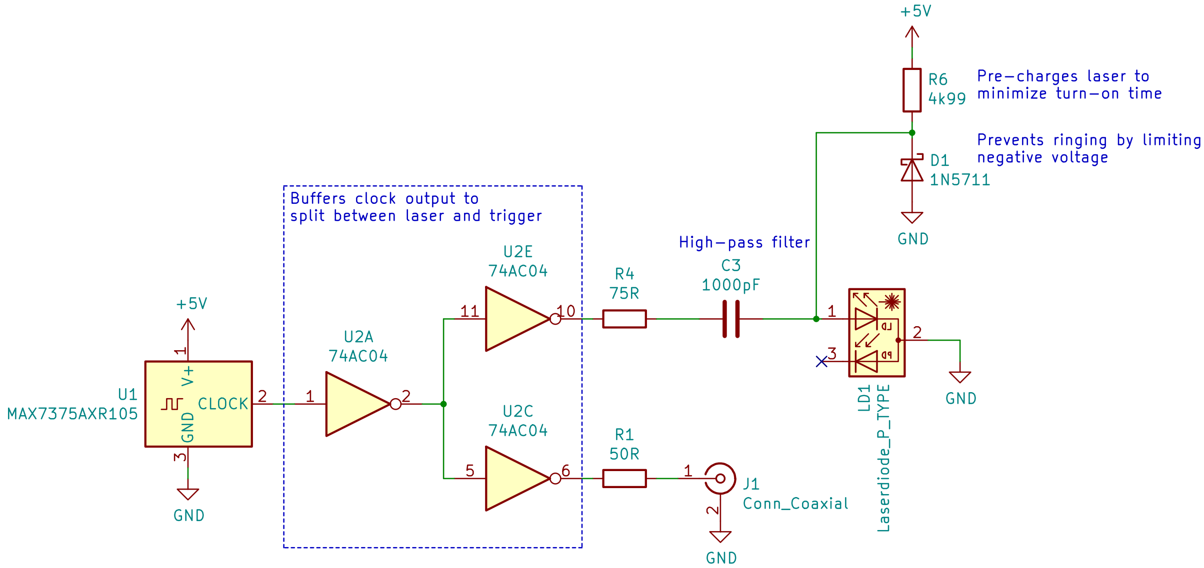

Figure 1.1: Circuit diagram for the pulsed laser diode.

signal to indicate the time at which the pulse was sent. The circuit for pulsed laser diode assembly we will be using is shown in Fig. **??**. You will recognize the passive components consisting of resistors, diodes, and capacitors. The MAX7375 (square symbol) is a silicon oscillator which produces a 1 MHz square wave function. The 74C04 (triangle symbol) is technically an inverter, but here they are used to simply produce two independent copies of the square wave function output. One copy of the square wave function is sent to a BNC connector, as the time reference for sending the laser pulse. The other copy is send through a capacitor, which acts as a high-pass filter, converting the step function into very narrow positive and negative pulses. The diode D1 rectifies this AC signal, so that only the positive signal is used to drive the laser diode, causing a brief pulse of laser light, in sync with the square wave signal which will be available on the scope.

We'll detect the flash of light using a photo-diode. The photo-diode is placed in reverse bias, creating a depletion zone. When photons strike the depletion zone, they excite electrons to create electron-hole pairs, which allows a current to flow. The receiver circuit is shown in Fig. **??**. The photo-diode D1 is held under reverse bias by the externally supplied DC voltage. The current pulse created when the laser light reaches the photo-diode is amplified by the SKYC5017 broadband amplifier. All amplifiers have limits to their bandwidth, but this amplifier is fast enough to handle the brief laser pulse that we are sending. The input connector for this device has an internally generated DC voltage, so we use the capacitor C5 to isolate this DC voltage from our circuit. The high-frequency AC signal pulse we wish to amplify will see this capacitor as effectively a short-circuit. All amplifiers require external DC power, but this one is a bit peculiar in that the DC power is supplied at the output pin. This explains the use of inductors L1 and L2 and capacitor C6. Remember inductors are a short-circuit to DC and an open circuit to AC, where as capacitors are an open-circuit to DC and a short-circuit to AC. The DC supply is provided to the output pin through the inductors, but the amplified AC output signal passes through the capacitor.

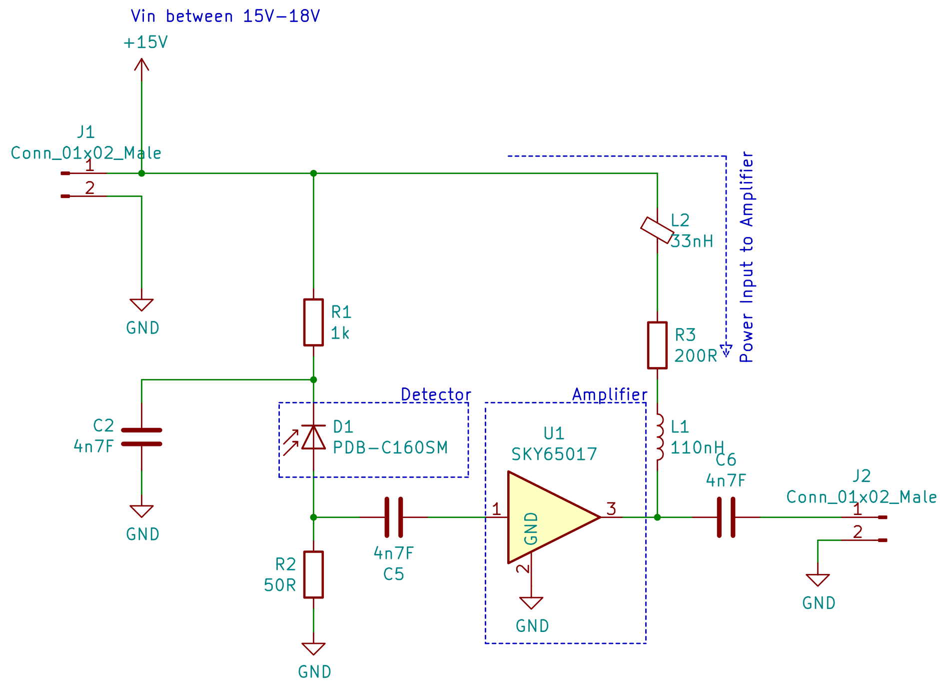

Figure 1.2: Circuit diagram for photodiode detector.

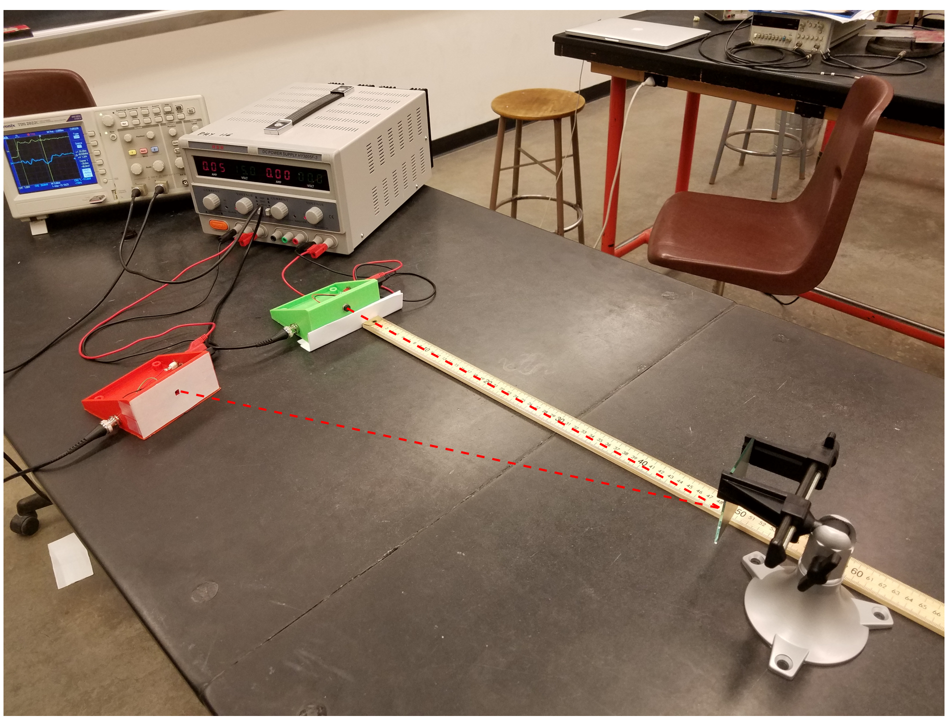

Figure 1.3: Setup.

1.4 Experimental Setup

The setup is shown in Fig. **??**. You will use your bench-top DC power supply to power the pulsed laser diode and the photo-diode receiver assemblies. The right most pair of output from your supply provides a fixed 5 V DC output, which you will use to power the pulsed laser diode assembly (transmitter). The transmitter is housed in the green box. The reference signal for the transmitter is output on the BNC connector, and should be connected to your channel 1 of your scope, **using a 50 Ω terminator.**

The photo-diode receiver circuit is housed in the red box. It should be powered at 15 V from your bench-top DC power supply. The amplified signal output on the BNC connector should be connected to channel 2 of your scope, **using a 50 Ω terminator.**

To suppress high-frequency noise, you can try installing RF chokes around your coaxial cable near the receiver and transmitter.

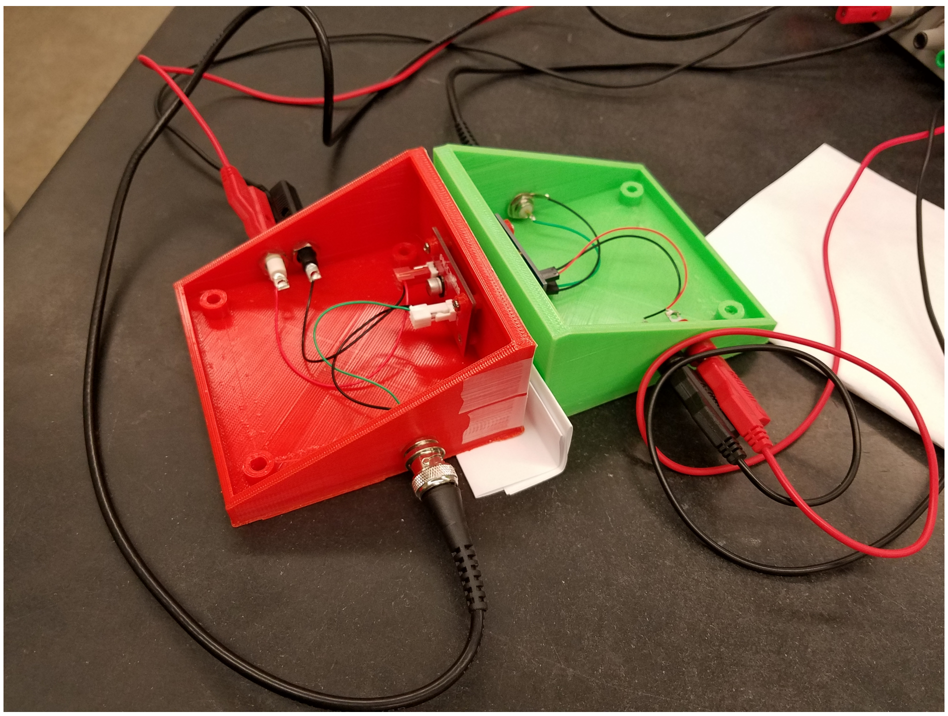

Figure 1.4: Initially, point the laser directly into the receiver.

To test your setup and the equipment, point the laser directly into the receiver as shown in Fig. **??**. Use folded printer paper to adjust the height and orientation of the boxes as needed.

Make certain you have a scope with a bandwidth of 100 MHz. The receiver signal is the most intermittent, so to avoid seeing empty wave-forms, you should always trigger on the receiver signal. Set both channels to AC coupling and make certain that the bandwidth limit is off. Set the time-scale to 5 nanoseconds. Then measure the time offset (Δt at zero distance) using your scope, as shown in Fig. **??**. Ideally, when making a timing measurement, you should use a sharp edge. This is why the reference signal is measured on the rising edge. The receiver signal, however, is quite noisy, so the edge is easily distorted. A slightly more reliable measurement comes from the using the minimum of the pulse. There is significant variation of the pulse height, so it helps to set the trigger level to only select the largest pulses (by moving the trigger threshold as far toward the bottom of the screen as possible). Because of timing jitter, you want to acquire a single waveform

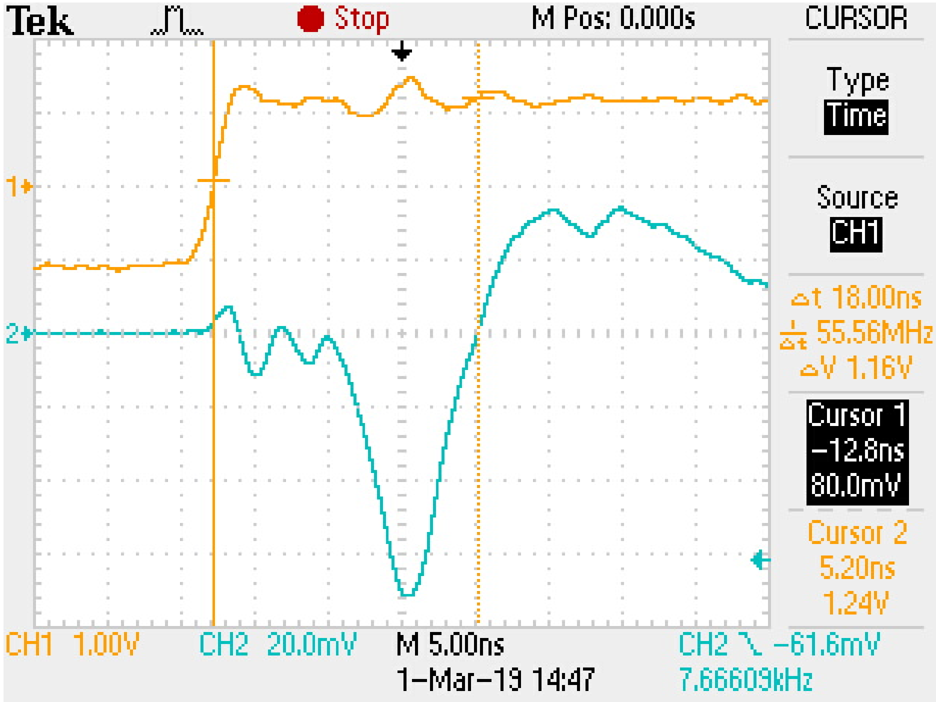

Figure 1.5: Measure the time interval from the receiver reference signal (yellow, offset by two divisions) crosses zero to the lowest point in the signal pulse (blue).

to make the time measurement, using the scopes run/stop or the single button. At each position, you should make at least three measurements. Despite the jitter, you should see that the time interval measurements are fairly stable, varying by about 0.2 nanoseconds, the cursor resolution at the five nanosecond scale. For **Measurement 1**, record the results of your time offset measurement and estimate it's uncertainty.

1.5 Speed of Light Measurement

Install a mirror in your swivel mount vise as shown in Fig. **??** Move the transmitter to point the beam down the long access of your lab bench. Place the mirror approximately 25 cm away from the transmitter as measured with a meter stick. Using a piece of white paper to track the beam spot, adjust the transmitter until the beam is pointed at the mirror. Place the receiver next to the transmitter and pointed at the mirror. Adjust the mirror until the beam is directed back to the receiver.

Once you have the beam pointed toward the receiver, orient your scope display so that you can see it clearly from the mirror. Set the trigger to just below the noise level, and adjust the mirror until the beam points into the receiver and a clear signal appears on your scope. Tighten the swivel mount to hold the mirror in place. You may find that the mirror moves slightly after you remove your hands and the signal is lost. If this is happening, try gradually tightening and adjusting the mirror, or lightly tapping it while the swivel-mount is tight. Continue adjusting until you have a clear signal.

Measurement 2: Each lab partner should make their own measurement of the time difference between the transmitter and receiver signals, and record all measurements in your logbooks. Then

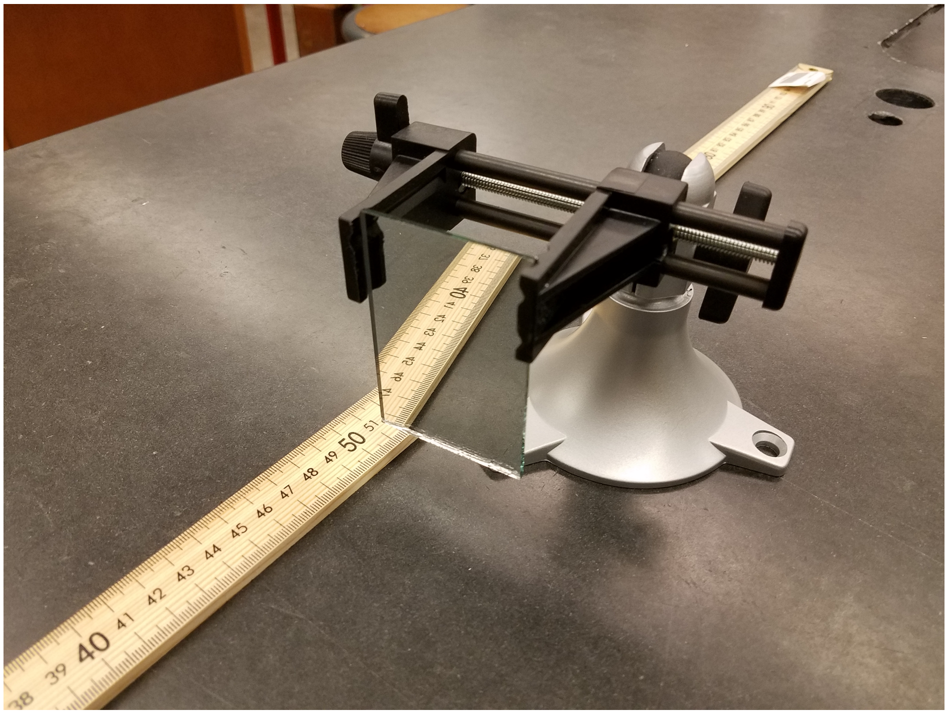

Figure 1.6: Mirror held in a swivel-mount vise

each lab partner should make a measurement of the total beam distance to the nearest 0.5 cm. Record all measurements in your logbooks. Estimate the uncertainty on your measurement. The resolution of the cursor time measurement at the 5 ns scale is 0.2 ns. The meter stick has a resolution of about 0.5 cm. If your measurements are consistent with one another, you can use these resolutions as your uncertainties. From these measurements and the timing offset measured previously, calculate the speed of light and an uncertainty. **this is a sign-off point for the lab**.

Measurement 3: Repeat the measurement for a starting position of the mirror at 50 cm, 75 cm, and 100 cm.

1.6 Analysis

Plot 1: Plot the data with the x-values populated by the quantity with smaller uncertainty and y-values populated by the quantity with the larger uncertainty. Include x and y-uncertainties in the plot. Perform a straight line fit using `curve_fit` function. Include y-uncertainties in the fit and be sure to set `absolute_sigma=True`. From the fit values calculate the speed of light together with its uncertainty.

A major source of systematic uncertainty in this measurement comes from the timing measurement. The transmitter reference has a nice sharp edge, but the signal pulse is distorted by amplification. As distance traveled by the light pulse increases, the signal becomes smaller, and the signal shape changes, which changes the measured time interval. This introduces non-linearity into the relationship between the distance and your measured time.

To estimate the size of this effect, you can simply set `absolute_sigma=True`. This setting instructs the curve_fit function to adjust the uncertainties until they are consistent with the linear relationship assumed in the fit. You can then interpret the parameter uncertainty as including both the statistical uncertainty and the systematic uncertainty due to this non-linearity.