Fiber Optic Project

Vincent Edwards, Ali Mortada

Mt. San Antonio College, Physics 4C, CRN 20889
Dec 5, 2023

1. Purpose and Hypothesis

The goal of the experiment is to examine the relationship between the speed of light in a vacuum and wavelength of light. Using the *Industrial Fiber Optics Speed of Light Apparatus* and an oscilloscope, the time for light to pass through a fiber optic cable of known length and index of refraction can be measured. From there, the speed of light can be calculated. Wavelength will be varied by soldering different colored LEDs onto the apparatus. In theory, wave speed should be independent of wavelength.

2. Materials

- Caliper
- Tray
  - Large enough to support the long fiber optic cable
  - As lightweight as possible
- Balance 1
  - Able to support the short fiber optic cable
  - More precision, lower weight limit
- Balance 2
  - Able to support the tray and the long fiber optic cable simultaneously
  - Less precision, higher weight limit
  - This balance did not end up being needed, as balance 1 was sufficient and had higher precision
- *Industrial Fiber Optics Speed of Light Apparatus*
  - Also referred to as the "speed of light kit"
  - Top part is the circuit board, which is screwed onto a base
- 110 VAC-to-DC power adapter
- Short fiber optic cable
  - About 15 cm long
- Long fiber optic cable
  - About 20 m long
  - Note that cables shorter than 20 m may be tried if the light cannot be detected through it, but could be detected through the short cable
- Dual-channel oscilloscope and its power cable
- 2 oscilloscope probes
- Fiber optic red LED
  - IF-E96E

  - Included with the speed of light kit
- Fiber optic green LED
  - IF-E93
- Fiber optic blue LED
  - IF-E92B
- Infrared LED
  - IR333-A
- Phillips head screwdriver
- Pliers
- Circuit board holder
- Soldering iron
- Solder
- Desoldering solder sucker **OR** Desoldering wick
- If fiber preparation is required
  - 600-grit polishing paper
  - Polishing liquid (water, glycerin, or light oil)
  - Sharp knife or single-edge razor blade

3. Procedures

1. Check the ends of the fiber optic cable to see if they are polished and flat. If not, they need to be prepared.
   - Cut 1 to 2 mm off the end of the fiber cable with the sharp knife or single-edge razor blade. Try to get as square a cut as possible.
   - Wet the 600-grit polishing paper with the polishing liquid (water, glycerin, or light oil) and place the paper, abrasive side facing up, on a hard surface.
   - Polish the end of the fiber by moving it in a "figure 8" pattern while holding it perpendicular against the polishing paper.
   - Check the end of the fiber. If it is cloudy, not flat, or has scratches, repeat the previous step.
   - Repeat the previous two steps for both ends of each fiber.
2. If needed, desolder the two pins that connect the fiber optic LED to the speed of light kit. Afterwards, different fiber optic LEDs can be swapped in and out of the slot without re-soldering.
   - Unscrew the 6 screws connecting the top of the speed of light kit, the circuit board, to its base.

- Remove the screw and nut keeping the LED secure on the circuit board. Pliers might be helpful for keeping the nut in place while the screw is loosened.
- Wet with water the sponge used for cooling the tip of the soldering iron.
- Plug in and turn on the soldering iron. Wait for it to get hot (about 750°F).
- Turn on the overhead vent to capture any fumes.
- Use the circuit board holder to keep the board secure, with the pins to be desoldered easily accessible.
- Use the soldering iron to melt the solder at the pins where the fiber optic LED is connected to the circuit board. Use the solder sucker or the desoldering wick to remove the solder, and ultimately remove the LED. Alternatively, use pliers to gently wiggle and pull the LED away from the board. At the same time, use the soldering iron to heat each pin.
- Reattach the LED and secure it with the screw and nut.
- Reconnect the circuit board to its base, and secure it with the 6 screws.

3. Measure the length of the short fiber optic cable.
   - Using the caliper, measure the length of the short fiber cable. Make sure the cable is straight.
4. Measure the mass of both the short and long fiber optic cables.
   - Using balance 1, measure the mass of the short fiber optic cable.
   - Place the tray on balance 2 and zero the balance.
   - Place the long fiber optic cable on the tray, and measure the mass of the cable using balance 2.
5. Connect both the speed of light kit and the dual-channel oscilloscope to power and to each other.
   - Connect the oscilloscope to power and turn it on.
   - Connect one of the oscilloscope probes to channel 1, and the other probe to channel 2.
   - Connect the probe of channel 1 to the blue test point marked "REFERENCE" on the speed of light kit. Connect the ground lead of the same probe to the test point labeled "GND" just below the "REFERENCE" test point.
   - Connect the probe of channel 2 to the blue test point marked "DELAY" on the speed of light kit. Connect the ground lead of the same probe to the test point labeled "GND" just below the "DELAY" test point.
   - Using the 110 VAC-to-DC power adapter, connect the speed of light kit to power.
6. Calibrate the speed of light kit using the short fiber optic cable.
   - Turn the "Calibration Delay" knob on the speed of light kit to the 12 o'clock position.

- Loosen the fiber optic cinch nuts on the fiber optic LED and detector. Insert one end of the short fiber optic cable into the LED until it is seated, then lightly tighten the cinch nut. Afterwards, insert the other end of the cable into the detector until it is seated, then lightly tighten the cinch nut. If the LED does not have cinch nuts, then simply hold the end of the cable steady against the LED.
- Set the triggering mode of the oscilloscope to auto, channel 1, rising edge. Adjust the trigger level so that the pulses on channels 1 and 2 can be seen.
- Adjust the voltage scaling and offset for both channels so that the pulses can be clearly seen.
- Adjust the time scaling and offset such that only one pulse from each channel is fully visible on the screen.
- Using the measure functionality, set the oscilloscope to measure the time between the first rising edge of channel 1 and the following first rising edge of channel 2 at the 50% crossing (Channel Delay FRFR[1-2]). Make sure the statistics display is on.
- Using the measure functionality, set the oscilloscope to measure the time between the first rising edge of channel 2 and the following first rising edge of channel 1 at the 50% crossing (Channel Delay FRFR[2-1]). Make sure the statistics display is on.
- If pulse 1 occurs before pulse 2, then FRFR[1-2] will give a reading and FRFR[2-1] will not. If pulse 2 occurs before pulse 1, then FRFR[2-1] will give a reading and FRFR[1-2] will not. Turning the "Calibration Delay" knob on the speed of light kit will move pulse 2 left and right, changing the time it occurs. Adjust the calibration knob such that the two pulses occur at the same time. This will be the case when FRFR[1-2] and FRFR[2-1] repeatedly toggle between which one is giving a reading.

7. Measure the time for light to pass through the long fiber optic cable.

   - Loosen the fiber optic cinch nuts on the fiber optic LED and detector. Remove the short fiber optic cable.
   - Insert one end of the long fiber optic cable into the LED until it is seated, then lightly tighten the cinch nut. Afterwards, insert the other end of the cable into the detector until it is seated, then lightly tighten the cinch nut. If the LED does not have cinch nuts, then simply hold the end of the cable steady against the LED.
   - If needed, adjust the time scaling and offset such that only one pulse from each channel is fully visible on the screen.
   - FRFR[1-2] should be giving a reading, while FRFR[2-1] should not be reading. Turn the statistics menu off and back on, as this will clear the data it has measured already. Allow FRFR[1-2] to take at least 1000 time measurements. Then, record the mean and standard deviation.

- With the measurement made, the speed of light kit and oscilloscope can be turned off. Loosen the fiber optic cinch nuts and remove the long fiber optic cable.

8. Switch out the fiber optic LED for one of a different color.
   - Unscrew the 6 screws connecting the top of the speed of light kit, the circuit board, to its base.
   - Remove the screw and nut keeping the LED secure on the circuit board. Pliers might be helpful for keeping the nut in place while the screw is loosened.
   - Pull out the old fiber optic LED.
   - Attach the new fiber optic LED and secure it with the screw and nut.
   - Reconnect the circuit board to its base, and secure it with the 6 screws.
9. Repeat steps 5-8 for the each fiber optic LED color (red, green, blue, infrared).
   - The kit starts with the red LED installed, so start with that color and install it back at the end.
   - Note that cables shorter than 20 m may be tried as the long fiber optic cable if the light cannot be detected through it, but could be detected through the short cable. This was tried for the infrared LED.

4. Results

Table 1 contains the measured properties of the short fiber optic cable. l is the length of that cable, and m is the mass of that cable.

Table 1. Short Fiber Optic Cable Properties

Property	Measurement
l	148.8 ± 0.2 mm
m	0.57 ± 0.01 g

Table 2 contains the main measurements made for the various colors of light and long fiber optic cables used. λ is the peak wavelength output by the LED used. M is the mass of the long fiber optic cable used. t is the travel time for the light pulse to pass through the long fiber optic cable. Note that only trial 1 had a successful measurement for t.

Table 3 contains the calculated speed of light (c) for the trials. Since a successful time measurement was only made for trial 1, only one experimental speed of light value could be calculated.

5. Uncertainty and Equations

The length of the short cable (l) was measured using a caliper. It had a labeled uncertainty of 0.2 mm, so that was used as the uncertainty. The masses (m and M)

Table 2. Main Measurements
Note: UTD means "unable to detect"

Trial	Color	λ (nm)	M (g)	t (ns)
1	Red	645	75.10 ± 0.01	99.85 ± 1.53
2	Green	522	75.10 ± 0.01	UTD through short cable
3	Blue	470	75.10 ± 0.01	UTD through short cable
4	Infrared	940	75.10 ± 0.01	UTD through long cable
5	Infrared	940	37.08 ± 0.01	UTD through long cable
6	Infrared	940	3.75 ± 0.01	UTD clearly through long cable
7	Infrared	940	1.87 ± 0.01	UTD clearly through long cable

Table 3. Calculated Speed of Light

Trial	c (m/s)
1	$(2.93 \pm 0.07) \times 10^8$
2	NA
3	NA
4	NA
5	NA
6	NA
7	NA

were measured using an electronic balance that reported values to within 0.01 g, so that was used as the uncertainty.

The material the fiber optic cable is made of has an index of refraction (n) of 1.49, according to the datasheet. Thus, light slows down when traveling in the cable compared to the speed of light in a vacuum (c, accepted value of 3.00×10^8 m/s). Equation 1 can be used to calculate the speed of light in the cable (v).

$$v = \frac{c}{n} \tag{1}$$

The length of the long fiber optic cable (L) was determined indirectly based on its mass (M) and the linear density of that type of cable (μ). The linear density can be calculated using equation 2, which uses the more easily measured mass (m) and length (l) of the short fiber optic cable.

$$\mu = \frac{m}{l} \tag{2}$$

From there, the length of the long cable L can be calculated using equation 4.

$$L = \frac{M}{\mu} \tag{3}$$

$$= \frac{Ml}{m} \tag{4}$$

Taking the distance traveled (L) and dividing by the time (t) gives the speed of light in the cable (v), as shown in equation 5. That equation can then be combined with earlier equations and rearranged to yield equation 7 an expression for the speed of light in a vacuum (c) in terms of the measured quantities.

$$v = \frac{L}{t} \tag{5}$$

$$\frac{c}{n} = \frac{Ml/m}{t} \tag{6}$$

$$c = \frac{nMl}{tm} \tag{7}$$

The uncertainty in c is given by equation 9.

$$\Delta c = \left[\left(\frac{\partial c}{\partial l} \Delta l \right)^2 + \left(\frac{\partial c}{\partial t} \Delta t \right)^2 + \left(\frac{\partial c}{\partial M} \Delta M \right)^2 + \left(\frac{\partial c}{\partial m} \Delta m \right)^2 \right]^{\frac{1}{2}} \tag{8}$$

$$\Delta c = \frac{nMl}{tm} \left[\left(\frac{\Delta l}{l} \right)^2 + \left(\frac{\Delta t}{t} \right)^2 + \left(\frac{\Delta M}{M} \right)^2 + \left(\frac{\Delta m}{m} \right)^2 \right]^{\frac{1}{2}} \tag{9}$$

6. Conclusion

The calculated value of the speed of light in a vacuum (c) with the red LED was $(2.93 \pm 0.07) \times 10^8$ m/s. The experimental value is about 0.07×10^8 m/s lower than the accepted value, 3.00×10^8 m/s. This difference is within uncertainty. However, since none of the time measurements using different wavelengths of light were successful, there is not enough data to compare the speed of light for different wavelengths. The hypothesis cannot be supported nor rejected.

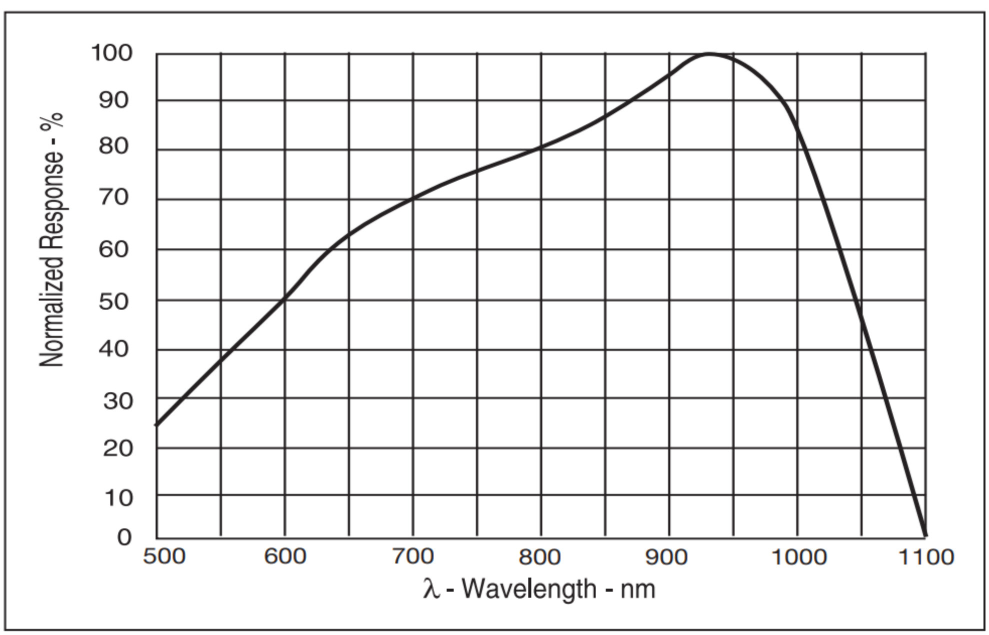

Figure 1. Detector Response vs Wavelength

The speed of light (c) with the blue, green, and infrared LEDs could not be calculated since the travel time (t) could not be measured successfully. For the blue and green LEDs, the light could not be detected after passing through the short cable. This was possibly a result of the photodiode, the component used to detect the light pulses, being less sensitive to lower wavelengths of visible light. According to the data sheet for the photodiode, the peak sensitivity is between 900 and 950 nm. Figure 1 shows that the sensitivity for the red LED's wavelength, 645 nm, is around 60%. But, the sensitivity for the green LED's wavelength, 522 nm, is only around 30%, and the sensitivity for the blue LED's wavelength, 470 nm, is too low to be shown on the graph.

Since the blue and green LEDs did not have their light detected due to sensitivity issues, perhaps using an LED with a wavelength the photodiode was more sensitive to would work. The infrared LED's wavelength, 940 nm, was very close to the photodiode's peak sensitivity. As a result, the light could be detected through the short fiber optic cable. But when connected through the 20 m long cable, the light could not be detected; the oscilloscope reading was identical to noise with no LED connected. Perhaps the light from the infrared LED was too dim and was dissipating before it could reach the detector, especially since there was no cinch to focus the light through the cable. If that were the case, then passing the light through a shorter fiber optic cable would allow more light to reach the detector. Trying this with a 10 m fiber optic cable, the infrared light could still not be detected, so even shorter cables were tested. Trying this with the 1 m and 0.5 m cables, the infrared light could be detected. However, the resulting voltage curve on the oscilloscope was wobbly/noisy. With the red LED, the voltage had a steady increase up to the global maximum. But with the infrared LED, the voltage would increase, decrease for a bit, and increase again repeatedly until reaching the global maximum. As a result, the time measurement would fluctuate so much (equaling 0 at some instances) so as to make it unusable. Perhaps the infrared LED, which was not designed for fiber optic uses, did not have a switching time fast enough to keep up with being blinked 500,000 times per second. If so, the LED would not have fully dimmed before being given voltage again. Some light would continuously be traveling through the cable, thereby adding noise and small fluctuations in the voltage graph as those stray photons hit the detector.

7. Citations

[1] Karen Schnurbusch, *Physics 4C Equations*, Mt. San Antonio College, 2023, pp. 1, 5.

[2] Industrial Fiber Optics, *Fiber Optic Speed of Light Apparatus Instruction Manual*, 2018, https://i-fiberoptics.com/pdf/if-sl_man.pdf

[3] Industrial Fiber Optics, *Fiber Optic Red LED Manual IF-E96E*, 2/20, https://i-fiberoptics.com/pdf/ife96e-2-20.pdf

[4] Industrial Fiber Optics, *Fiber Optic Green LED Manual IF-E93*, 11/20, https://i-fiberoptics.com/pdf/ife93-11-20.pdf

[5] Industrial Fiber Optics, *Fiber Optic Blue LEDs Manual IF-E92*, 2/20, https://i-fiberoptics.com/pdf/ife92-2-20.pdf

[6] Industrial Fiber Optics, *Fiber Optic Photodiode Manual IF-D91B*, 1/20, https://i-fiberoptics.com/pdf/ifd91b-1-20.pdf
[7] Mitsubishi Chemical Corporation, *SH-4001 Manual*, 2019, https://i-fiberoptics.com/pdf/sh-4001.pdf
[8] Everlight *Technical Data Sheet 5mm Infrared LED IR333-A*, 2005, https://cdn-shop.adafruit.com/datasheets/IR333_A_datasheet.pdf