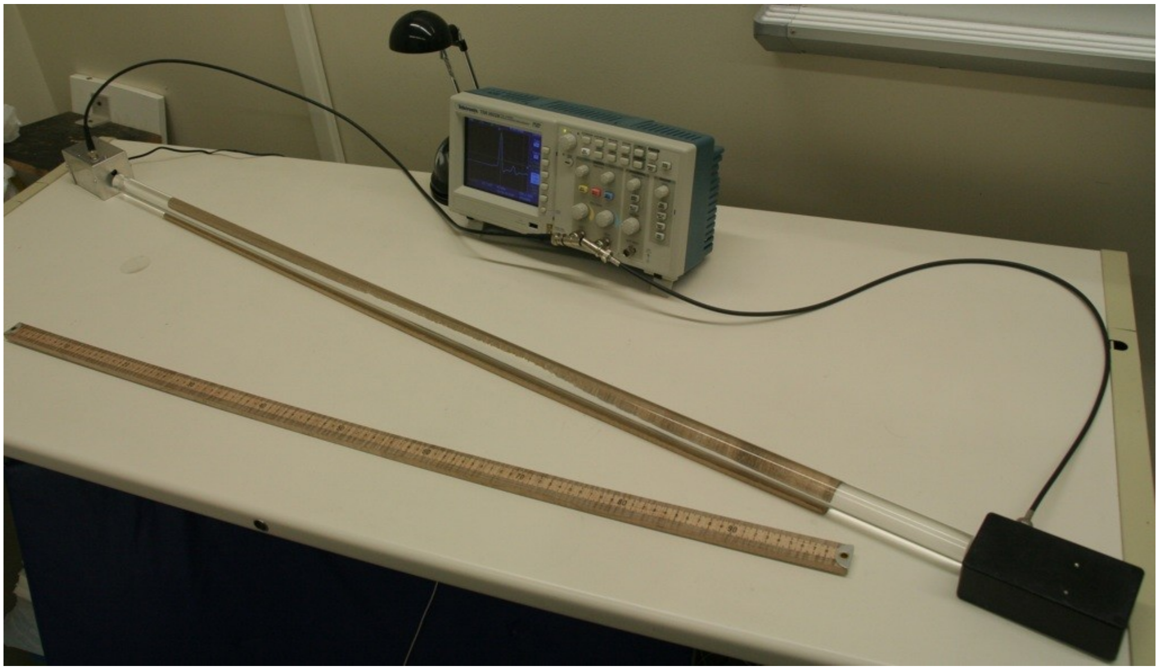
Speed Of Light: Using A Nanosecond Stopwatch



Objective: To learn how to use a high-resolution (200 Mhz) digital oscilloscope. To determine the speed of light by directly measuring the time interval required for light to traverse a fixed distance on the lab table.

Apparatus: Tektronix TDS 2022B Digital Oscilloscope, red laser (battery operated), diode detector (with AC adapter), 50Ω (thinner) coaxial cable (2), 75Ω coaxial (thicker, "RG59" imprint) cable (1), coaxial T-connectors (2), 50Ω cable terminator (2), meter stick, desk lamp, blue jacks (2, for height adjustments)

Introduction

The speed of light is an important quantity because it is the speed at which all electromagnetic waves (recall your RLC Circuits lab from last semester) propagate and poses **a strict limit on how fast matter, energy and information can travel***. In this lab you will not only measure the speed of light pulses but also hopefully gain some experience with transmission lines (cables), reflections within them (and how to minimize these), and some sophisticated measuring equipment.

Information in telecommunications is carried in the form of waves or pulses through air or through some waveguide, like a fiber-optic cable or copper wire. Morse code is a basic way to transmit sequences of letters via radio waves; you already have built a tunable circuit to receive voice and music transmissions. There you noticed that the quality of the reception was dependent on the wave being properly guided to the circuit – you probably had to establish a connection from it to the vertical rod on your lab table, and from that to the antenna that extended outside the Physics Building. Your signal was also dependent on such things as the ionosphere (the Sun no longer ionizes it at night, so that radio waves bounce off it more effectively then), the location of the station (WCTC is closest) and other metallic obstructions that caused interference.

In cables, signals also encounter such discontinuities (kinks in the wire, imperfections in media) or boundaries (connections) that alter them, or make them bounce back. You may already be familiar, from Mechanics, with an upward (positive) wave pulse that hits a rigid wall and bounces back in the downward (negative) position; if the wall wasn't so rigid then the energy is dissipated and the wave pulse is made to die ("terminated") at the wall. Such *terminators* reduce or eliminate the reflected wave; this is important because, as you've seen, reflected waves interfere with incident waves and cause weakening or corruption of the original signal. You will use a terminating resistor in this experiment; you will also find that the *impedance* (the AC equivalent of resistance) of this terminator and the that of wire used must be matched to minimize signal reflection and hence maximize signal transfer. This is similar in Mechanics to tying the end of a thin bungee cord to the end of a thick one, plucking the thin cord and having the wave pulse bounce back once it encounters the thick cord – in electronics we call this poor *impedance matching*.

***Faster Than Light?** Note that it is indeed possible for things to travel faster than the speed of light, but these are neither matter, energy nor information. As an example, consider a powerful laser pointer aimed at the Moon. A slight and slow movement of your hand can result in the projected spot traveling astonishingly quickly across the surface of the Moon, from simple geometry ($v=r\omega$). However what seems to travel across the moon are not the same photons (particles of light) but in fact different photons from the same light source on earth, about 2 light-seconds away. In the direction perpendicular to the pointer beam they convey no energy or information; it is just the (useless) effect that travels faster than light. If you can think of a scheme to transmit information faster than c, the Nobel committee might want to have a talk with you!

Theory

Speed of Propagation

The speed of light is simply $c=\frac{\Delta x}{\Delta t}$; however, since the two signals as displayed on the oscilloscope travel not only through air (you will be measuring this distance) but also through the coaxial cable you will have to account for this travel path. In addition, there is also the delay in amplifying the signal at the detector diode. Since it is difficult to figure this into the calculation, we can eliminate the cable and circuitry-related delay simply by taking two different readings of position (and the corresponding time reading on the oscilloscope) to effectively eliminate it, since both readings have the same delay in common:

$$c=\frac{x_2-x_1}{t_2-t_1}$$

It is also possible to determine the speed of light through a medium other than air by placing that material between the laser and detector. Note that the speed of light in other media varies from $c=3\,x\,10^8\,m/s$ based on its index of refraction n:

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

In air, n = 1.0003.

Impedance

As mentioned previously, impedance (represented by Z)is the AC equivalent of resistance. AC circuits differ from DC circuits in that their behavior is dependent on the frequency of oscillation (for DC circuits the frequency $\omega=0$). The equivalent of Ohm's law is now:

$V=IZ$, where Z is the impedance of an AC circuit. For the RLC circuit you put together last semester (and only for an RLC circuit), the impedance is:

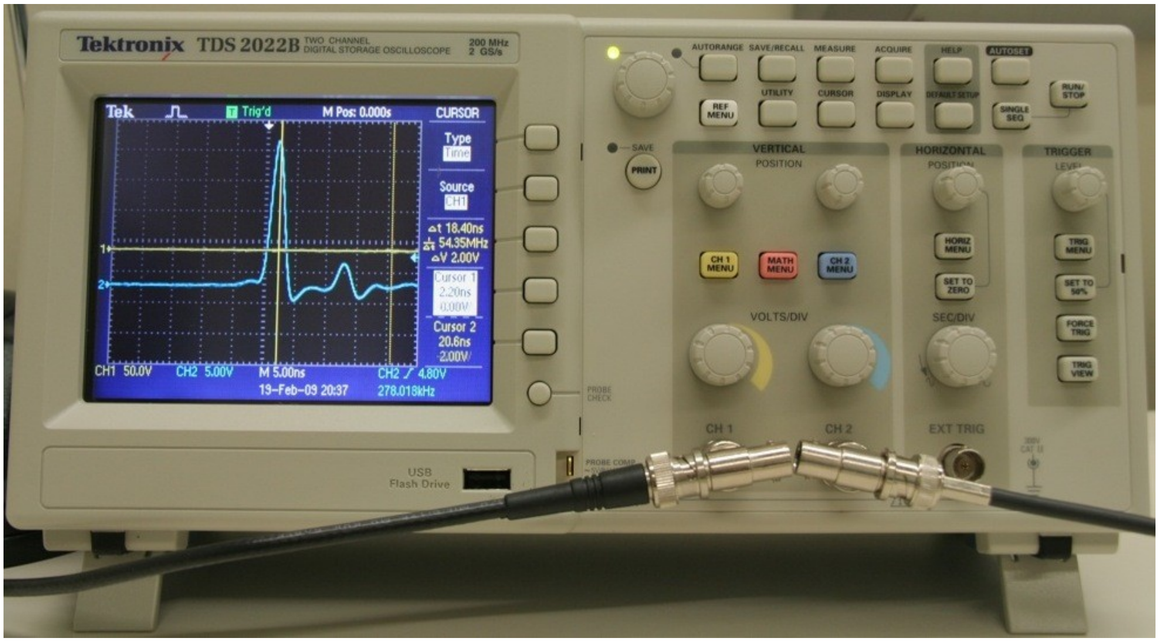
$$Z=\sqrt{(R^2+(X_L-X_C)^2)}$$

where R is the usual resistance of the resistor, $X_L=\omega L$ is the *inductive reactance* of an inductor and $X_C=\frac{1}{\omega C}$ is the *capacitive reactance* of the capacitor. The last two terms are clearly frequency-dependent, as is the impedance of the circuit – reactance increases. It is for this reason that inductors are employed to attenuate (reduce the amplitude of) the high-frequency response in *low-pass circuits*; conversely, capacitors are used to attenuate the low-frequency response in *high-pass circuits.*

Every transmission line (a coaxial cable is one example) has a *characteristic impedance* which is defined as the ratio of the amplitudes of a voltage and current signal running through it; it only depends on the cable's geometry and it's material construction. Here it is assumed that the cable is a *lossless line,* where there is no heat dissipated in the line and the only "resistance" comes from the reactances of the inductance and capacitance of the wire, so that the characteristic impedance is $Z_0=\sqrt{\frac{L}{C}}$.

When a cable is connected the *source* (where the signal comes from) or the *load* (what the signal is going into), it is important that the characteristic impedance matches their impedance otherwise signal reflection will occur. A terminator and cable with the same impedance rating should therefore yield minimal signal reflection at their junction. This is the concept behind impedance matching.

The Oscilloscope

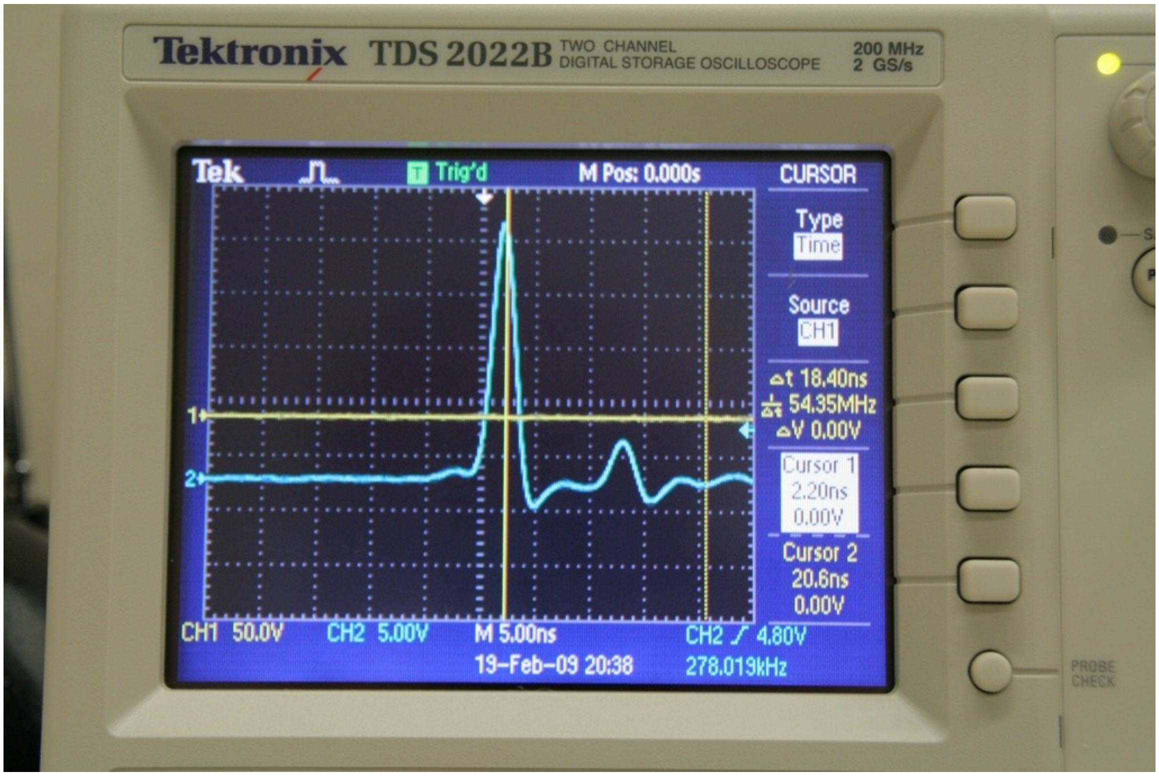


If you've done the Faraday's Law or RLC Circuits lab before, you're familiar with the basic operation of an oscilloscope. Essentially, the amplitude of a quantity (usually Voltage) is plotted on the screen as a function of time, in real-time. It is possible to display one or two channels (quantities) at the same time; in the Faraday's Law lab you monitored Driving Voltage and Induced Voltage. In the RLC Circuits lab you monitored the Voltage across the resistor. Here we will monitor the detector pulse on Channel 1 (CH 1, yellow trace) and the laser pulse on Channel 2 (CH 2), blue trace.

Procedure

A. Effects of no termination, shorting, termination, and cable change

Learn how to use a high-resolution oscilloscope. Send signal pulses from the colored box to the oscilloscope and see how the reflected pulse changes with cable used and method of termination.



1. Position the oscilloscope in front of you. If you wish you can gently flip out the front legs so that it is tilted upward for easier viewing. Make sure no cables are plugged into the front of the scope for now (T-connectors are okay though). Press the ON button on the top left of the scope and wait 35-40 seconds for the grid to show on the display (ignore the Language selection screen). If the scope is already on, press the DEFAULT SETUP button on the top-right.

2. You should see two baseline “noise” traces – Yellow for CH1 and Blue for CH2; this is merely background noise since nothing is yet plugged into the scope.

a. Experiment with adjusting the vertical position of both traces by adjusting the Vertical Position knobs above the CH1 Menu and CH2 Menu buttons – this will allow you to arrange your plots so that they are not on top of one another.

b. Now fiddle with the Sec/Div knob – this sets the size of your time window (horizontal axis). If you set the value (look at the “M” value right above the date/time on the bottom of the screen) to something like 500ms, it'll look like one of those patient monitoring displays at the hospital. The M value is the time interval you'll be observing; you can set a large value to observe many pulses or a small value to zoom in on a single pulse. **Note that this scope will let you examine time window a time window on the order of a few nanoseconds – an extremely short instant of time.**

c. Restore the Sec/Div knob to some intermediate value and now adjust the Volts/Div on each channel – this adjusts the gain, or sensitivity of the trace. At the highest setting the traces will fluctuate wildly (but randomly); at the lowest setting they'll be relatively calm.

3. If there aren't any T-connectors on the CH1 and CH2 jacks, connect them by inserting and gently turning the ribbed tightener grip clockwise (this is a bayonet mount; *gently* turn counterclockwise and pull to remove). Let's now plug in the laser (colored box with push-button and jack sticking out) by connecting it to CH2 of the scope using one of the short black coaxial cables. Remember, you'll have to connect to the T-connector plugged into that channel (no T-connector on laser end). Leave the other end of the T-connector open.

4. Turn on the laser by pressing the pushbutton, and make sure that the red beams comes out of the one of the short sides of the box; just make sure the beam is not shining in anyone's eyes. You should now see a pulse (blue trace) on the screen - “zoom in” on the pulse using Volts/Div and Sec/Div knobs. Immediately to the right of the big pulse (the pulse coming out of the laser) is a smaller pulse of roughly the same shape and polarity (upward pulse) – this is the reflection off a cable which is not terminated (no terminator in T-connector). **The pulse is best viewed at 1 V/Div.** Sketch both pulses in the hand-in sheet.

NOTE: If you don't see any pulses, first make sure that the “M Pos:” value at the top of the screen reads “0.000s”. Then raise the Trigger Level knob until you see the pulse(s). This adjusts the *triggering* – the scope's capability to properly track a single waveform (remember, these waveforms are traveling in time as signals are constantly being emitted by the laser box) and hold it steady for your to examine and measure.

Also, ensure that the scope is triggering off CH 2 – this will be the case if the color of the “Trig'd” label on the top of the screen (say, green) is the same as the color as the “CH 2” label at the bottom left of the screen. If not, press the Trig Menu button at the right of the scope and choose CH 2 from the selection buttons to the right of the screen.

If you're still having trouble locating the pulse, press the DEFAULT SETUP button and go back to Step 2 above.

5. Now grab a paper clip and bend it so that it forms a U-shape. You will use the two ends of the clip to “short” the inner and outer connectors on the open end of the CH2 T-connector. The waveform on the screen should change radically – sketch this new waveform in your hand-in sheet. Remove the paper clip.

6. Let us now terminate this cable. Gently insert a 50Ω terminator into the T open end and observe the reflection pulse – what happens to it? Write in hand-in sheet.

7. With the 50Ω terminator still in place, connect another (thin) coaxial cable to the one you've been using coaxial cable (*please be gentle with the bayonet connectors*), so that the total cable length between laser and oscilloscope is (very roughly) twice its original length – what happens to the reflection pulse now? Explain why this change occurred in the hand-in sheet.

B. Speed of the signal in the cable

Measure the round-trip time of a signal pulse through a wire and back by noting the time interval between the original and reflected pulse.

1. Remove the terminator so that the reflection pulse is again prominent. You will now measure the time interval between the original and reflection pulses. Press the Cursor button near the middle of the dozen buttons at the top of the face of the scope – this will now change the on-screen Menu on the right of the scope screen. The Menu selections can be made by pressing on the buttons immediately to the right of the screen; press the button to the right of Type so that the Time cursors are activated – you should now see two vertical lines on the screen.

2. The currently-controlled cursor should be highlighted in white on the right of the screen; select Cursor 1, then turn the Multipurpose knob (leftmost knob, with green LED) to adjust its position so that it lines up with the first peak. Then switch to Cursor 2 and line it up with the reflection peak. The time difference Δt can be read and recorded immediately. From this, and from the length of the cable, you should be able to find out the speed of the signal in the cable. Express this in units of c (speed of light) and record in hand-in sheet. (Hint: for a reflection to occur, what direction(s) does a pulse need to travel in the cable?)

C. Speed of light in air

Measure how long it takes from the pulse to leave the laser and arrive at the diode detector.

1. **First, turn the classroom ceiling lights off.** It will be much easier to align the laser beam with the detector with the lights off. Desk lamps should be turned on.

2. Plug in the detector to CH1 using the other shorter coaxial cable. Make sure the T-connector on that channel is properly terminated.

3. You will have to shoot the laser beam into the detector hole, and ensure that the tiny beam is directly on the tiny detector diode. This will take many adjustments and some patience. Use sheets of paper **(only a few sheets, preferably used, and fold them)** to elevate the laser and/or detector boxes to the proper height. You can also use the supplied lens, positioned somewhere along the light path, to position the beam spot on the detector – this is best done with two lab partners working together.

4. Use the skills you have learned in Part C above to measure the time values for two different laser-detector distances (one really close, one as far as possible on your lab table). When you have the distances recorded, and their corresponding time values, calculate the speed of light in air. (HINT: it is not necessary to know the cable length, how much time the signal spends in the cable, nor the delay time of the amplifier circuitry)

D. Speed of light in transparent plastic

Measure how long it takes from the pulse to leave the laser and arrive at the diode detector while traversing an Acrylic rod.

1. This is a particularly challenging task, since you will not only be aligning the laser beam with the detector – you will also have to contend with a clear plastic rod in between them which will potentially be bouncing the beam all over the place!

2. Measure the length of the acrylic rod and record it. **DO NOT SCRATCH THE ENDS OF THE RELATIVELY SOFT ACRYLIC ROD; THIS COULD AVERSELY AFFECT THE RESULTS OF THE EXPERIMENT.** Position the laser and detector such that the laser points into one end of the rod (almost touching), shoots the beam through its length, and comes out the other end directly into the detector (also almost touching). ***You will have to take pains such that the center (axis) of the tube and the beam are co-linear; this can best be accomplished by positioning both laser and detector at the center of the ends of rod.*** (TIP: Position the laser and detector about a rod's length from each other at about the same height (using the blue jacks under them to control their height), about the length of the rod apart. Then, cradling the rod with your palms under each end and the backs of your hands resting on the table, align the rod with the beam.)

3. In a calculation similar to that you did for the speed of light in air, determine the speed of light in acrylic. Calculate the index of refraction n from this and write both in hand-in sheet.

4. Turn off the laser (pushbutton) and the detector (lever switch).

Questions (Write in hand-in sheet)

1. In air, $n=1.0003$. Can materials have $n<1$? Why or why not?

2. Consider the equation you used to calculate the speed of light. How would you still be able perform your experiment if you didn't have a high-precision oscilloscope available – what changes would you make to your set-up?

3. Many years ago it was postulated that light waves traveled in a medium called the "aether" that pervaded the whole Universe (much like water waves need water, and sound waves need air as their respective media). If such medium did in fact exist, what extra precautions would you take to obtain an accurate reading for the speed of light considering the fact that your laboratory would be moving with respect to the aether?

4. Were you able to completely eliminate the reflection pulse by using a terminator? If not, would a greater selection of terminating resistors have helped you? Why or why not?

5. The reflected pulse has the same polarity as the original pulse when there is no terminator in place, yet it has the opposite polarity when you use a paper clip to "terminate" the cable – explain this in Mechanical terms, i.e., using a wave pulse along a

string which is anchored on one end and may or may not be anchored on the other end.

6. Companies that manufacture photographic lenses often put multi-coatings on their lenses. These are thin, transparent films of slightly different indices of refraction. The idea here is to help match the “impedance” of glass (n=1.5) to air (1.0) so that less light is reflected back from the lens (that's why lenses always look dark – look at your camera's lens). Detail how you would place 9 such coatings on the lens surface, and what indices of refraction should they each have.