SPEED OF LIGHT

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This experiment measured the speed of light in air. Light emitted from a pulsed laser was directed, by means of a beam splitter towards two mirrors, one placed close to, and the other at a finite distance from the laser. The two beams thus formed had different path lengths. Upon reflection off the mirrors, the beams were made to be incident on a photo diode . The ratio of the effective distance traveled by the two beams to the difference in time taken by the two beams to reach the diode gave the speed of light. The value found experimentally was $(3.008 \pm 0.014) \times 10^8$ m/sec and it had a comparative percentage error of approximately 0.37% with the known value of the speed of light in air, which is 2.99792458×10^8 m/sec.

INTRODUCTION

For many centuries it was believed that the speed of light, c, was infinitely large. It was not until the 17th century that evidence was obtained to show that the speed of light, though enormous, was finite.

In 1600, Galileo attempted to measure the speed of light by covering, and uncovering a lantern at night, and timing how long the light took to reach an observer a few miles away.[1] This experiment was a failure, due to the enormous speed of light. The first successful attempt to measure the velocity of light was made by a Danish astronomer, Roemer, in 1676.[1]

Roemer recorded the date and time for the eclipse of one of Jupiter's satellites, and he found that the expected eclipse was 16.5 minutes later than expected. Deducing this to be the time taken by light to travel across the diameter of the earth's orbit ($\approx 2.2 \times 10^{11}$ m), he found the velocity of light to be $\approx 2.14 \times 10^8 \text{ms}^{-1}$. Bradley in 1728, observed the star of Draconius and found that its position apparently changed in a manner that could not be attributed to parallax.[2] He proceeded to compare the actual movement of stars with the motion of the earth round the Sun, and found that the velocity of light 301,000 km/sec. [2] In 1849, Fizeau was the first to measure the time interval occupied by light in traveling a relatively short distance on the earth's surface, and in doing so, he introduced a principle fundamentally important in measurement. Using his 'Toothed Wheel'[2] he estimated c to be 313,000 km/sec, but he never reported the details of his experiment.

The second successful determination was made by means of a rotating mirror by Foucault in 1862 who found the velocity of light to be $(298{,}000 \pm 500)$ km/sec. He also went on to show that c was less in water than in air, and thus proved Newton's 'corpuscular theory' to be untrue.[2] An American physicist, A. A. Michelson, spent many years of his life in measuring the speed of light, and the method he devised was considered as one of the most accurate. He used a Rotating Prism method[2] and found c to be approximately 2.99774×10^8 m/sec.

After this, Maxwell's Theory of Electromagnetic Radiation led to another method of finding c.[3] The speed of light was now found as the product of the frequency and the wavelength of an electromagnetic wave. This method was first used by R. Blondit, and it proved to be an accurate measure of c.[3] In 1958, K. D. Froome reported c to be approximately 299,792,500 m/s. He measured both the frequency and wavelength of millimeter waves from klystron oscillators to obtain this result.[2] The major uncertainty lay in the measurement of the wavelength of the radiation, and this was soon overcome by the usage of the stabilized laser. Because of the stability and the reproducibility of the stabilized lasers, separate frequency and wavelength measurements were sometimes combined to give independent values of c.[3] For the first time ever, the values of c were in agreement and in 1974, the Consultative Committee for the definition of the meter recommended that 299,792,458 m/s be the value for c.[3] The meter is thus defined as "the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second."

THEORY

The speed of light, although a very large quantity, is but a speed. Thus, it can be expressed as a ratio of the finite distance covered by a beam of light to the time taken in covering that distance. On a comparative scale, for two different distances d_1 and d_2, if the times taken by the beam of light to cover these distances are t_1 and t_2 respectively, then we can say that $c = \frac{\Delta d}{\Delta t}$. Thus, we needed to find a convenient way to measure accurately the ratio involving Δd and Δt. As will be explained in the procedure, a photo diode was used to find Δt. Photo diodes are widely used in the detection of optical radiation.[5] They are compact, inexpensive, and do not require too much power to operate. Since they have a rapid response time they are compatible with pulsed lasers. This fact was utilized in selecting the apparatus for this experiment.

If a beam of light from a pulsed laser could be made to travel two distinct finite distances, and the time taken in covering theses distances could be measured accurately, then we could find c. As will be shown in the procedure, this was exactly what was done. Using a beam splitter, the beam was made to travel a long and a shorter distance. The time taken for the light to cover both these distances were recorded using a photodiode. Δt was the time interval between the beams covering the long and the short distance and this was read off an oscilloscope after the beams were detected by a photodiode.

PROCEDURE

The laser used was a VSL 337 nm, N_2 pulsed laser. It emitted 3 nsec pulses, and was set at 20 pulses per second. The photodiode used was Hamamatsu S4753PIN and the convex lens had 48 mm focal length. A 24 Volt power supply was used to operate the photodiode whose voltage was measured with a HP 54510B 1 GHz Digitizing Oscilloscope. The schematic is shown in Fig 1.

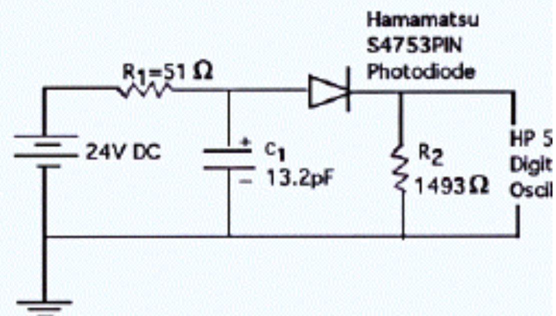

Fig. 1 Circuit schematic for the experiment.

Our objective was to attain Δt and Δd, in order to find the speed of light, c. The first step was to set up the apparatus.

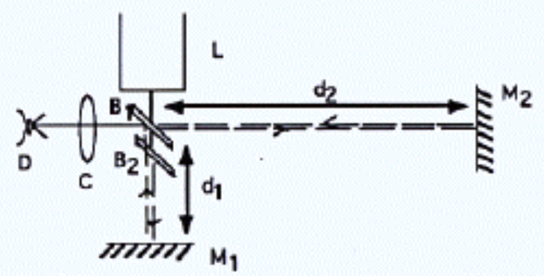

Fig. 2. Top view of the setup involving the pulsed laser, L, mirrors M1, M2, beam splitters B1, compensating glass plate B2, the converging lens, C, and the photodiode, D.

The pulsed laser was directed at the beam splitters and the mirror M1 (Fig. 2). The second mirror, M2, was placed at a finite distance across the room, thus making d2 >> d1. The laser was positioned so that the beam hit the center of M1 and the portion of the beam that was directed towards M2 by B1 was aligned. The reflected beam (off M2) was guided back into the convex lens C, situated just behind B1. This beam reflected from M2 was the 'long beam'. The leveling screws behind M1 were used to direct the reflection off M1, so that, after hitting B1, it would follow the long beam into C. This was the 'short beam'. From Fig. 2, it can be seen that $\Delta d = 2(d_2 - d_1)$.

The oscilloscope screen displayed voltage across the resistor R_2 (Fig. 2) against a time scale (nsec). As long as no light fell on the photodiode, a constant voltage was observed on the screen. As soon as the photodiode was illuminated (by either the long or the short beam), the voltage dropped and this was observed on the screen. Since the short beam would take less time to complete its journey to M1, and back, the first trough corresponding to the voltage drop would be as a result of the photodiode receiving the short beam. The long beam would follow and would result in a trough in the voltage displayed on the screen.

The time difference between the occurrence of the two troughs could be determined by positioning vertical cursors on the oscilloscope screen. But, since the lowest peaks of the troughs were not very evident, a special feature on the oscilloscope was utilized to make a good estimate. The long beam was blocked and the resulting pattern was subtracted from the pattern presently on the screen and stored in memory. So, when the long beam was allowed to hit the photodiode, the oscilloscope subtracted the stored pattern from the pattern including the second trough and thus generated a smoother version of the second trough. Several trials were taken.

An additional set of data was acquired using LabVIEW 2 program on the Macintosh. The objective was to reproduce the oscilloscope screen on the computer, so that the data obtained could then be further processed using Igor. Our objective was to transfer at least one set of acceptable data from the oscilloscope to the computer. We were successful in computer data acquisition, and this added a new dimension to the experiment. In addition to the observations on the oscilloscope, a set of data could be transferred to the computer, and then analyzed on Igor, so as to find a value for Δt. This value could then be used to get an estimate for c. The troughs, as seen on the computer are shown in Fig. 3.

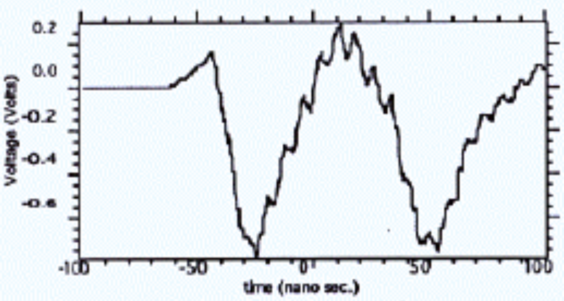

Fig. 3. Voltage across the photodiode versus time as seen on the computer. In the next section, this plot has been smoothened using Igor so as to get values for the time interval between the troughs.

DATA & ANALYSIS

An average of the measured values of Δd and the observed Δt was used to estimate our experimental value of c.

$$c = \frac{\Delta d}{\Delta t} = \frac{(22.73 \pm 0.05)\text{m}}{(75.56 \pm 3.45)\text{ns}}$$

$$= (3.008 \pm 0.014) \times 10^8 \text{m / sec}$$

The error for Δt included the value obtained from the computer data acquisition. In this context, we should note how that value was obtained from the computer. The plot given in Fig. 4 was smoothened repeatedly (100 passes) and then, using cursors, a Gaussian fit was administered. From history in Igor, the values for the lowest points in the trough, and the corresponding errors were found.

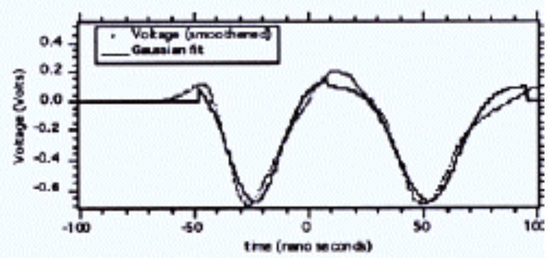

Fig. 4: This plot was used to get Δt from the computer acquisition. $\Delta t = 51.84 + 23.88 = 75.72$ nsec. The error involved is 0.36 nsec. Therefore $\Delta t = 75.72 \pm 0.36$ nsec.

The value of c that we obtained experimentally had very good agreement with the known value of 2.99792458×10^8 m/sec. It was within 1 standard deviation of the known value and had a comparative percentage error of approximately 0.37 %. It is not surprising that we achieved such accuracy. The apparatus that we used was extremely sensitive, and this enabled us to get good agreement.

CONCLUSIONS

Both manual and computer data acquisition were done in this experiment. It was evident, that upon using the computer, a number of horizons opened up. The data could be smoothened, for one, and value for Δt could be attained with ease. By placing markers on the plot, sections of the data could be isolated and investigated. This could not be done with the hard copies. But then again, we obtained more data using the hard copies, since there was not time for us to program the computer to control the oscilloscope dynamically. From Fig. 2, we can see that the gaussian fit for the first trough is shifted to the right. This was because the data was not uniform about the center of the waves (Voltage). This could also explain why the Δt obtained from the computer was slightly more than most values Δt obtained manually.

The speed of light is a quantity that has been measured on numerous occasions in the past, and it has been declared a constant: $c=2.99792458 \times 10^8$ m/sec. In our experiment, we used a pulsed laser as a light source to determine the speed of light. Using a photodiode to indicate the time interval between a long and a short beam, experimental c was found as a ratio of distance to time. We found c to be $(3.008 \pm 0.014) \times 10^8$ m/sec. This value of c had a comparative percentage error of about 0.37% of the constant value and was within 1 standard deviation of it. The use of sophisticated, sensitive apparatus enabled us to get this good agreement. We can conclude that a good value for the speed of light in air can be obtained using this type apparatus.

REFERENCES

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[4] D. O'Shea, R. Callen & W. Rhodes, Introduction to Lasers and their applications 2nd ed. (Addison—Wesley Publishing Company, MA, 1978), page 228.