PHYS 605 Final: Experiment for measuring the speed of light

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1 Introduction

Measuring the speed of light was an important exercise for several reasons. In the interest of good science, understanding how information is obtained is essential. So, we wanted to measure the speed of light ourselves to confirm that the speed of light is, in fact, about three hundred million meters per second. It also seemed well within the spirit of this class to execute this technically tricky experiment. So, in this report, I discuss the experiment that my lab partner and I performed in the pursuit of this measurement.

There are a couple of nuances that ought to be covered when discussing the measurement of the speed of light which are important to note. Firstly, we measured the two way speed of light, because it's impossible to measure the one way speed of light. How would you be certain, for a one-way experiment, that two clocks not in the same location are synchronized? It's actually impossible, and the laws of physics work regardless of if the speed of light is different in opposite spacial directions. We need only establish by convention that the two-way speed of light is the same as the one-way speed.

Also, because the speed of light is a defined quantity (from which the meter is defined), it could be argued that we merely measured the distance of the hallway where this experiment was conducted. Because the speed of light is a far more interesting quantity than the length of Demerit Hall, I'll instead use an inertial definition of a meter and second to see how close we can get to the defined value of c using the equipment we have on-hand.

We used the following equipment:

- Analog Discovery 2 (used as a signal generator)
- Rigol DS1102E Oscilloscope
- Laser Diode - 5mW 650nm Red (with integrated driver)
- Pin diode
- Two mirrors

The original idea was to simply switch on the laser and to measure how long it took for us to see the corresponding turn-on signal on the pin diode. There were many issues with this premise, as we will see.

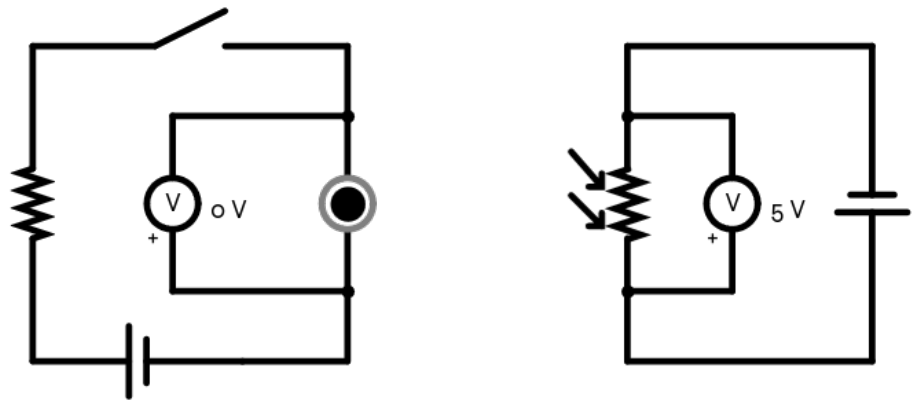


Figure 1: The original concept.

2 Turning on the laser

The first issue is the idea of "switching on" the laser diode: physical switches and buttons have a "bounce" that occurs where the circuit bounces between being on and off rapidly before reaching a steady DC state. We don't notice this bounce at perceptible timescales, but when each nanosecond matters, a bounce state which can last for milliseconds is unacceptable here.

The next logical step in figuring out how to turn on the laser precisely was a transistor, and indeed transistors are the way to go in applications where you need to turn something on quickly. They can act as a precise relay switch and are electronically controllable, which lets you turn a signal on far faster, at least for simple resistive circuits. (The signal can still be subject to other effects, like stray inductance and capacitance, but that can be eliminated with shorter cables or shielding.) However, even with a transistor, we were still getting a strange noisy signal when we closed the circuit that we could not explain.

We also tried using an avalanche oscillator, a device which brings transistors to their breakdown voltage, forcing transistors to let current through in the opposite direction they normally want to. This happens randomly, without any particular pattern or rhythm.

In this circuit, the capacitor is slowly charged up, bringing the transistor closer and closer to its breakdown voltage, at which point it will let a lot of current though the LED at once. This happens randomly, giving pulses with a sharp rise-time. We were going to use this instead of an electronic switch (such as a signal from the Analog Discovery), because it would hopefully have a sharper rise-time than an electronic switch. However, it still didn't fix the issue of the laser signal being noisy when we turned it on.

It turned out that the noisy signal from the circuit being completed came from the laser diode itself, not the switch. The laser diode we were using also had an integrated driver, we hypothesized that this driver was what created the strange signals we were seeing. We tried other laser pointers, but we couldn't get any of them bright enough to aim down the hallway. We had to think outside of the box.

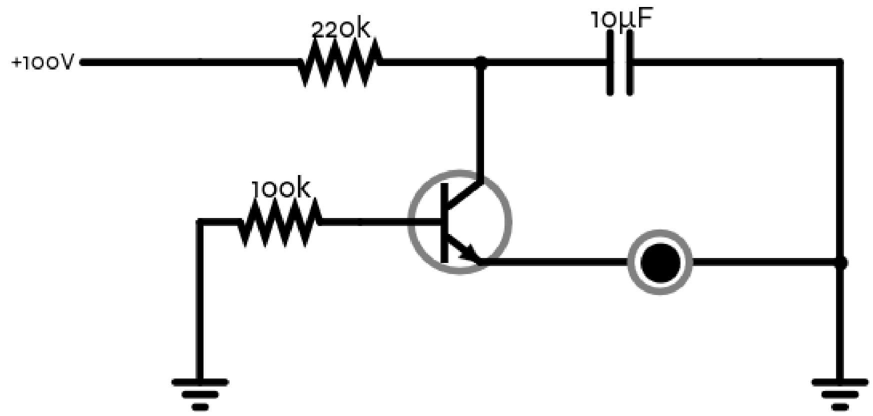


Figure 2: Avalanche Oscillator.

3 Laser Modulation

We settled for not even turning the laser on and off: If the integrated driver doesn't like being turned on and off all the time, we reasoned, then we could just leave it on and modulate the power the laser used. This method was also used by Murray, although he also saw how the signals from the lightspeed delay and no-lightspeed delay constructively or destructively interfered; we measured their phase shifts directly (Murray). (If we had wanted to do it that way, we could have used a beam splitter.)

Possibly the greatest challenge in this project was finding exactly what frequency, amplitude, and voltage offset to have the laser modulate at. The wave generator on the Analog Discovery could keep up with most of the signals we threw at the laser, but the laser itself couldn't keep up with too great of an amplitude at high frequencies (it would reduce the amplitude of the modulation). Furthermore, we found that the pin diode was particularly picky about the intensity of the light that was hitting it. It had a hard time differentiating bright light and really bright light, so we had to dim the laser in order to get a response which was preserved at high frequencies.

The necessary frequency was actually the easiest to find, as it didn't need trial-and-error to get the signal to work. Let's say we want a 90° phase shift between the close measurement and the far measurement. One cycle would be the following:

$$c = df \rightarrow f = \frac{c}{d}$$

The two-way distance of the hallway was measured already to be 89.4 meters. That gives us a necessary frequency of 3.36 MHz for a full period, or 840 kHz for a 90 degree phase shift.

The amplitude and the voltage offset were more tricky, because the signal would deform as we increased the frequency, especially once received by the PIN diode. After trial and error, we finally got a respectable signal with a sine wave, an amplitude of 300 mV, and an offset of 2.37V. We noticed at that offset and amplitude that even though the difference between high and low voltage wasn't that great, the laser visibly turned on and off at low enough frequencies.

4 Hallway Setup

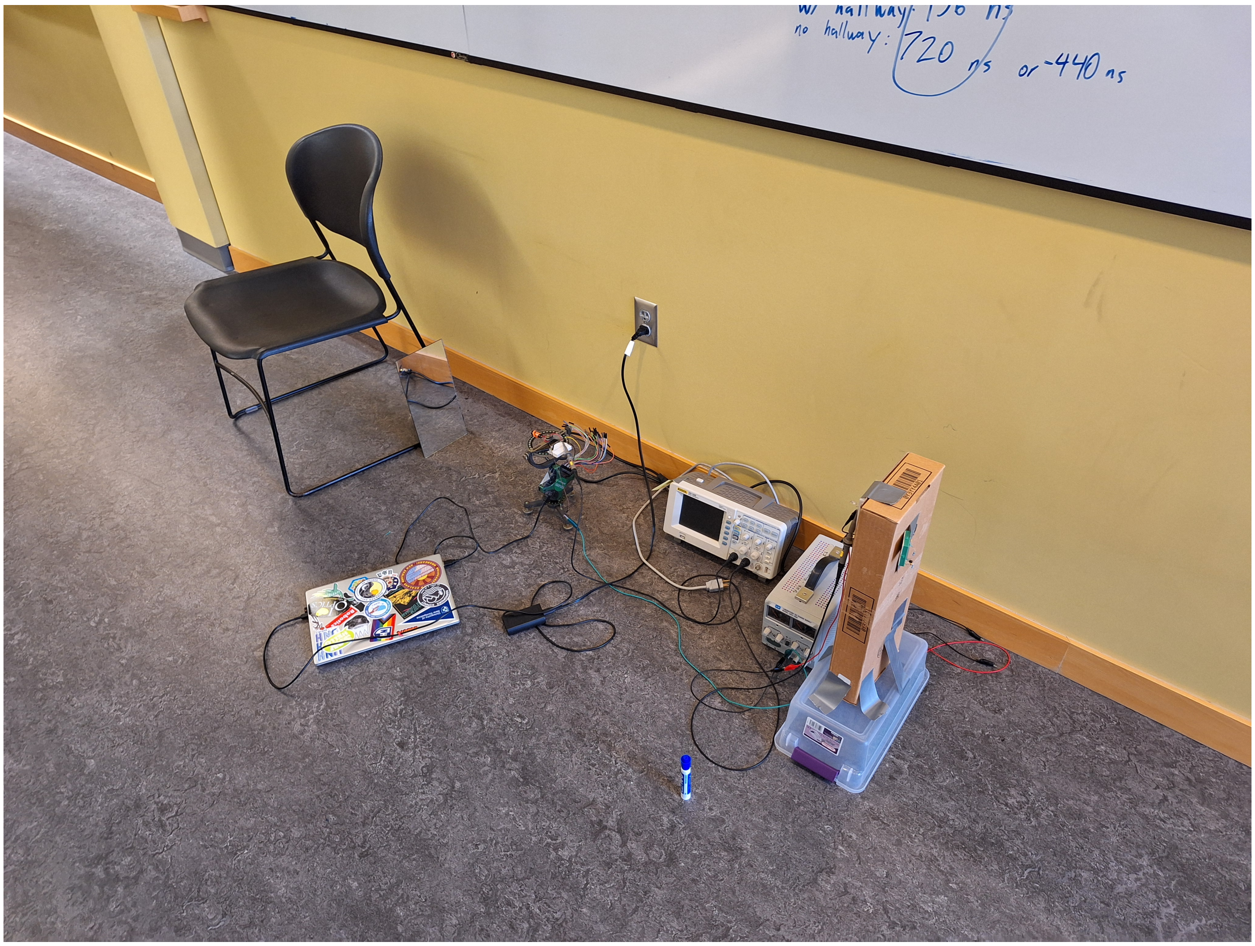


Figure 3: Hallway setup. Top left: Mirror balanced against chair, aimed at PIN diode. Directly to its right, there is our laser stand: we attached the laser diode via rubber bands to an optical angle-measuring device on a stand, then also attached its own breadboard and even the Analog Discovery to minimize the risk of knocking one of its cables. (The AD2 is connected to my laptop, center left.) Then, against the wall, we have the oscilloscope and the power supply (which we never wound up using, because the PIN diode was less noisy without an applied voltage). Lastly, the cardboard box taped to the plastic bin had, on the other side, a breadboard with the PIN diode hooked up to the oscilloscope.

The one-way length of the hallway is 44.7 meters, measured with a tape measure. The mirror on the far side was leaned against the wall, but everything else was not – it was about

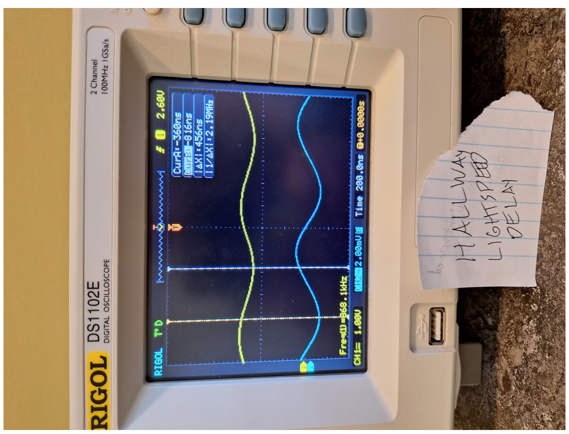
3-4 meters away from the other end of the hallway. Accounting for this, the distance the laser light traveled was about 81.8 meters.

When we stuck a mirror close by (to cut out the hallway's lightspeed delay), we got 1.88 meters, so ultimately we should see 79.9 meters of lightspeed delay.

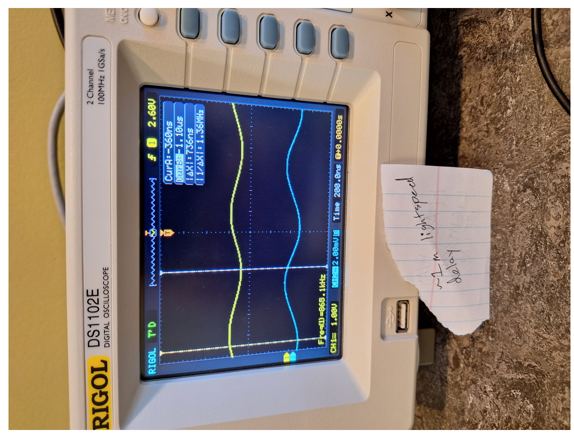
4.1 Aiming the system

Aiming the system was one of the most tedious parts of the process. We essentially had two days where we were trying to do this experiment, and on each day, the aiming process alone took about two hours. This is between trying to get the mirror angle correct, aiming the laser stand we had assembled (see photo), and eventually moving the PIN diode to wherever the laser light wound up with the strange cardboard-box apparatus.

5 Results



(a) With Lightspeed Delay



(b) Without Lightspeed Delay

Figure 4: Oscilloscope view of the full system, with and without the hallway's lightspeed delay

We measured the phase shift between the input laser signal and the received pin diode signal, crest to crest. Note that the phase shift is greater for the shorter distance than it is for the longer distance. This was extremely confusing for me when I saw it, but if you think about how a function $f(x)$ shifts to the left if you add some a to x, as in $f(a+x)$, then it makes sense that a greater time delay results in a shorter phase shift in this context.

Unfortunately, in my excitement about having gotten the setup to work and to give a number which was correct, I neglected to take multiple measurements to get a better average and uncertainty. By looking at the display in these photos, however, it's possible to look at individual pixels, so I emulated taking multiple measurements by deducing that each pixel of the oscilloscope is 8 ns in time. So, with the hallway lightspeed delay, I got that the time delay was 452 ± 3.26 ns, and without it (the first image), I got the time delay was 732 ± 5.65 ns. Propagating uncertainty, the total time delay is 280 ± 2.39 ns.

The speed of light is in meters per second, so let's divide the distance over the time delay:

$$\frac{79.9m \pm 0.1m}{280ns \pm 2.39ns} = 285,360,000 \pm 2,790,000m/s$$

The discrepancy here from the actual value, defined at 299 792 458 m/s, is strange. Ultimately, there is a good chance that there is some discrepancy in the distance that the light traveled, and I also have not accounted for the refractive index of air, but that is only 1.000293 and wouldn't bring it to the necessary value. It's entirely possible that I measured the distance wrong: if you interpret this measurement as a distance measurement using a constant speed of light, the distance of the hallway is 83.9 meters, which is possible (albeit unlikely). The thing is, any delays or uncertainties caused by electronics are unlikely to influence the result of this measurement, because the only thing we changed between the two measurements was the placement of the mirror.

Regardless, our percent error for this measurement is -4.82%, which, given our equipment and time constraints, is commendable. We set out with a main goal to get within 5% of the accepted speed of light, and through precise and careful measurements, we accomplished this.

6 Works Cited

Murray, Andrew James 2020 *Eur. J. Phys.* **41** 045704