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VELOCITY OF LIGHT

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A He-Ne laser and a rotating mirror are used to measure the velocity of light. The measurement is based on the displacement of the laser beam as a function of the mirror's rotational frequency.

I. INTRODUCTION

The velocity of light is an important quantity in physics because it plays a fundamental role in electromagnetism and relativity and because its measurement forms a significant chapter in the evolution of physics[1]. Attempts to measure the speed of light were made by Galileo by uncovering a lantern and having an observer on a distant hill uncover his lantern when he first saw the light. The idea was to time the light for a round trip. Needless to say, these early attempts were unsuccessful.

The Danish Astronomer Olaf Roemer made the first successful measurement of the velocity of light in 1675. Roemer based his measurement on the observations of the eclipses of one of the moons of Jupiter. He noticed that the duration of these eclipses was shorter when the earth was moving toward Jupiter than when the Earth was moving away, and correctly interpreted the results as resulting from the finite velocity of light. From observations of the eclipses over many years, he determined that the velocity of light was 2.1×10^8 m/s.

In 1849, the French scientist Fizeau was the first to successfully measure the speed of light over terrestrial distances. He used a rapidly revolving cogwheel to chop a beam of light into short pulses. A distant mirror reflected this light back to the rotating cogwheel. Depending on the position of the cogwheel when the light pulse returned, it would either block the pulse of light or pass it through to an observer. Using this method Fizeau measured the velocity of light to be 3.15×10^8 m/s.

Foucalt improved upon Fizeau's method by using a rotating mirror instead of a cogwheel. In 1878, Michelson modified the geometry of Foucault's method to measure a remarkably accurate value for the velocity of light. The best of his measurements gave a value of

2.99774×10^8 m/s compared to the currently accepted value of 2.99792458×10^8 m/s. It is the method of Michelson that is used in this experiment.

II. EXPERIMENTAL METHOD

The overall layout of the apparatus is shown in Fig. 1. Light from the He-Ne laser pass through a partially reflecting beam splitter and then strikes the rotating mirror (RM) where it is reflected through a lens L onto mirror M_1 and then onto mirror M_2. The light reflected from M_2 is then made to reverse its path back to the rotating mirror. When the light

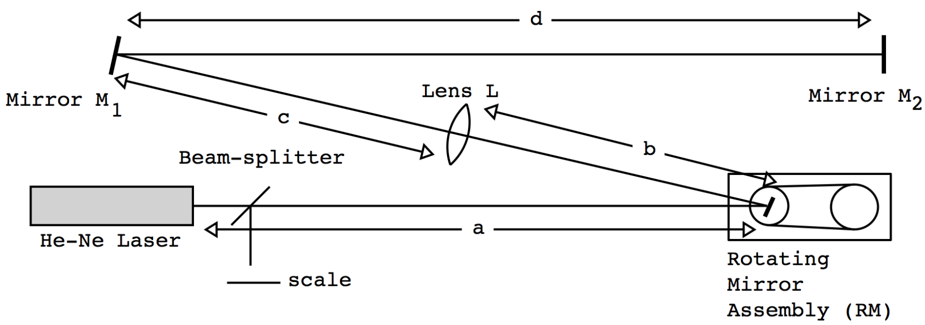

FIG. 1: Diagram of the experimental apparatus used for the measurement of the velocity of light.

returns to the rotating mirror, the mirror will have turned through a small angle $\Delta\theta$, so that the return path of the light from the rotating mirror to the beamsplitter will not exactly duplicate the original outward-bound path. The beam splitter deflects the returning light where it forms an image of the source. This image will appear at different positions on the scale as the angular velocity of the rotating mirror is varied. By measuring the deflection of the image as a function of the angular velocity of the rotating mirror, the velocity of light can be determined.

III. OPTICAL CONSIDERATIONS

In order to have the light form an image at $\mathtt{M}_2$ (which is then the source for the return path), the thin lens equation requires that

$$\frac{1}{f} = \frac{1}{a+b} + \frac{1}{c+d}, \tag{1}$$

where f is the focal length of the lens L. The distance a should be chosen so that the laser beam approximately *fills* the rotating mirror. This distance will depend on the divergence angle of the He-Ne laser. Note that the rotating mirror acts as an aperture or entrance pupil for the optical system. But the same rotating mirror also acts as an aperture for the return beam. To just fill the rotating mirror for the return beam we require a symmetric optical path where

$$a + b = c + d. \tag{2}$$

On combining Eqs. 1 and 2, we have

$$a + b = c + d = 2f, \tag{3}$$

so that for a focal length of $f \approx$ 5m, then $a + b = c + d \approx 10\,\mathrm{m}$.

The round trip time for the light to go from RM to $\mathtt{M}_2$ and back to RM is

$$\Delta t = \frac{2(b + c + d)}{v}, \tag{4}$$

where v is the velocity of light in air. During this time, the rotating mirror has moved through a small angle

$$\Delta\theta = \omega\Delta t, \tag{5}$$

where ω is the angular velocity of the rotating mirror. **Show that** this results in a displacement s of the image on the scale of

$$s = \frac{4a\omega(b + c + d)}{v}. \tag{6}$$

Thus the slope of the straight line on a graph of s as a function of ω is

$$m = \frac{4a(b + c + d)}{v}. \tag{7}$$

IV. EXPERIMENTAL PROCEDURE

Turn on the He-Ne laser and direct the beam to the center of the rotating mirror. Check that the laser beam is horizontal by measuring the position of the beam at the laser and at the rotating mirror. Move the aluminum wheel on the rotating mirror assembly so that the beam is directed back to the laser. (Keep your hands away from the thin mylar tape which is used as a drive belt.) Adjust the rotational axis of RM perpendicular to the beam so that the beam is reflected directly back into the laser. Rotate RM so that the beam is centered on the mirror M_1 and is then reflected to the center of mirror M_2. Insert the lens into the beam path so that the beam is centered on the lens. Note that a lens is used to focus light, not to bend its path. Adjust the position of mirror M_2 and/or the lens L so that an image of the source is formed at M_2. A small hand held paper screen placed in front of RM, L, M_1, and M_2 in turn will facilitate these adjustments.

The light reflected from M_2 must retrace its original path to the rotating mirror. This alignment requires special attention because we are dealing with two overlapping beams of light and the only way to retrace the path is by watching the light spots on the mirrors and the lens. There will be two sets of spots on M_1, L, and RM; one coming and one going. This adjustment is best carried out by inserting the corner of a white card into the path of the light. Care must be taken not to block out all of the light with the card. Thus it should be inserted into the beam about half-way. In this manner you only block out half of the beam and can see the reflected return beam on the card. Then insert the card from the opposite side. By doing this you can tell when the two beams overlap.

The beam of light reflected from RM now travels back toward the laser and is partially reflected by a beam splitter set at 45°. There may be two images on the glass scale, from front and the back surfaces of the beam splitter. The ground glass scale should be placed at the same distance from the beam splitter as the laser is. The scale should be moved laterally so that image is centered on one of the division marks on the scale and provides a zero reading. The image on the scale when the rotating mirror is stationary is many orders of magnitude brighter than it will be when the mirror is rotating since very little light is returned during rotation.

When the apparatus is aligned and the beam image is in sharp focus, turn on the power supply to the rotating mirror and set the direction switch to CW. Let the motor warm up at about 300 revolutions/sec for a few minutes. Whenever the motor is accelerated, the red LED on the control box will be illuminated. As the speed stabilizes, this light should go out. If it does not, then turn off the motor, since something is interfering with the motor rotation. Never run the motor with the MAX REV/SEC button pushed for more than one minute at a time. The speed of the motor should be turned down except when you need to have a high angular velocity. This will significantly prolong the life of the motor, drive belt, and bearings.

Measure the displacement of the image on the scale as a function of the angular velocity of the rotating mirror. Be sure to use both clockwise and counter-clockwise values of ω.

V. DATA ANALYSIS

Determine a best-fit slope from a graph of displacement s as a function of the angular speed of the rotating mirror. From the slope, find a value of the velocity of light in air. Discuss the uncertainty in your measurement.

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[1] For a detailed guide to the literature on measuring the speed of light see: H.E. Bates, *Resource Letter RMSL-1: Recent measurements of the speed of light and the redefinition of the meter*, Am. J. Phys. **56**, 682 (1988).