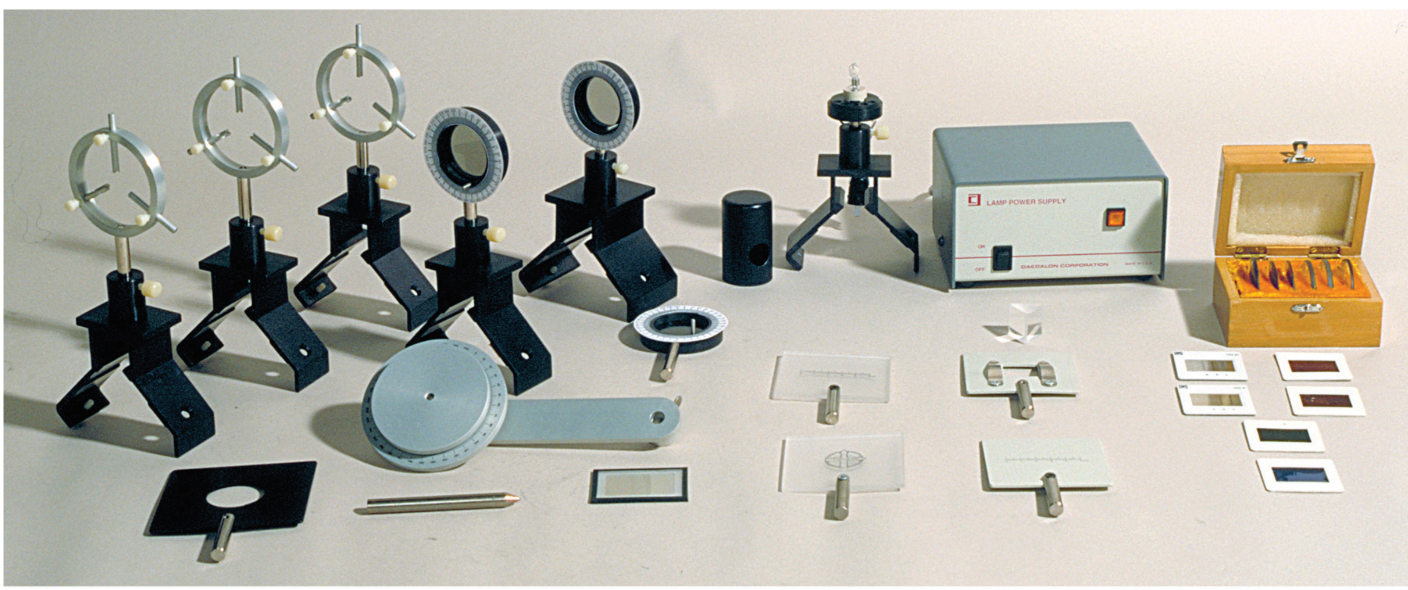
#EO-10 DAEDALON BASIC OPTICS SET

INTRODUCTION:
The EO-10 Basic Optics Set provides all of the components needed for an introductory course in optics.

EXPERIMENTS COVER:
Snell's Law
Image Formation
Gaussian Optics
Interference
Diffraction
Polarization

The experiments are described separately so that topics may be omitted without loss in continuity.



Thin Lenses

The formation of images is a fundamental concept of optics. The EO-10 Basic Optics set includes a box of six lenses having positive and negative powers. The lenses represent all of the permutations of surfaces: biconvex, plano-convex, a positive concavo-convex, biconcave, plano-concave and a negative concavo-convex. The two strong positive lenses are +5 diopters, while the two strong negative lenses are -5 diopters. A diopter is a convenient measure of the strength of a lens and is equal to the reciprocal of the focal length in meters. Stronger lenses that form an image closer to the lens have greater diopter numbers.

The experiment with thin lenses deals with the basic image forming qualities of lenses. The most important single parameter is the measurement of focal length. This is relatively easy for positive lenses, but a little more complicated for negative lenses.

Positive Lenses

Measurement of Focal Length

1. Select the biconvex lens and install it in the EO-20 Lens Holder. The three posts on the Lens Holder have V grooves to hold the edge of the lens. They should be adjusted so that the lens is centered in the ring, then gently tightened. For these experiments exact centering is not required.

2. Place a Daedalon Air Track on a laboratory bench so that it can point at a distant object. Looking out a window is the best location since the scene out of the window is distant and bright.

3. Place the Lens Holder with the biconvex lens into an EO-01 Optical Bench Carrier and place it onto an Air Track. The hole in the skirt of the Carrier should be on the meter tape side of the Track.

4. Place an EO-26 Opaque Screen in a second Carrier and place it on the Track. The Lens Holder should be at the and of the Track pointed at the window with the Screen behind it. The scale on the screen should face the Lens.

5. Slide the screen back and forth on the Track until an image of the scene outdoors appears on the Screen. The distance will be about 20cm. Does the orientation of the image surprise you?

   Record the position of the Lens Holder and the Screen as measured on the meter tape. Since only a little of the scale can be seen through the hole, it is useful to lift the Carrier up a little to make sure of the position on the scale.

6. Repeat the measurement several times.

The focal length of a lens is the distance behind the lens where parallel rays are brought together at a point. Since the light coming from an outdoor scene is almost parallel, the separation of the lens from the screen is the focal length of the lens. The power of the lens is

$$Ø = 1/f \quad (1)$$

where Ø is the power in diopters and f is the focal length in meters. Repeat the measurement for the planoconvex and the positive concavoconvex lenses.

Image Formation by Thin Lenses

Most of the time lenses are not forming images from parallel light. An astronomical telescope is an exception to this, of course. It is important to see how a lens forms images when the object is closer than infinity where the rays are parallel. The relationship between object and image is given by

$$1/s' = 1/f + 1/s \quad (2)$$

where s is the distance from the object to the lens and s' is the distance from the image to the lens, while f is the focal length of the lens measured in the same units. The sign convention in this equation is important. In this manual the following sign convention will be used:

A. Heights about the optical axis are positive. Heights below the optical axis are negative.

B. Distances to the left of a reference point are negative, to the right positive. The center of a thin lens will be the reference point for the next experiment.

C. The focal length of a converging lens is positive and the focal length of a diverging lens is negative.

Other conventions can be used but these will be used throughout this manual.

7. Place the EO-75 Target in one of the Carriers. The Target has two arrows so that the orientation of the image can be easily determined. It also has a 1cm long double arrow which can be used to measure magnification.

8. Place the Target on the Track at about 120cm on the scale. Record its position carefully.

9. Place the Lens at about 90 cm

10. Place the Opaque Screen at about 30cm with the scale side facing the lens.

11. Place the ES-16 High Intensity Light Source on the Track about 5cm behind the Target. This is the only position that is not important to the experiment.

12. Turn on the Light Source so that it illuminates the Target.

13. Slide the Lens Carrier back and forth until an image of the Target is formed on the Screen. Adjust the vertical height of the components until the Target one centimeter image falls on the Screen's centimeter scale.

14. Record the positions of the Screen Carrier, the Lens Carrier and the Target Carrier on the meter scale.

15. Record the length of the 1cm image on the Screen.

16. Move the Screen closer to the Lens, refocus and repeat the measurements. Four or five Screen positions are enough.

Since the distance from the lens to the target and the lens to the image have both been measured, Equation 2 permits the calculation of the focal length. Typical results are shown in the following Table.

Target Position	125.0cm	125.0cm	125.0cm	125.0cm
Object Distance	30.0	32.0	33.0	34.0
Lens Position	95.0	93.0	92.0	91.0
Image Distance	62.0	54.3	51.5	49.0
Screen Position	33.0	38.7	40.5	42.0
Focal Length	20.2cm	20.1cm	20.1cm	20.1cm
Image Width	2.1cm	1.8cm	1.7cm	1.5cm
Magnification	2.1	1.8	1.7	1.5

The focal length was calculated from Equation 2. It is constant within the experimental error. It should be the same as measured in the first part of the experiment as well. When making this calculation remember that according to our sign convention, the object distance is negative.

The magnification of the image can be determined by measuring the length of the 1 cm target by the scale on the screen. There is a second method of measuring the magnification which will give the same result. The magnification is also given by

$$M = s / s' \qquad (3)$$

where s is the distance from the lens to the object and s' is the distance from the lens to the image. Since s is negative, the magnification is negative which defines the image as inverted, which is true. The value in the Table is only the magnitude of the magnification and has ignored the sign. Compare the magnification determined in these two ways from the measurements.

Negative Lenses

Negative lenses act somewhat differently than positive lenses but the same laws can be applied. The principal difference between positive and negative lenses is that a negative lens is a diverging lens that does not produce a real image. A real image is an image that can be focused on a screen as shown in the first part of this experiment.

17. Use the same set-up as in the first part of the experiment, but replace the biconvex lens with the biconcave lens. Since its edge is thick, it doesn't fit into the Lens Holder as well as the biconvex lens. It will hold the lens but installing it is a little awkward.

18. Move the Lens Carrier back and forward on the Track. There is no place where an image is formed on the screen.

19. Remove the Screen from the Track and look at the target through the negative lens. As the lens is moved forward, the image of the target gets smaller.

Clearly, the negative lens is forming an image but, because it is smaller than the target, the magnification is less than unity. This can only be true if the image is farther away than the target. This suggests that this image, called a virtual image, is formed behind the target. Furthermore, it is not inverted, as the image formed by the positive lens was, but erect. Consequently, the magnification is positive but less than unity.

These observations do not offer a method of measuring the focal length of a negative lens. We will have to seek another method.

Two Thin Lenses

Most optical systems have more than a single component. The purpose of this part of the experiment is to see the effect of adding a second lens to the image forming characteristics of the system.

20. Set-up the components in the same positions used in Step 8 through 12 with the lens at 90 cm on the Track.

21. Mount the planoconvex lens in a Lens Holder and place it on the Track at 85 cm.

22. Move the Screen until a sharp image is found. Record its position.

23. Move the first lens to 95 cm. the second lens at 85cm and record the position of the Screen image.

24. Repeat for two more positions.

When the two lenses are very close together, closer than we can get them in the Lens Holders, their powers add, so that the combination has a power equal to their sum as measured in diopters. This is the principal reason for using diopters: it makes it easy to estimate the power of a combination. The power of the combination is given by

$$Øab = Øa + Øb - d\, Øa\, Øb \quad (4)$$

where Øa and Øb are the powers of the two lenses in diopters and d is the separation between them (in meters). From this formula, the power of the combination equals their sum if d is small. As d increases, the power is less than the sum.

Calculate the power of the system for each of the arrangements in the previous part of the experiment. Does the power decrease as the lens separation increases?

This suggests a way to measure the power of negative lens elements. If a negative lens is added to a known positive lens, the overall power of the combination makes it possible to calculate the power of the negative lens. A simple example of this can be produced using the lenses in the EO-48 Lens Set. The biconvex lens has been measured in the first part of this experiment to have a power of about +5 diopters. If the biconcave lens is placed close to it, the power of the combination is approximately 0, showing that the biconcave lens has -5 diopters power. If there is time, it is worth setting this up on the Track to make careful measurements. If not, holding them up to your eye and looking through them demonstrates the principle.

Telescopes

Despite the simplicity of the combination of a positive and a negative lens, there are a number of useful applications. A simple telescope can be made by placing a positive lens at one end and a negative lens at the eyepiece end. It was with a telescope of this sort that Galileo discovered the moons of the planet Jupiter. It is a simple telescope of limited magnification but it served the purpose.

To set up a Galilean Telescope on the Track select one +3 lens (fl = 0.33 m) and two -5 lenses (fl combination = 0.1 m). The magnification is equal to

$$M = -fo / fe \qquad (5)$$

where fo is the focal length of the objective lens, fe is the focal length of the eyepiece lens and M is the magnification. The magnification is positive which means that the image is not inverted because the eyepiece lens has a negative focal length.

25. Place the positive concavoconvex lens which has a power of about +3 in a Lens Holder at a convenient place on the Track i.e., 75 cm. Tighten the locking screw.

26. Place the two -5 lenses in separate Lens Holders and Carriers at about 100cm. The two carriers should be as close together as they can be. This will leave the lenses about 4cm apart. Tighten the locking screws on each. These two negative lenses will act as a single lens having a power of about -10.

27. It is helpful to have a light shield in front of the positive lens. An EO-28 Stray Light Screen works very well or a shield can be improvised with a hole cut in a piece of cardboard.

28. Point the Track with the optical components at a distant object. With your eye close to the negative lenses, move them back and forward until the image comes into focus. Estimate its size. Is the magnification about what was predicted?

Looking through this telescope points up its greatest weakness. Notice how small the field of view is. As the magnification increases, the field of view gets smaller and smaller. This telescope has a magnification of about three. Try to imagine the telescope that Galileo used which had a magnification of twenty. The field of view for such a telescope is extremely small. Galileo's telescopes are in good repair and on display in the Museum of Science in Florence Italy. If you ever have a chance, you should make a point of seeing them.

Two of the telescopes used by Galileo are in the museum. The first has a magnification of 14x with a biconvex lens with a focal length of 1.53 m and an aperture of 2.6 cm. The eyepiece lens of this telescope is planoconcave. The second telescope has a magnification of 20x but the objective lens is biconvex and only 1.6 cm in diameter and has a focal length of 96 cm. The eyepiece lens in this telescope is biconcave. Can you explain how the second telescope has a shorter focal length objective but has higher magnification?

Because of the small field of view, Galilean telescopes are only used in Opera Glasses where a magnification of two or three is satisfactory.

Used in reverse with the light entering the negative lens end, this optical system is used as a laser beam expander. The telescope forms no real image: parallel light enters and parallel light leaves. Hence the image is upright which is a considerable simplification.

Astronomical Telescopes

Telescopes used for astronomical observations form a real image which is viewed with an eyepiece. The advantage of this design is a much wider field of view and the possibility of placing a reticule in the image plane for measurement purposes. The image is inverted but this makes little difference for astronomical purposes. Surveying instruments also use this simple design with an inverted image.

To set up this telescope

29. Place the positive concavoconvex lens which has a power of about +3 in a Lens Holder at a convenient place on the Track i.e., 40 cm. Tighten the locking screw. Point the end of the Track at a distant object: out a window is the best idea.

30. Place the EO-27 Diffusing Screen in a carrier and move it back and forth to find the focus of the lens. This is the position of the real image in the telescope. It will be at about 72 cm on the meter scale. If a reticule were to be used, this is the point in the system where it would be placed. After the position of the real image is determined, remove the Diffusing Screen. The Carrier can be left there if you wish.

31. Place two +5 lenses in separate Lens Holders and Carriers at about 81 and 85 cm. The two carriers should be as close together as they can be. This will leave the lenses about 4 cm apart. Tighten the locking screws on each. These two positive lenses will act as a single lens having a power of about +10.

32. It is helpful to have a light shield in front of the positive lens. An EO-28 Stray Light Screen works very well, but it can be improvised with a hole cut in a piece of cardboard.

33. Point the Track with the optical components at a distant object. With your eye close to the eyepiece lenses, move them back and forward until the image comes into focus. Estimate its size. Is the magnification about what was predicted? Is the image upright or inverted?

The field is much larger than for the Galilean telescope and the design has the possibility of much higher magnifications, several hundred times in fact. Actual telescopes of this type have a field lens placed at the image position to improve the uniformity of illumination across the field. Since this field lens has no effect on image formation, we can omit it for this experiment. In addition the objective lens would not be a simple concavoconvex lens but would have two or more elements designed to correct aberrations in the image.

The equations used in this manual can be found in most text books of introductory optics. The specific reference used for this manual was:

Modern Optical Engineering, Smith Warren J. McGraw-Hill Book Co. New York (1966)

Instruction Manual

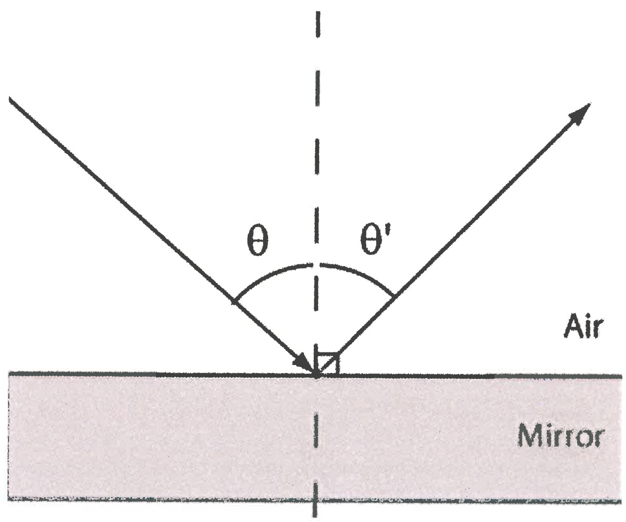
Optics Experiments

REFLECTION

Discussion

Optics, the study of the propagation of light, can be divided into two broad subsections: geometric optics, which assumes that light travels in straight lines, or rays; and physical optics, which deals with the implications of the wave nature of light. Geometric optics is applicable for most cases in which the objects encountered by the light rays are much larger than the wavelength of the light, and will be the focus of the first half of this manual.

Much of optics involves the analysis of the behavior of light at interfaces, or transitions between two media. This behavior is described in terms of reflection and refraction. Refraction involves the transmission of light through the new medium, and reflection describes the return of light to the original medium. The goal of this experiment is to derive the law of reflection from experimental evidence.



Apparatus

Air Track
Optical Bench Carriers:
- 2x 30mm (EO-01)
- 1x 65mm (EO-02)

Plane Mirror (EO-50)
Prism Table and Lateral Arm (EO-32)
Opaque Screen (EO-26)
Filter Holder (EO-25)
Single Slit Slide (EO-72)
Lamp w/ Power Supply (ES-17)
Optional:
- Diode Laser 4mW (ES-12)

Method

1. Assemble the air track as necessary and place it on a stable, level surface.
2. This experiment can be performed with either the incandescent lamp (ES-17) or the diode laser (ES-12). The lamp is supplied with the EO-10 kit, but creates a less intense image for measurement. The diode laser allows for greater precision and can be used in a brighter lab setting.

   Install the light source on the air track. For first time users, this is accomplished by inserting the vertical post on the light into the center column of an optical bench carrier (30 mm length), then placing the bench carrier on the track and tightening the nylon screw found on the bottom of the carrier skirt.
3. Place the 65 mm bench carrier on the track 30 cm away from the laser and secure it in place. Place the lateral arm and marked platform in the bench carrier and rotate the marked scale so that the zero mark points along the bench towards the light source. Tighten the nylon screw in the bench carrier to hold this piece in place. Insert the shaft on the base of the prism table into the hole at the center of the platform to complete the assembly.
4. Mount the opaque screen in the rotating arm. Swing the arm around to the 180˚ mark on the platform.
5. Turn the light source on.

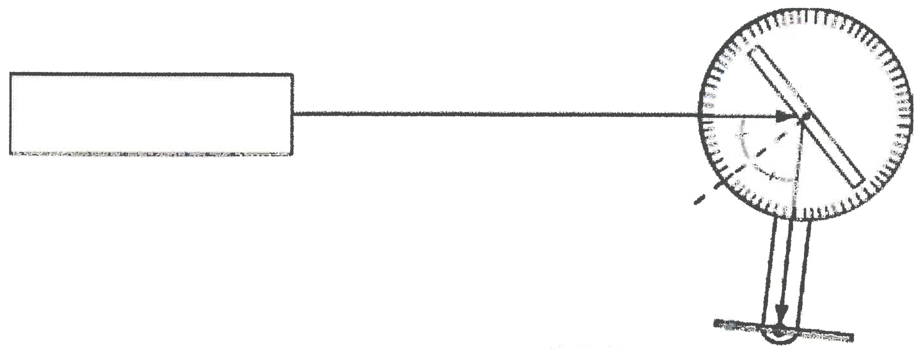
   Caution: Laser light may damage the human eye. Never allow the beam to reach eye level. Beware of stray reflections, and try to contain the beam with obstacles and screens when possible.

   Laser: Adjust the focus so the beam comes to a point at the screen. Raise or lower the post in the lateral arm until the beam roughly crosses the center of the screen. Finally, adjust the laser laterally until it hits the screen directly on or over the center of the centimeter scale.

   Incandescent Lamp: Insert the slide of single slit patterns into the filter holder and attach this to a bench carrier. The largest slit should be centered in the holder. Block any remaining exposed slits or gaps with scrap paper. Place this apparatus immediately in front of the prism table and raise the filter holder in its mount so the light passes immediately above the surface of the table. Center the resulting beam of light on the centimeter scale of the opaque screen.
6. Place the EO-50 Plane Mirror in the center of the prism table. The mirrored face should lie along the diameter of the table. Start the mirror at 90˚ (the face of the mirror should follow the line between 90˚ and 270˚).

7. The corner of the mirror pointing to the 90˚ mark will be used as an angle indicator for the rest of the experiment. Rotate the mirror to 100˚ for the first measurement.

8. Position the opaque screen so that the reflected beam hits the center mark. Record the angular position of the screen.

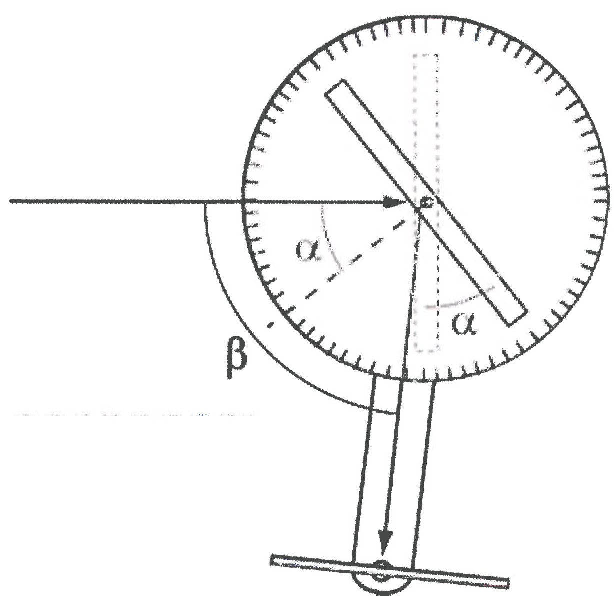


9. Rotate the mirror to 110˚. Repeat step 8, and continue this procedure at 10˚ intervals until you reach 180˚.

Analysis

Conventionally, the trajectory of a light ray is given by the angle it makes with respect to a line drawn perpendicular to the surface of the interface at the point the ray makes contact with the second medium. This line is referred to as the normal. We start our analysis by finding the angle of the incident ray, the ray which travels from the laser to the mirror.

We will begin by assuming that, at our given zero angle for the mirror, the normal is parallel to the incident ray. After rotating the mirror, we can see that the angle of rotation, α, should also be the resultant angle between the normal and the incident ray. Further geometric analysis can confirm this intuition.



The measured angle between the zero for the screen and the reflected ray is depicted above as angle β. Given α and β, we can find the angle of reflection by subtraction.

Construct a table of the angle of incidence vs. the angle of reflection.

Conclusion

What do you observe about the tabulated values? As best you can, quantify the relationship between the two angles. Are they proportional? What is the constant of proportionality?

The law of reflection can be concisely expressed as

$$\theta = \theta'$$

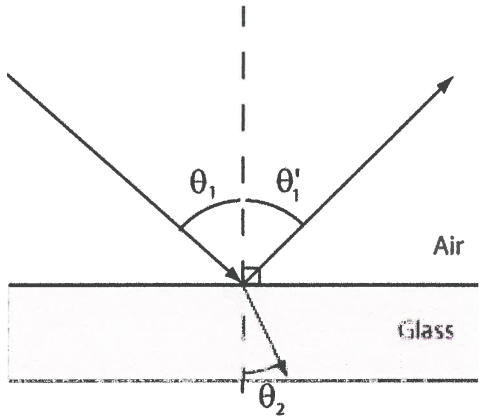
which means that the angle of incidence should equal the angle of reflection. This law can be proved through various means, but for now will be given without proof.

How well do your results coincide with the law of reflection? What would account for any errors?

REFRACTION

Discussion

When light strikes an interface, it can be reflected back into the original medium, transmitted through the second medium, or, most commonly, some combination of the two. The previous experiment showed the relationship between the incident ray and reflected ray in one such interaction. This experiment concerns refraction, in which the trajectory of a light ray is altered as it passes from one medium into another.



The speed of light varies according to the medium in which it travels. The optical properties of a material are largely defined by its index of refraction, given as the ratio of the speed of light in a vacuum to the speed of light in that medium:

$$n = \frac{c}{v}$$

The refracted light ray is again characterized by the angle it makes with the surface normal. This angle is dependent on the incident angle and is related by Snell's law, also known as the law of refraction:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

This experiment examines the interface between air and a glass/acrylic plate in order to find the index of refraction of the plate.

Apparatus

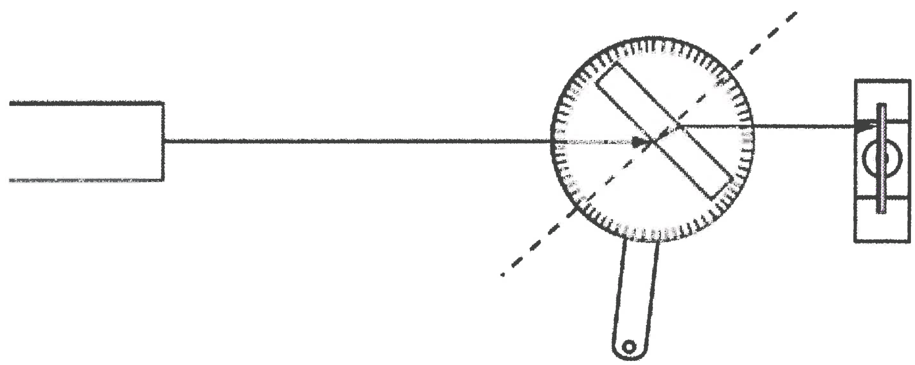
Air Track
Optical Bench Carriers:
- 1x 30mm (EO-01)
- 1x 65mm (EO-02)

Glass/Acrylic plate (EO-55/56)
Prism Table and Lateral Arm (EO-32)
Opaque Screen (EO-26)
Filter Holder (EO-25)
Single Slit Slide (EO-72)
Lamp w/ Power Supply (ES-17)
Optional:
- Diode Laser 4mW (ES-12)
- Equilateral Prism (EO-59)

METHOD

1. Assemble the air track as necessary and place on a stable, level surface.
2. Setup the light source as in the previous experiment.
3. Secure the lateral arm and prism table apparatus to a 65 mm bench carrier. Clamp the carrier to the track 30 cm from the laser.
4. Mount the opaque screen in a bench carrier and orient it so the marked scale faces the laser. Fasten the screen to the track 20 cm from the center of the prism table.
5. **Laser**: Adjust and focus the laser so that it comes to a point at the center mark of the screen scale.

   Lamp: Mount the single slit slide in a filter holder and place in a bench carrier. Secure the bench carrier to the track immediately in front of the prism table. Align the slide so that the light from the largest slit falls on the center mark of the screen scale, and block any remaining light with paper.
6. Place the acrylic or glass plate on the prism table so that the front face lies along a diameter of the table. Orient the plate so that the laser continues to come to a point at the center of the screen. Adjust the outer scale as necessary so that the plate lies along the 0-180 diameter, and fix this piece in place with the nylon screw in the bench carrier.
7. Angle the plate 10˚ with respect to the angular scale. Again, keep the face of the plate along a diameter of the table. Take care not to rotate the scale so that the zero reading can be used as a reference throughout the experiment.



8. Measure the distance between the center mark of the scale (the original position of the beam) and where the beam lands after the rotation.
9. Repeat this measurement for a series of plate angles.
10. Repeat the experiment for a plate of a different material if available.

Analysis

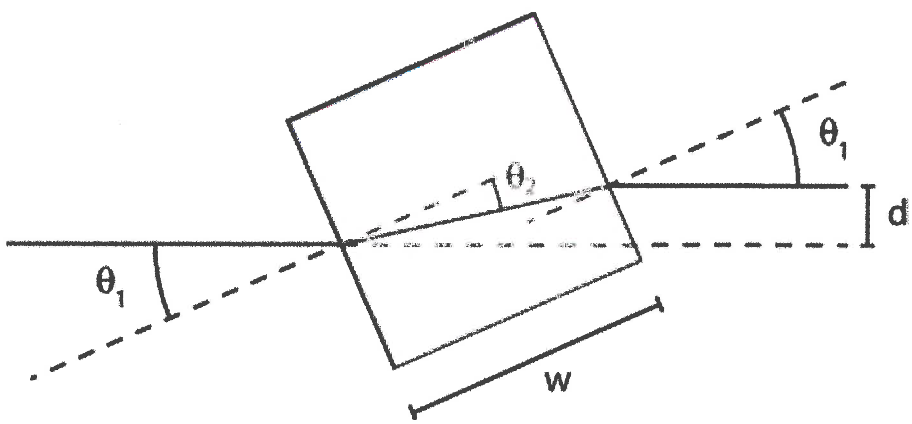
The experiment is designed to determine the index of refraction of the plate material. Assume for the purposes of this analysis that the index of refraction of air is equal to 1. Given that

$$\sin\theta_1 = n_2 \sin\theta_2$$

we now need only to find the incident and refracted angles to characterize the plate medium.

The incident angle is given by the orientation of the plate with respect to the beam of light. The zero angle was measured under conditions in which the surface normal was parallel to the beam of light, so rotating the plate away from this angle creates a corresponding angle between the beam and the normal.

Deriving the refracted angle from the data requires much more effort. As an exercise, construct a geometrical model of the plate-beam system and develop an expression for the refracted angle in terms of the incident angle, the depth of the plate, and the measured displacement of the beam. Remember that refraction occurs at both the air-to-glass and glass-to-air interfaces.



Your result should be equivalent to the equation

$$\theta_2 = \tan^{-1}\left(\tan\theta_1 - \frac{d}{w\cos\theta_1}\right)$$

Use this result to calculate the index of refraction at each measured angle of incidence.

Conclusion

What did you calculate the index of refraction to be for each material? Compare these values to the following accepted values for common optics materials.

Acrylic	1.49
Crown Glass	1.52
Flint Glass	1.62

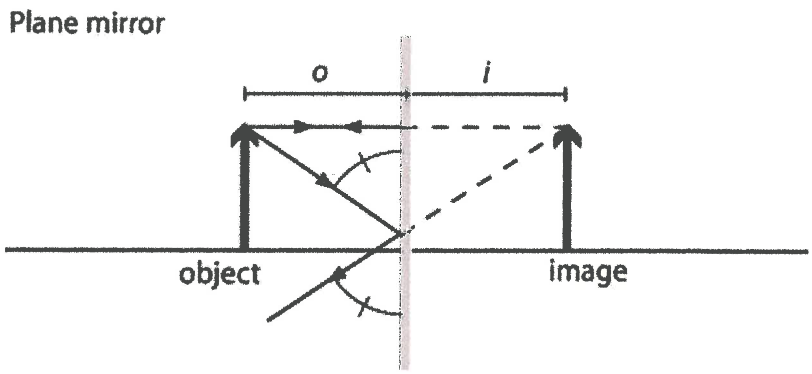
The optical properties of glass vary widely according to the materials and process involved in its creation. Which of the previous types of glass seems most likely to be represented here?

How well do your results agree with these accepted values? Quantify this relationship by calculating the percent difference between the measured values and the standard. What parts of the experiment might account for the differences you find? How could the experiment be improved?

LENSES + MIRRORS: CONCAVE MIRROR

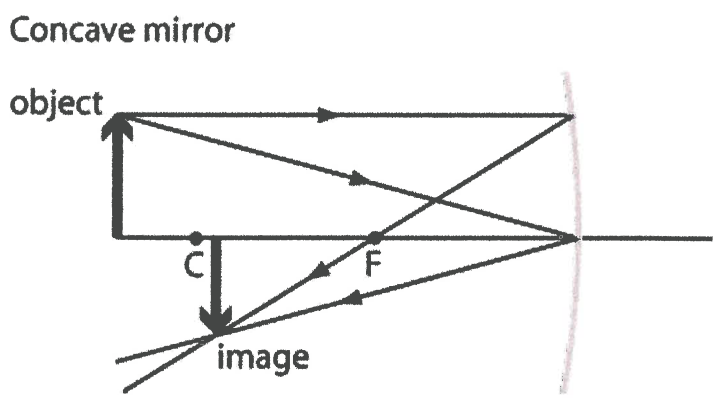
Discussion

As light reflects off a mirrored surface, it presents a problem for the human eye. The brain interprets visual input in a way that assumes the light reaching the eye has traveled in a straight line, which leads to illusory perceptions when that straight line path is altered. For example, consider a plane mirror facing some object to be observed:



This diagram illustrates a technique called ray-tracing, used to characterize the image created by the optical surface. If the two rays pictured are viewed by some observer, the observer will infer that the object is located at the point of intersection, distance *i* behind the plane of the mirror. Using the properties of similar triangles, it can be shown that *o* and *i* are of equal magnitude, a result which holds for all plane mirrors.

In the case of the plane mirror, the observed image is virtual; no light physically passes through the location of the image. This is not always the case, however. Consider a spherically curved mirror, with a center of curvature located on the same side as the object (concave mirror).



C is the center of curvature of this mirror (not to scale), and F is the focal point. The focal point has two properties which make it important for optical applications: 1) any light originating from this point will reflect off the mirror parallel to the axis, and 2) any light striking the mirror parallel to the axis will be reflected through this point. In this example, the reflected rays meet at a point on the real side of the mirror, meaning that the light rays form an image that can be directly observed, as this experiment will show.

Apparatus

Air Track
Optical Bench Carriers:
2x 30mm (EO-01)
Concave Mirror (EO-52)
Adjustable Lens Holder (EO-20)
Opaque Screen (EO-26)

Optional:
Lamp w/ Power Supply (ES-17)
Optical Bench Carrier – 30mm (EO-01)

Method

Far-field object:

1. Set up the air track so that one end points toward a distant light source, like a window or lamp.
2. Mount the concave mirror in the lens carrier. Center the mirror as best as possible and align the face of the mirror with the plane of the lens holder. Using a bench carrier, mount this assembly on the air track, at least 40 cm from the end nearest the light source.
3. Seat the opaque screen in a bench carrier and place it on the air track between the source and the mirror. Do not tighten the carrier onto the track.
4. Face the mirror towards the distant source. There should be a blurry image of the source formed on the screen. Adjust the mirror and screen until that image is roughly centered.
5. Move the screen along the bench until you find the point of greatest clarity, at which the image is most focused. Record the distance between the mirror and the screen.

Near-field object:

1. Set up the air track on a flat, stable surface. This experiment will work best in a dim room.
2. Mount the concave mirror in the lens carrier. Center the mirror as best as possible and align the face of the mirror with the plane of the lens holder. Using a bench carrier, attach this assembly near the center of the air track.
3. Assemble the light source on a bench carrier and mount this near the mirror on the air track. Make sure the cylindrical light shield is *not* placed over the light source.
4. Seat the opaque screen in a bench carrier and place it on the air track so that the source is between it and the mirror. Do not tighten the carrier onto the track.
5. Adjust the height of the lens holder so that the light source is approximately level with the center axis of the

mirror. The screen should show a circle of light reflecting from the mirror.

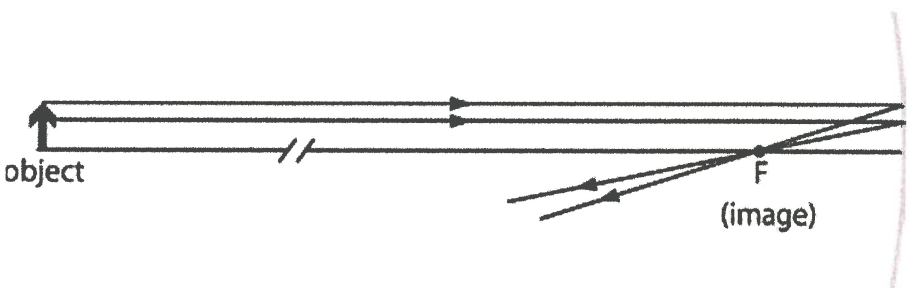
6. Move the screen along the track to get a sense of how the size of the image changes with distance. If the image gets larger as the screen moves away from the mirror, the source is inside the focal point and should be moved away from the mirror. If the image gets smaller, it is beyond the focal point and must be moved closer.

7. Continue to sample the image and adjust the position of the source until the image does not perceptibly change as the screen moves. Record the distance between the source and the mirror.

Analysis

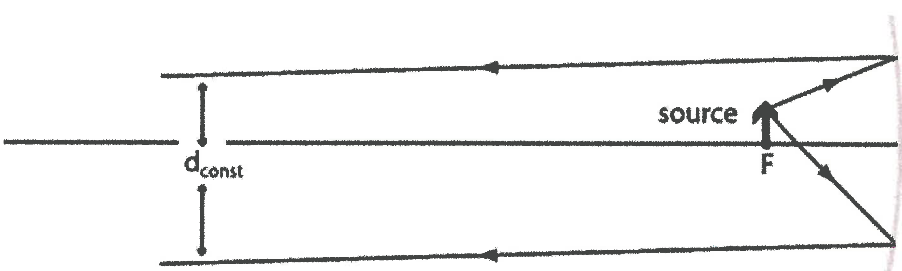
Far-field object:

The large distance between the object/source and the mirror make it reasonable to assume that all rays reaching the mirror from a given point on the object are travelling parallel to one another. With this assumption, and the fact that the axis of the mirror is roughly aligned with the direction of the light rays, we conclude that the light will be redirected to the focal point. Images are formed where rays intersect, so it stands to reason that the image will be found at the focal point.



Near-field object:

Light originating from the focal point will be reflected in parallel rays. Parallel rays should maintain their spacing as they travel to the screen, so the size of the image will remain constant regardless of the distance covered.



Conclusion

At what distance is the focal point for this mirror? How does this compare with the rated value of 20 cm?

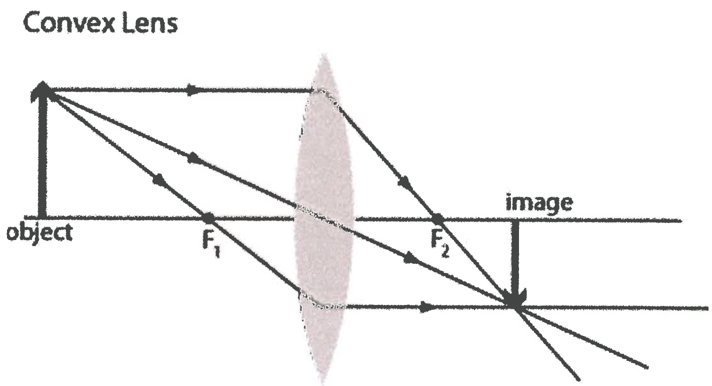
What complications did you encounter in this experiment? How would you characterize the images you used to find the focal point? Comment on the clarity of the image, and how you think this might be improved.

LENSES & MIRRORS: CONVEX LENS

Discussion

As with mirrors, refracting surfaces can be used to alter the perception of an object. Refraction bends light with respect to the surface normal of the transmitting material; varying the surface normal warps the trajectory of the light rays in accordance with the law of refraction.

As with mirrors, lenses can be analyzed in terms of the images, both real and virtual, that they project. Consider the following ray tracing diagram:



These three rules can be used to simplify the ray-tracing process:

1) A ray travelling parallel to the axis from the object will be refracted to the second focal point.
2) A ray crossing the lens at the axis will remain effectively unchanged.
3) A ray travelling through the first focal point will be refracted parallel to the axis. These three rays should meet at a point, and the intersection gives the position of the origin point on the image.

Clearly, the focal point plays an important role in predicting the image formation behavior of a lens. Finding the focal point is the object of this experiment.

Apparatus

Air Track
2 - 30mm Optical Bench Carriers (EO-01)
Set of Six Lenses (EO-48)
Adjustable Lens Holder (EO-20)
Opaque Screen (EO-26)

Optional:

Lamp w/ Power Supply (ES-17)
Optical Bench Carrier – 30mm (EO-01)

Method

You may use either of the following procedures to find the focal point.

Far-field object:

1. Set up the air track on a flat, stable surface, so that one end of the track points towards a window or other distant light source.
2. Select the biconcave lens from the set of six lenses. It should be the thinnest of the lenses, when looking at the edge.
3. Place the lens in the lens holder and tighten down the notched posts. Try to center the lens and align it with the face of the holder as best as possible.
4. Mount the lens holder in a bench carrier and fasten the carrier to the air track.
5. Mount the opaque screen in a bench carrier and place the carrier on the track so that the lens lies between the screen and the light source. You should see a blurred image of the source fall on the screen. If there is no image, adjust the height and position of the screen until the image appears.
6. Move the screen along the track until you find the point of greatest clarity for the image. Record the distance between the lens and the screen at this point.
7. **Optional:** Repeat this procedure with the other convex lenses.

Near-field source:

1. Set up the air track on a flat, stable surface. This experiment will work best in a dim room.
2. Select the biconcave lens from the set of six lenses. It should be the thinnest of the lenses, when looking at the edge.
3. Place the lens in the lens holder and tighten down the notched posts. Try to center the lens and align it with the face of the holder as best as possible.
4. Assemble the light source on a bench carrier and mount this near the lens on the air track. Make sure the cylindrical light shield is seated on top of the source.
5. Insert the opaque screen in a bench carrier and place it on the air track so that the lens is between it and the source. Do not tighten the carrier onto the track.
6. Adjust the height of the lens holder so that the light source is approximately level with the center axis of the lens. The screen should show a circle of light refracted from the lens.

7. Move the screen along the track to get a sense of how the size of the image changes with distance. If the image gets larger as the screen moves away from the lens, the source is inside the focal point and should be moved away from the mirror. If the image gets smaller, it is beyond the focal point and must be moved closer.

8. Continue to sample the image and adjust the position of the source until the image does not perceptibly change as the screen moves. Record the distance between the source and the lens.

9. **Optional:** Repeat this procedure with the other convex lenses.

Analysis

Far-field object: Rays originating from any point on the object will reach the lens travelling roughly parallel. These rays, refracted to the focal point, will reproduce the image of the object at the focal length of the lens. Therefore, the measured distance is the focal length.

Near-field object: Rays originating from the focal point will be refracted in parallel, and will neither converge nor diverge as the distance to the lens increases. The result is a beam of light of constant diameter. When this result is observed, the distance between the source and lens is equal to the focal length.

Conclusion

What is the measured focal length of the biconcave lens? How does this compare to the rated value of 20 cm?

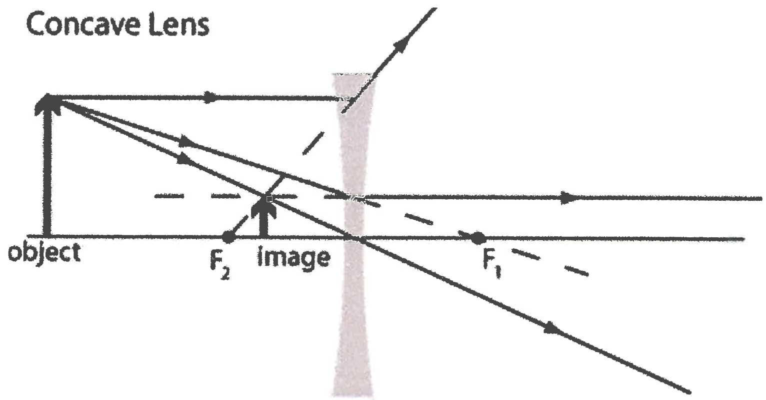
If possible, complete both the far-field and near-field procedures and compare the two measurements. How closely do these results agree with one another?

Describe the image generated by the lens. How does it differ from the ideal focused/parallel image? Can you think of anything that would explain these discrepancies?

LENSES & MIRRORS: CONCAVE LENS

Discussion

A concave lens causes light to diverge as it passes through the refracting interfaces, which complicates the established ray-tracing procedure.



For this ray tracing, note that the first and second focal points have been reversed. Rays in line to intersect the focal point beyond the lens are refracted parallel to the axis, and parallel rays are refracted along a line which crosses the near focal point. Like the concave mirror, the intersection of these rays must be found by extrapolation, creating a virtual image.

This experiment uses the first focal point to create parallel rays as a means of characterizing the focal length. This requires first focusing light at a known point, achieved by a convex lens whose focal length has already been measured. On the air track, the distance to the light source must be finite, so we must find the point of focus using the following relation

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f}$$

where o is the distance from the lens to the object, i is the distance from lens to image, and f is the focal length of the lens.

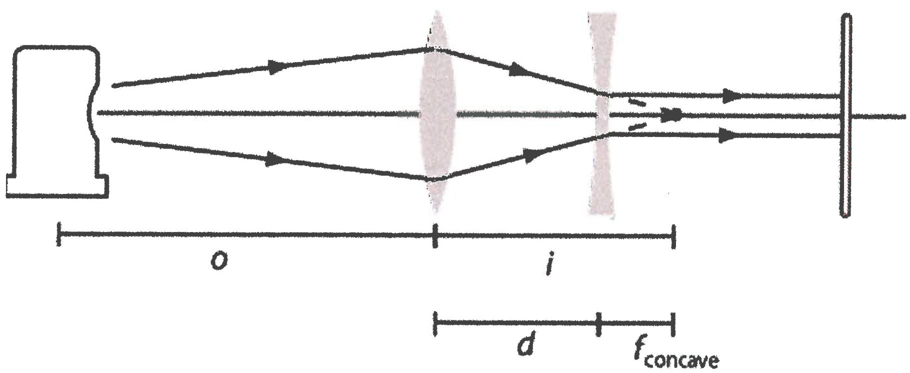
Apparatus

Air Track
4 - 30mm Optical Bench Carriers (EO-01)
Set of Six Lenses (EO-48)
2 - Adjustable Lens Holder (EO-20)
Opaque Screen (EO-26)
Lamp w/ Power Supply (ES-17)

Method

1. Set up the air track. Place on a stable, level surface.
2. Assemble the light source and mount it on a bench carrier at the zero end of the track.

3. Choose a convex lens and mount it in a lens holder. Secure the holder in a bench carrier and place on the air track.
4. Place the opaque screen in a bench carrier. There is no need to place it on the track at this time.
5. If you have not already measured the focal length of this convex lens, do so now. Refer to the previous experiment for instructions.
6. Choose a concave lens from the case. You may wish to start with the biconcave lens, identified by the wider rim. Mount this lens in a lens holder and bench carrier. Place this on the track.
7. Fix the convex lens so that there is 1 meter of separation between the light source and this lens. Use the equation provided in the discussion section to predict the location of the focused light. Check this prediction with the opaque screen and note any significant discrepancies.
8. Place the concave lens at the point of focus.
9. Move the concave lens back towards the convex lens, testing for parallel rays by moving the screen. When the spot on the screen remains at a constant size as the screen is moved along the track, record the distance between the two lenses.



10. Repeat for other lenses if time allows.

Analysis

In this procedure, the focal length is derived from the relationship

$$i = d + f_{concave}$$

$$f_{concave} = i - d$$

The focal length of the convex lens must be measured to calculate *i*, and it is worth double-checking the result using the screen to get a sense of the accuracy of this prediction. The distance between the lenses, *d*, is the measured value in the experiment.

Conclusion

What is the measured focal length of this lens? How does this compare with the rated focal length of 20 cm?

How accurate was your calculation of the image length for the convex lens? What effect does this have on the final result?

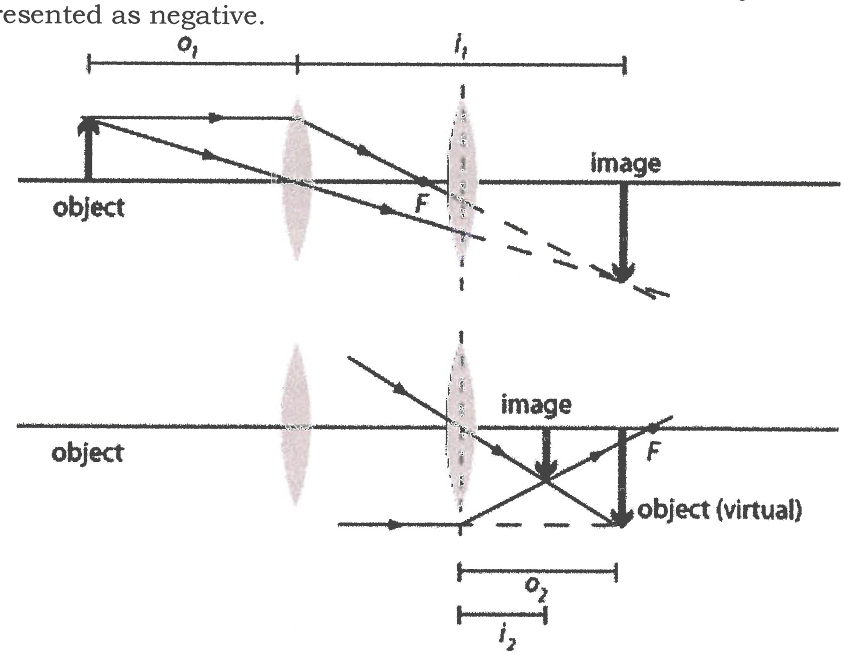
Could you devise a "far-object" procedure to take advantage of the concave lens' effect on parallel incident rays? If so, describe in general terms how you would accomplish this. If not, identify the problem that makes this measurement impractical.

LENSES & MIRRORS: COMPOUND LENS

Discussion

The previous experiment used the image from one lens as an intermediate step to create the desired image in the second. This principle is not limited to coaxing measurable effects out of a diverging lens. Lenses in compound formations are often used in optical instruments to create systems more flexible than single lenses.

The mathematics that govern single-lens systems apply to combinations with little change. Each lens can be considered in sequence, with the image of the previous lens used as the object of the current lens. Note that in all previous examples, there has been a clear set of sign conventions based on the placement of the object and image. These still apply: the object has a positive distance from the first lens, and images are labeled with positive distance when real or negative distance when virtual. When using an image as an object, there exists the possibility that light travelling to the lens will not be diverging, as is the case with all physical objects. In this case, the distance to the object-image is represented as negative.



The diagram above shows the two-step process used to predict the location of an image created by a system of two convex lenses.

Optical instruments are designed to magnify images, usually so they can be perceived in greater detail. Magnification is measured as the ratio of the size of the image to the size of the object, and is commonly expressed as

$$m = \frac{i}{o}$$

where o and i are the distances from the lens to the object and the image, respectively. These lengths can be substituted for the object sizes due to the properties of similar triangles, which you can prove with a ray-tracing diagram.

Apparatus

Air Track
4 - 30mm Optical Bench Carriers (EO-01)
Set of Six Lenses (EO-48)
2 - Adjustable Lens Holder (EO-20)
Opaque Screen (EO-26)
Target (EO-75)
Lamp w/ Power Supply (ES-17)

Preparation

This experiment will examine two-lens compound systems. This will require data on the focal points of the lenses in your kit. If there is no data available, use the procedures in the previous two experiments to measure those focal lengths now.

Begin by choosing a convex lens to use as an objective lens, the lens closest to the object. Assuming this lens is placed 10 cm from the object, design a compound system that produces a magnification of ±4. (Hint: It may be easiest to choose a second lens arbitrarily and work from there). For this combination of lenses, what distance between the lenses would produce a magnification of ±1?

When designing this system, bear in mind the fact that the magnification at each step builds upon the effects of the previous step. Use the following relationship to determine the total magnification of the system.

$$m = m_1 m_2$$

Method

1. Set up the air track and place on a flat, stable surface.
2. Mount the lamp on a bench carrier and place at the zero end of the track.
3. Mount the translucent target screen on a bench carrier and place it immediately in front of the lamp.
4. Mount the objective lens in a lens holder and bench carrier, centering the lens in the socket. Set up this piece 10 cm away from the target.
5. Mount the second lens in a holder and bench carrier, centering the lens in the socket. Place this lens at the point on the track which should yield a magnification of ±4.
6. Mount the opaque screen on a bench carrier and place beyond the second lens.
7. Turn on the lamp. Adjust the position of the screen until a focused image of the target falls roughly in the center of the marked scale.
8. Measure the distance from the second lens to the image, and the size of the image. Use either the length of an arrow or the interval labeled “1 CM” for the size measurement. Take note of which method you use, and

record the size of that feature on the original target alongside your data.

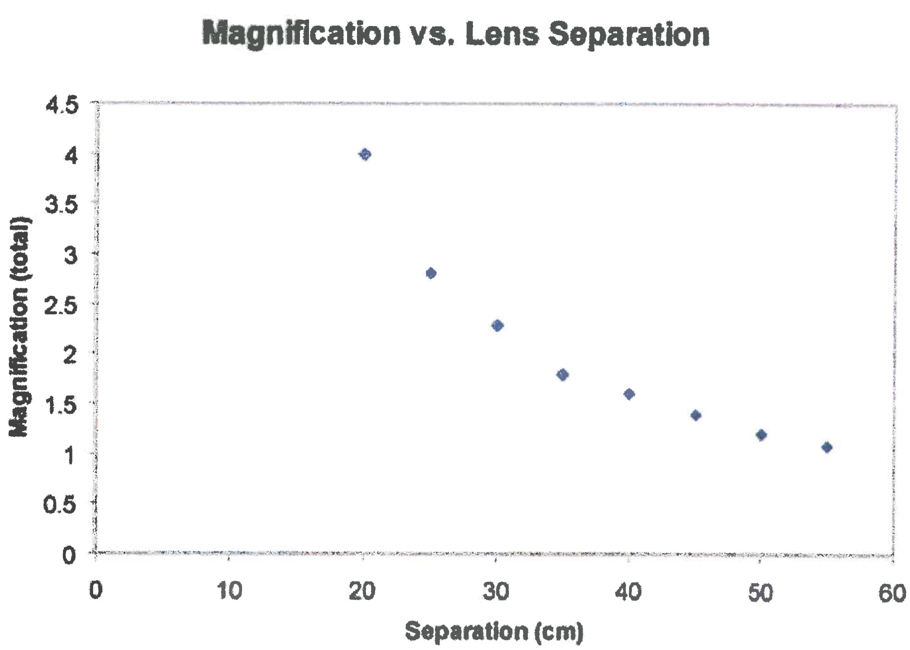
9. Move the second lens in intervals from its current position to the point at which a magnification of ±1 is expected. Record the position of the image relative to the second lens and the size of the image at each step.

10. This procedure can be repeated for other lens combinations if time allows.

Analysis

Much of the analysis work for this experiment comes in the preparation phase. Compare the predictions made in this step with the observations made during the experiment and be prepared to comment on the accuracy of those calculations.

Chart the magnification of the image against the separation between the two lenses. Compare this to the derivations required to predict the point of magnification.



Conclusion

What was the actual magnification of the image at the points you predicted? Quantify the difference between the predicted values and the measurements.

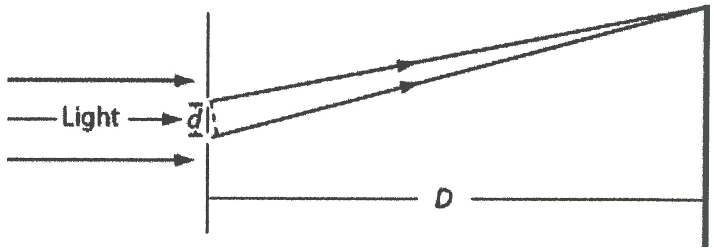
What is the nature of the relationship between lens separation and magnification? What type of equation does it most resemble? How does this compare to the equations you encountered while making predictions? Which terms seem most influential in the relationship? Which seem to have little effect?

DOUBLE SLIT INTERFERENCE

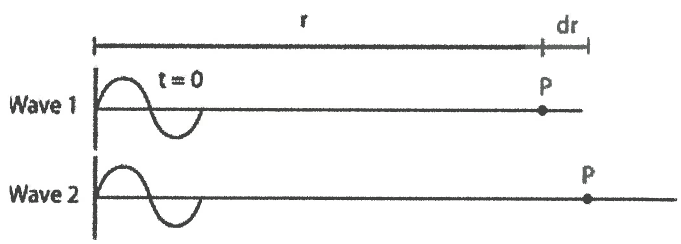
Discussion

The conclusions drawn by assuming that light travels in simple rays are accurate to a degree, and acceptable for many practical applications. However, the composition of light is more complex and less intuitive than these descriptions would imply. The next experiment focuses on the wave nature of light, as manifested in interference patterns.

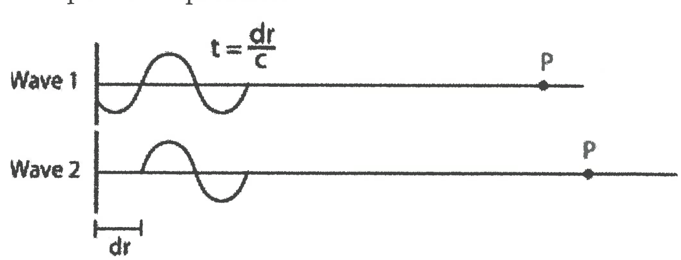
Interference occurs when two waves interact to create a distinctly new waveform. In many cases, light from different sources is subject to fluctuation on a time scale much smaller than the eye can perceive, leading to what seems to be a uniform distribution of the combined light. However, the effect can be made visible if light from two separate but coherent, or synchronized, sources is made to interact.



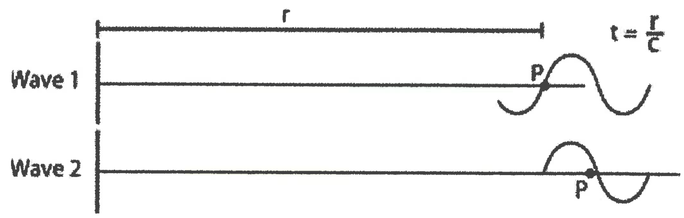
In the diagram above, coherence is enforced by using light from a single source, split in two by a screen with a pair of thin slits. The light which reaches the far screen is a combination of light from each slit. Consider a single point on the far screen, and the two light waves which illuminate it. The waves share a source, so at any given point in time the light leaving from both slits has the same amplitude.



From the perspective of point P, the light from the lower slit has been delayed by the longer path length. In other words, the light following the longer path lags behind that from the near source, meaning the two waves reach point P at different points in their oscillation. This discrepancy is called a phase difference, and it determines how the waves interfere at the point in question.



The intensity of the light at P is given by the sum of the two wave amplitudes as they reach the point.



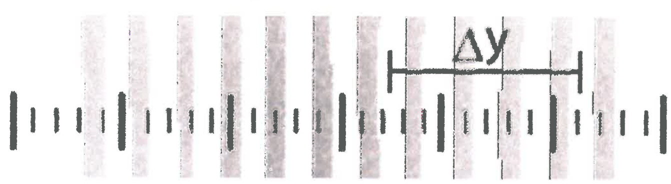
In this example, the light will be dimmer, but still visible. The intensity is at a maximum when the phase difference is equal to a full wavelength, and at a minimum when the phase difference is equal to a half wavelength.

Apparatus

Air Track
Optical Bench Carriers -- 3x 30mm (EO-01)
Double Slits (EO-73)
Filter Holder (EO-25)
Opaque Screen (EO-26)
Diode Laser 4mW (ES-12)

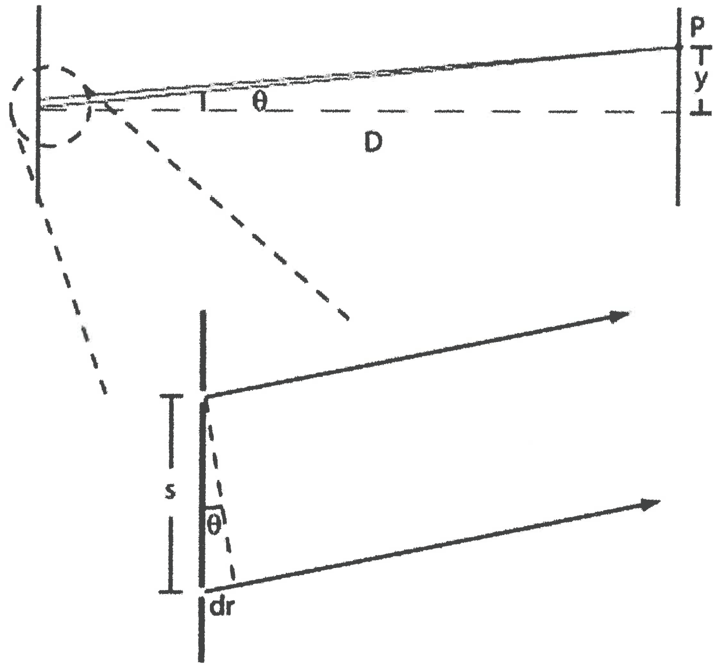
Method

1. Set up and align the air track. Place the track on a flat, stable surface.
2. Mount the laser on a bench carrier and place at the zero end of the track.
3. Secure the slide containing the double slits into the filter holder. Mount the holder on a bench carrier and place on the track, over the 10 cm mark.
4. Mount the opaque screen on a bench carrier and place as far down the track as possible. Record the distance between the filter holder and the screen.
5. Turn the laser on and direct the beam through the double slits. Align the components on the track so that you are able to observe a number of bands of light on the opaque screen.
6. Measure the distance between bands in the light pattern. Take a measurement that spans 5 or six such patches and calculate the average distance.



Analysis

Since the light from both slits is coherent, any difference in phase is due to the difference in path length. How, then, is the path difference related to position on the opaque screen?



Consider two rays, intersecting at point P on the screen. P is located at a distance y from the center axis bisecting both screens. Assume P is a maximum of light intensity, meaning that the rays arrive at P exactly in phase. This means that the path difference must be some integer multiple of the wavelength of the light source.

$$dr = n\lambda \qquad n = 0, 1, 2, \ldots$$

As in the figure above, the path difference can be depicted geometrically as the segment of the longer ray that begins at the origin of the ray and ends at a distance *r* from point P. To find the length of this segment, construct a triangle by adding a line from the end of the segment to the origin of the other ray. Given that distance *s* is much smaller than distance *D*, assume that the two rays are parallel. The added line between the two rays can be considered perpendicular to both. With these assumptions, the two triangles in the figure are similar.

If angle θ is small, the small angle approximation completes the derivation.

$$\tan\theta = \theta = \sin\theta \qquad \text{(small angle approximation)}$$

$$\frac{y}{D} = \tan\theta = \sin\theta = \frac{dr}{s}$$

$$\frac{y}{D} = \frac{n\lambda}{s}$$

$$y = n \cdot \frac{\lambda D}{s}$$

In the experiment, you measured the spacing between maxima on the interference pattern. Use this measurement and the result of the derivation above to calculate the wavelength of the laser light.

Conclusion

What is the calculated wavelength of the laser? How does this compare with the rated value of 670 nm? How do the assumptions made in the analysis affect the final outcome? Do these contribute significantly to the error in the experiment? Identify any other possible sources of error, and how they might relate to the numerical approximations.

CHROMATIC DISPERSION

Discussion

Visible light is made up of electromagnetic radiation ranging in wavelength from approximately 400 nm to 700 nm. The human eye interprets these various wavelengths as different colors, ranging from red at longer wavelengths to violet at the shortest. Where light of one wavelength is more prevalent than others, the eye perceives that color; where light of many wavelengths is nearly equally prominent, the eye perceives some shade of grey. The white light emitted by the Daedalon Light Source is evenly distributed across most of the visible spectrum.

When studying refraction, the refractive indices of the materials used were presented as constants, independent of the composition of light passing through the object. Although effective as an approximation, this model is not entirely accurate. In reality, the refractive index depends on the wavelength of the incident light. This experiment explores the composition of white light using this variable refraction to separate the light.

Apparatus

Air Track
5 - 30mm Optical Bench Carriers (EO-01)
1 - 60mm Optical Bench Carrier (EO-02)
Set of Six Lenses (EO-48)
Adjustable Lens Holder (EO-20)
2 – Filter Holders (EO-25)
Opaque Screen (EO-26)
Equilateral Prism (EO-59)
Color Filters (EO-62, 63, 64, 65)
Slide with Single Slit Pattern (EO-72)
Lamp w/ Power Supply (ES-17)
Optional:
Stray Light Screen (EO-28)

This experiment requires a darkened room for observation.

Method

1. Set up the light source. Attach the lamp to a bench carrier and place over the zero mark on the track. Make sure the lamp cover directs light down the track.

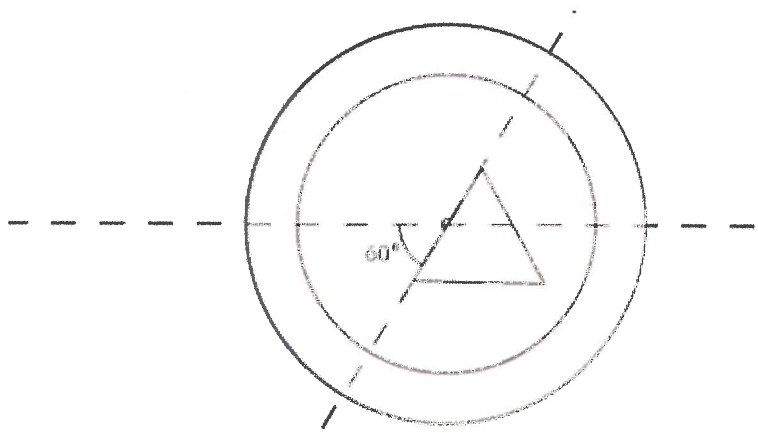
2. Mount a convex lens of known focal length in a lens holder and place on the track in a bench carrier. Position the lens so that the light source is at the focal length, creating a beam of parallel rays.

3. Attach the stray light screen to a bench carrier and place this assembly immediately behind the lens. Adjust the height of the screen so that the beam from the lens is roughly centered in the gap in the screen.

4. Create two filter mounts by attaching the filter holders to bench carriers. Place these one after another, with the first located 10 cm from the convex lens. Insert the single-slit slide into the first holder. Leave the second empty.

5. Mount the prism table on the largest bench carrier and place this immediately behind the filter holders. Secure the opaque screen on the rotating arm.

6. Place the prism on the prism table so that it makes a 60 degree angle with the line of the air track. The center of the prism table should be directly under the center of the incident face of the prism.



7. Adjust the slit so that light passes through the largest aperture and hits the prism at or near the center of the incident face. Cover any remaining gaps in the slide with paper to prevent additional light from reaching the prism.

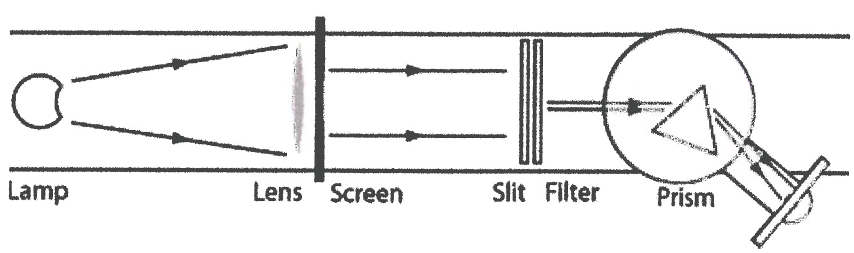
8. Rotate the arm of the prism table so that the refracted light is centered over the 3 cm mark on the opaque screen.

9. Note the distribution of color on the image projected on the screen. Can you draw any conclusions about which wavelengths are refracted more than others?

10. Insert the red slide into the second filter holder. Now only red light should be represented in the image. Record the position of the center of the image using the marked scale on the screen. You may need to block any extraneous light reaching the screen in order to make the image visible.

11. Repeat step 10 with the green filter.

Full Assembly:



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Analysis

Sketch the system of the prism and the path of the refracted light. Recall that the prism measures 3 cm on each side, and the opaque screen is 15 cm from the center of the prism table. Based on this figure, derive an expression for the angle at which light leaves the prism in terms of the index of refraction and the incident angle of the light.

(**Hint**: Complete the derivation in three steps, one for each missing angle in the two interfaces along the path of the light.)

Now, use this formula to predict the separation between the red and green light passing through the prism. The expected index of refraction for each color is

$$n_{red} = 1.509$$

$$n_{green} = 1.515$$

Compare this predicted separation to the measured separation from the experiment.

Conclusion

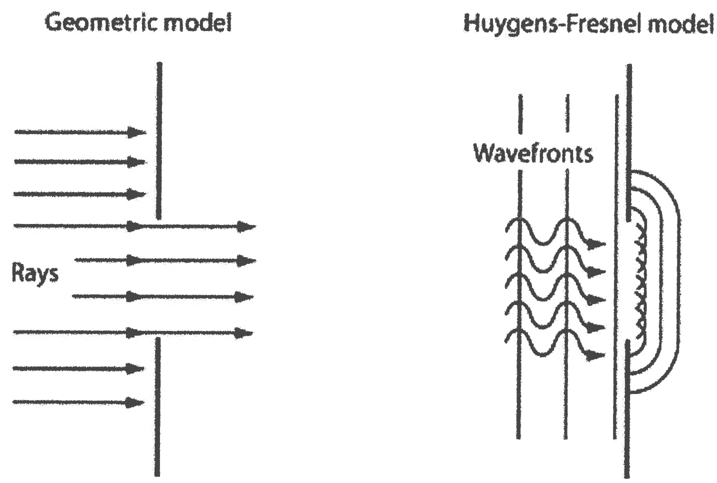
Based on your initial observations, can you establish which color in the visible spectrum is most refracted? Least refracted? How close do your results in the filtering step match your predictions for the red and green separation? How accurate do you consider these results? What factors contribute to any uncertainty in your measurements?

SINGLE-SLIT DIFFRACTION

Discussion

It is important to remember that geometric optics, with its techniques of ray tracing, is limited in its description in the behavior of light. It is an approximation, useful for many applications but dramatically deficient in others. Nowhere is this more evident than in the observation of diffraction, the tendency of waves to bend around obstacles.

Diffraction is best explained by the Huygens-Fresnel principle, which substitutes wavefronts for rays as the principle focus of analysis.



A wavefront represents the line of equal amplitude created by a two-dimensional swath of coherent waves. In the Huygens-Fresnel model, each point on the wavefront is considered to be an origin of a spherical wavelet for the purpose of predicting the location of the wave at a future point in time. As these wavelets propagate, they generally retain the shape of the wavefront. However, interacting with an obstacle like the one pictured above distorts this shape and creates the bending effect as the area in the "shadow" of the obstacle becomes filled by light which originated at the aperture.

This experiment explores the counterintuitive observations associated with diffraction and uses the fringe pattern created by diffraction to infer the wavelength of light.

Apparatus

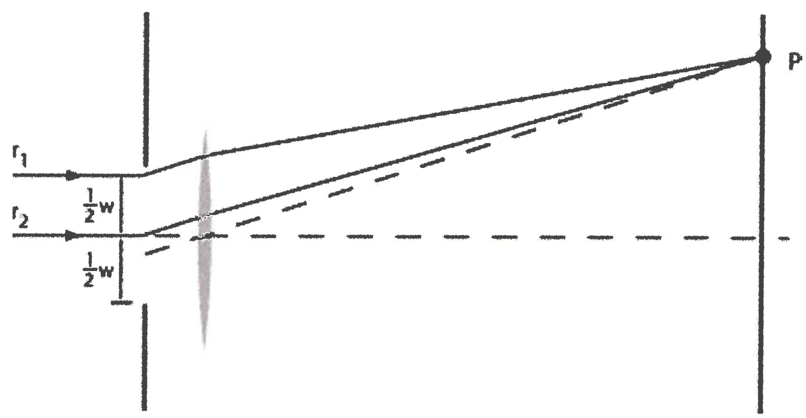
Air Track
Optical Bench Carriers -- 3x 30mm (EO-01)
Single Slits (EO-73)
Filter Holder (EO-25)
Opaque Screen (EO-26)
Adjustable Lens Holder (EO-20)
Convex Lens (EO-48)
Diode Laser 4mW (ES-12)

Method

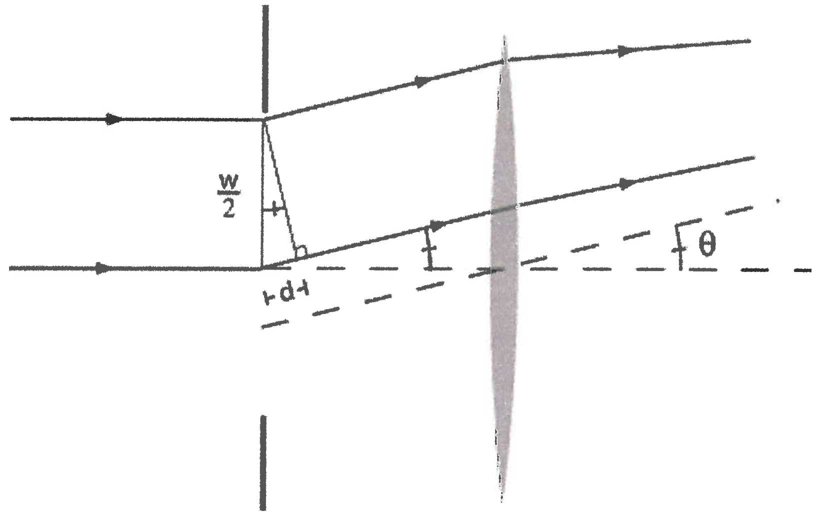
1. Set up the air track as necessary.
2. Mount the diode laser on the zero end of the track using a 30 mm bench carrier.
3. Insert the slide containing the single slit patterns into a filter holder and mount the holder in a bench carrier 20 cm down the track from the laser.
4. Secure a convex lens in the lens holder and place the lens on the track in a bench carrier located immediately behind the slide holder.
5. Place the opaque screen in a bench carrier at the focal length of the convex lens.
6. Focus the laser so that the beam is approximately collimated.
7. Align the slide so that light falls on the slit of your choosing. Record the width of this slit for future calculations.
8. Continue to tune the alignment of the system until the light pattern is roughly centered on the opaque screen. You should see a pattern of spots extending perpendicular to the orientation of the slit.
9. Analysis will require the position of the minima in the observed pattern. Measure the distance from the center of each visible gap along the horizontal axis of the pattern to the center of the pattern.

Analysis

As with the double-slit interference experiment, analysis begins with a pair of rays. This time the rays are taken from two distinct points on a continuous distribution across the width of the strip.



Path difference is once again determined by constructing a right triangle between the two rays and calculating the additional length on the lower ray.



Looking at the intersections of parallel and perpendicular lines leads to the conclusion that the marked angle of the triangle is the same as angle **θ**. Knowing this, we can express d as

$$d = \frac{w}{2}\sin\theta$$

The light at P will be at a minimum of intensity when d induces a phase difference equivalent to half a wavelength.

$$\frac{\lambda}{2} = \frac{w}{2}\sin\theta$$
$$\lambda = w\sin\theta$$

This method holds true for any even-sectioned division of the slit width. Incorporating the results of all such divisions into a single solution gives

$$m\lambda = w\sin\theta \qquad \text{where } m = \pm 1, \pm 2, \pm 3 \ldots$$

Calculate the value of λ to fit each measured minimum.

Conclusion

How do the measured values of the wavelength of the laser light compare to the laser's rated wavelength of 670 nm? Include values for the percent error in your report. Do you observe any trends in the error values?

POLARIZATION

Discussion

Electromagnetic radiation, including light, is in most cases a transverse wave, meaning that the electric field is oriented along an axis perpendicular to the direction of wave propagation. The direction of this axis is the polarization of the wave.

Most of the time, the light we observe on a regular basis is comprised of waves of different polarizations, such that the varying orientations are roughly equally represented. Special filters, however, can screen out light such that only one type of orientation remains. This experiment uses two such filters to illustrate the consequences of the polarization of light.

Apparatus

Air Track
Optical Bench Carriers -- 3x 30mm (EO-01)
Polarizing Filters – 2 (EO-33)
Opaque Screen (EO-26)
Adjustable Lens Holder (EO-20)
Convex Lens (EO-48)
Lamp w/ Power Supply (ES-17)
Optional:
Photometer

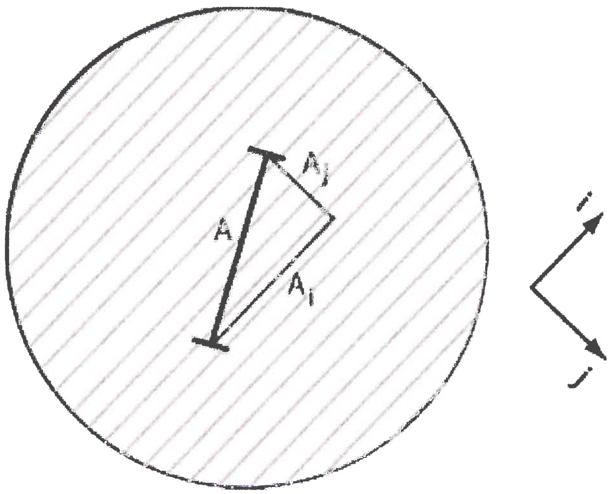
Method

1. Set up the air track
2. Mount the lamp on a bench carrier and place at the zero end of the track.
3. Attach bench carriers to the two polarizing filters and place them, one after the other, on the track. The first should be approximately 10 cm away from the light source, the second approximately 5 cm behind that.
4. If using the photometer, you will need to place the fiber optic line behind the second filter so that it collects light passing through the arrangement. If not using the photometer, mount the opaque screen behind the filters.
5. This experiment is best performed in a low-light environment. Remove or block as many external light sources in the area of the experiment as is practical.
6. Rotate both filters to the zero orientation. Note the intensity of the light passing through the filters, either quantitatively with the photometer, or qualitatively by describing the image on the opaque screen.
7. Rotate the second filter 10 degrees and repeat the observation. Continue at 10 degree intervals up to 180 degrees.

8. For an additional perspective, return the second filter to zero degrees and repeat the procedure with the first filter. Describe any differences in the results.

Analysis

Imagine a light wave traveling along an axis perpendicular to the face of this page. Its amplitude can be represented by some line segment in the plane of the page, as shown in the figure below. In the ideal case, the polarizing filter only allows light parallel to its specific orientation, shown by the parallel lines across the surface, to pass through.



The wave amplitude can be broken down into two perpendicular components, one parallel to the orientation of the filter (the **i** direction), and one perpendicular (the **j** direction). After passing through the filter, the perpendicular component is removed from the wave, leaving only the $\mathbf{A_i}$ component as the wave continues through space.

This process occurs with every ray passing through the first filter, so that while each ray is filtered to a different extent, the light which remains is uniformly polarized.

Model the effects of the second filter on this polarized light and predict the conditions for a minimum of light intensity to pass the combined filters. Compare this model with your results.

Conclusion

Describe the model you derived using the component vectors of the light amplitude. How does this vector representation simplify the work? How well do the experimental results match the modeled outcome? To what would you attribute any discrepancies? How might you change this experiment to come to a conclusion faster or more accurately?

DIFFRACTION GRATING

Discussion

A diffraction grating is a collection of thin, opaque, parallel wires, small enough to be imperceptible to the naked eye. The grating can produce a similar effect to a double or single slit, splitting laser light into a pattern of minima and maxima. More commonly, however, a grating can be used to split light into its component wavelengths. Unlike a prism, which relies on variation in the index of refraction across wavelengths, the diffraction grating exploits the dependence of interference patterns on wavelength. The result is that a given color will appear at a maximum where others cancel, creating a visible spectrum across the diffracted image.

The images created by a diffraction grating follow the same mathematical formula outlined in the single-slit diffraction experiment,

$$d = w\sin\theta$$

where d is the path difference between any two rays, w is the width of a gap between two wires, and θ is the outbound angle of those rays as they leave the diffraction grating. This path difference determines the intensity of light at that angle, with a maximum occurring when the path difference is equal to the wavelength, so that we expect

$$m\lambda = w\sin\theta$$

for integer values of m. In this experiment, you will only deal with first- and possibly second-order images, so named for the number of wavelengths in the path difference.

Apparatus

Air Track
Optical Bench Carriers -- 3x 30mm (EO-01)
Filter Holder – 2 (EO-25)
Opaque Screen (EO-26)
Single Slits (EO-72)
Diffraction Grating (EO-77)
Lamp w/ Power Supply (ES-17)
Optional:
Diode Laser 4mW (ES-12)

Method

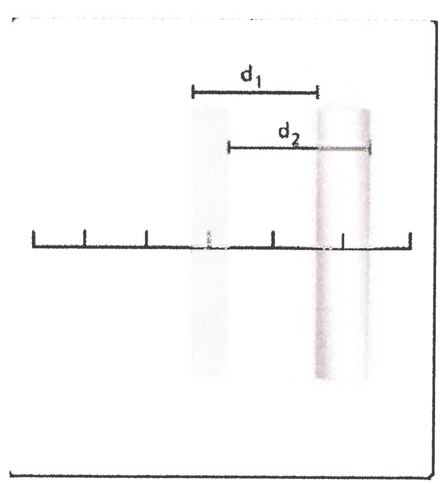
Measuring the spacing of the diffraction grating:

1. Set up the air track as needed
2. Piece together the laser and a bench carrier and mount at the zero end of the track.
3. Place the opaque screen in a bench carrier and mount 15 cm away from the laser. Focus the laser so that the light comes to a point at the screen.

4. Slip the diffraction grating into the filter holder and place in a bench carrier. Mount this on the track 10 cm from the laser. If the grating is producing images along a vertical axis, rotate the slide 90°. Adjust the laser and filter holder so that the laser strikes the approximate center of the grating and the undiffracted part of the beam falls on the center of the opaque screen.
5. The angle of the diffraction grating may cause uneven image spacing. Adjust the filter holder by rotating it around its post until the intervals between the first-order images and center point are equal.
6. Record the distances between the center point and each first-order image.
7. For additional data, you may use a meterstick to extend the opaque screen in order to find the second-order images.
8. **Analysis:** Solve the expression in the Discussion section for the unknown width of a grating interval. If possible, solve for both first and second-order images and compare the results. Quantify the difference between the two.

Measuring the range of the visible spectrum:

1. Set up the air track as needed.
2. Follow the instructions in the previous procedure to set up the diffraction grating and opaque screen.
3. Place the incandescent lamp on a bench carrier and mount at the zero end of the track.
4. Adjust the spacing between the opaque screen and grating so that the first-order images just barely fit within the marked scale on the screen.
5. Measure the distance from the edge of the centered image to the like edge of the first-order image. See the figure below.



6. **Analysis:** Use the distances above to calculate the angle of diffraction for those colors on the extremes of the visible

spectrum. Now use the formula from the discussion, along with the grating spacing calculated above (or 1.4887 microns per interval, if the first part was skipped) to find the wavelengths associated with these extremes. This should be the range of visible light.

Conclusion

Find a credible reference for the width of the visible spectrum and compare your results to the expected values. Where do your measurements fall short of or exceed the expected results? Can you put forth any explanation that would cover these discrepancies?

As an additional experiment, you can employ the color filters to look more closely at individual color responses. Do these results support the full spectrum conclusions? Are there any surprises?