Experiment 1
Measurement of the Speed of Light in Air and Water

The speed of light is an important constant in the theory of Special Relativity and is challenging to measure due to its large value. Galileo was one of the first to document its measurement using two people with lamps at a large distance from one another. After this experiment, you may better appreciate his result: "very fast".

To measure the speed of light in air, we will use the Q-switched, diode-pumped Nd:YAG laser in Dr. Andrew's lab. It will be used primarily because its light output is delivered in pulses with very narrow width. In this sense, it will act as a light source that is turned on very rapidly-for a time so short that it is commensurate with light traveling less than a meter. It is this rapid turn-on rate that will allow a speed of light determination using distances on the order of the optical bench.

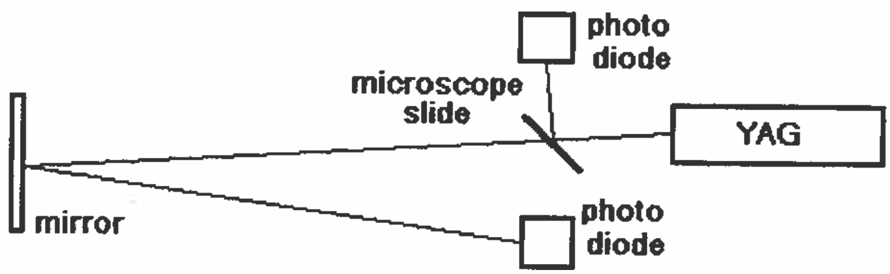
The YAG Laser As with any laser, the one we will use requires a medium with at least four accessible energy levels. The highest energy level is the excited state, then the upper laser level, the lower laser level, and finally the ground state. The trick is to set up such a system where the ground state can be excited to the excited state (in our case with light from a diode laser), followed by the emission of light (not the laser light-just a warm glow) to leave the system in the upper laser state. The upper laser state must long-lived or disconnected from the ground state (metastable). If light with the proper frequency draws near the system in the upper laser state, the light will induce decay to the lower laser state (stimulated emission). In addition, if the lower laser state is short-lived (it quickly decays to the ground state), then the same light which might cause absorption from the lower laser state to the upper laser state (stimulated absorption) will usually NOT be absorbed. In this laser, Neodymium ions are imbedded in a purple transparent solid made of Yttrium-Aluminum-Garnet to create this type of system. The Nd ions have energy levels with the previously mentioned characteristics.

The Q Switch The rapid pulse of the laser is generated by a technique called Q-switching or quality factor switching. The quality factor of a periodic system is the ratio of the resonant frequency to the damping rate. In the YAG laser, the Q of the optical cavity is varied by an EOM (electro-optic modulator). When the modulator is off, the cavity has very low Q and a build-up of the upper laser level easily occurs as the light of resulting decay from upper to lower laser levels does not stay within the cavity long enough to cause stimulated emission. The EOM can be turned on quickly causing a large change in Q which acts to contain light from laser decay within the cavity and generate a lot of stimulated emission in a short time.

Part 1. Measurement of the speed of light in air using ir light.

ALWAYS WEAR THE PROPER SAFETY GOGGLES WHILE THE LASER POWER SUPPLY IS ON!! The safe use and monitoring of the laser beam will be demonstrated for you by Dr. Sturrus for this laser. The light emitted from the YAG is infrared at a wavelength of 1.064:m. You can view the location of the beam with the ir card. You will notice that the beam diverges slightly. Even so, you will not need to focus the beam to perform this part of the lab.

Begin by setting up the laser and photodiodes as shown in the diagram. Note the photodiodes need 50 Ohm termination which may be provided by the digital oscilloscope. The distance from the YAG to the mirror should be several feet. You need to measure the distances in the diagram as carefully as possible. If the output from the diodes is put into the fast digital oscilloscope, you should be able to see a definite offset in time for the two signals from the diodes. Your goal is to measure, as accurately as possible, the time difference between the rising edges of these pulses. it is sometimes necessary to misalign the laser beam somewhat to strike only the edge of the detector-this helps keep the diode output small enough to see on the oscilloscope.



Try to accustom yourself to the use of the fast digital oscilloscope. When you have both diode outputs on the same screen, you can save the data by taking the following steps:
1. place a 3.5' floppy disk into the drive.
2. Press the Run/Stop button on the right to freeze the data screen in memory.
3. Press the yellow Ch 1 button to select the channel 1 output.
4. Press the Save/Recall button at the top to activate the save menu.
5. if the file called "Tek????.csv" is not highlighted, rotate the knob near the SELECT and COARSE switches until "Tek???.csv" is highlighted.
6. Press the screen button labelled "to file" with the floppy disk picture near it.
7. Press the screen button labelled Save Ch 1 to selected file.
8. Repeat from step 2 above, using the blue Ch 2 button and Ch 2 throughout.
9. Take the floppy disk to a computer and read BOTH files into EXCEL and look at graphs of each to be sure you have the data saved on disk.

Once these files are stored on disk, you should estimate the time difference from the scope screen to compare with your more accurate determination from fitting the data. To avoid any photodiode or cable delays, you probably should switch the two diodes and repeat the measurements. The easiest way to do this and include any timing differences due to the cables, is to switch the cables at the scope channel inputs. You will find that data fit pretty well to a function of the form

$$V(t) = A_1 + (A_2 t + A_3)\left[1 - e^{-\left(\frac{t}{A_4}\right)^{12}}\right]$$

If you want to improve on this formula, feel free. You may fit the data using any program you are comfortable with, or I can provide a FORTRAN fitting program for which you must provide the function and derivative subroutines. You should be able to get values for the time difference that are good to a couple per cent.

Part 2. Measurement of the speed of light in water.

If you try to measure the speed of light in water, by placing an aquarium in the beam for example, you will notice that the ir light is absorbed by the water and you are unable to complete the measurement. It would be nice if the laser would produce visible light so water would not absorb it. It turns out that green visible light can be created by the YAG by focusing it into a frequency doubling crystal. The crystal is called a KDP or potassium dihydrogen phosphate crystal. This crystal converts the 1.064:m light from the YAG into .532:m green light using a non-linear optical effect. The electrons attached to the molecules in the KDP crystal are over-driven into oscillation until harmonics of the incident beam are produced. This requires an optical electric field on the order of the size of the electric field holding the electrons to the crystal. For this reason, the YAG light must be focused into the KDP crystal. By conservation of energy, two photons of YAG light are necessary to produce one photon of green, and by conservation of momentum and some other factors relevant to phase, the angle of the crystal determines the efficiency of conversion to green.

Use a lens to focus the ir beam into the KDP crystal. You will need a second lens to "straighten the beam" after the crystal. Now send the green beam through the fish tank, filled to about one third its volume, so that the green beam passes through the water. Repeat the activities of Part 1 to get the changes in time for the water in place. You should measure the path length in the water with a meter stick as best you can also.