Speed of Light — c

George R. Welch
2 February, 2018

1 Introduction

The purpose of this laboratory is to introduce the student to measurments 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, $c \equiv 299792458$ m/s. Combined with the definition of the second in terms of the hyperfine splitting of cesium, 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.

Reference [1]: "International System of Units (SI),"
`http://www.nist.gov/pml/div684/fcdc/upload/si_brochure_8.pdf`, p 112.

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). We operate the laser with a very low duty cycle so that it's output power is quite low and safe, but nonetheless you should never state directly into a laser beam or carelessly reflect laser beams.

Do not operate the laser yourself. Your instructor or teaching assistant will turn the laser on before you start the experiment.

The laser output is pulsed and controlled with an electronic pulse generator (Global Specialties model 4001). Do not adjust this controller. Ask the instructor or teaching assistant to do it. We will 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. 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.

In order to measure the time it takes for the laser to travel some distance, you 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 impedence 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 photodector and is registered on channel 2 of the scope.

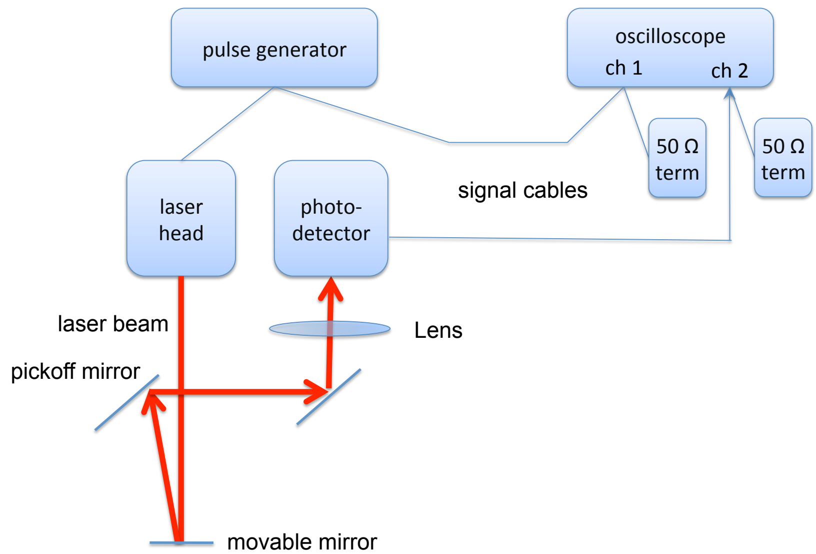

Figure 1: Optical and electronic arrangement.

2.2 Optics

The laser is firmly mounted on an optical breadboard facing the rear of the laboratory. You can adjust the breadbord slightly to make sure the beam travels safely toward the back of the lab. 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 a pickoff mirror at 45° which reflects the beam off another mirror and then through a lens onto a fast detector (Thor Labs DET-10A).

You should understand this layout, especially the purpose of the pickoff mirror and the lens. The point of the pickoff mirror is so that you can reflect the light backwards very nearly parallel to itself, so that as you move the moveable mirror there is very little trigonometric correction to the distance that the light travels. Each time you move the stand with the movable mirror, adjust it so that the light hits the same spot on the pickoff mirror, then adjust the pickoff mirror and the other mirror on the breadboard so that the beam hits the photodector.

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 with a lens, you get the entire laser beam on the active area and get a much larger signal. It is very useful to have the signal level the same each time you move the moveable mirror.

3 Measurements

Once the pulse generator is correctly triggering the scope and laser, and the laser beam is returning on the detector, you should be able to see something similar to Fig. 2 on your scope. In this Figure, the yellow trace is channel 1. This appears to show the

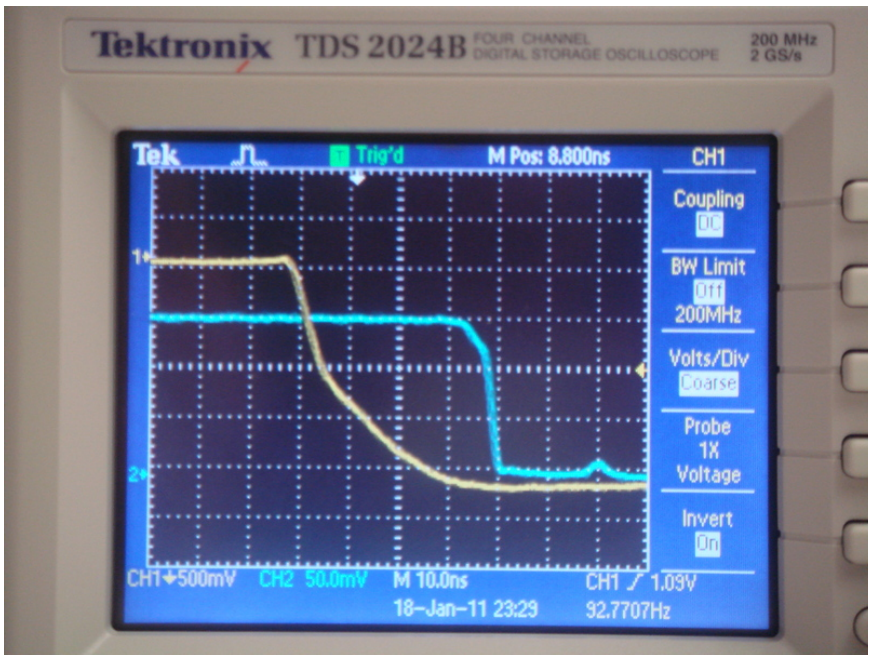

Figure 2: Oscilloscope display when experiment is working.

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 Data taking

- 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. Measuring the position of the moveable mirror can be a challenge, and many students have attacked it in different ways. If you are clever, you should certainly be able to know how much you have moved the mirror by to within 1 mm.
- Repeat the previous step, for about 5–10 positions of the mirror, spanning the range of a few (preferable as much as possible) meters. Here are example data that I took in the lab using this setup.

Mirror position m	Delay time ns	uncertainty ns
0.4584	13.8	0.1
0.7699	16.0	0.1
1.1601	18.4	0.1
1.6081	21.4	0.1
1.8661	23.4	0.1
2.1225	24.8	0.1

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

5 Analysis

For each measurement, plot the delay time versus the position of the mirror (you can call the first measurement position, or anything else). 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. For the data above this is shown in Fig 3

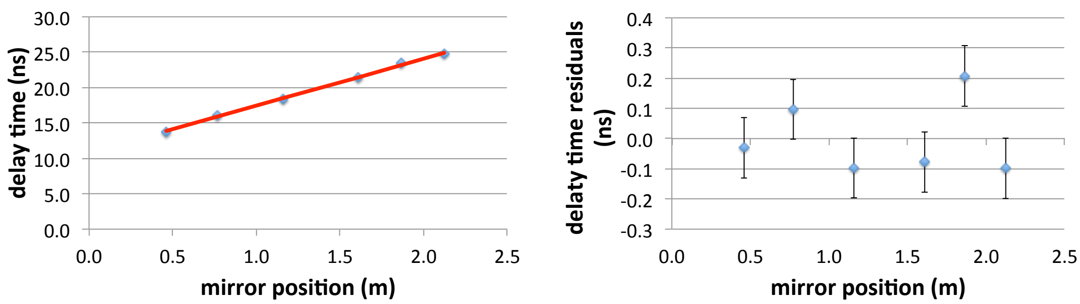

Figure 3: Sample data, the best-fit line, and residuals from the fit.

These data do not show any systematic trend from a straight line, and their scatter is consistent with the size of the error bars. The slope of the best-fit line is 6.651(69) ns/m. This gives us $c = 3.007(31) \times 10^8$ m/s. This is 0.3% high from the known value, and well within the uncertainty of the measurement.

6 Questions

- Explain why the slope is $2/c$ instead of $1/c$!
- What is your value for c and the uncertainty in your mesurement?
- 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?