# Laboratory 5: Speed of Light

The purpose of this lab is to measure the speed of light. You know from physics classes that the speed of light is approximately 3.0 x $10^8$ m/s, it is one of the fundamental physical constants. In this lab you will use two different techniques to measure the speed of light in air. The first is to use the time difference between two light waves that have travelled different paths. This method directly measures c by measuring how long it takes light to travel a known distance. The second method relies on the fact that the speed of light shows up in Maxwell's equations and is equal to $c = {}^{1}\!/\!\sqrt{\varepsilon_o\mu_o}$, where $\varepsilon_o$ is the permittivity of free space and $\mu_o$ is the permeability of free space.

## Equipment for First Method:

1. A modulated laser to supply the source of light.
2. A beam splitter (half-silvered mirror) and mount. Place it no farther than 10cm from the light source.
3. A detector box (DB) which has two light detectors for the laser beams. (Be sure the beam is not scattering off the sides of the holes but is actually on the photodiodes inside the holes.)
4. Function generator to produce a 1V ($2V_{pp}$) 1MHz sawtooth signal to drive the laser.
5. A dual channel oscilloscope to measure the time difference. (You also have access to BNC coaxial connector and various electrical wires.)
6. Several mirrors and mounts.
7. One 5-meter focal length lens to focus the light beam.
8. Meter stick/tape measure.

**SAFETY NOTE: *NEVER* LOOK DIRECTLY AT THE LASER.**

## Experimental Procedure for the Time of Flight Method:

### Setting up the beam paths:

In order to measure the speed of light, you need to design an experiment in which you firstly split the laser light into two beams, then you let the 2 beams travel *different* distances. Make one beam travel a small distance from the laser, through the beam splitter ending at one light detector. Make the second beam can travel a longer path from the laser to the other light detector in the DB using mirrors. The laser beam will start to disperse along the long path so use the lens to focus the beam that has travelled a longer path back down to a point at the detector.

Once you collect both light beams in the DB, you will read the time difference of the two light waves on the oscilloscope screen and calculate the speed of light.

## Setting up the control and detection electronics

The laser will be damaged if you apply control signal that is too large (more than 1.5V amplitude). ***Confirm the signal you will be sending into the laser with the oscilloscope before you plug it into the laser.***

Use Coax cables to connect the DB to the oscilloscope using banana-BNC adaptors at the DB box. Be sure to plug the ground tab of each converter into a black terminal on the DB. The blue AUTO button on the oscilloscope can be helpful when trying to find your signals.

If you do not obtain an acceptable value for the speed of light, follow the following steps:

1. Repeat your measurements, if you still get a large error go to step 2.
2. Inspect every step of your experimental design to find the main problem, if you find any problems, fix it then repeat your measurements, if you still get a large error go to step 3.
3. Redesign your experiment by changing the variables one at a time, take new data and repeat your calculations.

### Some further notes on using the oscilloscope:

1. Connect channel B of the oscilloscope to the black and red banana posts corresponding to photo-detector 1. Connect channel A of the oscilloscope to photo-detector 2. Make sure the audio switch on the DB is in the off position.
2. Switch the DB power switch on. The trick is to get strong signals from both beams on the oscilloscope. Adjust the oscilloscope until two sinusoidal wave forms are visible on the scope. Both waves should be 1 MHZ over 2 volts peak to peak. For the best measurement procedure, adjust the amplitude of both signals to be the same. Do this in the DC coupled mode.

**Note:** If either of the signals is weak, it means you are not receiving the signals directly into the photo-detector. Think about adjustments you can make to get stronger signals.

Measurement of the speed of light for at least three path lengths (for the long path).

When writing up your paper on this lab it may be helpful to consider the following two questions:

1. How can you measure the time difference between the two beams from the readings on the oscilloscope screen? You might show by making a drawing of the oscilloscope screen.
2. How can you relate the time difference to the speed of light?

## Equipment for Circuit Resonance Method:

- A capacitor (Leybold Didactic)
- An inductor
- A decade resistor box
- A function generator
- An oscilloscope
- Wires for connections

## Experimental Procedure for Circuit Resonance Method:

It was Maxwell who first noticed that the velocity with which an electromagnetic wave propagated, in his theory, $c = (\varepsilon_0\mu_0)^{-1/2}$, was numerically identical to the measured velocity of light. This observation led him to a conclusion that was not obvious at the time: that light is an electromagnetic wave. In his *Treatise on Electricity & Magnetism,* Vol. 2, Chapter XX (3rd. editions, 1891, republished by Dover Press, 1954), Maxwell argues "If it should be found that the velocity of propagation of electromagnetic disturbances is the same as the velocity of light...we shall have strong reasons for believing that light is an electromagnetic phenomenon..." Whether these two velocities are indeed the same is precisely what you will find out in this experiment.

In this method, the inductance L and capacitance C of a simple circuit are calculated from their dimensions by standard electromagnetic theory, and $\varepsilon_0\mu_0$ is calculated from the product LC , which can be found by measuring the resonant frequency of the LC circuit. The air-spaced capacitor consists of two circular disks with radius *r* and spacing *d*. The inductor is a coil of length *l* and mean radius *r* with *N* uniformly spaced turns wound.  Derive relations for the capacitance and inductance of these two by making necessary measurements and using their geometries, your expressions must be in terms of $\varepsilon_0$ and $\mu_0$. The resonant frequency of the LC circuit is given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where *C* is the *total* capacitance in series with the inductor *L*. Some of this capacitance may come from the inductor itself. If the resonance frequency, $f_r$ is measured for a circuit in which $C/\varepsilon_0$ and $L/\mu_0$ are known, $\varepsilon_0\mu_0$ and hence the speed of light can be obtained from:

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} \tag{2}$$

Connect the inductor and capacitor in series as shown in Figure 1. By measuring the resonant frequency, $f_r$, of the LC circuit, you should be able to extract c, the speed of light. In order to get a more accurate measure of the resonance frequency take at least 15 to 20 measurements of the output voltage across the resistor using the oscilloscope for frequencies between roughly $f_r$-5% and $f_r$+5% (the exact range will depend on your choice for R). Near the peak the curve will look like a parabola. Using the data points close enough to the peak (for the approximation that the curve is parabolic to be a good one) fit a quadratic polynomial and, from this equation for the best fit curve, determine $f_r$ analytically. Estimate the error in your calculations of L and C (due to your estimates for the geometric parameters), and the error in $f_r$ (which can be determined by the uncertainty in the fit parameters of your parabola). What is the resulting uncertainty in c? (**Hint:** It should be very small if the experiment is done properly.)

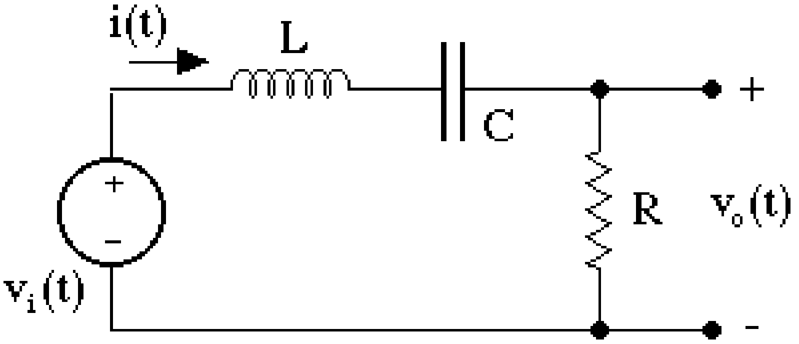

Figure 1: Series LC circuit.

If you are unsatisfied with the agreement you find between the predicted and observed speeds of light, you should consider varying the capacitor plate separation and extrapolating from the measured speed of light for finite plate separation to speed of light for infinitesimal plate separation. This is a way of eliminating the systematic error introduced by an overly simplistic estimate of the capacitance.

Think about the following questions and write your answers:

1. How do inductance L and capacitance C relate to directly observable quantities?
2. What is the problem with just connecting the inductor and capacitor in series with the function generator?
3. What considerations led you to determine the value for the resistor R?
4. Why should the speed of light have anything at all to do with this circuit's resonant frequency?

**WHEN YOU FINISH: DISCONNECT ALL WIRES LEAVE THINGS AS YOU FOUND THEM!**