

## Determining the velocity of light by means of the rotating-mirror method according to Foucault and Michelson

Measuring the image shift for the maximum rotational speed of the mirror

### Objects of the experiment

- To measure the shift  $\Delta x$  of the image of the light source for a rotary mirror
- To determine the velocity of light  $c$  from the rotational speed  $\nu$ , the shift  $\Delta x$  and the light path  $\Delta s$  between the rotary mirror and the end mirror.

### Principles

Measurement of the velocity of light by means of the rotary mirror method utilizes a concept first proposed by L. Foucault in 1850 and perfected by A. A. Michelson in 1878. In this method, light travels along a known path in both directions between two mirrors; the transit time required for this is initially unknown. During this time, the first mirror rotates at a known, very high frequency. Consequently, the returning light beam is incident on the rotary mirror at an altered angle, and is also reflected by this mirror. The position of the reflection is read from the scale, and this value is used to calculate the rotational angle of the mirror, and thus the transit time of the light.

In the experiment setup described here, the lamp used as a light source in earlier versions has been replaced by an He-Ne laser (see Fig. 1). The light source  $S$  is placed at a distance  $a$  from the rotary mirror (1). The light reflected by this mirror is incident on lens (2), which is set up at a distance equivalent to its focal length  $f$ . This produces an image  $S'$  of the light source on one of the planar end mirrors (3) set up at a distance  $b$  from the lens. The reflection of the light beams at the end mirror and their re-reflection at the rotary mirror produces an image  $S''$  of the original image  $S'$  at the emission aperture of the laser.

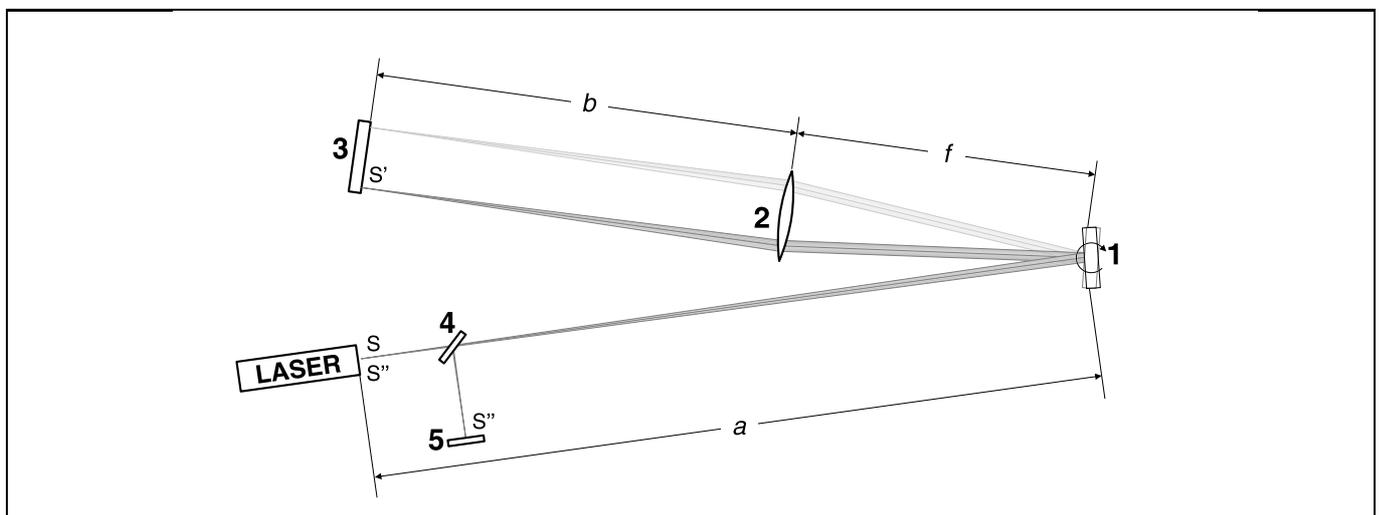
When the rotary mirror turns, image  $S'$  moves across the end mirror. Between the lens and the end mirror, the main beam

runs parallel to the axis of the lens, because the rotary mirror is in the focal point of the lens. At the end mirror, the main beam is reflected into itself, and returns along the same path to the rotary mirror, and from there to the emission aperture of the laser. The image  $S''$  is always in the same location, regardless of the position of the rotary mirror, when the mirror is stationary or turning slowly. The images  $S'$  and  $S''$  are generated for as long as the primary beam from the rotary mirror is within the aperture angle of the lens. Thus, when the mirror is rotating, the brightness of images  $S'$  and  $S''$  is greater, the larger the usable width of the lens is.

A beam splitter (4) reflects a part of the returning light onto a glass scale (5). The optical path from the rotary mirror to the glass scale is also  $a$ , so that image  $S'$  also appears on the glass scale.

Fig. 1: Beam path for determining the velocity of light using the rotary-mirror method

- 1 Rotary mirror
- 2 Lens,  $f = 5\text{ m}$
- 3 End mirror
- 4 Beam splitter
- 5 Glass scale



**Apparatus**

1 Rotary mirror with motor, for determining the velocity of light . . . . .	476 40
1 He-Ne laser, linearly polarized . . . . .	471 840
1 Front silvered mirror, 120 mm dia. . . . .	463 20
1 Lens, $f = 5$ m . . . . .	460 12
1 Beam splitter . . . . .	471 88
1 Holder with spring clips . . . . .	460 22
1 Glass scale . . . . .	311 09
1 Rheostat 1000 $\Omega$ . . . . .	537 22
1 Rheostat 320 $\Omega$ . . . . .	537 23
1 Measuring junction box . . . . .	502 05
1 Two-way switch . . . . .	504 48
5 Safety connecting leads, 100 cm . . . . .	500 64
1 Stand rod, 100 cm . . . . .	300 44
1 Stand rod, 47 cm . . . . .	300 42
1 Stand base (large), V-shape . . . . .	300 01
4 Stand bases (small), V-shape . . . . .	300 02
2 Leybold multiclamps . . . . .	301 01
1 Wooden ruler, 1 m . . . . .	311 03

In the time  $\Delta t$  which the light requires to travel the path

$$\Delta s = 2 (f + b) \tag{I}$$

from the rotary mirror to the end mirror and back, the rotary mirror rotating at a high value for  $\nu$  turns by the measurable angle

$$\Delta\alpha = 2\pi\nu \Delta t \tag{II}$$

This causes a shift in the position of image  $S''$  on the glass scale by the amount

$$\Delta x = 2a \Delta\alpha \tag{III}$$

Thus, we may say:

$$c = \frac{\Delta s}{\Delta t} = \frac{8\pi\nu \cdot (f + b) \cdot a}{\Delta x} \tag{IV}$$

The distances  $a$  and  $b$  cannot be set to just any values independently of each other. As the light source is sharply imaged on the end mirror, the law of imagery applies:

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{a + f} \tag{V}$$

Consequently, for the velocity of light, we ultimately obtain the relationship

$$c = 8\pi \cdot (f + 2a) f \cdot \frac{\nu}{\Delta x} \tag{VI}$$

Thus, producing the greatest possible shift  $\Delta x$  requires the highest possible rotational speed  $\nu$  and the longest possible focal length  $f$  and distance  $a$ . The rotary mirror for determining the velocity of light (476 40) has a speed of  $\nu = 450$  Hz, and the lens (460 12) has a focal length  $f = 5$  m. In principle, any value can be selected for the distance  $a$ . However, one must then be willing to accept intensity losses due to the divergence of the laser beam, as well as a more painstaking adjustment process. The arrangement shown in Fig. 1 represents a viable compromise, in which the laser and the end mirror are positioned side by side, i.e. the relation  $a = f + b$  applies. By inserting equation (V), we can calculate

$$b = \sqrt{2} \cdot f = 7.1 \text{ m and}$$

$$a = (1 + \sqrt{2}) \cdot f = 12.1 \text{ m.}$$

The distance  $a$  between the laser and the rotary mirror corresponds to the overall length of the setup.

**Setup**

*Adjustment of the optical components is much easier when the arrangement is set up by two persons. The beam path should be as horizontal as possible.*

*Select an area with a flat floor surface, and clamp the rods of the optical components in the apex of the stand bases (see Fig. 2) so that they extend about 1 cm from the bottom of the stand bases and touch the floor (beam height: 15 cm).*

*If the floor is noticeably uneven, clamp the rods in the middle strut of the stand bases, and leave some play for height correction.*

*Check the beam height with a ruler.*

**Laser, lens and end mirror:**

- On the floor, mark position  $P_1 = 0$  for the rotary mirror,  $P_2 = 5$  m for the lens and  $P_3 = 12.1$  m for the end mirror and laser (see Fig. 1).
- Mount the laser on the rod and tape a piece of white paper around the emission aperture; this will make subsequent observation of the returning laser beam much easier.
- Clamp the rods of the laser, the lens and the end mirror into one small stand base each.
- Align the rods as precisely vertical as possible using the adjusting screws on the stand bases.
- Set up the laser and the end mirror next to each other at  $P_3$ , with a distance of 30–40 cm between midpoints (see Fig. 1 and Fig. 2).

**Electrically connecting the motor:**

- Prepare the motor circuit for connection to the AC mains as shown in Fig. 3 (connect the center tap of the rheostats to the red sockets).
- Practice running up and decelerating the motor smoothly.

Running up the motor:

- First set all rheostats to their maximum value and turn the selector switch to position **(b)**; then turn the motor on.
- Reduce the 1000  $\Omega$  resistor to about one third.
- Set the two-way switch to **(a)**.
- Reduce the 300  $\Omega$  rheostat to the minimum value.

**Safety note**

The He-Ne laser fulfills the German technical standard "Safety Requirements for Teaching and Training Equipment – Laser, DIN 58126, Part 6" for class 2 lasers. When the precautions described in the Instruction Sheet are observed, experimenting with the He-Ne laser is not dangerous.

- Never look directly into the direct or reflected laser beam.
- Do not exceed the glare limit (i.e. no observer should feel dazzled).

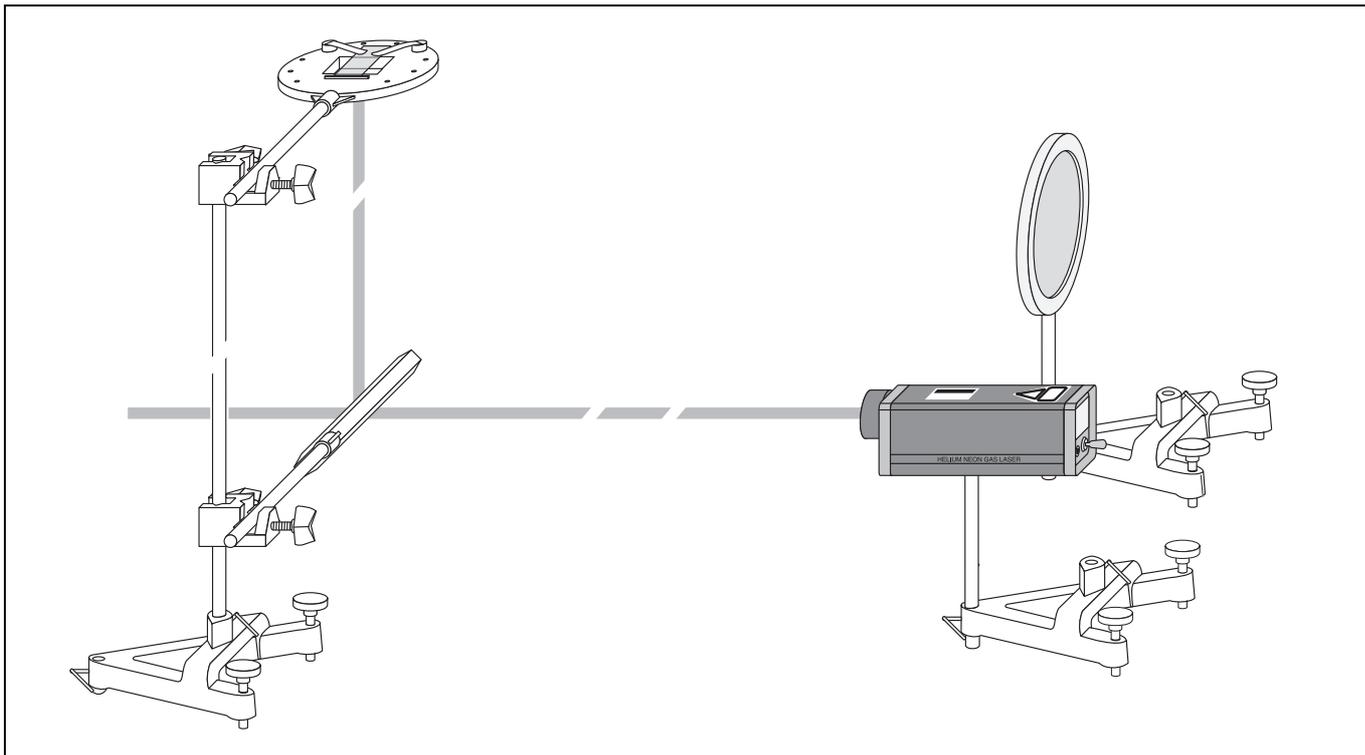


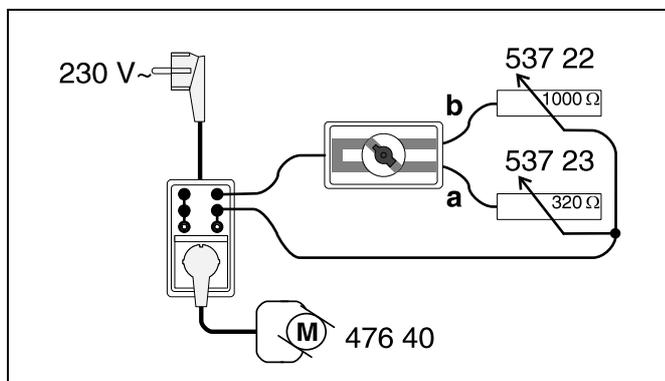
Fig. 2: Partial experiment setup with laser, end mirror, beam splitter and glass scale; distances between the apparatus are not drawn to scale

Fig. 3: Diagram showing connection of the motor of the rotary mirror to the AC mains; with measuring junction box, two-way switch and rheostats

Fig. 4: Mounting the rotary mirror

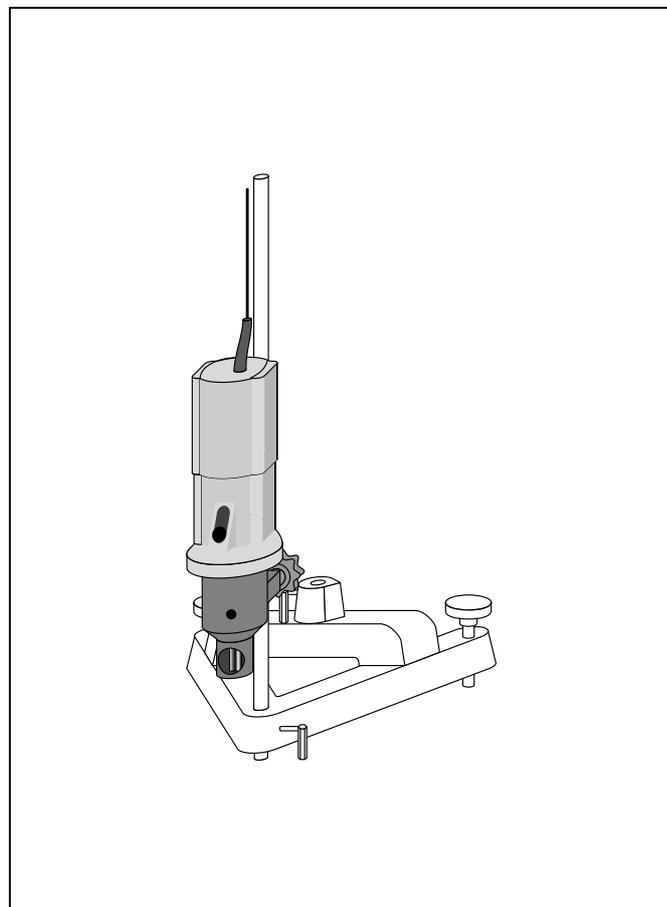
#### Decelerating the motor:

- Increase the  $300\ \Omega$  rheostat to its maximum value.
- Set the two-way switch to **(b)**.
- Increase the  $1000\ \Omega$  resistor until the motor turns slowly.
- Disconnect the motor mains plug to switch it off.



#### Rotary mirror:

- Clamp the stand rod at the apex of the stand base so that it extends about 1 cm from the bottom of the stand base and touches the floor.
- Attach the rotary mirror for determining light velocity to the stand rod so that the center of the mirror is on the level of the beam (see Fig. 3). Do not insert the adjusting wrench yet. Check the beam height with a ruler.
- Set up the rotary mirror at point  $P_1$  and align the rotational axis of the mirror as precisely vertical as possible using the adjusting screws on the stand base.
- Weigh down the stand base so that it cannot slide.
- Plug in the motor, run it up and check whether the stand base of the rotary mirror moves when the motor is running at top speed.



## Adjustment

- Decelerate the motor and disconnect its plug.
- Using the adjusting wrench, turn the mirror side to the front.
- Switch on the laser and, by turning and moving the stand base and varying the adjusting screws, align the laser beam so that the rotary mirror is symmetrically illuminated.
- Using the adjusting wrench, turn the rotary mirror until the laser beam is reflected on the end mirror (initially without the lens). Use the adjusting screws on the stand base to position the reflected beam on the center of the end mirror. If necessary, carefully turn and move the stand base.
- Readjust the laser as necessary.
- Set up the lens at position P<sub>2</sub> so that it is perpendicular to the beam in the beam path between the rotary mirror and the end mirror (see Fig. 1). Align the lens so that the light beam passes through the center of the lens and strikes the center of the end mirror.
- Hold a sheet of paper between the lens and the end mirror and check whether the smallest beam diameter is at the mirror, i.e. image S' is sharply focused; you may need to remove the end mirror.

If the image is not sharp, carry out the following steps (the cross-shaped interference pattern, in the origin of which the image rests, is due to diffraction at the edges of the rotary mirror, and is unavoidable):

- Remeasure positions P<sub>2</sub> and P<sub>3</sub> and correct the setup.
- By carefully turning the stand base and varying the adjusting screws, align the end mirror so that it reflects the light beam through the center of the lens precisely onto the rotary mirror.
- Turn one of the adjusting screws on the end-mirror stand base one turn inward and outward and check whether the returning light beam falls on the laser emission aperture, and whether the diffraction pattern formed together with image S'' is symmetrical with respect to the aperture.
- If necessary, correct the alignment of the end mirror.

### Fine adjustment:

- Using the adjusting wrench, slowly turn the rotary mirror and check whether the reflected beam passes horizontally through the middle of the lens and the end mirror, and whether image S'' remains stable during this process.
- If necessary, correct the alignment of the rotary mirror using the adjusting screws on the stand base.
- Then, turn the rotating mirror back to the initial position.
- Readjust the lens and end mirror as necessary.

### Beam splitter and glass scale:

- Mount the beam splitter (4) and holder with spring clips (5) and place them in the setup in the beam path between the rotating mirror and the laser (see Fig. 1 and Fig. 2; distance from beam splitter to laser aperture = distance from beam splitter to holder).

- Turn the beam splitter to face 45° upwards, so that the beam coming from the rotary mirror is reflected straight up.
- Attach the glass scale in the holder with spring clips so that the reflected beam is incident approximately in the middle. Use a piece of paper as an adjusting aid, and correct the alignment of the beam splitter and the holder as necessary.

If the laser beam no longer falls on the center of the rotary mirror after the beam splitter is set up:

- Readjust the alignment of the laser.

## Carrying out the experiment

- Remove the wrench from the rotary mirror.
- Read position x<sub>0</sub> of image S'' from the glass scale and write it down.
- Plug in the motor, and initially allow it to run slowly.
- Check the quality and position of image S'' on the glass scale (S'' should remain in approximately the same position; however, it is fainter when the mirror is rotating).
- You may want to clamp a thin piece of paper between the holder and the glass scale to maximize the contrast of the actual image of the light source and screen out the weaker diffraction phenomena.
- Run up the motor to its maximum speed.
- Read position x of image S'' from the glass scale and write it down.

## Measuring example

Table 1: Position x of image S'' for rotary mirror at rest and rotating

$\nu$ Hz	$x$ mm
0	10.0
450	16.0

## Evaluation and result

Using the values from Table, 1, we can calculate

$$\frac{\Delta x}{\nu} = 13 \cdot 10^{-6} \frac{\text{m}}{\text{Hz}}$$

Using equation (VI), we can calculate the velocity of light as

$$c = 2.8 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

Literature value:

$$c = 3.00 \cdot 10^8 \frac{\text{m}}{\text{s}}$$