Lab 4 - Speed of Light

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I. Purpose

In 1676, Danish Astronomer *Ole Roemer* discovered that the speed of light is finite using the movement of Jupiter in the night sky. Since then, the speed of light has been calculated and refined up to its current value of,

$$c = 299792458 \ \frac{m}{s} \tag{1}$$

Using a solid state laser, a photo-detector, and an oscilloscope we will be measuring the delay in time between turning a our laser off and when our photo-detector stops detecting the signal at different distances which will allow us to calculate the speed of light using

$$c = \frac{\Delta m}{\Delta t_d} \tag{2}$$

where Δm is the difference in distance of our measurements and Δt_d is the change in time delay at the corresponding distances.

II. Layout and Equipment

A. Equipment

- Pulse Generator *(Global Specialties Model 4001)*
- 639 nm Red Laser *(Power Tech. model LDCU5/5894)*
- Photo Detector *Thor Labs DET-10A*
- Oscilloscope *Tektronix 2024B*
- Movable Mirror
- Two Adjustable Pick off mirrors
- Lens
- Two 50 Ω Terminators

B. Setup

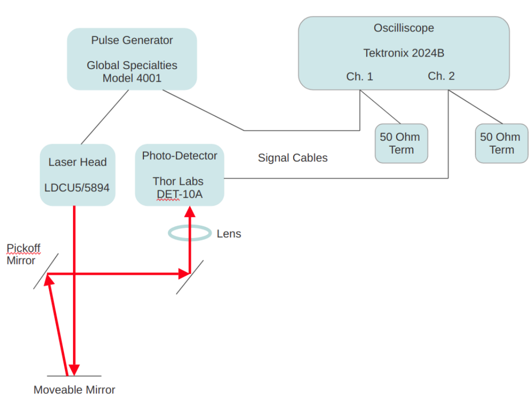

Fig. 1. Speed of Light Experiment Setup

Begin by mounting the Laser Head to a breadboard and using signal cables to connect one pulse generator output to the Laser Head and another output to one of the 50Ω Terminators and connecting the terminator to channel one of the Oscilloscope. Place the Photo-detector across from the Laser head and using another signal cable to connect its output to another 50Ω Terminator feeding it into channel two of the oscilloscope. Set up the movable mirror $\leq 1m$ away from the Laser head and place the pick off mirrors at approximately 45 degree angles directly adjacent to each other so that the first one picks up the laser from the movable mirror and the other catches the laser from the first pick off mirror feeding it through the lens into the photo detector.

Turn on all equipment so that the laser is operating and the oscilloscope is reading signals. Set the Pulse Generator to produce a a rectangular wave-form of 1-100 kHz range with a very high duty cycle so that the Laser will be off most of the time and on for a very short period, allowing safe operation of the laser while being able to read the time delay of the Laser. Set the oscilloscope to 10 ns divisions for reading the cutoff time.

C. Measuring the Time Delay

Begin by measuring the distance of the laser head to the movable mirror, recording this value in meters along with its distance doubled since the laser has to travel to the movable mirror and back. If this value is not doubled then the resulting speed of light would be half of the expected value. Ensure that the Laser is reflecting off each mirror and into the sensor of the photo-detector without the lens in place by adjusting each mirror using their adjuster screws so that each mirror reflects to the center of the next and the last mirror reflects precisely into the center of the photo-detectors sensor; check that the oscilloscope has registered a cut off signal from the photo-detector to ensure the laser is accurately placed. At larger distances the light will scatter and this could cause the detector to only pick up a small portion of the light which will greatly reduce your signal. In order to fully utilize the photo-detectors capability to read high frequency signals place the lens in front of the photo-detector adjusting it left, right, forward, and backwards until the oscilloscope is reading the maximum cut off signal.

The Oscilloscope should be displaying a yellow signal from the pulse generator and a blue signal from the photo-detector with a slight delay from between the beginning of their signal falling off. Using the cursor function on the oscilloscope, set cursor one approximately where the yellow signal begins to fall off; it is important this value stays constant through the experiment in order to record accurate data.

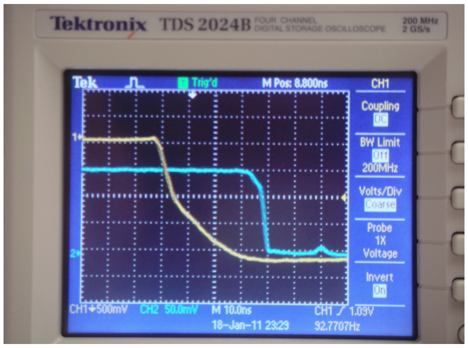

Fig. 2. Oscilloscope shot of the Time Delay

Set cursor two approximately where the blue signal begins to drop off. The difference between the two signals is the time delay between the pulse generator dropping to 0 volts and the photo-detector registering that the laser has turned off; record this value along with its uncertainty. Repeat this procedure 4 to 5 times increasing the distance of the mirror for each trial ensuring that the chosen pulse generator signal on the oscilloscope does not change.

Create a plot of Delay Time vs Position of the mirror with the position of the mirror as the independent variable and delay time as the dependant variable along with error bars from the uncertainty of the Time Delay. Since this plot should be linear, in order to account for the uncertainty and any outlying data points, plot a best fit line using the *Weighted Least Squared* method. Finally find the speed of light by calculating the slope of the *Weighted Least Squared* Best Fit line and compare it to the currently known speed of light. Also plot the residuals from the experiment in a separate plot setting the Mirror position as the independent variable and the Delay Time Residual as the independent variable.

III. Data and Graphs

Mirror Position(m)	Delay Time(ns)	Uncertainty(ns)
0.77	20.0	0.4
1.42	22.4	0.1
1.86	24.4	0.5
2.63	26.4	0.1
3.01	27.6	0.1
3.63	29.6	0.1
4.18	31.4	0.1

Fig.1. -Data

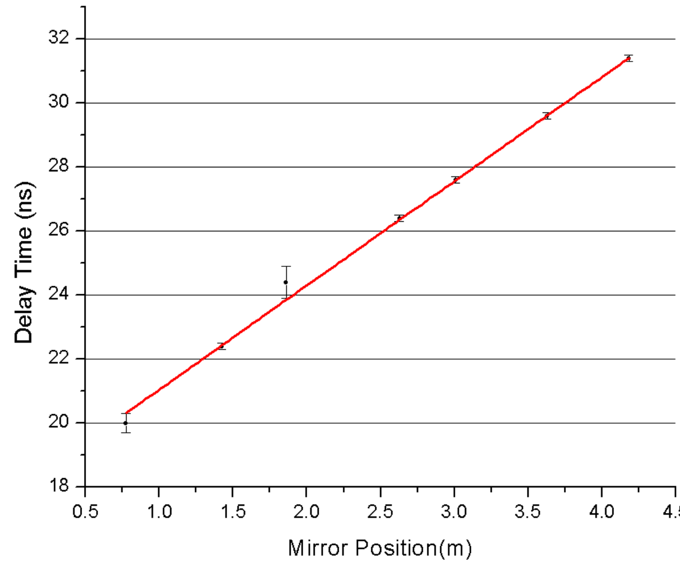

Figure 2. Slope for Speed of light

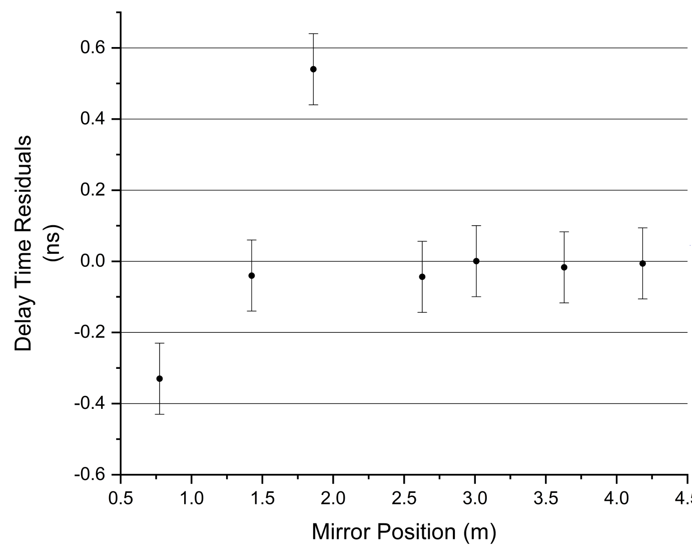

Figure 3. Residual of Data

IV. Calculations

In this lab for the speed of light one equation was integral for the data. This equation is the correction for the laser bouncing off two times the original path form the unfixed mirrors. This means that the length needs to be doubled and a constant value is also subtracted because the mirror and the pick off mirror are at an angle and not perfectly parallel. This means that the light bouncing off could add a very small length. This minor constant is negligible, and does not change the uncertainties in all values.

$$M_p = 2x - 0.078(7) - (1)$$

Another alteration in data was adding a better fitting slope with the least squares formulas. The new fit was added into figure 2.

$$original : y_t = 3.27(10)x + 17.78(10) - (2)$$

$$New : y_t = 3.254(45)x + 17.805(141) - (3)$$

V. Analysis and Critique

The main purpose of this lab was to obtain the measurement relatively close to the speed of light. The speed of light is measured to be 299 792 458 m s-1 and usually is notated by $3 * 10^8 ms^-1$. The result obtained in this experiment is $1/c_p = c_e$. In this case c_e is the experimental speed of light calculated by the data in figure 1, and c_p is the slope in figure 2. The value of c_e is $3.072(42) * 10^8 ms^-1$ relatively close to the speed of light, so the difference between them is a minuscule 2.4%.

The uncertainty of c_e is $.000(42) ms^-1$ which is negligible to some extent. This uncertainty comes from the uncertainty in the data. In figure 2 there are two points that stand out and both have a uncertainty greater than .1. These errors could come from measurements that were not optimal during the experiment.The instrument used for measurement is a measuring tape. This tape increases by increments of .2 inches, and adds the task of converting that to meters as well.This means the data taken is itself less accurate.

With the least weighted squares formulas the uncertainty was reduced. In the data in figure 1 there are two points that are relatively out-liars. The least weighted squares formulas allow for a better fitting data for the slope in figure 2. This slope is used to accurately measure the speed of light. The least weighted squares can alter the data to fit better. An example would be the data point 1.86m and its delay time 24.4 ns. Inserting the 1.86m into equation (2) the result is 22ns, and inserting it into equation (3) its 23.9ns. This allows for a better slope and data correlation.

The systematic uncertainty mostly comes from the delay in electronics. The oscilloscope can accurately measure to nano-seconds, but itself as build in delay. Another error with the oscilloscope would be the uncertainty in properly recording data. The period between the shut off time in the laser and the photo-detector is hard to pinpoint in the oscilloscope. This could also lead to faulty data.

VI. Conclusion

In this experiment the speed of light is concluded experimentally, and is only off by 2.4%, relative to the real value. The uncertainty accumulated during this experiment is mainly due to inexact measurements on various lengths between the movable mirror and the laser head.