Measuring the Speed of Light with a Modulated Laser

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Abstract

Because the speed of light notoriously fast, measuring its value in a laboratory setting requires suitably precise technology. By modulating a laser with a sine wave and detecting a distance-dependent phase shift, we found values for the speed of light consistent within error to the accepted value. We performed two experiments: first, we approximated the phase difference by measuring peak to peak values, and second, we found the actual phase difference using a sinusoidal fit of the data. In the the first experiment, we found the speed of light to be $2.96 \times 10^8 \ \mathrm{m\,s^{-1}} \pm 9.3\%$, and the second, more accurate experiment, we found the speed to be $3.004 \times 10^9 \mathrm{m\,s^{-1}} \pm 1.02\%$.

1 Introduction

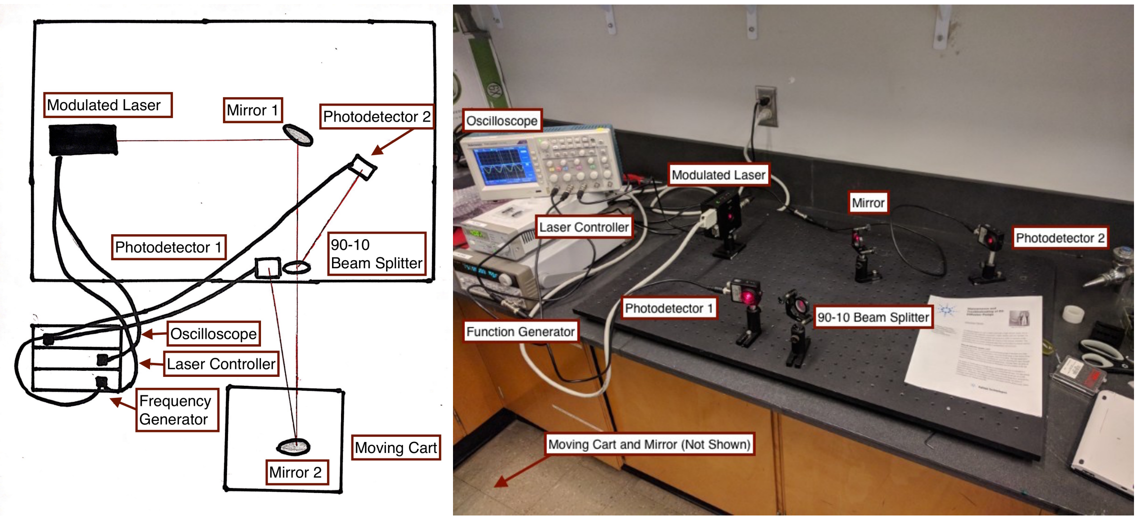
Historically, many scientists believed that the speed of light was infinite [1]. This conclusion, while false, is not surprising, as light travels approximately 300,000 kilometers in a single second [2]. Not everyone in the scientific community agreed that light traveled instantaneously, however, and some scientists designed experiments to measure the speed of light. Unfortunately, these early experiments failed, including work done by Galileo Galilee, who set up lanterns on two hills a known distance apart and attempted to measure the time it took to an assistant observe light from his lantern. He concluded that light must be too fast to measure over even distances considered "long" on Earth [3]. In fact, the first successful approximation of the speed of light was conducted by astronomer Ole Roemer in 1676, who studied how the finite speed of light caused a time delay in observation of the eclipse of Jupiter's moons when Earth was farthest in its orbit from Jupiter [1].

As technology advanced, new equipment has allowed for the measurement of the speed of light across distances much smaller than Galileo's hills or Roemer's solar system. Throughout the 1800s, scientists used mirrors and wheels rotating at high speeds to take their measurements, resulting in much more accurate values of light's speed [5]. Today, it is easy to acquire equipment precise enough to measure the speed of light in relatively short distances. In fact, using a technique involving laser modulation, we were able to measure the speed of light in under six meters.

2 Experimental Setup and Procedure

Modulating a laser causes the amplitude of the light to rise and fall in a sinusoidal pattern [5]. As a result, the intensity of the light rises and falls as well. When modulated light travels through space and falls on a detector, the sinusoidal pattern will appear slightly phase shifted relative to the reference. When the modulation frequency is high, this phase shift is highly responsive to changes in distance. Figure 2 displays such an observed phase shift.

We use a diode red laser, a function generator, an oscilloscope, and a photodetector to perform our measurements of the speed of light. Using a Thor Labs laser diode controller, we power the laser



(a) The experimental design.

(b) The experimental setup.

Figure 1: Light modulated by a sine wave reflects off of the mirror centered on the optical bench and into a 90-10 beam splitter. The intense part of the light travels down the room to a distance determined by the experimenters, reflects off another mirror, and lands on photodetector 1. The weak part of the beam reflects onto photodetector 2. The oscilloscope displays the function generator wave that modulates the laser as well as the two photodetector waves.

with approximately 40 mA. The intensity of the beam is modulated by the function generator in a sinusoidal pattern, which is displayed on the oscilloscope. For the modulation, we applied a frequency of 15 MHz, sufficiently high to perform measurements of the phase shift across small changes in distance. We provided an amplitude ranging between 0.8-1.5 $\mathrm{V_{pp}}$ to ensure that the detected intensity of the light would have measurable peaks. To protect the laser, which is not rated for negative voltages, we provided an offset of 400 mV.

The beam of the laser travels along the path in figure 1. It passes through the 90-10 beam splitter, with 90 percent of the beam's intensity traveling to the mirror on the moving cart and 10 percent traveling directly to the reference photodetector. The photodetectors send readings of the intensity of light to the oscilloscope, where they are displayed alongside the frequency generator wave. However, the reference photodetector displayed electronic pickup caused by to the frequency generator. Due to the uncertainty in the phase shift this caused, we chose to perform our measurements of phase shift against the frequency generator itself, as this decision would not affect our measurement of the speed of light.

Before taking our measurements, we collimated the laser to decrease the loss of detected beam intensity over long distances. To take our measurements, we moved the cart backwards and measured the corresponding phase difference Δt for each new position in space Δx, giving us a relationship between time and distance traveled. We performed two experiments to measure of the speed of light: first, we found Δt by measuring the peak-to-peak phase difference between the detected beam and the frequency generator, and second, we fit the sinusoidal wave data for both the reference and photodetector in Python and comparing the fitted phase shifts to find Δt.

3 Results and Discussion

Both of our experiments resulted in accurate values for the speed of light, which we found by performing a linear fit of the graph time vs. distance. As expected, the sinusoidal fit experiment (figure 3b) gave the most accurate with the least uncertainty: it found the speed of light to be equal to 3.004×10^9 $\mathrm{m\,s^{-}1}$ $\pm 1.02\%$, which is consistent within error to the actual value of 2.9979×10^8 $\mathrm{m\,s^{-1}}$. The peak to peak experiment (figure 3a) yielded a less-accurate value of 2.96×10^8 $\mathrm{m\,s^{-1}}$ $\pm 9.3\%$, though it is still consistent.

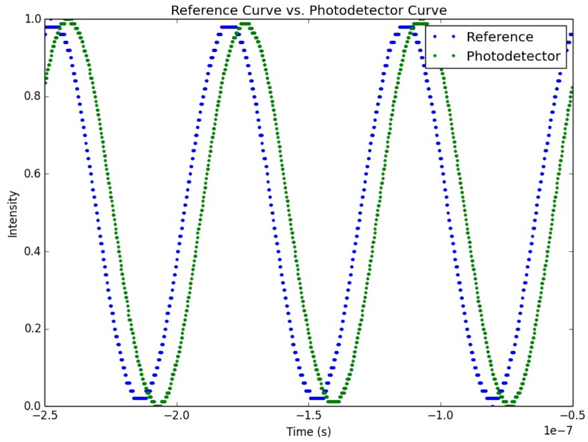
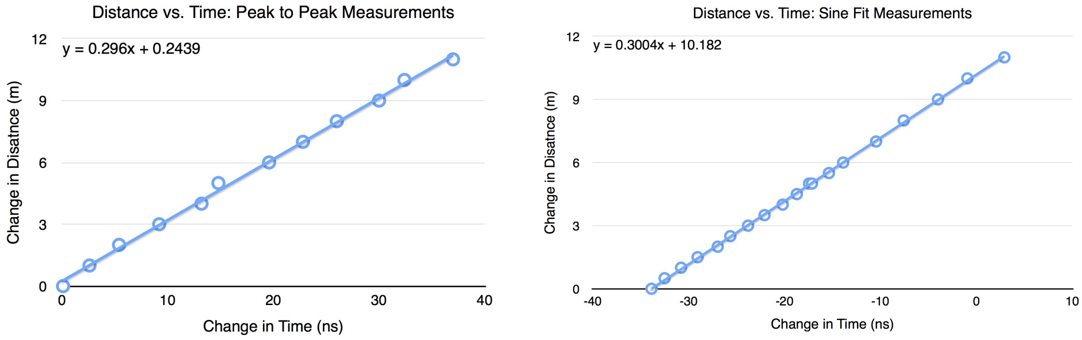


Figure 2: The oscilloscope display of the reference wave from the function generator and the photodetector wave. Notice that the photodetector wave is a shifted slightly to the right; this is shift is dependent on the distance the light travels before it reaches the photodetector.



(a) **(b)**

Figure 3: In experiment (a), the phase shift Δt was determined by measuring the time delay between intensity peaks on the oscilloscope. In experiment (b), the the phase shift Δt was measured by performing a sinusoidal fit on the photodetector curve and extracting the phase shift value, which yielded a more accurate measure of the speed of light.

Both experiments also resulted in a nonzero intercept in our linear fit, which represents a distance offset in meters. This offset appears because our chosen reference location when performing distance measurements was a non-zero distance away from the source laser and because there is some unknown constant offset due to the frequency generator, but it does not affect our measurement of the speed of light.

4 Conclusion

The two values we measured for the speed of light are consistent within error to the accepted value for the speed of light. Performing a sinusoidal fit to the oscilloscope data is a more accurate method because it takes into consideration a broad range of data compared to peak-to-peak measurements, which use only one data point per measurement. It therefore resulted in a more accurate value for the speed of light with a percent difference of only 0.20%, whereas the peak-to-peak measurements had a percent difference of 1.26%.

The random uncertainty was determined using the linear fit of our graphs: we compared the difference between the actual value of the distance measured and the expected value predicted by the linear fit equation. The systematic uncertainty was found by approximating the uncertainty in time at 1 ns (the smallest unit of measurement on the oscilloscope) and the uncertainty in distance at 0.01 m (a rough estimate of our ability to accurately measure distance). Finally, the total uncertainty was found by adding the random and systematic uncertainties in quadrature.

Because the values for the speed of light that we obtained were consistent within error, we conclude that both experimental methods are effective. However, because the sinusoidal fit measure of the speed of light is more accurate but not significantly more difficult to perform, we recommend improving upon this method when performing this experiment in the future.

One suggested improvement is to take more measurements in a shorter range. Taking more measurements reduces the random uncertainty, and the measurements are most clear at short distances. When the cart and mirror are five meters away, the light the reaches the photodetector must travel 10 meters, and the intensity greatly dims due to light scattering in the atmosphere. This causes the sinusoidal wave pattern to have a very low amplitude, which is both difficult to detect by eye and difficult for Python to fit successfully. Therefore, increasing the number of measurements taken in the range of zero to three meters away from the optical bench where the intensity is still high will increase the accuracy of the sinusoidal fit and improve the determined value for the speed of light.

In conclusion, our technique allows for a consistent measurement of the speed of light in small distances, as laser modulation and data analysis in Python are two effective tools in accurately measuring a value as large as light speed.

References

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[5] *Electro-optic Modulators* (RP Phototonics Encyclopedia: https://www.rp-photonics.com/electro_optic_modulators.html).