Measuring the Speed of Light with a Pulsed Laser

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Abstract

The speed of light is an important physical quantity that is present in the description of nature at all scales. We determined the numerical value of the speed of light in this experiment by measuring the time of flight of a laser pulse at various laser-to-detector distances. Using this technique, we measured a value $c = 3.0 \times 10^8 \pm 0.1 \times 10^8$m/s. This value agrees with the accepted value of the speed of light, 299792458 m/s.

1 Introduction

1.1 Physics Motivation

When James Clerk Maxwell published his paper *A Dynamical Theory of the Electromagnetic Field* in 1865, he revolutionized theoretical physics by describing light as waves in the electromagnetic field. [1] This was an important result, as it linked together light, electricity, and magnetism. Efforts to measure the speed of light over the years showed that it seemed to have the same measured speed regardless of whether the light source was moving towards or away from the observer, a result that clashed with Galilean relativity. [2] This strange finding led to Einstein's Special Theory of Relativity and changed our view on space and time. Although the speed of light is now a defined quantity, we aim to measure it in this experiment because doing so is instructive and provides an important view into the history of physics. [3]

1.2 Theoretical background

The electromagnetic field is a theoretical construct which is used to describe the motion of charged objects and how they affect each other. Every charged particle generates an electromagnetic field which permeates the space around it. Charged objects in an electromagnetic field experience a force that can be calculated if the field at the object's location and the charge and velocity of the object are known. [4] Maxwell is best known for producing the set of equations (known as Maxwell's equations) that govern the behavior of the electromagnetic field. Solutions to Maxwell's equations in charge-free regions take the form of waves that propagate with speed $c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$, where ϵ_0 and μ_0 are two fundamental constants of nature, the permittivity of free space and the permeability of free space, respectively. [1] The permittivity of free space and the permeability of free space are defined independently of the speed of light to be the constants that relate the charge and velocity of particles to the strength of the electric and magnetic fields they produce, respectively. [4] Numerically, $c \approx 2.998 \times 10^8$, which Maxwell noticed to be remarkably close to the measured value of the speed of light. This led Maxwell to hypothesize that light was a wave in the electromagnetic field. [1]

In Maxwell's day, many physicists, including Maxwell himself, thought of electric and magnetic fields as stresses and strains in an invisible substance called the "aether" which filled space. [4] This led physicists to believe that the calculated value of c from Maxwell's equations was the speed of light relative to the aether, and that measurements of the speed of light would vary depending on the light source's motion relative to the aether. Several experiments were conducted in an attempt to measure the relative motion of objects through the aether, the most famous of which being conducted by Albert A. Michelson and Edward W. Morley in 1887. They used an interferometer to discern differences in the speed of two light rays traveling in perpendicular directions. If the Earth was moving through a stationary aether, then the speed of light would differ in the two directions. However, Michelson and Morley discovered that there was no appreciable difference in the speed of light, regardless of the motion of the light source. [5][2]

The fact that the speed of light appeared to be the same regardless of one's motion relative to the source was a serious blow to the aether theory. Albert Einstein decided to dispense with the aether and hypothesized that the speed of light really was the same in any inertial reference frame. Einstein used this novel hypothesis to deduce revolutionary ideas about the nature of space and time. These ideas culminated in his Special Theory of

Relativity in 1905. [2] Special Relativity showed that the constant c has far reaching influence that extends beyond electromagnetism and the motion of objects. Einstein showed that the speed of light is a proportionality constant that relates mass and energy, an idea that revolutionized particle physics. [6] Einstein's results prove that the speed of light is a quantity that is relevant at all scales, from the size of the universe down to the subatomic level. Due to the fact that the speed of light is an invariant quantity, the meter was redefined in 1983 to be the distance that light travels in a vacuum in $\frac{1}{299792458}$ s, thereby fixing the value of the speed of light to be $c = 299792458$ m/s. [3]

1.3 Our approach

Historically, measuring the speed of light has proven to be very difficult because light travels very fast by terrestrial standards. The first estimates of the speed of light were made using astronomical observations. Ole Christensen Rømer made the first such estimate in 1676. [7] When timing devices became sufficiently precise, time of flight measurements were able to be performed. These techniques involve measuring the time it takes for a light ray to travel a known distance, and calculating the speed from these measurements. In the past half-century, the most accurate measurements of the speed of light have been made by determining the frequency, f, and wavelength, λ, of a light beam and using the relation $c = f\lambda$. This method was used by K. M. Evenson, J. S. Wells, F. R. Petersen, B. L. Danielson, and G. W. Day to produce a value $c = 299792456.2 \pm 1.1$ m/s. [8]

Our approach to measure the speed of light was a time of flight method. We used a function generator to drive a laser to produce regular pulses. The laser pulses were allowed to travel a measured distance and then the pulses were detected by a photodiode. We then used an oscilloscope connected to both the function generator and the photodiode to measure the time delay between the drive signal and the photodiode's detection of the light pulse. We performed this measurement for several different laser-to-photodiode distances and fit a line to the resulting data points to obtain a value for the speed of light.

2 Experimental setup

2.1 Apparatus

To generate the voltage that drives the laser, we used a function generator set to produce a square wave with a frequency of 2.0 MHz. To observe the waveforms produced by the function generator and the photodiode, we used a Tektronics oscilloscope. We set the oscilloscope to trigger on the sync output of the function generator in order to ensure a consistent trigger. We then split the signal from the function generator and connected it to both a red diode laser and Channel 1 of the oscilloscope.

Next, we connected the photodiode to the oscilloscope. We did this by connecting a BNC tee into Channel 2 of the oscilloscope, connecting the photodiode to one end of the tee, and putting a 50Ω terminator on the other end of the tee. This type of connection is crucial to the experiment because it prevents the photodiode from becoming overloaded. When a photon strikes the semiconducting material in the photodiode, it removes a valence electron from one of the atoms of the semiconducting material. This produces an electron and a positive ion (an electron hole), often called an electron-hole pair. The electron and its electron hole partner then move along different paths in the coaxial cable that connects the photodiode to the oscilloscope due to their difference in charge. Now, if the coaxial cable was plugged directly into Channel 2 of the oscilloscope, these electron-hole pairs would never get a chance to recombine. This would lead to a buildup of electrons in the photodiode, which would eventually stop the flow of current. However, when the coaxial cable is terminated with the 50 Ω terminator, it allows the electron-hole pairs to recombine and prevents this buildup. We used a mirror to redirect the laser beam such that it could shine into the photodiode. We then calibrated the amplitude of the function generator's output to a level where the laser produced enough light to be detected by the photodiode, but not so much that it saturated the photodiode. The experimental set-up is shown in Figure 1.

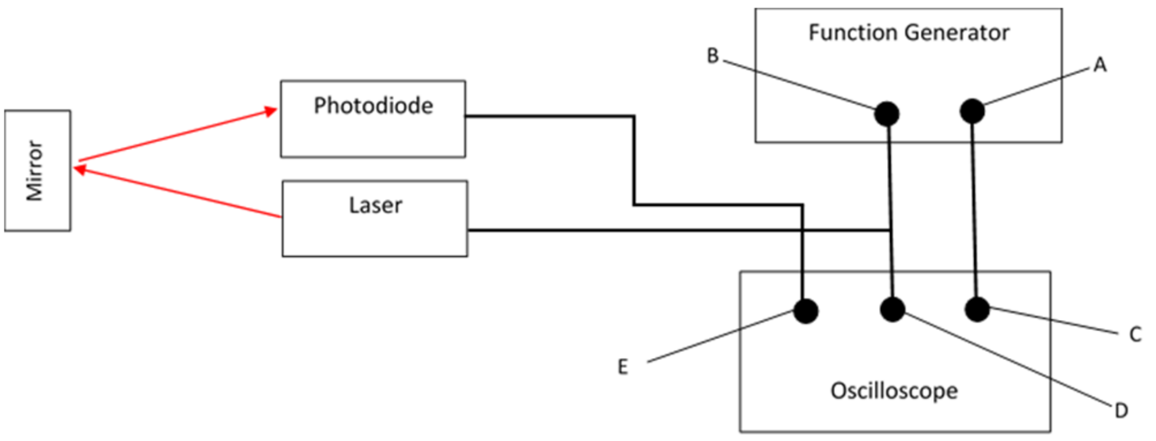

Figure 1: A schematic diagram of the experimental setup.
A: The SYNC OUT output of the function generator.
B: The function output of the function generator.
C: The external trigger port of the oscilloscope.
D: The channel 1 input of the oscilloscope.
E: The channel 2 input of the oscilloscope.
The red arrows represent the laser beam.

2.2 Data Collection

The data that we collected from this experiment was a set of distances from the laser to the photodiode and the corresponding time delay between the laser pulse and its detection by the photodiode. We obtained these data by measuring the distance from the laser to the photodiode using a meter stick, and measuring the time delay using the oscilloscope. After obtaining this information, we moved the mirror away from the laser in roughly 0.25 m increments, and repeated the measurements of distance and time delay.

The distance measurements were made in two parts because of the way the laser beam was redirected. One measurement was the distance from the laser to the mirror, and the other was the distance from the mirror to the laser. These measurements were summed to obtain the total distance that the light traveled from the laser to the photodiode. The oscilloscope measurements were made using the built-in delay measuring function of the oscilloscope. The delay function of the oscilloscope measures the time interval between when the oscilloscope detects the rising edge of the square wave from the function generator and when the oscilloscope detects the rising edge of the square wave from the photodiode. This delay corresponds to the time-of-flight of the laser beam. A typical oscilloscope measurement is shown in Figure 2.

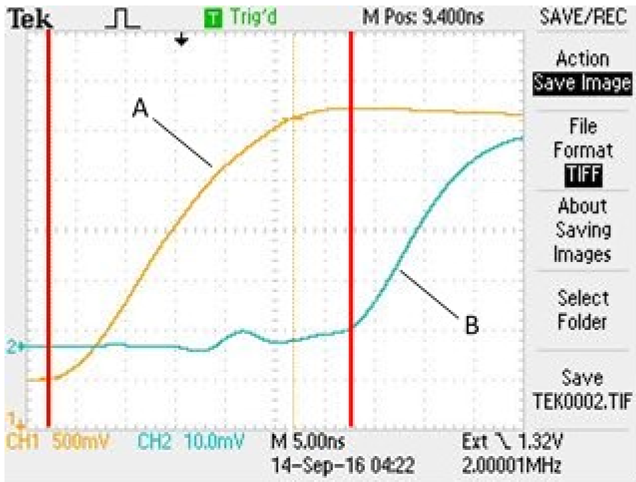

Figure 2: A screen capture from the oscilloscope showing the signal from the function generator (A) and the signal from the photodiode (B). The vertical red lines illustrate the time delay between the detection of the signals due to the finite speed of light.

3 Data Analysis and Results

After obtaining measurements at 15 different laser-to-photodiode distances, we processed the data and made a graph that showed our results. For each distance, we had measurements of the distance from the laser to the mirror, the distance from the mirror to the photodiode, and the time delay between the two signals fed into the oscilloscope. We estimated a measurement uncertainty of 0.7 cm in the distance measurements. This uncertainty was determined by having different people make multiple measurements of the same distance and determining the average difference between these measurements. We also estimated an uncertainty of 0.1 ns in the time delay, which corresponds to an uncertainty of ± 1 in the last digit of the value given by the oscilloscope. We summed the two distance measurements to obtain the total laser-to-photodiode distance at each interval, and we propagated the measurement error to estimate an uncertainty of 1.0cm in this total distance.

We then imported the total distance and corresponding time delay data into *Mathematica* and used a least-squares linear regression to generate a best-fit line to our data points. The best fit line had the equation

$$d = (3.0 \times 10^8 \pm 0.1 \times 10^8 \text{ m/s})t + (-5.6 \pm 0.3 \text{ m})$$

where d is the laser-to-photodiode distance and t is the time delay. The uncertainties in the fit parameters are the standard errors in these quantities, as calculated by *Mathematica*. The slope of this best fit line is our measurement of the speed of light, therefore our measured value is $c = 3.0 \times 10^8 \pm 0.1 \times 10^8$ m/s. A plot of the data points and the best fit line is shown in Figure 3. Our use of the standard error as the uncertainty in the measurement quantities is based on the assumption that the error in our measurements is purely random. However, as shown in Figure 3, several of our data points for the middle distances are significantly displaced from the fit line. This is likely due to a technical error in the oscilloscope's delay measurement, rather than random error. For this reason, the uncertainty in the fit parameters could be inaccurate.

Our measured value for the speed of light, $3.0 \times 10^8 \pm 0.1 \times 10^8$m/s agrees with the accepted value of the speed of light, 299792458 m/s. [3] Although our value is acceptable, we could have improved our result in several ways. We could have made a more accurate measurement of the distance from the laser to the photodiode, perhaps by stretching a piece of string between the points and measuring its length, rather than using solely a meter stick. We also could have made multiple measurements of the time delay at each distance and took an average. This would have been particularly helpful in reducing the anomalous results that we obtained at the middle distances. These outlying data points were likely caused by a technical error in the oscilloscope's delay measurement, which could have been corrected for by making multiple measurements.

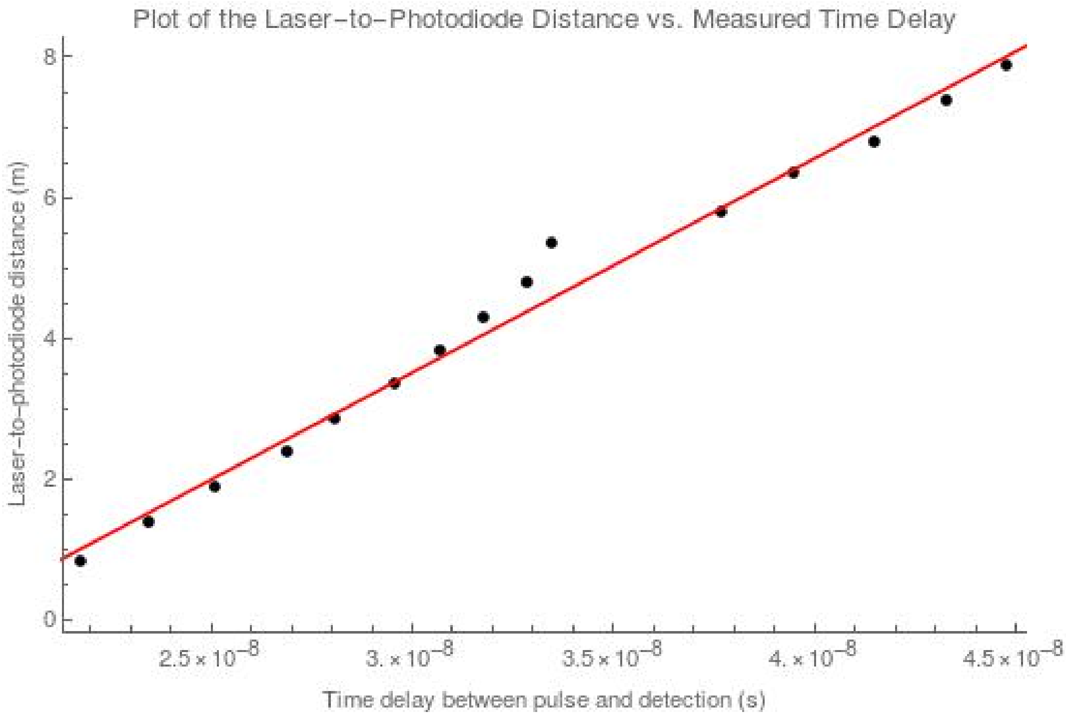

Figure 3: A graph of the data points we obtained and the best-fit line with equation $d = (3.0 \times 10^8 \pm 0.1 \times 10^8 \text{ m/s})t + (-5.6 \pm 0.3 \text{ m})$. Note that the error bars on the plot are too small to be visible, due to their small size relative to the range of measurements that were made.

4 Summary and conclusions

Our experiment measured the speed of light using a time-of-flight technique in which a laser was set to pulse at regular intervals. The pulses were detected by a photodiode and the time delay between the generation of the pulse and its detection was measured by an oscilloscope. This measurement was done for several distances, and a line was fit to the data points. Our measured value of the speed of light, $3.0 \times 10^8 \pm 0.1 \times 10^8$ is consistent with the accepted value of the speed of light and with other measurements that have been made of the quantity. [3][8]

References

[1] J. Maxwell, "A Dynamical Theory of the Electromagnetic Field", *Phil. Trans. R. Soc. Lond.*, **155**, 459 (1865)

[2] A. Einstein, "On the Electrodynamics of Moving Bodies", *Annalen der Physik*, **17**, 891 (1905)

[3] International Bureau of Weights and Measures, *The International System of Units (SI)*, p. 112, 2006

[4] D. Griffiths, *Introduction to Electrodynamics*, Pearson Education, 2013.

[5] J. W. Rohlf, *Modern Physics from α to Z_0*, John Wiley, 1994.

[6] A. Einstein, "Does the Inertia of a Body Depend Upon its Energy Content?", *Annalen der Physik*, **18**, 639 (1905)

[7] M. Romer, and I Bernard Cohen, "Roemer and the First Determination of the Velocity of Light (1676)", *Isis*, **31**, 327 (1940)

[8] K. M. Evenson *et al.* [National Bureau of Standards], "Speed of Light from Direct Frequency and Wavelength Measurements of the Methane-Stabilized Laser", *Phys. Rev. Lett.*, **29**, 1346 (1972)