Speed of Light Lab

Trevor Smith, Alex Storrer*
Northeastern University
(Dated: June 13, 2021)

Nothing is here

INTRODUCTION

The speed of light is foundational to our understanding of the universe, as it is in fact not just the speed photons travel at, but rather a universal speed limit. However, even though photons do always travel at the speed of light, we can measure the net wavefront in a material at lower speeds, due to the absorption and re-emission of new photons by atoms in a medium. This "speed of light in a medium" is usually thought of not as a speed, but as a ratio $v/c = n$, the refractive index. The refractive index is so called because light follows Snells law, where its direction will be refracted proportional to this refractive index depending on the refractive indeces of the two mediums.

It is, however, also useful to think of "speed of light in a medium" as a speed, because the speed of communications in our incredibly connected world is crucial. Even electrical signals, governed by the electromagnetic force which is mediated by photons, propogate through electrical circuits and cables not at the drift speed of electrons but rather at the speed an electric field propogates through them. A major advancement in communications, however, came from using photons themselves rather than electrical signals to communicate over long distances, using Fiber-Optic (FO) cables. These cables take advantage of differences in the refractive index of glass and another material to create total internal reflection of all photons input at the end of a long and thin glass tube. These cables are capable of transmitting great amounts of information in a very thin tube, as, while conductors permit more information to flow through them limited by their circumference, FO cables use their entire cross-sectional area to transmit information.

In this lab, we will measure the speed of light (and the effective speed of light) through different mediums, in order to calculate refractive index. The core technique will involve using a laser and a beam splitter to pass two beams through paths of very different lengths, collecting the signals on two photodiodes (PD), and measuring the relative delay of the longer path compared to the shorter one on an 0.5 GHz oscilloscope. This laser will be triggered on and off with a nonosecond pulse generator. All factors: the pulse generator, the beam path lengths, the sample rate, and the comparison between the two PD input signals for their time delay, will introduce sources of uncertainty that must be minimized by careful measurements and signal processing.

The mediums considered will be air, glass (FO cable), and water. The effective index of the coax cables connecting the PD and oscilloscope will also be measured.

APPARATUS

The apparatus consisted of the following.

- Oscilloscope, Tektronix TDS210
- OpenChoice Desktop, Oscilloscope Software
- Optical breadboard
- Beam splitter, 2 mirrors, focusing lens
- Focused laser diode
- 2 Amplified high-speed silicon photodiodes
- Water-Filled optical cell
- Fast edge nanosecond pulse generator
- Fiber Optic Cable with mount
- BNC cables and male-male BNC connector
- Spectrometer and Quantum software, Amadeus
- Jupyter, Python compiler

PROCEDURES AND RESULTS

Test Pulse, Scope and Laser Diode

The fast edge nanosecond pulse generator uses six74AC14 Schmitt Triggers as shown in fig. 1, hand mounted to a copper circuit board.

The pulse generator was connected directly to the oscilloscope, and adjusted until several cycles were visible on the display. This output was analyzed to verify the setup. These square pulses are shown in fig. 2. We can observe an approximate amplitude of 5.60 mV, and using fourier analysis we can verify that the

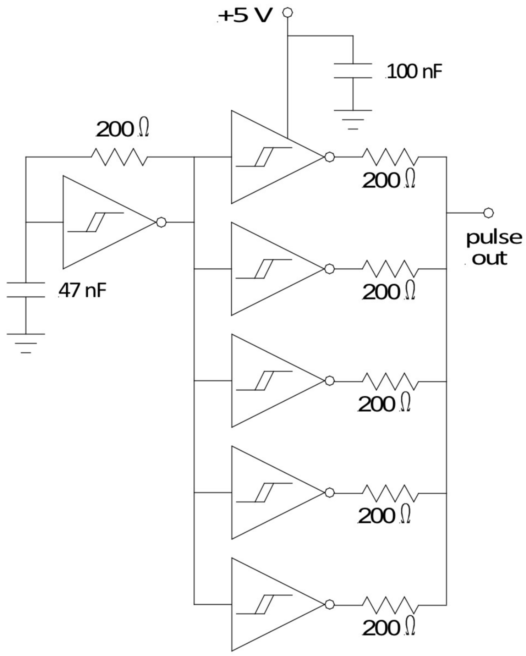

FIG. 1. Circuit diagram of the nanosecond pulse generator

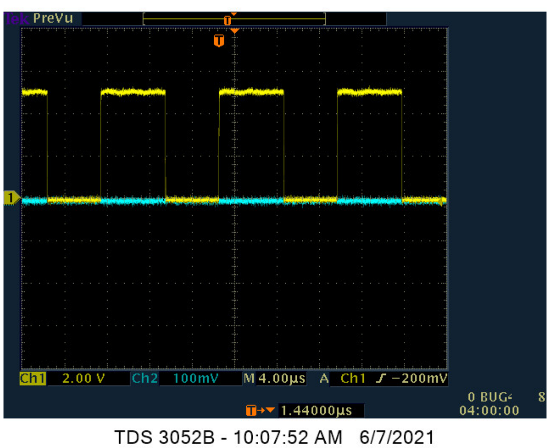

FIG. 2. Measured square waves on the oscilloscope.

fundamental frequency is 90 kHz.

The pulse generator will be used to power the laser, creating a wave front that propogates simultaneously through two paths of different lenghts.

Optical Setup

Next, the two paths were configured, based on 4. We will consider only the distances of the paths after the beam splitter, as the paths up until that point are equivalent. The path measured by PD1 is given by length 1 alone, and the path measured by PD2 is given by lengths 2-5. These lengths are given in I, with all measurements performed with a tape measure. After completing all measurements in the span of two days, a final re-demonstration of the lab was performed in a single day, and it is these results that are shown below, with the geometry of the setup unchanged for the entirety of the lab.

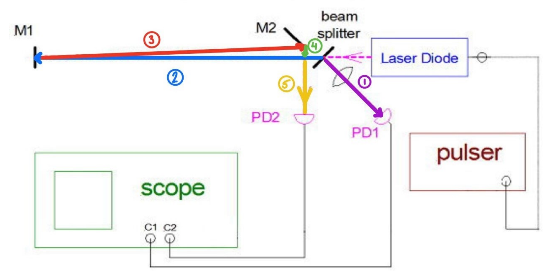

FIG. 3. Annotated test setup.

TABLE I. Lengths of various paths shown the optical setup

length #	Color	Length (mm)
1	Purple	168.5
2	Blue	917.5
3	Red	730.0
4	Green	5.0
5	Mustard	124.5

Before measuring distances PD1 and PD2 were connected to the oscilloscope, and the signal was isolated on the oscilloscope, triggered by PD1, as shown in 4, where a visible time shift can be observed. By referencing the oscilloscope output, the setup was optimized for the strongest signal by adjusting the beam splitter and M2.

Measurements were then recorded for analysis, as shown in fig. 5. It should be noted that for a perfect experimental setup, these signals would appear as simple step functions or square waves. However, producing such a sharp signal is very difficult, and as such more detailed analyis must be done to compare the two signals than simply looking at the step time. The “10-90” rise times were used to compare flight times of the two signals, in addition to the min and max of the signals. These values are shown in table II.

From table II, the time delay between PD1 and PD2 was calculated, with the mean and the standard deviation being taken as the recorded measurement and uncertainty, at 5.2 ± 0.2 ns. The high uncertainty in this

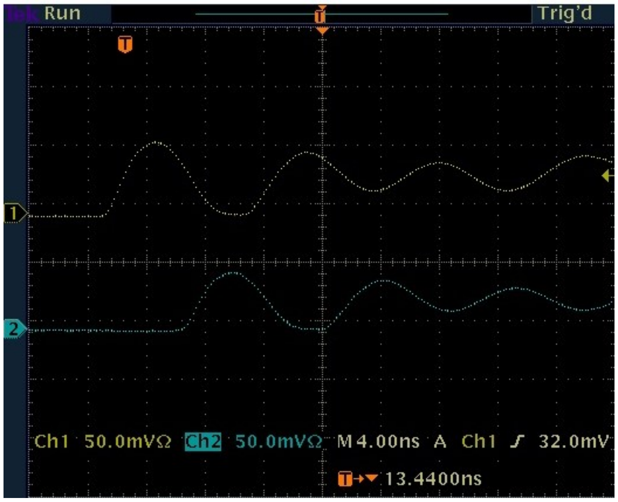

FIG. 4. Oscilloscope output for test setup with equal length BNC cables. Signals PD1 and PD2 are labeled on the left 1 and 2 respectively.

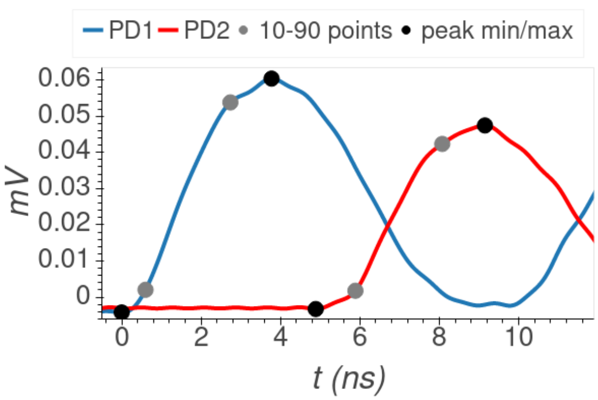

FIG. 5. Oscilloscope data comparing reference points for PD1 and PD2.

measurement can be attributed to the difference in the peak shapes, where the full-width half-max (FWHM) for PD1 was calculated to be 4.657 ns, and the FWHM for PD2 was calculated to be 4.534 ns. This error is compensated for in future measurements, but in this case is less relevant.

TABLE II. Time values of the first nanosecond peaks for equal length BNC cables

PD #	Start (ns)	End (ns)	10% (ns)	90% (ns)
1	0.0	2.47	0.67	2.02
2	5.4	7.79	5.97	7.27

Next, the BNC cable connecting PD2 to the oscilloscope, which originally was of equal length to the cable connecting PD1, was replaced with a significantly longer cable in order to explore such a scenario, and calculate the effective refractive index of the BNC cables. The scope output is shown in . 7, and the graph with reference points included is shown in fig. 6. The values for the 10-90 rise time, min, and max are shown in table III.

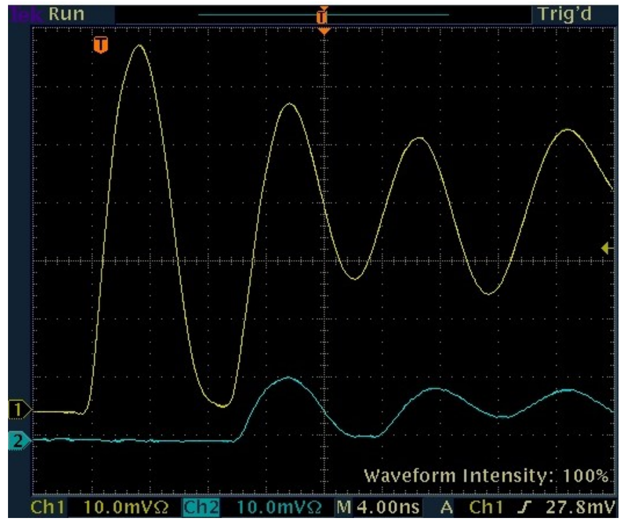

FIG. 6. Oscilloscope output for test setup with different length BNC cables. Signals PD1 and PD2 are labeled on the left 1 and 2 respectively.

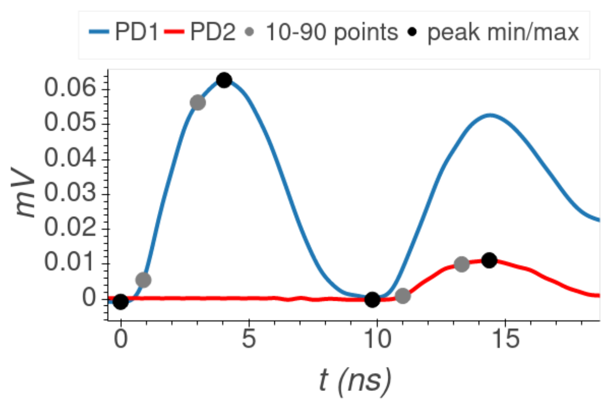

FIG. 7. Oscilloscope data comparing reference points for PD1 and PD2, where PD2 has been delayed using a longer BNC cable.

A plot showing both sets of captures, with extra cable and without extra cable, is sown in fig. 8. The extra delay due to the extra cable length can be seen clearly.

TABLE III. Time values of the first nanosecond peaks for different length BNC cables

PD #	Start (ns)	End (ns)	10% (ns)	90% (ns)
1	0.00	4.04	0.89	3.01
2	9.82	14.39	11.01	13.31

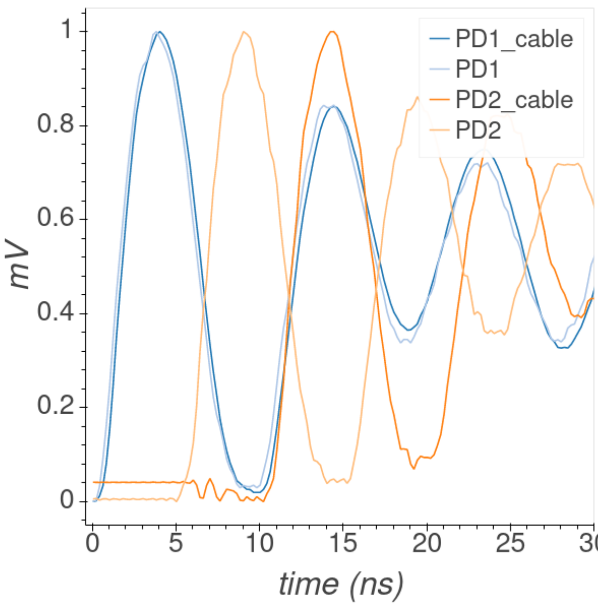

FIG. 8. Normalized comparison of the signals from PD1 and PD2 for equal length cables as well as the inequal length cables, denoted by the suffix "_cable".

TABLE IV. Measured and accepted values of the speed of light and refractive index of various materials.

Apparatus	η (%)	Accepted η value	Refs.	Deviation
Photovoltaic Cell	15 ± 2	17 ± 2.5	[2]	0σ
Elecrolyzer	87 ± 6	80	[3]	2σ
Hydrogen Fuel Cell	49 ± 5	60	[4]	-3σ

$$\eta_{PV} = P_E/P_L \tag{1}$$

Conclusions

SUMMARY

* smith.tr@northeastern.edu; https://github.com/trevorm4x/

[1] Wikipedia, Heat of Combustion: https://www.wikepedia.com

[2] Energysage, Most Efficient Solar Panels https://www.energysage.com/

[3] Carbon Commentary, Hydrogen made by Electolysis https://www.carboncommentary.com

[4] Energy.gov, Fuel Cell Fact Sheet https://www.energy.gov