Measuring the speed of light

LASER is an acronym for "Light Amplification by Stimulated Emission of Radiation". The He-Ne (Helium-Neon) laser was the first continuous wave (CW) laser invented. The principle of the experiment dates back at least a few hundred years to that of Galileo. We obtain the speed of light from the time of flight by measuring the time light takes to travel a certain distance and back. In order to measure the speed of light we must follow a transient change in the light intensity and measure the time it takes that transient pulse to move. Even though our laser is considered a CW laser, there are fortunate operational conditions that produce very rapid short lived repeated pulses in the laser intensity. Such pulsing effects relate (in a primitive manner) to pulsed laser effects known as Chirping—for which Dr. Donna Strickland won the 2018 Nobel Prize in Physics. The experiment uses the very rapid pulses that happen to be produced by unique properties or a long tube He-Ne laser, and an oscilloscope to measure the time of flight of these pulses.

I. Introduction

You will use a Helium Neon laser (wavelength 632.8nm), a 50% beam splitter, two photodiode detectors, and fast digital oscilloscope to measure the speed of light in air. You will measure the change in time taken for light to reach the signal detector as the signal detector is moved some distance. In order to do this we use pulses of light that are naturally produced by the laser. These pulses are produced with a frequency that depends on the length of the laser cavity. This spacing relates (to a very good approximation) directly to the longitudinal mode spacing in the laser (this is similar to standing waves on a string). The use of naturally occurring laser beats due to the mode spacing in this particular type of laser makes this lab a very unique method of measuring the speed of light.

II. Learning goals

At the end of this lab you should be able to

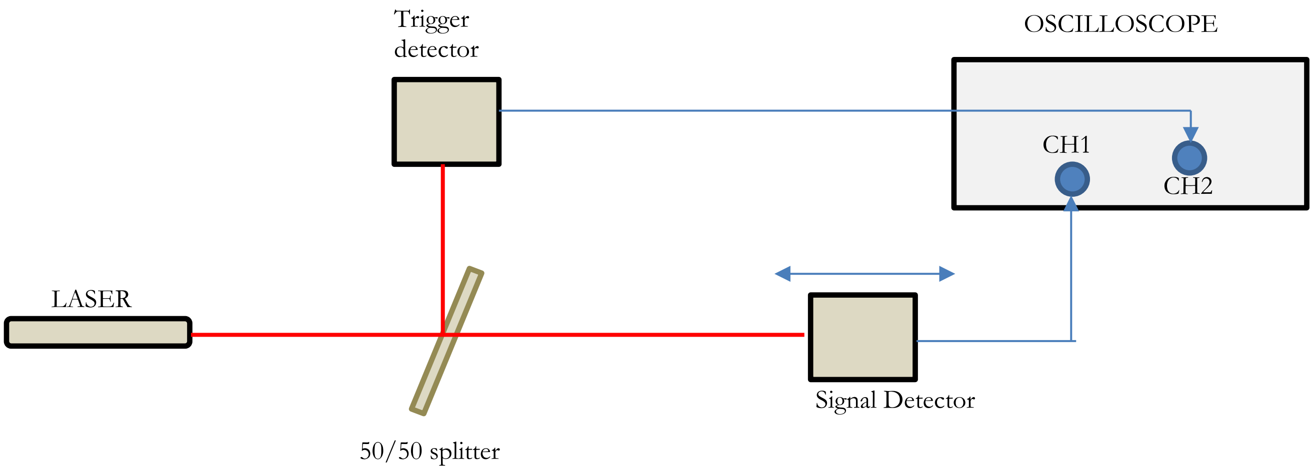
- Determine the speed of light without using external light modulation
- Use linear fit to calculate slopes (with uncertainty) and make high quality plots
- Compare your result to expected values
- Determine the longitudinal mode frequency spacing of laser from your measurements
- Keep organized data and other relevant work in a lab notebook

III. Procedure

IMPORTANT

- Before you start this lab, please remove any jewelry, watches, rings, etc. as reflecting surfaces will interfere with your measurements. Place those somewhere safe where you will find them when you are finished.
- Every time your turn on the laser, you must turn laser warning sign on.
- Be careful of this laser beam. Do not stare into "direct" reflections off the lens or other surfaces.

Experimental setup



Trigger detector. This detector will remain stationary during the whole experiment. Do not move it, it is already aligned and ready for data collection. If you move it, you may take some time reacquiring a good trigger signal, **and you will need to restart your data acquisition**. You should connect the trigger signal to channel 2 of the oscilloscope. A rising edge on a light intensity pulse reaching the oscilloscope is used to prompt the oscilloscope to start data acquisition. Once the trigger detector and level is set these must not be disrupted for the remainder of your experiment (doing so affects the timing). It is useful for both triggering setup and measurements to know that pulses of light are approximately 2 to 3 ns apart, and have width of approximately 1 ns.

Movable signal detector. Connect the signal detector to channel 1 of the oscilloscope. You will need to find a lateral detector position such that the detector is not saturated, but also receiving sufficient signal. Your signal may resemble a sine wave. You are looking at fast signals, so to reduce time constant you must use low impedance on the scope (50Ω termination).

Oscilloscope. See appendix

Data acquisition

1. Once you have good triggering on Channel 2 (trigger detector), turn that off and view only Channel 1. **Activate the cursors**. Place both cursors (*a* and *b*) on the very first signal peak at the left edge of the screen.
2. Record the time of that first peak on the oscilloscope, and also the physical position of the signal detector along a meter stick or measure on the table.
3. Leaving cursor *a* at the first peak, move cursor *b* to the position of the second peak. Record the time of cursor b and subtract it to cursor *a* to determine the time between peaks.
4. As you move the detector, the detector signal will shift in time on the oscilloscope. Readjust cursor *b* to the new time of the peak for each movement of the signal detector. Record positions and cursor *b* times. Your signal detector should start close to the laser, and move away in increments of 30.0 cm or less. You will need to adjust the lateral (side to side, and height) your detector position carefully each time you move in order to reacquire good

signal. (Note the signal cable should provide sufficient length and must not be changed during the experiment)

5. Repeat this as many times as the length of the table allows you. The 20 ns full screen time scale on the scope (2ns per box) should easily allow for movement of the signal detector for the full length of the table.
6. While taking data you should carefully consider uncertainty in determining positions and times. It may be wise to repeat one data point by going back to the same position a few times and see what the experimental variation is. I should expect to see such a measurement in your lab notebook.
    a. You should look at a single peak several times by pushing "run" and "stop" to reacquire data---and see if that particular peak moves. Several such measurements gives your uncertainty in time.
    b. Make good estimates of your position repeatability that include all motions of the mount, detector, and any measurement tools.
7. Additionally, you should record sources of uncertainty in all your measurements, significant figures, scope configuration and any other necessary variables. Note that uncertainty is not the smallest digit on the instrument, but instead has to do with repeatability (repeat your readings).
8. Make sure that you measure the pulse full width half max (maybe a few times) and also the pulse to pulse spacing (again perhaps several times).
9. You may want to take pictures of the setup to include in your final draft lab report, though block diagrams with labels are required. You could also include a sample image from the oscilloscope screen in your lab report. You can retrieve images from the oscilloscope using the USB port and a flash drive.
10. Before you leave, use your first and last data points to check your collected data is correct. You MUST do a reasonable job of estimating results prior to leaving lab. Without this---you don't know if you can leave!!!!!!!!
11. Disconnect detector cables from the oscilloscope.

<u>Data analysis</u>

1. Pulse spacing of the laser. This spacing relates directly to the longitudinal frequency mode spacing in the laser (why). You will **determine the frequency** this by measuring the time between two consecutive peaks. There are two possible cases for results, either $f=1/T=c/2L$ (just like frequencies for standing waves on a string or in an infinite square well) for the polarized laser or $f=1/[2\ T_{unpol}]=c/2L$ for a unpolarized laser. The unpolarized laser has two modes that spread out equally spatially and in time. So the measured time between the two closest peaks we observe is half that time that relates to a round trip time in the laser---so we double that time. This is due to both polarizations acting independently, so the measured time occurs twice as often as the "T" we really want. You will need to check to see if our model laser is polarized or unpolarized.
    a. You have measured T—as the space between two consecutive peaks. You may find other laser information posted on the course website (JDSU HeNe laser manual /specs). You will report "f", the fundamental mode frequency (with uncertainty)
    b. You may look on the laser to determine if polarized or not.

c. Your result for f, the fundamental mode frequency you determine, should be compared to the manufacturer listed fundamental mode spacing for the laser.

2. With your position of a well tracked pulse and time measurements, determine the speed of light in air. Remember, the fitting is not complete if uncertainties are missing. Professional quality graphs are expected. I accept the statistical uncertainty in a fitted parameter determined by a data analysis program. However that uncertainty should roughly agree with a rough estimate of uncertainty that derives from your individual measurements.
   a. In general you should not have 20% uncertainty in time, and then yield a 0.5% result for the speed of light.
3. Compare your measurement with the expected value of the speed of light.
   a. You have a measurement for $c_{experimental} \pm \sigma$ and also know c_{theory}.
   b. I want you to report how many uncertainties (standard deviations, σ) off your result is from the theoretical result (difference divided by σ) .
4. Explain why it is not recommendable to move the detector more than 30.0 cm in each step.
5. There are other factors that are unique to this lab that you should consider discussing in your final lab report:
   a. Understanding the pulse width, spacing, and fundamental mode frequency (longitudinal). WHY?
   b. Investigating differences in mode spacing for other lasers.
   c. The effect of polarization.
   d. Mode stability laser bandwidth.
   e. Historical reference (regarding speed of light measurements).

OSCILLOSCOPE

The oscilloscope is basically a graph-displaying device – it draws a graph of an electrical signal. In most applications the graph shows how signals change over time: the vertical (Y) axis represents voltage and the horizontal (X) axis represents time.

<u>Important concepts</u>

Input Impedance. When signal frequencies get very high, even a small impedance (resistance, capacitance, or inductance) added to a circuit can affect the signal. Every oscilloscope will add a certain impedance to a circuit it is reading, called the input impedance. Input impedances are generally represented as a large resistive impedance (>1 MΩ) in parallel with small capacitance (in the 10's to 100's pF range—cable dependent). It is often desirable to have high input impedance as this helps to amplify the signal from optical detectors, which are often low current (from pico-Amps to milli-Amps) sources (V=IR). However, the impact of high input impedance is more apparent, and detrimental, when measuring very high frequency signals or fast transient signals, and the probe or cables you use may have to help compensate for it. With high impedance there is a long RC time constant that prevents viewing rapid transient events on the oscilloscope. The transient signal can get smeared out in time.

Our oscilloscope has a button to select either 50Ω or 1MΩ input impedance. **We <u>must</u>** select 50Ω to observe the rapid pulses in this lab. Note that one may construct any "termination input resistance" and place it in parallel to the signal at the end of the cable regardless of a button available on the oscilloscope. Often such impedance termination choices are built into oscilloscope probes.

Trigger System. The trigger section is devoted to stabilizing and focusing onto the appropriate oscilloscope signal and time frame. The trigger tells the scope what parts of the signal to "trigger" on and start measuring. If your waveform is periodic, the trigger can be manipulated to keep the display static and unflinching. A poorly triggered wave will produce seizure-inducing sweeping waves. The trigger ensures that the repeated signal overlays a later repetition of the signal with the same starting locations on the screen. Since we will use signal averaging it is critical that we have a stable trigger.

The trigger section of a scope is usually comprised of a level knob and a set of buttons to select the source and type of the trigger. The level knob can be twisted to set a trigger to a specific voltage point. YOU SHALL BE REQUIRED TO RE-ESTABLISH TRIGGERING FROM SCRATCH.

A series of buttons and screen menus make up the rest of the trigger system. Their main purpose is to select the trigger source and mode. There are a variety of trigger types, which manipulate how the trigger is activated:

- An edge trigger is the most basic form of the trigger. It will key the oscilloscope to start measuring when the signal voltage passes a certain level. An edge trigger can be set to catch on a rising or falling edge (or both).—We use this.
- A pulse trigger tells the scope to key in on a specified "pulse" of voltage. You can specify the duration and direction of the pulse. For example, it can be a tiny blip of 0V -> 5V -> 0V, or it can be a seconds-long dip from 5V to 0V, back to 5V.

- A slope trigger can be set to trigger the scope on a positive or negative slope over a specified amount of time.
- More complicated triggers exist to focus on standardized waveforms that carry video data, like NTSC or PAL. These waves use a unique synchronizing pattern at the beginning of every frame.

You can also usually select a triggering mode, which, in effect, tells the scope how strongly you feel about your trigger. In automatic trigger mode, the scope can attempt to draw your waveform even if it doesn't trigger. Normal mode will only draw your wave if it sees the specified trigger. And single mode looks for your specified trigger, when it sees it, it will draw your wave then stop.

Most oscilloscopes have an indicator to tell you that triggering is occurring successfully. Look for "Trig'd"

The trigger circuit acts as a comparator. You select the slope and voltage level of one side of the comparator. When the trigger signal matches your settings, the oscilloscope generates a trigger as a "start time" to then acquire data for some length of time.
• The slope control determines whether the trigger point is on the rising or the falling edge of a signal. A rising edge is a positive slope, and a falling edge is a negative slope.
• The level control determines where on the edge the trigger point occurs.

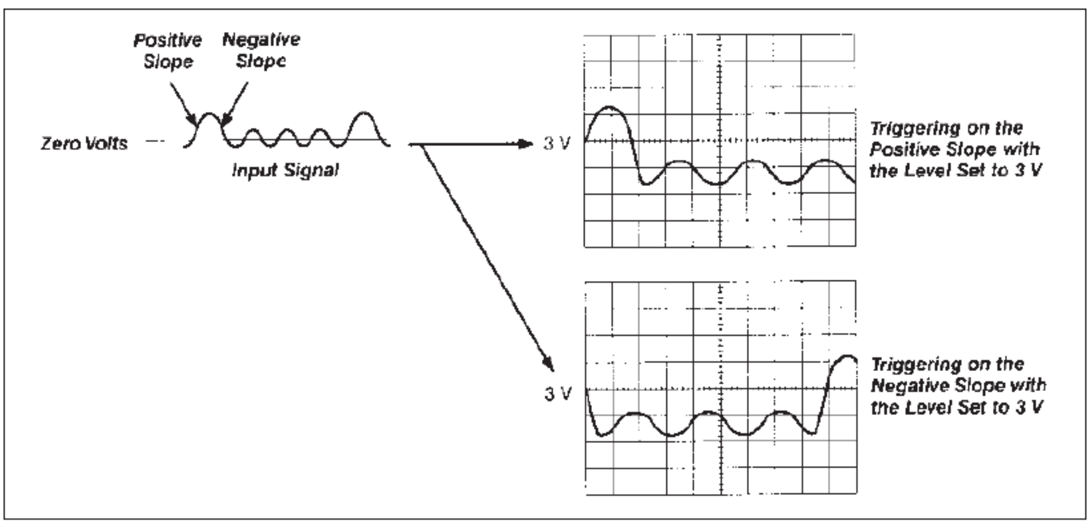


Figure 35. Positive and negative slope triggering.

SETTING UP THE SCOPE

Some typical settings for both channels are:
- Note the indicator displays "Trig'd", that indicates successful triggering.
- Also note the Run/Stop button
    - We use this to freeze frame the screen so we can take data with the cursors

    - Pushing Stop avoids any signal drift that occurs while data acquires (such drift does occur).
- Set Ch. 1 to 50 Ohm (signal) and Ch. 2 to 50 Ohm (trigger)
    - Now you can connect cables to sensor photodiodes.
- Set DC for both Ch.1 and Ch. 2.
- Band Width full
    - Using less than full bandwidth can allow for faster internal processing on digital equipment.
    - But we need the full frequency bandwidth to resolve fast time signals.
- Vertical scale: about 50 mV/division (from 2.0 to 100 may be typical).
- Horizontal scale: 2.00ns/division. This gives you 20.0ns across the screen.
    - The horizontal position can also be adjusted to place zero-ish, near the left side of the screen (convenient, but not necessary).
- Find the "Acquire" button, press it and make sure the mode you are in is:
    - Average 512: Averaging for 512 triggers gives you clean looking signals with well-defined peaks.
    - Record length may be 1000 points or more.

Now turn Ch.1 off so that you display only Ch. 2 and run through your triggering setup by selecting the trigger menu button: Edge → Source 2 → Slope up → Mode normal
Adjust the trigger level until good signal (note you may have to adjust the detector position). A trigger level high up on the peak seems to maintain a more stable signal (cherry picking data). Once you have good triggering, do not adjust the laser or the trigger detector position. Note the **"trig'd"** indicator on the upper right of the screen.
Triggering can be difficult. There can be several aspects of how the laser beam hits the detector that impact triggering. Different detectors may also change things. For our detectors we must be careful to hit the detector element inside the glass diode detector package. The detector can saturate, masking the signal. You may need to make very small minute position and or angle adjustments to trigger properly (and also to set up the signal detector). It is also important that the laser beam hit the detector squarely, so the light makes it to the actual detector inside the glass envelope.

You should see roughly a peak signal from ~10 to 100 mV.

<u>Using the cursors</u>
Hit the cursor button (while viewing good Ch.1 signal).
You will have two cursors, *a* and *b*. For now, set both on top of one another at a peak as far to the left edge of the screen as possible and make sure you record the time for cursor *a*. That is your starting time. If your signal is fluctuating too much you may use the run/stop button to freeze the display. Because our method uses an unstable laser you may see the signal shape change (cyclic through "good" to messy and back). It is helpful to use the run/stop button and to wait for a "good" signal picture to occur –then use "stop" to freeze the screen, prior to using cursors to take data. The image on the oscilloscope does cycle in and out of set modes, so your data should be taken for similar looking picture each time (you may need to wait for this—be patient).