1 Speed of Light — Introduction

The purpose of this laboratory is to introduce the student to measurements of high speed signals by measuring the speed of light \( c \), and to learn about measurements with offset data.

Essentially we will measure the speed of light with a ruler and a stop watch, but we will use a very nice stopwatch. Of course, it is silly to “measure” the speed of light because that speed is a defined quantity, \( c \equiv 299792458 \text{ m/s} \). Combined with the definition of the second in terms of the hyperfine splitting of the cesium nucleus, the numerical definition of the speed of light effectively defines the meter in terms of reproducible physical quantities [1]. Nonetheless, measurement of \( c \) using good equipment is fun and instructive.


2 Experimental Layout

2.1 Electronics

Our laser is a Power Technology model LDCU5/5894 solid state laser. The output is at 639 nm (red) and the cw (continuous) output power is 8 mW which is very bright. Do not stare into the laser. In addition to the cable that connects to the control unit, the laser tube has a coaxial cable input that switches the light on and off depending on whether the voltage on the cable is “high” (a few volts) or “low” (near ground). Basically this input is designed for a standard TTL control voltage. Note that the operation is somewhat counter-intuitive: The control voltage must be low to turn the laser on, and a high control voltage turns the laser off.

We will switch the laser on and off with an electronic pulse generator (Global Specialties model 4001). Set the pulse generator to make a rectangular waveform with a frequency in the 1-100 kHz range and with a very high duty cycle (meaning the signal is usually high, but goes low for a short time each cycle). This will make the laser “off” most of the time, reducing its average power to a level that is perfectly safe. Anything around 90% (laser on only 10% of the time) is fine. The point is that it is the transition from on to off that we will be measuring, so we don’t need to keep the laser on most of the time.

The best arrangement is to use the TTL output of the pulse generator with the complement switch on. (Understand why.)

In order to measure the time it takes for the laser to travel some distance, we need to trigger a fast oscilloscope with the output of the pulse generator. This is a problem because the fast signal will propagate down a coaxial cable and reflect off the high impedance of the scope or laser. So, you must terminate the cable with a
50 Ω terminator. It is best to do that at the scope input, and use tees to connect this pulse from the scope input to the laser.

Figure 1 shows this layout. The pulse generator suddenly drops the voltage to 0, triggering the scope and turning on the laser. This should be displayed on channel 1 of the scope. Some time later (speed of light round trip time) light hits the photodetector and is registered on channel 2 of the scope.

![Electronic arrangement diagram](image)

Figure 1: Electronic arrangement.

2.2 Optics

The laser is firmly mounted on an optical breadboard, facing a mirror at 45°. This will direct the laser beam toward the rear of the laboratory. Be careful that the beam does not reflect randomly.

Some distance from the breadboard, the beam should hit a mirror on a moveable stand and reflect back to the optical breadboard. There it should hit another mirror at 45° which reflects the beam through a lens onto a fast detector (Thor Labs DET-10A).

You should understand the purpose of the lens. This detector is capable of high speed operation, with a rise-time of a nanosecond. To accomplish that, the active area must be small (why is that?!?). Because the active area of the detector is small, only a tiny fraction of the light may hit the detector which will greatly reduce your signal. By focusing the laser onto the detector, you get the entire laser beam on the active area and get a much larger signal.
3 Measurements

Once you have the pulse generator correctly triggering the scope and laser, and the laser beam returning on the detector, you should have something similar to Fig. 2 on your scope. In this Figure, the yellow trace is channel 1. This appears to show the falling edge of the output of the function generator, but the scope is configured to invert channel 1, so this is actually a rising edge, meaning it shows the laser turning off. The blue trace is channel 2 and shows the output of the photodetector.

Note the delay between the yellow and blue curves — this means there is a delay between when the laser is shut off and when the light stops falling on the detector. It is hard to measure this delay. If you measure from the center of the trace, the delay is about 3 divisions, or 30 ns since the scope is set for 10 ns/division.

When this trace was recorded, the reflecting mirror on the movable base was about 1.5 meters from the laser, so the round-trip travel time for light would be about 10 ns (3 meters/3 × 10^8 m/s). This is inconsistent with the value of 30 ns from the previous paragraph.

There are two problems here for you to deal with: The first is deciding where to read the yellow curve on the scope. The second problem is that you really have no idea what sort of delays are involved in the propagation of the pulses through the cables (it is close to the speed of light), or how long it takes the laser to turn off once it receives a signal.

Fortunately, both of these problems are solved the same way. If you measure the delay picking an arbitrary point on the yellow curve above, and then move the mirror...
by a known amount, then the *difference* between the delays in the two cases will be solely due to the movement of the mirror.

It is critical that you read and understand the paragraph above! Do not move on until you understand this.

4 Analysis

- Set up the experiment and get it working as described above, when the reflecting mirror is fairly close to the laser, \( \lesssim 1 \) meter.

- Pick a arbitrary point on the scope trace corresponding to the pulse generator (yellow curve in Fig. 2). Measure the delay between the electronic pulse and the light hitting the photodector.

- Move the mirror a known amount. Measure this carefully! Repeat the measurement of the delay time. Note that the trace corresponding to the pulse generator is unchanged — that is critical to your experiment.

- Repeat the previous step, for about 5 positions of the mirror, spanning the range of a few (preferable as much as possible) meters.

- For each measurement, plot the delay time versus the position of the mirror (you can call the first measurement position 0).

- The slope of this line will be \( 2/c \). Extract the slope and the uncertainty in the slope, and from that derive a value for \( c \) and the uncertainty in \( c \).

- Make sure you turn off the battery-operated photo-detector when you are finished.

5 Questions

- Explain why the slope is \( 2/c \) instead of \( 1/c \)!

- What is your value for \( c \) and the uncertainty in your measurement?

- Discuss the sources of uncertainty in your measurement.

- Compare your value to the known value. Does your measurement lie outside the uncertainty in your measurement?

- If your measurement differs from the known value by much more than its uncertainty, what sort of systematic effects could cause this?

- How could you improve this experiment?