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 ε_o is the permittivity of free space and μ_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 which must be placed no farther than 10cm from the light source. (Fig. 1, shows a schematic of the beam splitter.)
3. A detector control box (DCB) with 1MHZ oscillator, which has two input for the light beams. (The beam reflected back from the splitter enters photo-detector 2 in the DCB, and the rest of the beam must enter photo-detector 1. Be sure the beam is not scattering off the sides of the holes but is actually on the photodiodes inside the holes.)
4. A dual channel oscilloscope to measure the time difference. (You also have access to BNC coaxial connector and various electrical wires.)
5. Two mirrors.
6. One 5-meter focal length lens to focus the light beam.
7. Meter stick, and paper shim for adjustments.

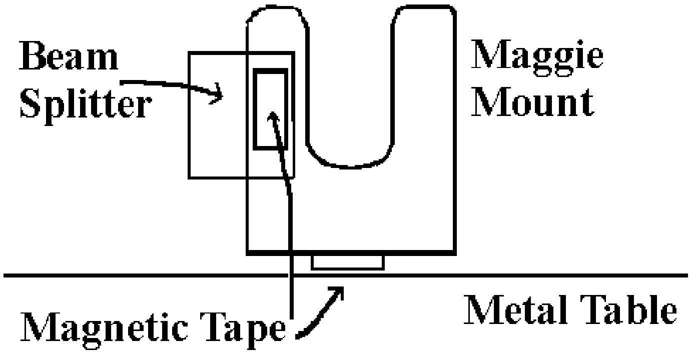

Figure 1: Magnetic mount and beam splitter.

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

Experimental Procedure for the First Method:

In order to measure the speed of light, you need to design an experiment in which you firstly split the laser light into 2 beams, then you let the 2 beams travel *different* distances. One can travel a small distance to and back from the beam splitter and the second beam can travel a longer path using the mirrors and be collected at the DCB. You might need to use the lens to focus the beam that has travelled a longer path. Once you collect both light beams in the DCB, you can read the time difference of the two light waves on the oscilloscope screen and calculate the speed of light. 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.

You should repeat the above steps as many times as it is required for you to get a value for the speed of light with a small percentage error.

In your laboratory write-up include a detailed procedure for measuring the speed of light from the time difference between the two beams; include an error analysis section and schematic drawings of the experimental setup and the oscilloscope screen. Think about the following questions:

1. How can you measure the time difference between the two beams from the readings on the oscilloscope screen? Show this in your drawing of the oscilloscope screen.
2. How can you relate the time difference to the speed of light? Show this in your calculations of the speed of light.

Some notes on using the oscilloscope:

1. Connect the BNC coaxial connector to the video input on the back of the laser and the 1 MHZ banana binding posts at the other end. To complete the setup, 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. Connect the sync output to the oscilloscope external trigger. Make sure the audio switch on the DCB is in the off position.
2. Switch the power to the on position. 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.

Equipment for Second Method:

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

Experimental Procedure for Second 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 ε_0 and μ_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/ε_0 and L/μ_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 2. 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 end effects and 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 polynomial). What is the resulting uncertainty in c? (**Hint:** It should be very small if the experiment is done properly.)

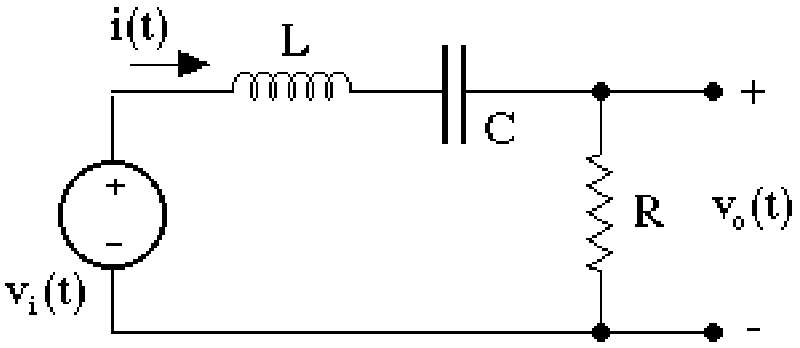

Figure 2: Series LC circuit.

Think about the following questions and write your answers:

1. Why should you not just connect L and C in series with the function generator?
2. What considerations led you to determine the value for the resistor R?
3. 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!