Speed of Light

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1 Results and Analysis

We used a pulse modulated laser and an assortment of mirror arrangements to measure the effective speed of light in air by recording the path length and travel time for laser light to reach a fast photodiode. After triggering the laser to turn off, we measured the total time between the trigger event and when the photodiode reported an absence of incident light. Our results for the distance-time data pairs are shown in Table 1, where we have attributed a 0.2 ns uncertainty on our oscilloscope readings and a 0.33 cm uncertainty in distance measurements per application of our length measuring instrument.

Time measurements are uniformly increased by signal delay that can be determined, along with a measured value for the speed of light, by fitting a line of the form

$$t = d/c + t_{delay} \tag{1}$$

to the data of Table 1, which is shown in Figure 1, where t is the total time, d is the path length, c is the measured value for the speed of light, and t_{delay} is the delay time.

We found the speed of light to be $(2.89 \pm 0.04) \times 10^8)$ m/s, which is within three standard deviations of the defined value 299,792,458 m/s. Our loose agreement with the accepted value is mainly due to a discrepancy between the first two (shorter) path length measurements, which must be the result of an error in scope measurements, since distance uncertainties are negligible. Additionally, we found the delay time to be 13.0 ± 0.3 ns, which is the sum of times associated with the laser response, cabling, photodiode response, and oscilloscope processing.

In order to determine the speed of light in an optical fiber, we repeated the same procedure as above, except replaced the beam path with identical optical fibers of various lengths. In this case, light travels at speed $v_c = c/n$, where n is the refractive index of the fiber, thus the travel time is determined by

$$t = d/v_c + t_{delay} \tag{2}$$

where v_c is the speed of light in the fiber. Table 2 shows our distance-time pair measurements and Figure 2 shows the results of a weighted least squares to this data with Equation 2.

Table 1: Elapsed time for laser light in air along a mirrored path.

Distance (cm)	133.1 ± 0.66	347.5 ± 0.66	347.5 ± 0.66	482.6 ± 0.66	586 ± 1.33	682.1 ± 1.33	796.5 ± 1.33
Time (ns)	18 ± 0.2	18.4 ± 0.2	25.2 ± 0.2	29.6 ± 0.2	33.4 ± 0.2	37.0 ± 0.2	40.4 ± 0.2

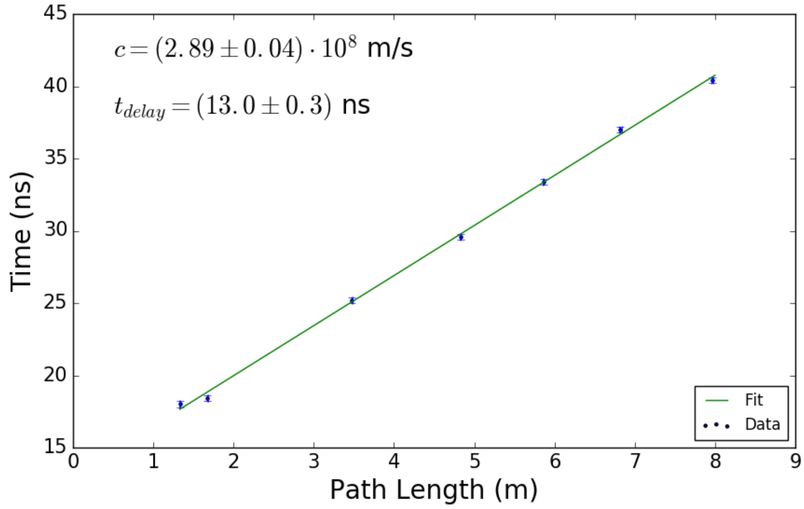

Figure 1: Weighted least squares linear fit to the data of Table 1 with Equation 1 for determining the speed of light in air c and the signal delay time t_{delay}. Uncertainties in both time and distance are shown, although distance uncertainty appears negligible.

Table 2: Elapsed time for laser light in optical fibers of various lengths.

Distance (cm)	66.4 ± 0.2	79.4 ± 0.2	124.8 ± 0.2	209.0 ± 0.2	466.6 ± 0.2	468.6 ± 0.2	702.4 ± 0.2
Time (ns)	17.4 ± 0.2	17.4 ± 0.2	19.6 ± 0.2	24.2 ± 0.2	37.2 ± 0.2	37.6 ± 0.2	48.8 ± 0.2

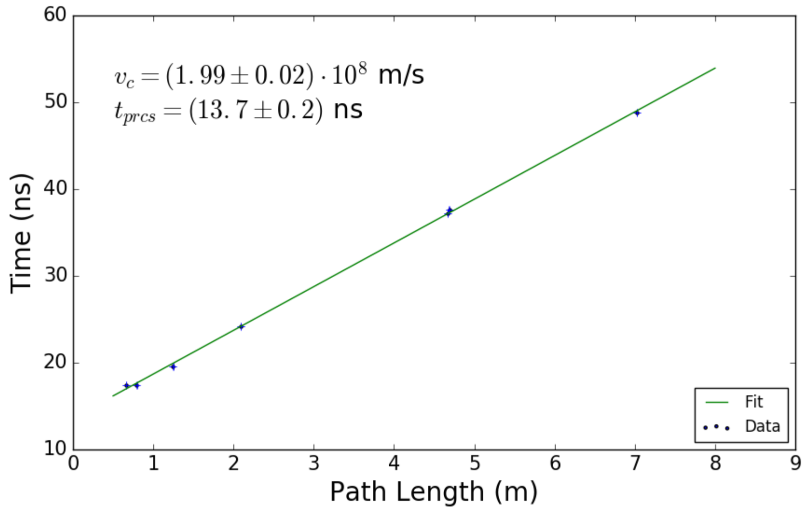

Figure 2: Weighted least squares linear fit to the data of Table 2 with Equation 2 for determining the speed of light in the optical fibers c and the signal delay time t_{delay}. Uncertainties in both time and distance are shown, where, as before, distance uncertainty appears negligible.

We measured the speed of light in the fiber to be $(1.99 \pm 0.02) \times 10^8$ m/s, corresponding to a refractive index of 1.45 ± 0.2, which a reasonable value for silica fibers. We also found the processing time in this case to be 13.7 ± 0.2 ns, which is statistically similar our previous result of 13.0 ± 0.3 ns.

The speed of an electrical signal along a waveguide, such as a long coaxial cable, depends on properties such as the cable geometry, cable insulation, and the wave frequency. We found the signal wave required a time interval of 2.65 ± 0.1 μs to travel the entire length of a 1000 ft coaxial cable, which amounts to a propagation speed of $(1.15 \pm 0.04) \times 10^8$ m/s, or expressed as a fraction of the speed of light, (0.383 ± 0.014)c. If the cable is terminated by a resistor that does not match the cable impedance, a portion of the signal will be reflected. This is in analogy with waves traveling along a string, where in the extreme case of a string attached to an immovable object, the traveling entire wave is reflected when it reaches the attachment point. We observed the reflected wave to be inverted relative to the source when the coaxial cable was terminated by a weak resistor (effectively a short), and not inverted when the cable was terminated by a strong ($\sim$ 1000 Ω) resistor. In this way, analysis of the reflection of pulses within a damaged circuit could provide information to identify whether the circuit is shorted or lies open.

We matched the impedance of the cable to the terminator resistance by tuning the terminator resistance until the reflected wave was minimized, from which we found the impedance of the coaxial cable to be $70 \pm 25\Omega$, which has a large relative uncertainty since the reflected wave is never entirely eliminated and its quick passage causes a response in the circuitry, leading to a voltage bump at the pulse arrival and an inverted voltage bump as it leaves.

2 Conclusion

We used a series of mirrors to measure the speed of light, for a value of $(2.89 \pm 0.04) \times 10^8)$ m/s, within four standard deviations of the accepted value 2.99792458×10^8 m/s and we determined the delay time of our apparatus to be 13.0 ± 0.3 ns. Then, we found the refractive index of a set of optical fibers, which we found to be 1.45 ± 0.2, by measuring the effective speed of light within the fiber. Lastly, we investigated the propagation of an electromagnetic signal along a coaxial waveguide, where we found the propagation speed to be (0.383 ± 0.014)c, the impedance of the cable to be 70 ± 25 Ω, and observed the reflected wave to be an inverted portion of the original wave when the cable was terminated was a resistance less than that of the cable impedance.