Rotating Mirror Determination of the Speed of Light

Introduction

You will use a rotating mirror to measure the speed of light in a manner similar to that used by Foucault. Light hitting the mirror when it is rotating will reach an observation location at a different position than when the mirror is not rotating. From the distance between these points, the frequency of rotation of the mirror, and a consideration of the distance that the light travels, we can determine the speed of light.

Equipment

This experiment requires the Leybold Speed-of-Light kit[1] (including a high-rpm rotating mirror and a 4.75m focal length lens), a Variac, a laser with a narrow beam spot in the horizontal direction or a use of the narrow slit available in the kit, a 50-50 beam splitter, front surface plane mirrors (the number depends upon your setup), some kind of detection system capable of precise determination of the final position of the beam after its round trip through the system, the variable density optical filter, and rigid supports for all components. The detection system may be as simple as a sheet of paper on which the locations of beam positions are marked. More precise work will be possible with an electronic detector moved by a calibrated screw across the observation plane. A Pasco Linear Translator provides such a screw movement. Pasco photometer apertures and optical fiber may also be useful. Either a strobe light, or a photodetector and oscilloscope may be useful in the determination of the mirror frequency. The Variac will provide adjustment of that frequency.

Background/Theory

Fig. 1 shows the path of the light through one possible setup. The light beam starts at the laser, travels to the End Mirror and then back to Beam Splitter where some of the light is reflected to the detection point. This established a reference position for when the Rotating Mirror is actually stationary. When the Rotating Mirror is rotating at a high angular speed, by the time the light returns to this mirror, the mirror has turned through some angle; consequently, the light will be reflected to a different detection point than when the mirror was not rotating. It can be shown that if the mirror turns through an angle θ, the light reflected from it toward the Beam Splitter will make an angle of 2θ with the direction that this light would have take without the mirror rotating. The lens is used to focus the light so that the beam size at the detection point is roughly the same size as it was exiting the laser. (You actually need to consider the beam waist near the center of the laser since this is the smallest beam size). For this method to work properly, the beam must be well focussed at the detector. Hence, it is very important that care be taken to insure that the distances

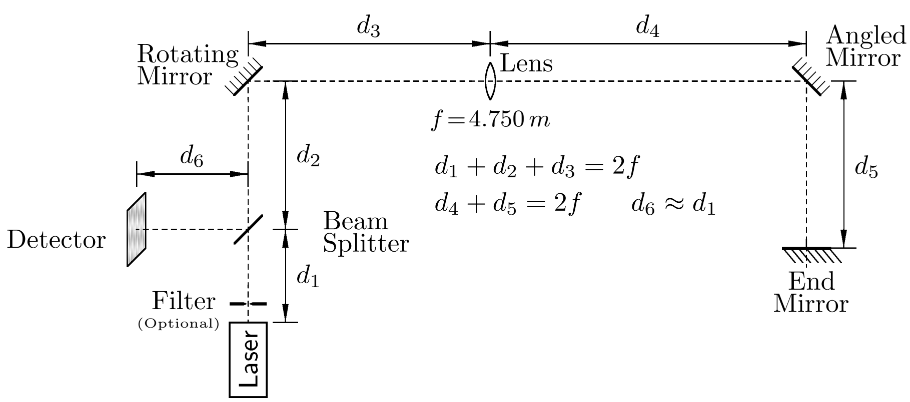

Figure 1: Schematic diagram of the setup.

from the Laser (beam waist) to the Lens and from the Lens to the End Mirror are exactly twice the focal length of the lens. (If you don't understand why, just look into the optics equations.) The distance from the Beam Splitter to the detector needs to be adjusted to insure that the best focus possible is achieved.

The idea is simple: speed equals the distance traveled divided by the time taken. The time taken is determined from the distance that the rotating mirror moves the returning light from where it would be if the mirror were not rotating. A little careful thought will indicate which distance the light traveled during this time. You should start by deriving the equation for the speed of light in terms of the measurable quantities. All of the measurable quantities can be found to very good precision except the distance of the shift in the beam spot which will be on the order of a few millimeters. In order to obtain a better result, you should consider your equation for the speed of light and determine the optimal position for the Rotating Mirror relative to the Lens within the setup to obtain the maximum shift.

Procedure

The lens, mirrors, and other optical elements will need to be secured by rigid mounts and aligned carefully so that they are all in the same plane. The mounting for the Rotating Mirror especially needs to be firmly fixed since vibrations during rotation can cause the setup to become misaligned. Hence, start by setting up and firmly affix the Rotating Mirror and base the remaining setup from this placement.

Next, lay out the basic setup from the Laser to the End Mirror using approximate distances so that you know all of the components will fit in your laboratory area. (You do not need to include the Beam Splitter at this time.) The Angled Mirror is used in the setup since the laboratory space you will have available does not allow a straight shot from the Lens to the End Mirror. Once you are sure the components will fit, carefully measure and adjust the positions of the Lens, Angled Mirror, and End Mirror so that $d_4 + d_5 = 2f$ as close as possible. Note that the distances are measured from the center of the Lens and the front surfaces of the two mirrors. It will be easiest to do this step by setting the Lens to Angled Mirror distance, and then adjust the End Mirror position to be the proper total distance. You might want the End Mirror to be on an optical rail so that it can be easily along the optical axis. Now place the Laser in position so that $d_1 + d_2 + d_3 = 2f$ as close as possible. You will want to be able to move the laser along the optical axis in order to adjust the focus as described shortly.

Establish the laser beam along the optical axis, i.e. the dotted line in Fig. 1. Make sure the beam height is constant from the Laser to the Rotating Mirror, and adjust the vertical alignment of the Rotating Mirror so that the reflected beam remains in the same plane as the incident beam. You need to make sure the beam passes through the center of the Lens, and that the beam after the Lens follows the along the same straight line as the incoming beam to the mirror. This may require slightly adjusting the Lens angle to insure that it is perpendicular to the optical axis. Then adjust the Angled Mirror to reflect the beam to the End Mirror within the same plane as the rest of the beam and so that the laser beam hits near the center of the End Mirror.

Before attempting to adjust the return beam, it is important to test the focussing of the beam to the End Mirror. Place a sheet of paper over the End Mirror and adjust the Laser along the optical axis to test the focus. Depending on the intensity of the laser beam, you may want to place the variable density optical filter just after the Laser and use it to decrease the intensity of the beam spot at the End Mirror so that it is easier to view. Remember that the Lens has a very long focal length, so changes in the focus will be very slow. Just attempt to find a position which gives the optimal resolution for the beam spot. You can also adjust the End Mirror along the optical axis to test the focus. Once you are comfortable with the focussing of the beam, you should make sure all the components that have been placed are prevented from moving and their positions marked.

It is now time to work on the return beam. Insert the Beam Splitter and place a viewing screen (sheet of paper) at the position of the Detector. You should now be able to adjust only the End Mirror angles to have the laser beam reflect back along the optical axis to the viewing screen. You can trace the laser beam back through the setup by seeing if the return beam goes back to exactly the same spot on each component. Generally, it is only necessary to do this for the Angled Mirror. If necessary, you may need to make slight adjustments to the entire system to get a good beam spot at the Detector. Finally, adjust the position of the Detector to obtain a focussed beam spot. (Recall, $d_6 + d_2 + d_3 = d_4 + d_5$.) The better the focus, the

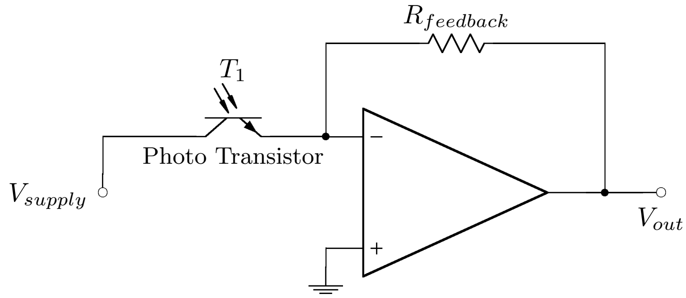

Figure 2: Circuit diagram for a possible detector.

better your final result.

With everything positioned, measure and record all of the distances as precisely as possible. Do not just string a flexible tape measure between the components since any sag in the tape will result in an incorrect measurement. Although the uncertainty in these measurements will have little affect on the uncertainty in your final value, getting the measurements wrong will severely affect your accuracy.

With the Rotating Mirror stationary, you will need to measure/mark the position of the beam spot at the Detector. You then turn on the rotation and measure the shift in the position of the beam spot. Using the Variac to power the Rotating Mirror has two advantages: 1) you can adjust the voltage to change the rotation frequency; 2) you can use the power switch on the Variac to turn the rotation on and off thereby avoiding disturbance of the optical alignment when using the switch on the Rotating Mirror. You also need to measure the frequency of rotation of the mirror which gives the measured shift. However, you need to realize that the frequency changes slightly over time as the motor warms up, and that the frequency depends on the voltage which you supply from the Variac. Hence, it is best to measure the frequency at the same moment as the measurement of the shift in the beam spot position.

Several methods are available to do the measurement of the shift in the beam position. The simplest is to use a fix sheet of paper at the Detector, and mark where the two beams of light hit the paper with a narrow lead pencil. Making the marks can be tricky since the beam spot has "size" so that you need to estimate the center. However, multiple measurements should allow you to obtain a good value and uncertainty. Measuring the rotation frequency can be made using a strobe light while taking into account the fact that the mirror has two reflective surfaces. However, the time needed to do the strobe light measurement makes it more difficult to obtain an accurate result wince the frequency may change.

A more sophisticated approach which measures the frequency of the mirror and also contributes to the detection system is as follows. We connect an optical fiber placed in a linear translator used as the Detector to an electronic detector[2] which is connected to an oscilloscope and through a *Science Workshop 750 Interface* to a computer and use *Data Studio* to record the data. When the mirror is stationary, we adjust the linear translator holding the fiber to determine the position of the beam spot by measuring output voltage versus position. When the mirror is rotating, we again translate the fiber to measure the position of the shifted beam spot. Of course a calibration of the linear translator will need to be made, but this method will allow you to determine the centers of the two beam spots to very high precision. (You can fit the measured voltages versus position using a Gaussian peak to find the centers.) The frequency of the rotation is measured using the oscilloscope, and it is easy to see that the mirror has two sides based on the slightly different intensities of the beam from the two sides.

There are numerous methods which range between the two extremes described above. You may want to choose something in between the two that uses aspects of each. For example, you could use a digital camera to take pictures of the viewing screen and analyze the pictures. Or you may be able to directly use a CCD camera by placing the CCD detector at the viewing position to directly detect the laser beam. Numerous designs for the light detector are also available. The circuit described in Ref.'[2] is fairly complex, so you could alternatively use a phototransistor and an op-amp in the current-to-voltage converter configuration shown in Fig. 2. In this case you can change the sensitivity by changing the feedback resistor. Whatever your choice, make the best measurement possible.

Finally, since it is possible to vary the rotation frequency with the Variac, you can greatly improve your measurement by determining the shift in the laser beam spot as a function of rotation frequency. You can then use a linear fit to extract the speed of light. You should be able to obtain a value which has a precision of better than 1% and which is accurate within the precision of your measurement.

References

[1] Instruction Sheet: Measuring the Velocity of Light According to the Method of Foucault and Michelson, (Leybold, 1959).

[2] A. J. Domkowski, C. B. Richardson, and N. Rowbotham, Am. J. Phys. **40**, 910 (1972).