Lenses Lab

Equipment optical bench, incandescent light source, laser, 3 lens holders, case of lenses etc., vernier calipers, 30 cm ruler, meter stick

Reading Your textbook

Optional Reading "Stargazer: the life and times of the TELESCOPE," Fred Watson (Da Capo 2004).

1 History

Lenses have been around awhile. The British Museum has a rock crystal lens called the Nimrud lens which has been reliably dated to the seventh century BC. (Nimrud is the Assyrian capital in which the lens was found.) Earlier lenses have been found. These lenses were short focal length lenses suitable for use as magnifying glasses. Spectacles using convex lenses, which are a help with far sightedness, probably first appeared in Italy late in the thirteenth century. Spectacles with concave lenses, a help with near sightedness, appeared in Italy in the middle of the fifteenth century. (Concave lenses are harder to make than convex lenses.) In spite of much conjecture, the telescope was probably not invented until early in the seventeenth century. A number of opticians at around the same time produced versions of this useful instrument. The refracting telescope (using lenses and not mirrors) requires a long focal length objective lens of some precision. The means of producing such a lens were not available earlier. Galileo was not the first to turn a telescope toward the heavens, but his observation that Jupiter had moons, which implied not everything revolved around the Earth, and that Venus had phases, which implied Venus revolved around the Sun and not the Earth, did not win him Brownie Points with the authorities.

2 Background

The two most common types of lenses are *converging* and *diverging* lenses. A converging lens is thicker in the middle than at the edge, having two convex surfaces, or one convex surface and a plane surface, or one one convex and one concave with the former having a smaller radius of curvature (more sharply curved). A diverging lens is thicker at the edge, with two concave surfaces, or one concave surface and a plane surface, or one concave and one convex with the former having a smaller radius of curvature. The symmetry axis of a lens is called the *optical axis.* Light rays parallel to the optical axis of a converging lens are made to converge to a point called the focal point of the lens. The distance from the center of the lens to the focal point is the focal length f, which is taken as positive for a converging lens. Light rays parallel to the optical axis of a diverging lens diverge on the other side of the lens so that they appear to be coming from a point behind the lens. This is the focal point of the diverging lens, and the focal length is taken to be the negative of the distance from the lens to the focal point.

The basic lens equation is

$$\frac{1}{s} + \frac{1}{i} = \frac{1}{f}, \tag{1}$$

where s is the distance from an object whose light passes through the lens and i is the distance to the image of the object produced by the lens. Distances are measured from the center of the lens. The side of lens from which the light approaches the lens is designated as "incoming", and the side of the lens from which the light recedes from the lenses is called "outgoing". The object distance s is taken as positive if the object is on the incoming side and negative if the object is on the outgoing side. The image distance i is taken as positive if the image is on the outgoing side and negative if the image is on the incoming side. This equation is appropriate for a lens that is much thinner than either s or i, and it is called the "thin lens formula." In this approximation, it does not make any difference which side of the lens light from the object approaches the lens. If the image distance i is positive the image is real, and can be observed on a screen. If i is negative the image is called a virtual image, and cannot be seen on a screen no matter where the screen is placed. A virtual image can be seen by looking through the lens toward the object. Real images appear inverted, while virtual images are right-side-up with respect to the object. If the incoming light rays are parallel to the optical axis (coming from $s = \infty$) the thin lens equation shows that the image is focused at $i = f$. Exploiting this fact gives one method of determining f for a converging lens.

The magnification m of a lens is given by

$$m = -\frac{i}{s}. \tag{2}$$

If the magnification is negative, the image is inverted.

In photography as well as for industrial applications, a lens is usually not characterized by its focal length but by its optical power D. The optical power is defined as the reciprocal of the focal length, so that

$$D = \frac{1}{f}. \tag{3}$$

If the focal length is given in meters D has units called diopters. A diverging lens is said to have negative power. The term optical power is a bit of a misnomer. It really refers to the "strength" of the lens.

3 Apparatus

There are an incandescent light source, a laser, and 3 lens holders that can be attached magnetically to an optical bench. The optical bench has a rail along one side against which the components should be pressed so as to assure that they are oriented correctly with respect to the axis of the optical bench. The optical bench has a cm scale along one side which can be used to measure the position of the components but it is more convenient to use a meter stick. The light source used should be attached at one end of the optical bench.

Some notation. The lenses, screen, and filters are supported by square frames we call *mounts*. The mounts attach magnetically to *holders* which attach magnetically to the optical bench. When measuring the distance between components, measure the distance between the centers of the components. This will mean the center of the mount which has the component in it.

The object you will use is two crossed arrows in a mount that attaches magnetically to the incandescent source There is also a circle in this object which is useful for measuring the size of a real image. You should measure the diameter of this circle. By measuring the diameter of the image circle you can calculate the magnitude of the magnification. When looking at an image also note whether it is inverted or not.

In the lens case there may be three convex lenses that are marked with focal length of 48 mm, 127 mm, and 252 mm, and one concave lens marked with a focal length of −22 mm. These focal length will be used in this describing the experiments. Some lenses have been broken and have been replaced with focal length lenses of not exactly these values. Use the closest approximation available to you.

There is a white screen with mm marks that attaches magnetically to a lens holder. Use this to observe a real image and measure its size. The screen should be moved so as to position the scale conveniently. PLEASE DO NOT WRITE ON THE SCREEN.

4 Qualitative observations

4.1 Convex Lenses

Use your three convex lenses as simple magnifiers. Hold a lens close to your eye and observe an object positioned less than a focal distance away from the lens. Is the image upright? Rank the lenses according to their strength as a magnifier. Does defining the "strength" of a lens as $1/f$ make sense?

Now look at objects that are further away from the lens than the focal length. Is the image upright?

4.2 Concave Lens

Look through the concave lens at objects various distances from the lens. Keep your eye far enough away from the lens so that the image is not blurred. Is the image ever inverted? Is it ever magnified?

5 Qualitative Observations With Laser

Mount the laser at one end of the optical bench, being sure the laser is pressed against the rail of the optical bench.

CAUTION

When the laser beam is reflected from the screen, the laser spot on the screen is uncomfortably bright. Attenuate the laser beam by putting the No. 13 Wratten filter in a lens holder and mounting this just in front of the laser. Keep the filter in place for all laser experiments.

Mount the screen in a lens holder and place it at a convenient distance from the laser (and filter). Put a lens holder between the laser and screen. One by one, put each of your four lenses in the lens holder and move the lens back and forth horizontally, observing the deflection of the laser beam as you do so. Does the laser beam deflect in the direction you expect it to? Is the deflection the same for the convex lenses and the concave lens? For the concave lenses, note how the strength of the lenses affects the deflection of the laser beam.

6 Measuring Focal Length With Laser

A thin beam of light along the optical axis of a lens will be undeflected. A thin beam of light that is not along the optical axis but is parallel to it will be deflected so that it either hits the focal point (convex lens) or can be extended back to the focal point (convex lens). These facts can be used to find the focal length of a lens. The most obvious way of doing this would be to move the laser beam back and forth horizontally, keeping the laser beam parallel to the optical axis, and then find the position of the screen where the laser spot on the screen did not move as the laser was moved back and forth. Our apparatus does not allow us to easily move the laser beam in this way. We adopt an alternative procedure which is essentially equivalent.

6.1 Focal Length Of Convex Lenses

Check that the laser beam is parallel to the axis of the optical bench by letting the laser beam hit a mark on the screen, and then moving the screen along the optical bench. The laser beam should not leave the mark. Use one of the longer cm marks on the screen, and orient this mark so that it is vertical. Now insert one of your convex lenses between the laser and the screen and move the lens horizontally so that the laser beam hits the same mark and the laser beam is undeflected and along the optical axis of the lens. Using Vernier calipers or a ruler, move the lens horizontally one cm. Now move the screen so that the laser spot is one cm from your original mark. The distance of the screen from the lens is the focal length. (One cm is not a magic distance. You can move the lens any distance as long as the laser beam is deflected the <u>same</u> distance on the screen.) In moving the lens one cm you have moved the optical axis one cm. The deflected laser beam crosses the optical axis at the focal point. Measure the focal lengths of your other two convex lenses by this method.

6.2 Focal Length of Concave Lens

Repeat the above procedure, except move the lens 4 mm (this is a smaller diameter lens) and move the screen so that the laser beam appear 4 mm from its original spot. Explain, perhaps with the help of a diagram, why this procedure works for the concave lens.

REPLACE LASER SOURCE WITH BULB SOURCE.
ATTACH CROSSED ARROW OBJECT TO THIS SOURCE.

7 Checking The Lens Formula

Put the 48 mm lens at various distances from the crossed arrow source, beginning with an object distance that is slightly more than a focal length and ending with an object distance that is quite far away. For each object distance move the screen so that the image is in focus. Measure the object and image distances and calculate the focal length in each case using the thin lens formula. Does the thin lens formula fit the data?

8 Two Lenses Close Together

If two thin lenses with focal length f_1 and f_2 are mounted close to each other, it can be shown that they act like a single lens of focal length f given by

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}. \tag{4}$$

Mount the 127 mm and 252 mm lenses on opposite sides of a single lens holder. Measure the focal length of this combination by measuring a few object-images distances and using the thin lens formula. Does your result agree with the above equation?

9 Qualitatively, Two Separated Lenses

Mount the 127 mm lens 15 cm from the arrow object and the 252 mm lens 15 cm from that lens. Move the screen so that the image is in focus. Now interchange the two lenses. Is the image still in focus? The two lenses of different focal lengths act like a thick lens and there are actually two focal lengths depending on which side the light comes from.

10 Quantitatively, Two Separated Lenses

Mount the bulb source at an extreme end of the optical bench. Mount the 48 mm lens 8 cm from the crossed arrow object. Mount the screen at the extreme other end of the optical bench. Put the 127 mm lens between the 48 mm lens and the screen, and adjust its position so that a sharp upright image is obtained on the screen. Measure the distances between the various components and the size of the image, and then use the thin lens formula twice to see if your results agree with the predictions of that formula, and if the magnification is predicted correctly. Note: The image of the 48 mm lens is the object for the 127 mm lens.

11 The Galilean Telescope

Move the optical bench so that one end is right at the end of the lab bench. Mount the −22 mm lens at this end of the optical bench. Mount the bulb source and arrow object at the other end of the optical bench (away from the end of the lab bench) with a piece of paper behind the arrow object to attenuate the light. Put the 127 mm lens near the focal point of the concave lens. Look through the concave lens and adjust the position of the 127 mm lens so that you see a clear upright image. This is the configuration of the telescope used by Galileo for his heavenly observations. It has a rather narrow field of view.

12 Questions

1. If you were to use a green laser beam to measure the focal length, would you get the same value? Does your answer bear on chromatic aberration in which a white object is focused as a somewhat blurred color image?
2. If two lenses have exactly the same dimensions but have different indexes of refraction, will their focal lengths be the same? Discuss.

3. Using Eq.(1) twice, prove Eq.(4).

13 Finishing Up

Please leave the bench as you found it. Thank you.