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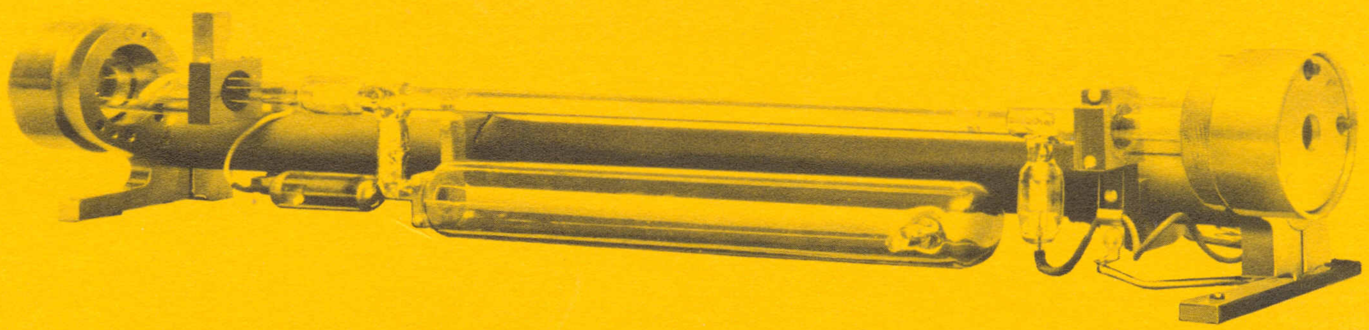

THE LASER

Modern Optics and Quantum Mechanics

THE LASER

A Module on Modern Optics and Quantum Mechanics

FVCC

Gary S. Waldman, Florissant Valley Community College
Bill G. Aldridge, Florissant Valley Community College
A. A. Strassenburg, State University of New York at Stony Brook

Bill G. Aldridge, Project Director

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Philip DiLavore . . . . Editor
Julius Sigler . . . . Rewrite Editor
Mary Lu McFall . . . . Copy and Layout Editor
B. W. Barricklow. . . . . Illustrator
Stacy Garrett. . . . . Compositor
Elsie Green . . . . Compositor
Donald Emmons. . . . . Technical Proofreader

In the early days of the Tech Physics Project A. A. Strassenburg, then Director of the AIP Office of Education, coordinated the module quality-control and advisory functions of the National Steering Committee. In 1972 Philip DiLavore became Project Coordinator and also assumed the responsibilities of editing and producing the final page copy for the modules.

The National Steering Committee appointed by the American Institute of Physics has played an important role in the development and review of these modules. Members of this committee are:

J. David Gavenda, Chairman, University of Texas, Austin
D. Murray Alexander, DeAnza College
Lewis Fibel, Virginia Polytechnic Institute & State University
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George Kesler, Engineering Consultant
Theodore Pohrte, Dallas County Community College District
Charles Shoup, Cabot Corporation
Louis Wertman, New York City Community College

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The Laser

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TABLE OF CONTENTS

The Laser

INTRODUCTION AND SPECIAL PREREQUISITES

In this module, you will use the laser to learn some of the principles of wave motion, physical optics, and modern physics.

Even though most of the concepts needed to understand the laser are presented within the module, there are a few things you should know to start with. These prerequisites concern wave motion and the concepts of energy, electric charge, electric potential difference (voltage), and kinetic energy.

Sections A and B of the module require only the prerequisites on wave motion, and these may be met by meeting the goals of *The Guitar* module. Other equivalent material could teach you the same concepts.

The prerequisites of Section C will be met if you have achieved goals similar to those in *The Pile Driver* module and *The Incandescent Lamp* module. These goals involve concepts of kinetic energy, potential energy, and thermal radiation. Several other Physics of Technology modules include the essential prerequisites for this module.

This module puts an emphasis on laboratory experience. As you come to the experiments, tear out the corresponding work sheets at the end of the module and fill them out.

GOALS FOR SECTION A

The following goals state what you should be able to do *after* you have completed this section of the module. These goals must be studied carefully as you proceed through the module and as you prepare for the post-test. The example which follows each goal is a test item which fits the goal. When you can correctly respond to any item like the one given, you will know that you have met this goal.

1. *Goal:* Explain the observational evidence for straight line propagation of light.

   Item: Why does an extended source produce fuzzy shadows while a point source produces sharp shadows?

2. *Goal:* Know the characteristics of interference patterns produced by thin films (e.g., a layer of air between two glass plates).

   Item: Two optical flats in contact are illuminated from one side with a laser beam. On the opposite side, light and dark bands appear on a screen. What happened to the laser light that would have been in the dark bands if the optical flats were absent?

3. *Goal:* Know the characteristics of double- and single-slit interference patterns.

   Item: When a laser beam is shined through two closely spaced slits, a number of spots of light can be seen on a screen. What change in the slits can reduce the number of light spots seen without changing their spacing?

4. *Goal:* Understand the concept of spectral and non-spectral colors.

   Item: Is white a spectral or non-spectral color?

5. *Goal:* Know the special properties of laser light which make it more useful than ordinary sources in special applications.

   Item: Which of the following laser light properties is most important in alignment applications:

   a. collimation
   b. power
   c. pure color
   d. short pulse time

Answers to Items Accompanying Previous Goals

1. The edge of an obstacle will block either all or none of the light traveling in straight lines from a point source to an observation point. With an extended source, the obstacle can block only part of the light to the observation point, giving a gray or fuzzy region to the shadow.

2. It appears in the reflected interference pattern.

3. Make the slits wider without changing their center to center separation.

4. Non-spectral because it does not appear in the spectrum.

5. a. collimation

SECTION A

Laser Light: How It Differs from Ordinary Light

INTRODUCTION

The laser* is a relatively new type of light source. Invented in 1960, the laser has been extensively developed since that time and many interesting uses have been found for it. (Actually, although we often speak of *the* laser, there are now many different kinds of laser, having some kinds of characteristics in common and others which are quite different.)

The light from some kinds of laser can bore a hole through a sheet of metal. Lasers are already being used to weld tiny wires in electronic circuits, to perform delicate surgery on human eyes, to cut suit patterns into cloth, and to do many other useful things. They soon may be used to build super-fast computers and to send thousands of simultaneous messages across long distances. Reflected laser light has been used to measure the distance to the moon within a few centimeters.

In this module, you will learn how laser light differs from ordinary light and you will use a laser to reveal the wave properties of light. The first laser was built in 1960 by T. H. Maiman at Hughes Aircraft Company. Energy was supplied to this first laser, whose main component was a ruby crystal rod, by a flash tube wrapped around the rod. Figure 1 shows a simplified diagram of an early ruby laser.

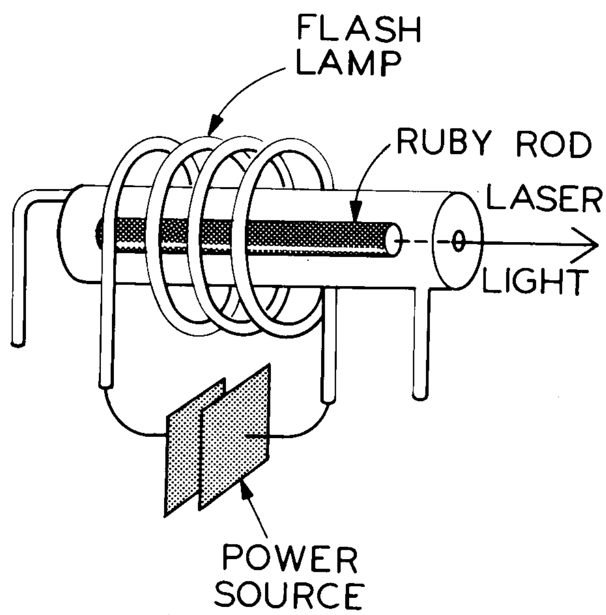

Figure 1.

Ruby lasers produce light only in short *pulses.* That is, light is emitted during a short period of time; then no light is produced until the next pulse. In 1961 a continuously operating laser was built by Ali Javan, at Bell Telephone Laboratories. He used a glass tube containing a mixture of helium and neon gases as the central element of the laser. Such a continuously operating device is called a *continuous-wave* (cw) laser. A schematic drawing of a simple helium-neon laser appears in Figure 2. Since then a great variety of pulsed and cw lasers have been made. They can produce a wide range of different power outputs (and light of almost any color).

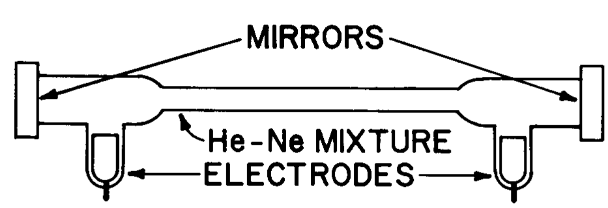

Figure 2.

*The word *laser* is formed from the first letters of *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation.

SOME FACTS ABOUT LIGHT

There are many properties of light which all of us have observed at one time or another in our lives. Let us list a few of the things which may be considered common knowledge about light. Most of these observations are necessary knowledge for what follows in this module. Some of these observations will be expanded in the module to add to your understanding of light, especially laser light.

Light Travels in Straight Lines

Light travels in straight lines if the properties of the matter through which the light travels do not change along the light path, and if no obstacles or apertures are inserted in the path. What evidence do we have to justify this statement? One common observation is that light casts rather distinct shadows of most objects which get in its way. For example, you can see the curve of the earth as its shadow crosses the moon during a lunar eclipse. "Sharp" shadows can be cast only if light travels in straight lines. (Do you see why?) Another way we know that light travels in straight lines is by observing a light beam from a spotlight in fog or in a smoke-filled area. As shown in Figure 3, you can see the path of the light beam as the light is scattered by the particles of fog or smoke.

Question 1. If light travels in straight lines, how can you account for the fact that inside a house in the daytime with the lights turned off you can see your surroundings? That is, how does the sunlight, which travels in straight lines, get into all parts of the house?

Transparent, Translucent, and Opaque Materials

Another fact about light is that it can go through some materials and not others. We know that light travels through air and empty space (vacuum). Light also travels through glass, water, and many other materials. Materials like clear glass, clear plastics, and water which let almost all the light through just as if the materials were not there are called *transparent.* However, light will not travel through many solid materials such as metal and wood. Substances which will not allow light to pass are said to be *opaque.* Other materials, like thin pieces of paper or frosted glass, let some or most of the light through but prevent you from seeing the detailed shape of things on the other side. Such materials are said to be *translucent.*

Question 2. In what way is fog like a translucent material?

Reflecting and Bending

Some materials *reflect* ("bounce" back) the light from an object in such a way that an object in front of the reflecting surface appears to be behind it. As you know, such a surface is called a *mirror.*

Another common observation may appear to contradict the fact that light travels in straight lines. When you observe a spoon

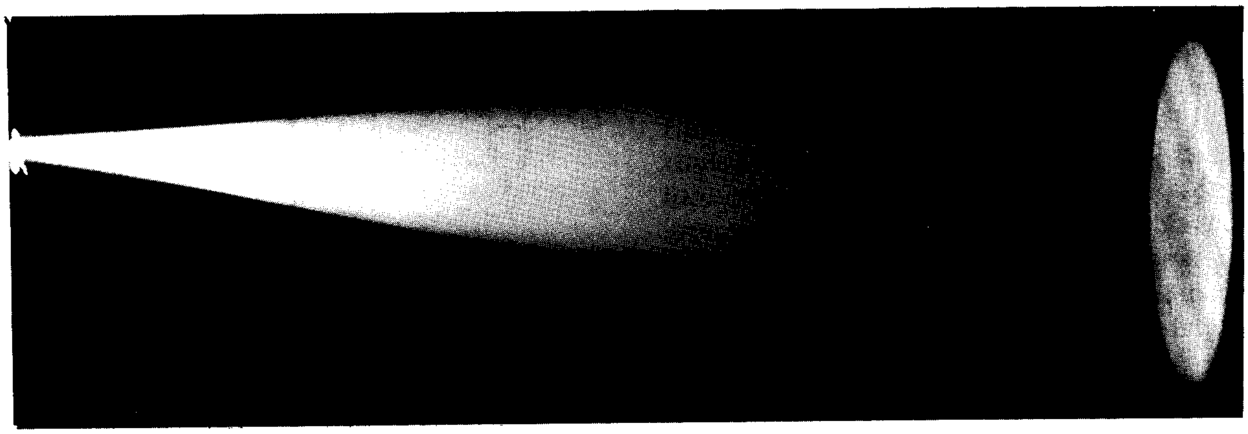

Figure 3.

partly submerged in a cup of water as shown in Figure 4, the handle of the spoon appears to be bent at the surface of the water. If you experiment further with this situation, you will find that light does travel in straight lines in a given material or medium. However, when light reaches the boundary between two different materials, the light may be bent. This phenomenon is known as *refraction.*

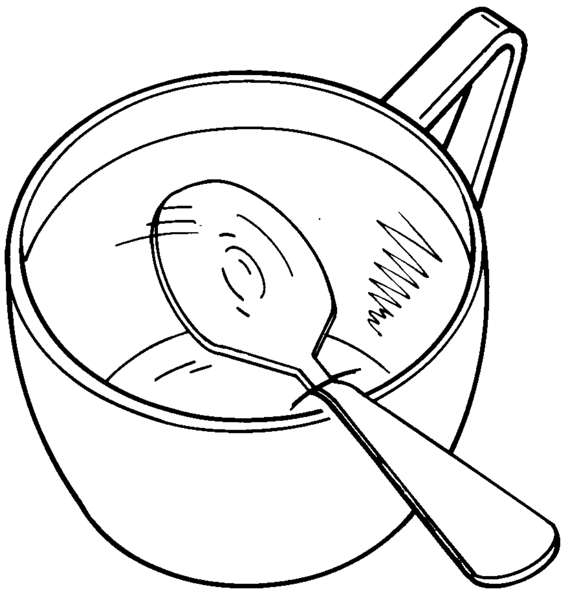

Figure 4.

Laser Light

The properties of light we have discussed in the preceding paragraphs apply to all kinds of light, including laser light. The light in a laser beam has very special properties which distinguish it from the light of ordinary sources. You will now discover some of these differences by doing Experiment A-1.

EXPERIMENT A-1. Observations of Light

CAUTION: You will be working with a laser when performing experiments in this module. Although you are working with a low-power gas laser, there are some precautions which should be taken:

1. Do *not* look directly into a laser beam or its reflection from a shiny surface.

2. Since you are probably working in a lab with other students, do *not* point the beam where others might accidentally look directly into the beam or its reflection.

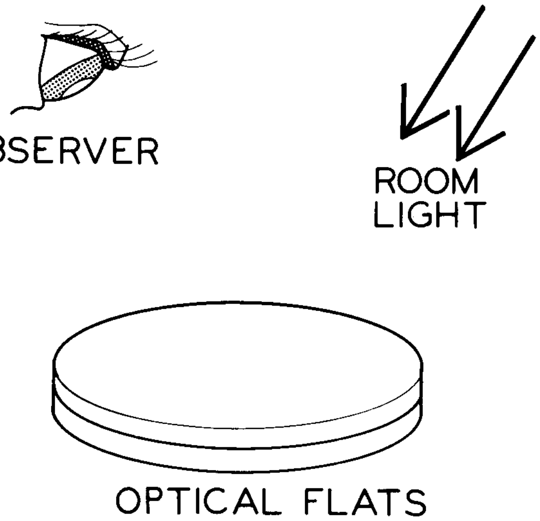

Figure 5.

Part I

You have been provided with two pieces of glass called *optical flats*. Place these optical flats one on top of the other on a clean white surface. Touch only the edges and be careful not to touch or scratch the surfaces of the optical flats. Now look down at the top of the optical flats so that you see the reflection of room light (from a fluorescent lamp or incandescent lamp). This arrangement is shown in Figure 5. (You may have to press the flats firmly together, *touching only the edges*.)

1. Do you see dark and light bands?

2. Do you see colors at the edges of the bands? What colors?

3. Sketch the pattern you see.

Now let's see what happens when laser light is used. Place the flats one on top of the other on the special holder. Pass the laser beam through the lens system which has been provided. This lens expands the laser beam so that it can shine on a larger area. The beam should be reflected from a mirror placed above the optical flats so that the beam illuminates most of the surface of the flats. Place a white screen beneath the flats and position another white screen above the flats so that the light reflected from the flats will strike this upper screen. Your apparatus should be arranged as shown in Figure 6.

Next, dim the room lights so that you can see the reflection of the laser beam on the upper screen and the transmitted portion of the beam (the part which passes through the optical flats) on the lower screen.

4. Sketch the reflected pattern (seen on the upper screen).

5. How is this pattern similar to what you saw using white light?

6. How is the pattern different?

7. How many colors do you see?

Rotate the upper flat around an axis

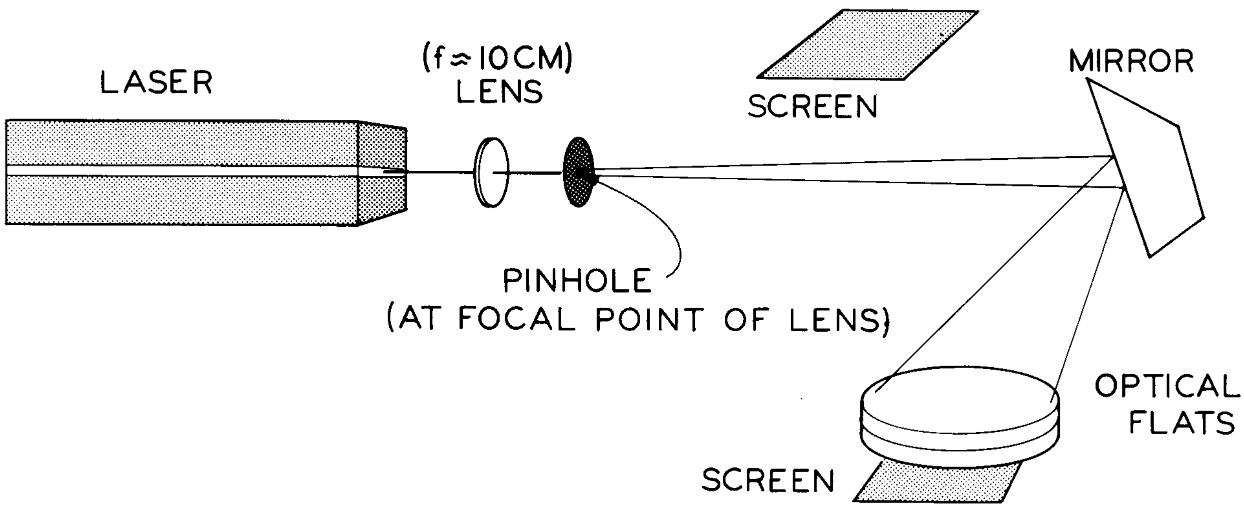

Figure 6.

perpendicular to its surface while holding the lower flat stationary.

8. What happens to the pattern as the upper flat is rotated?

9. Now look at and sketch the transmitted pattern (seen on the lower screen).

10. How is the transmitted pattern different from the reflected pattern?

Place a pointed object (such as a pencil) *lightly* on the surface of the upper flat. (Better still, just hold the pencil point slightly above the flats.) Position the pencil point so that it is on a bright band in the transmitted pattern. If the point is observed at more than one position on each screen, look at the darkest point.

11. Is the pencil point then on a bright or dark band of the reflected pattern?

12. Turn off the laser.

Part II

You should now observe the effects of passing light through narrow slits. You have been provided a glass slide containing single slits of various widths and pairs of slits of various separations. Find a pair of closely spaced slits. Hold the glass slide close to your eye and look through the pair of slits at a frosted light bulb about a meter away.

1. Describe what you observe. (Do you see two slits? Is the light uniform all the way across?)

2. Now use a straight-filament, clear light bulb. Turn the glass slide so that the slits are perpendicular to the filament; then look through the slits at the bulb. Describe what you see.

3. While looking through the slits, slowly rotate the glass slide until the slits are parallel to the filament. Describe what happens.

4. What colors do you observe? What are the relative positions of these colors?

5. Place the red and blue filters over the bulb (Figure 7) so that the filters meet but do not overlap. Look through the double slits at the bulb. Do the red bands and blue bands of light exactly line up? Sketch what you observe.

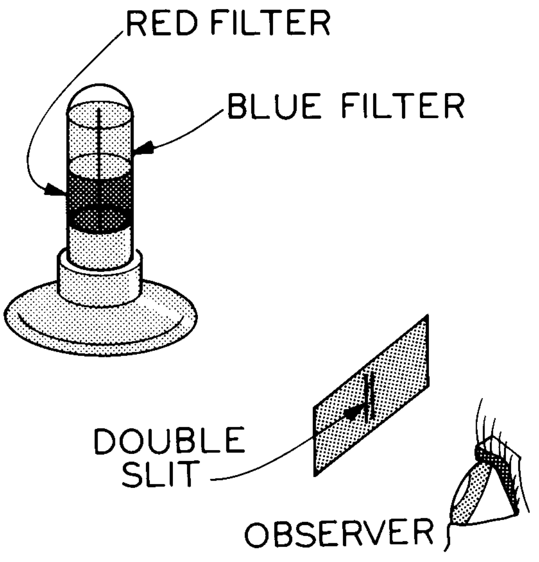

Figure 7.

Now place the glass slide as shown in Figure 8, so that the double slits are in the laser beam; observe the resulting pattern on a white screen about two meters away. **(DO NOT LOOK THROUGH THE SLITS AT THE LASER BEAM.)**

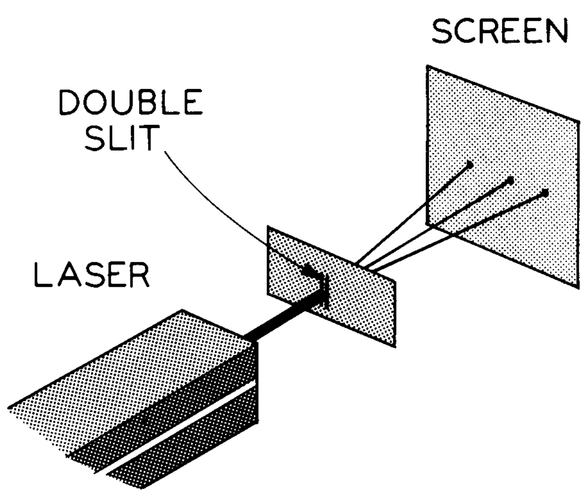

Figure 8.

6. Sketch the pattern you observe.

7. What colors do you see in the pattern?

8. Try other pairs of slits with different spacing between them. Sketch the patterns you observe as the spacing between slits changes.

Next place one of the single slits in the laser beam.

9. Sketch the resulting pattern.

10. Use single slits of various widths. Sketch the pattern you get for different slit widths.

11. Place the double slits in the beam. Are there any differences between this pattern and the single-slit pattern? What are they?

Part III

You should now find how much a beam of light spreads out along its length. Take the light from a small bright source, and try to produce a narrow beam which doesn't spread out very much. This is what a headlight does.

To do this, use the small bright source. Place a diaphragm* in front of it and adjust the opening to about 0.5 cm in diameter. Place the lens supplied between the diaphragm and a flat mirror as shown in Figure 9. Adjust the mirror so that the reflected light falls back on the source itself. Now move the lens back and forth until the light reflected back to the diaphragm produces the smallest possible spot. Leave the lens at this position and remove the mirror from the other side. Adjust the diaphragm until the resultant beam has a diameter of about 2 cm. The beam of light produced has rays which are as closely parallel as can be obtained with this apparatus. This beam is called a *collimated beam*, and the process you just used to achieve it is called *auto-collimation*.

1. At a distance of one meter from the lens place a white screen, so that you can measure the diameter of the collimated beam.

*A diaphragm is an opaque disc which has a variable-sized hole in its center.

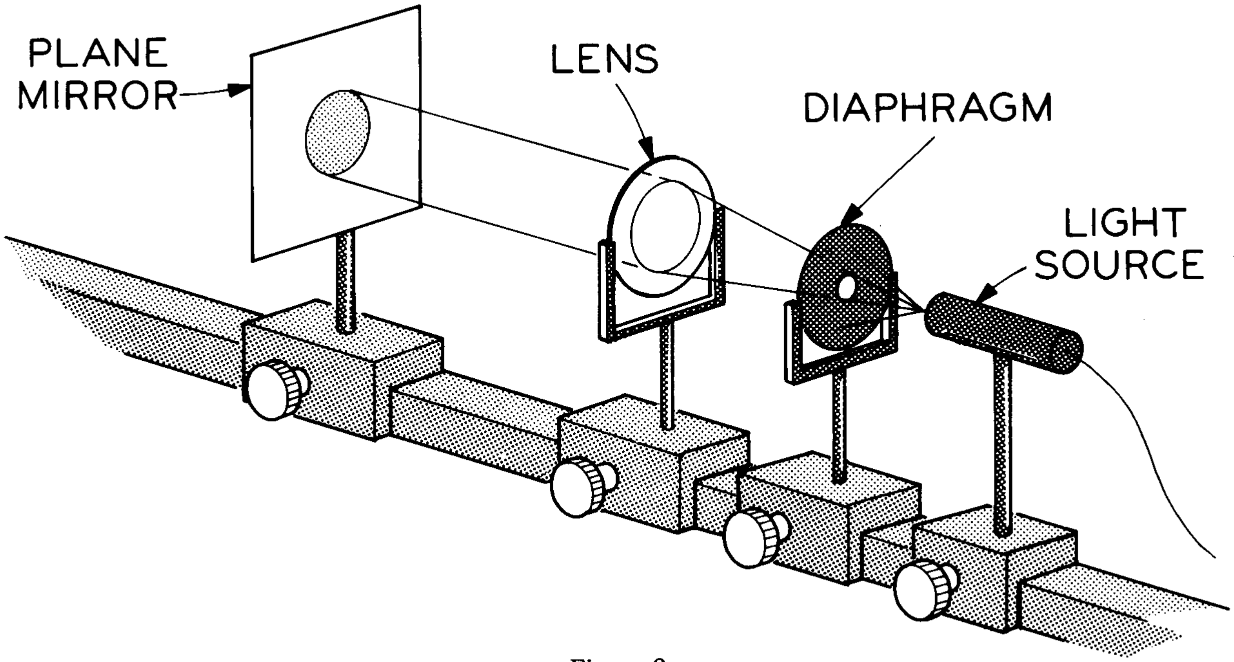

Figure 9.

2. Measure the diameter of the beam at a distance of two meters from the lens.

3. What is the ratio obtained by dividing the measurement of step 2 by the measurement of step 1?

4. Measure the diameter of the laser beam at a distance of one meter from the front of the laser.

5. Turn on the laser and measure the diameter at two meters.

6. What is the ratio obtained by dividing the measurement of step 5 by the measurement of step 4?

7. What can you conclude about the difference in spread between a collimated light beam and a laser beam?

DISCUSSION OF EXPERIMENTAL OBSERVATIONS

Ordinary Light Sources

Light sources can be classified in terms of various properties such as the color and brightness of the light produced, and so on. One very important classification is that of *extended source* versus *point source*. A *point source* is an idealization and it occupies no space. However, if the real source is small and the observer is far away, it may be a good approximation to a point source. An extended light source, such as a frosted light bulb, or the clouds on an overcast day, does not produce sharp shadows. Thus such sources cannot be used for projecting the pattern of spots produced by double slits, as you did with the laser. In order for extended sources to be used for such experiments, it is necessary to first pass the light through a slit to approximate a *line source*, which is like a point source in one dimension and an extended source in the other. This greatly reduces the amount of light available for the experiment. Often it is also advantageous to *filter* the light, allowing only one color to reach the slits. This further reduces the amount of light which reaches the screen, and the pattern produced is extremely dim.

You can demonstrate the effect of an extended source yourself. Find a fixture which has a single straight fluorescent lamp in it. Hold a pencil under the light, but as far away from it as you can. Observe the shadow produced on a nearby surface when the pencil is parallel to the lamp. Then turn the pencil so that it is perpendicular to the lamp, and look at the shadow. The fluorescent lamp may be considered a point source in one direction and an extended source in the other.

A point source is one which is sufficiently small and/or far away so that all of the light from the source appears to come from a point. We may also define a point source in terms of effects which can easily be seen or measured. One effect is, at least for large objects, that a point source will cast a sharp shadow. Any light source behaves as a point source if it is sufficiently far away. The stars are point sources by this definition, and even the sun may be considered a point source for some observations. A frosted light bulb about a meter away from you definitely is not a point source (as you might have discovered in Experiment A-1).

Monochromatic Light

We know that visible light includes a variety of *colors*. Generally we think of the color of light as a property of the source of the light or of the object which we see by reflected light. To some extent this is true. Different sources *do* give off different colors of light, and different objects do appear differently colored when seen in the same light. However, color is really a sensation caused by the light which is detected by our eyes. Therefore, color has as much to do with how *we* perceive the light as it does with the light itself. Later, we will define a quantity which corresponds to the color of the light. We must be careful to remember, however, that "color" is primarily a physiological and psychological process in the eye and brain.

In experiments like that with the double-slit apparatus, "white" light sources created patterns in which colors were visible at the edges of the bright bands. The laser produced similarly shaped light and dark patterns of one color. Such results suggest that the single color (*monochromatic*) light of a laser might in some way be simpler than white light.

Spectral Colors

In the seventeenth century Sir Isaac Newton (1642-1727) proved with a simple experiment that white light is a combination of light of various colors. He passed a narrow beam of sunlight through a prism, as shown in Figure 10.

As it passes through the prism, the white light is spread out into a band of colors: red, orange, yellow, green, blue, violet. This band of colors is called a *spectrum*, and the colors are called *spectral colors*. Some colors, such as tan and pink, can be produced by mixing spectral colors, but they appear nowhere in

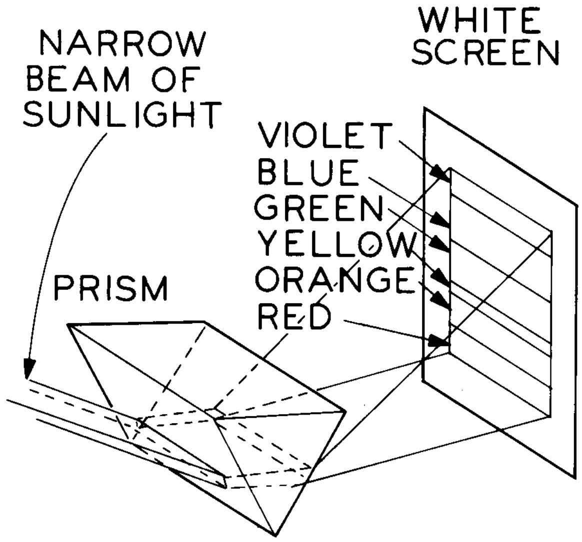

Figure 10.

the spectrum. They are therefore called *non-spectral colors*. For example, the non-spectral color purple is a mixture of the spectral colors red and blue. To assure that the color was not added by the prism, but was actually present in the white light, Newton refined the experiment further as shown in Figure 11.

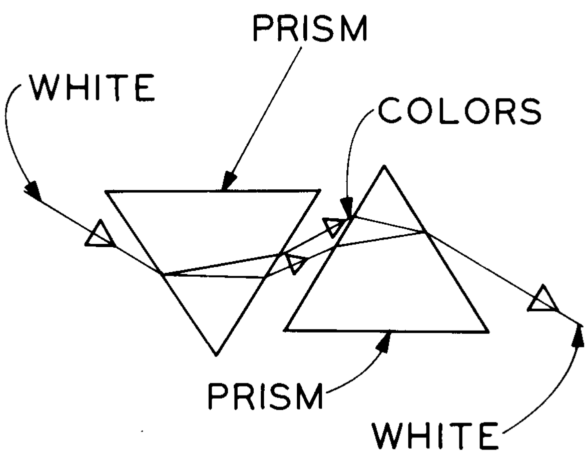

Figure 11.

When the light from the first prism is passed through a second prism, white light again emerges from the other side. Furthermore, passing any one of the spectral colors through a second prism does not further change its color. These experiments lead to the conclusion that white light is composed of all the colors of the spectrum. The prism bends different colors by different amounts to produce the separation of colors observed. The phenomenon of different colors bending by different amounts is called *dispersion*. We can conclude that "white" is the sensation produced by all of the spectral colors properly mixed together. As you may know, the sensation of white light may also be produced by properly mixing only three colors, like red, green, and blue, as used in color television.

Question 3. What non-spectral colors are you familiar with?

Question 4. Could a mixture of two spectral colors produce another spectral color? Why or why not?

The colored patterns produced when white light was used in certain parts of Experiment A-1 were not due to dispersion. They arose, however, because white light is a mixture of colors. The colored patterns can be thought of as the display of many different monochromatic patterns, each similar to that produced with laser light.

INTERFERENCE PATTERNS

Double-Slit Pattern

The previous discussion does not explain the observed alternating light and dark patterns produced by the double slits. Many people find these alternating light and dark bands particularly surprising. Why are there not just two bright bands coming through the two slits? We can only say at this point that the behavior of light is more complex than one might guess from everyday observations of light and shadows. Only detailed observations, similar to those you have done in the first experiment, can lead to a more basic understanding of light.

Single-Slit Pattern

The single-slit pattern is also unexpected. In this case there is a bright band in the center, and a number of smaller light bands on each side.

Diffraction

Both the single-slit and double-slit patterns you have observed suggest that light has a tendency to spread out into areas which you would expect to be in shadows. The smaller the opening through which the light passes, the greater the spreading. The bending of light around sharp edges into shadow areas is called *diffraction*. It is always present, but usually is hard to see.

Question 5. Look at a distant street light through a fine-mesh screen or through a linen handkerchief. Describe the pattern you see. Are there similarities between this pattern and the double-slit pattern you observed with a laser source? What are the major differences? In what ways does the pattern change when you look first at a mercury-vapor light (bluish-white) and then at a sodium-vapor light (yellow)?

Divergence of the Laser Beam

In many lasers conditions are present for producing a nearly perfect parallel beam. Such a beam is said to be *collimated*. The fact that the divergence of a laser beam is extremely small is a feature which has a wide variety of applications. The slight spreading that does occur in a laser—spreading which you measured in Experiment A-1—is similar to single-slit diffraction. The edges of the laser tube itself behave as a slit opening and thus diffraction occurs.

THE NATURE OF LIGHT

The light and dark patterns you have seen are *interference patterns* of light. In general, interference patterns are produced by combining two beams of light which originally came from the same source. In the experiments using flat glass plates, the light from a source was split into two parts. Then it was recombined by being partially reflected and partially transmitted at each side of the air film between the plates. In the double-slit experiment, the light was split by allowing only a part of it to pass through each opening; it recombined because of its own natural tendency to spread on the other side of the slits. White light interference patterns are multi-colored, and they have the same general shape as monochromatic light patterns. Monochromatic light is a component of white light. It is much easier to get bright, clear interference patterns with laser light than with light from ordinary white light sources, even if the latter is passed through a color filter.

ADVANTAGES OF LASER LIGHT

Diffraction, the tendency of light to spread out into shadow areas, is particularly easy to see using laser light. In the absence of other optical components, it is often the main reason for the spreading of the laser beam. In spite of diffraction, laser beam collimation is generally much better than one can obtain with ordinary light sources.

Many of the properties of laser light, such as a single spectral color, clearer interference patterns, and better collimation, suggest that laser light is somehow simpler than light from other sources.

Laser Power

In general, pulsed lasers are more powerful than continuous (cw) lasers. The high power of pulsed lasers results from the fact that, in a pulsed laser, a substantial amount of light energy is emitted in a very short time. Early ruby lasers typically had output powers of several kilowatts, with pulse times of several milliseconds. Later versions of ruby lasers have produced pulses of energy lasting for times as short as a nanosecond (ns, 10^{-9} second). The average power in such a short pulse can be as much as hundreds of megawatts.

Typical output powers of cw He-Ne lasers likely to be used in the classroom are about one milliwatt or less. However, cw lasers have been made using carbon dioxide as the active material that produce an invisible beam of infrared light with power as high as ten kilowatts.

The power density (power per unit area) which can be attained with lasers is even more impressive. This is because the simple, pure nature of laser light allows one to focus it into unusually tiny areas as small as 10^{-4} cm^2. A 10-kW beam focused onto that area would produce a power density of 10^8 W/cm^2.

LASER APPLICATIONS

Industrial Applications

Such extremely large power densities can melt or even vaporize most materials. Consequently lasers have been used to drill tiny holes or make small welds. One example is the use of a pulsed laser to drill holes in diamonds for industrial purposes, cutting the time required from two days for previous methods to two minutes. Another example is the use of a cw carbon-dioxide laser to automatically cut tailor-made suits, reducing the time over hand labor by a factor of 20. Lasers may soon be used to read codes on items at the grocery store, so that bills can be automatically totaled.

Medical Applications

Properties of laser light have been used in a number of medical applications. For example, tiny "spot welds" can be made in the eye to correct a condition known as "detached retina." The retina is the light-sensitive surface at the back of the eyeball. Under certain conditions the retina can peel away from the eyeball, causing blindness. A burst of laser light into the eye and focused on the retina will produce a tiny scar which prevents further detachment. The treatment is effective, painless, and requires no hospitalization. Another possible medical application takes advantage of the fact that dark materials absorb more light than do lighter materials. Skin cancers, which are darker than healthy tissue, may possibly be destroyed with large laser pulses. The same principle may be used to "drill" decayed teeth, since the decayed area is darker than the healthy tooth. Laser pulses are focused on the decayed area of the tooth. The darker decayed part absorbs the laser light and is vaporized without heating the healthy part of the tooth.

Laser "Weapons"

It might seem that these destructive properties of the laser could be used for weaponry. Although this aspect of lasers seems to have fascinated movie and television scriptwriters more than others, it is not a very promising area. Once it appeared to some that "laser guns" might have significant advantages in anti-ballistic missile defenses because the "light bullet" would reach the target extremely fast. Because of this speed, there would be no need for the complicated computations that are required if a slow projectile is to be launched at a moving target. However, tremendously powerful lasers are needed to do even a small amount of damage in the lab, and the emitted light is affected by atmospheric conditions. Fog or clouds or even dust in the air may quickly reduce the laser beam to a harmless intensity. As for putting holes in people, James Bond notwithstanding, ordinary metal bullets are much cheaper and work in all weather. There is still the possibility that large, pulsed lasers could be used as blinding weapons, since the eyes are much more susceptible to damage from light than the rest of the body, but other weapons uses are still highly speculative.

Range Finding

Besides using lasers as weapons, there are military applications which overlap with civilian applications. A laser beam can be used to illuminate a target for a guided missile. In this case, a very precise color filter in front of the missile's sensor will block essentially everything from its view except the laser light. Laser pulses used for range-finding ("laser radar") have both civilian and military use. A short pulse of light is reflected from an object and the distance to the object is computed from the time it took the pulse to get there and back. A pulse of one nanosecond duration is only about one foot long, since light travels about one foot per nanosecond. This pulse length allows range measurements to one foot accuracy. The technique has been used to measure the distance to the moon to within six inches. The laser beam is transmitted through a large telescope to a reflector package left on the surface of the moon by the Apollo 11 astronauts. A tiny fraction of the reflected beam is observed in the same telescope back on earth.

For military applications, the narrow beam of an infrared laser can be aimed much better and is less likely to be detected than the beam from a conventional (microwave) radar set.

Alignment

An even simpler use of the laser is for *alignment*. The beam from a cw laser makes a straight line for lining up equipment. A laser was used to align equipment digging a tunnel under San Francisco Bay for a new rapid transit system. Likewise the two-mile-long linear particle accelerator at Stanford University is kept in a straight line with the aid of a laser beam.

Holography

One of the most spectacular applications of lasers has been their use in a three-dimensional photographic technique called *holography*. Holography was invented in 1947, considerably before the laser, by the English physicist Dennis Gabor. However, the special properties of laser light make *holograms* easier to produce and more impressive. It is difficult to explain the technique fully, but a hologram is a photograph of an interference pattern, with laser light reflected from a scene. When the hologram is illuminated with laser light, a striking three-dimensional image of the original scene is produced. This process could have obvious potential uses in entertainment and advertising. Other possible uses will be discussed after you have learned more about light. The best way to appreciate the remarkable properties of holograms is to look at one, if one is available.

SUMMARY

The following statements summarize the concepts, definitions, and principles you have learned so far in this module.

The word *laser* is formed from the first letters of *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation.

In a given material, and in the absence of obstacles and openings, *all light,* including laser light, travels in a straight line.

A *translucent* material is one which allows some light to travel through it, but does not permit one to see clearly details of the light source on the other side.

A *transparent* material is one which allows most light to pass through it so that objects on the other side are clearly seen.

An *opaque* material is one which does not allow light to travel through it.

In general, light changes direction as it crosses a boundary between two transparent materials. This phenomenon is called *refraction.*

Color is a sensation in the brain and is a combination of a property of the light *and* of the physiological and psychological process in the eye and brain we call *seeing*.

A *point source* of light is one which is capable of producing sharp shadows of large objects. Alternatively a point source is any light source which, compared to its size, is a very large distance from the observer.

A *collimated* light beam is one which does not diverge.

Monochromatic light is light of a single color.

White light is a combination of all the colors in the *spectrum.* The sensation of white light can also be produced by a combination of other colors.

The fact that different colors bend different amounts when crossing a boundary between two different transparent materials is called *dispersion.*

A *color filter* is any material which is opaque to some colors and transparent to a narrow band of colors.

The alternating pattern of bright and dark bands produced when two light beams are brought together is called an *interference pattern.*

When light travels through very small openings or encounters small objects in its path, it is diffracted and produces an *interference pattern* (also often called a *diffraction pattern*).

GOALS FOR SECTION B

The following goals state what you should be able to do after you have completed this section of the module.

1. *Goal:* Understand the implications of the wave and particle models of light.

   Item: What would be the expected result in a double-slit experiment using the particle model if you widened both slits without changing their separation?

2. *Goal:* Understand the correspondence of wavelength to color.

   Item: If the light emitted by a helium-cadmium laser has a wavelength of 442 nm, what color will it be?

3. *Goal:* Know the relationship between the angular separation of the bright spots in Young's double-slit experiment, the wavelength of the light, and the slit separation.

   Item: Light from a helium-neon laser ($\lambda = 633$ nm) is shined through a pair of slits and produces an interference pattern with an angular separation of 3×10^{-4} rad. What is the slit separation?

4. *Goal:* Be able to calculate the frequency of light whose wavelength is given.

   Item: What is the frequency of light from the laser in Item 3?

5. *Goal:* Understand the wave model explanation of temporal and spatial coherence.

   Item: What temporal coherence condition on the waves passing through double slits is necessary for an interference pattern?

Answers to Items Accompanying Previous Goals

1. Still two peaks but each is broader.
2. Blue.
3. 2.11 mm
4. 4.74×10^{14} Hz
5. Wave trains must have a fixed relationship from one crest to the next.

SECTION B

Developing a Model for Light

SPEED OF LIGHT

Light originates at a source such as the sun, a flame, or a lamp. It travels away from the source and falls on objects. When light strikes an object, it can cause a temperature increase in the object, it can induce a chemical reaction (e.g., photosynthesis), or it can produce other effects. Light can enter our eyes directly from the source or after reflection from objects about us. When light enters our eyes, we "see." Seeing is largely responsible for our impressions of the shapes and colors of things in our environment.

Although light travels very fast, we know that some time always elapses between the instant light leaves a source and the instant it strikes an object. Several ingenious methods have been devised for measuring the speed at which light travels. The simplest of these (although not necessarily the easiest) is to measure a very large distance carefully, and then measure the time required for light to travel that distance. The speed of light is then simply the distance traveled divided by the time required to travel that distance. In empty space, the speed of light has been found to be 2.997925×10^8 meters per second (3×10^8 m/s $\cong$ 186,000 mi/s).

WHAT IS LIGHT?

Despite the fact that most of our perceptions of the world around us involve light and the sense of sight, light is not easy to study or understand. We cannot catch it, inspect it, or manipulate it the way we can a piece of matter. Perhaps we can better understand the difficulty in determining what light is by considering the following situation. You observe two people tossing some object back and forth between them. The object is moving too fast for you to see what it is, but you would like to examine it. You step in and catch the object and closely examine it. Let's say it turns out to be an ordinary baseball. The baseball in your hand is exactly the same baseball that was previously being tossed. The motion of the baseball had nothing to do with its being a baseball.

We would like to examine a light beam in the same manner, so we step in and "catch" the light beam in some appropriate material. As soon as we stop (absorb) it, we no longer have a light beam. We may have something else—heat, for example—but we don't have light. The motion of light is an intrinsic part of light. Without motion, light doesn't exist.

A MODEL FOR LIGHT

We cannot answer the question of what light is in this module, but we can learn a great deal about it. We will probe more deeply into the behavior of light, and try to predict its effects. We also wish to reveal any connections that might exist among the seemingly unconnected phenomena we observe. In order to do this we will try to develop a set of simple concepts that will help us to visualize what light is and how it behaves. Such a set of ideas is often called a *model.* A model is something people invent, thus a model for light is not light itself. Light reveals its true characteristics only through its observed behavior. In fact, the model we create may very well have some flaws in it which we can recognize but not know how to fix. Nevertheless, the model may help us to construct a set of mathematical equations that describe and predict the things that light does.

The model plus the set of equations constitute a *theory*. Because of their interpretive and predictive power, theories are very useful, though they must be discarded or modified if facts are discovered that are inconsistent with them.

Models of various kinds have played extremely powerful and useful roles in scientific thought. They have also proved to be tricky in many respects. For example, some models have proved to be consistent with limited ranges of measurements.

We shall develop a model for the behavior of light that has proved to be extremely useful in the range of *macroscopic* phenomena. In this module *macroscopic* implies situations like those we explored in the first part of this module, where light interacts with objects of substantial size such as reflecting and refracting boundaries, slits, gratings, films, etc. When it became possible to study the interaction of light with matter on a much smaller, *microscopic* scale (i.e., the interaction between light and atoms, molecules, electrons), it was found that a different model was needed to interpret that new range of experience.

Since light seems to involve some kind of motion, we shall refer to those kinds of motion with which we are familiar in everyday experience.

We know that light carries energy from one place to another, and so far no one has discovered or thought of any way to move energy that does not involve either the motion of matter (particles) or the propagation of a disturbance in matter without any flow of matter (waves). Does light behave like a stream of particles flowing from one place to another, colliding with and bouncing off obstacles as billard balls do? Or can we better understand the way light behaves by thinking of it as a wave? Our job is to try to predict how light would behave if it were either a stream of particles or some kind of wave motion. We must then compare these predictions with experimental observations, to determine which model fits the facts—if either does.

PARTICLE AND WAVE MODELS

The two models we have mentioned, the particle model and the wave model, are by no means new ideas. As long ago as the seventeenth century, both were offered as explanations of the behavior of light. Many eminent scientists of the day strongly supported the wave theory, and other equally eminent scientists argued strongly for the particle theory. In order to decide between two models, one must design an experiment whose outcome is predicted differently by the two theories. Then if the experiment is done carefully, the results from the actual performance will decide which model may be accepted. Even then, the model may be changed by new information.

You may now observe some of the behavior of waves and particles, and compare this with your earlier observations of light.

EXPERIMENT B-1. Particles and Waves

Part I

In this experiment you will study the behavior of particles and of waves and compare results with those for the behavior of light. In order to study particles, you have been provided with a box containing several small, spherical particles and several compartments in a row along the bottom of the box. This apparatus is shown in Figure 12. Several strips with single or double holes (analogous to slits) are also provided. These strips can be placed in the box. Select the strip with the most widely spaced pair of holes. Insert this strip through the slot on one side of the box and center the holes in the box. Turn the box upside down and shake it to get all of the particles in the upper portion of the box.

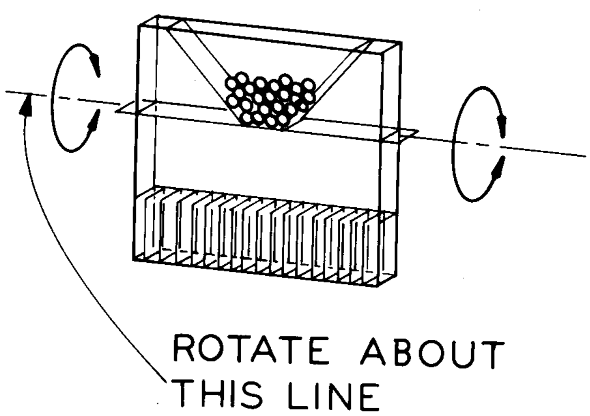

Figure 12.

Now, turn the box upright by rotating it about an axis parallel to the strip with the slits (keep the strip horizontal). Let the particles fall through the slits. (It may be necessary to tap the front of the box to get the particles to fall.)

1. Make a bar graph that shows the height of the column of balls found in each compartment.

2. Is the number of balls in the compartments between the slits larger than or smaller than the numbers in adjacent compartments?

Now change the strip in the box to one with the two slits closer together. Repeat the above procedure.

3. Make a bar graph showing the new distribution of balls in the compartments along the bottom of the box.

4. Did the distance between the two tallest bars on your graph increase or decrease after the slits were placed closer together?

Replace the strip with the one having the largest single slit. Repeat the procedure in 1 and 2.

5. As before, show the distribution of particles along the bottom of the box.

Change the strip to the one having the narrowest single slit. Repeat the procedure in 1 and 2.

6. As before, show the pattern of particles along the bottom of the box.

7. Did the pattern become wider or more narrow as the slit width became smaller?

Part II

In order to examine the behavior of waves, you will use a *ripple tank* arranged as shown in Figure 13. With the ripple tank, we can produce water waves and observe their behavior. Water waves are similar to other kinds of waves in many respects, and they are easy to observe. We study them here as a typical kind of wave.

Turn on the lamp above the tank and look at the white screen under the ripple tank. Using an eye dropper, release a drop of water so that it falls in the center of the tank.

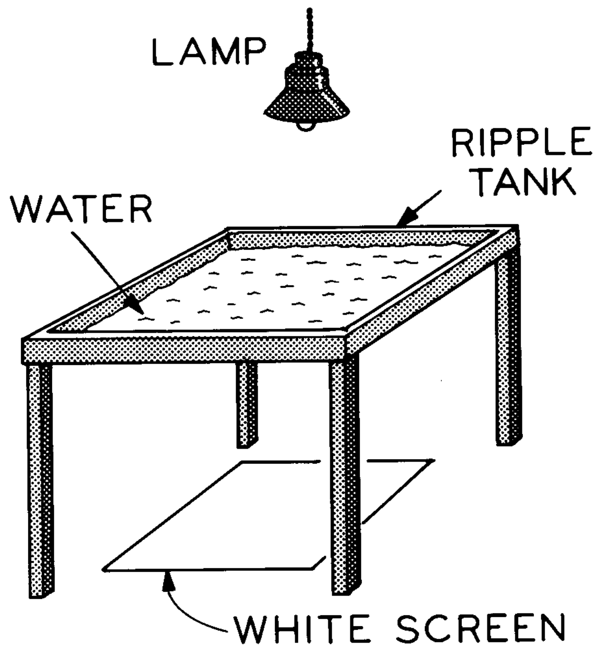

Figure 13.

Observe the resulting waves on the screen. You should see light and dark rings moving away from a center. This center corresponds to where the drop hit. If the rings are not distinct, lift up the screen until the rings are clearly seen on the screen. The light rings correspond to regions where the water is deepest (wave crests) and the dark rings correspond to regions where the water is most shallow (wave troughs).

You have been provided with a *straight-wave generator.* This generator consists of a straight piece of wood with a motor attached. Put the wood in the water and connect the motor to the battery. You should then observe straight waves moving away from the wave generator. Adjust the supports for the wave generator to give the straightest waves. Place three barriers about 10 cm in front of, and parallel to, the wave generator, as shown in Figure 14. The center barrier should be about 3 cm long and the width of the slit openings about 1 cm.

This arrangement provides a pair of slits through which the waves can pass. Thus it is analogous to the two-hole arrangement in the particle experiment and to the two-slit arrangement in the light experiment.

1. Sketch the pattern of waves seen on the screen beneath the ripple tank. Do this for waves on both sides of the barrier. The following questions will refer to the side of the barrier away from the wave generator.

2. Look at the surface of the water and identify the areas of maximum and minimum wave activity. Then identify the corresponding areas on your sketch.

3. Is the region along a line which is equidistant from the two slits one of maximum or minimum wave activity?

4. Draw a line along the central region of maximum wave activity (which is called a *maximum*). Draw a line along the adjacent region of minimum wave activity (which is called a *minimum*). Then draw another line along the maximum which is next to this minimum. Label each of these latter two lines and measure the angle which each line makes with the central maximum line.

Change the distance between the slits by replacing the center barrier by another barrier of a different length. Then readjust the outer

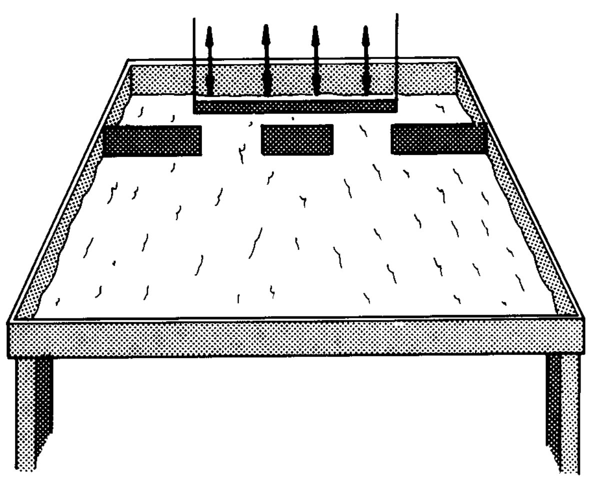

Figure 14.

barriers so that the width of each slit is the same as before.

5. Is the pattern seen on the screen generally the same as before? In what ways is it different?

6. As before, draw a line along the central maximum, the first minimum, and the next maximum. Measure the angles each of the latter two lines makes with the central maximum line.

7. How did the "spread" (the angles between lines drawn along adjacent maxima) of the pattern change as the distance between the slits changed?

Reduce the speed of the motor. This reduction of motor speed *increases* the distance between successive waves. (The distance between corresponding points on successive waves is called the *wavelength*.)

8. What effect does changing the wavelength have on the double-slit pattern?

Remove the center barrier and move the outer barriers to produce a single slit of about 10 to 15 cm width.

9. Sketch the resulting pattern of waves.

10. Move the barriers together to make a narrower slit (about 5 cm). Sketch the pattern.

11. Did the pattern become wider or more narrow as the slit width became smaller?

12. Place the barriers very close together (about 1 cm separation). Sketch the pattern as seen on the screen.

13. Do you see areas of maximum and minimum wave activity?

Part III

Look at the results obtained with light in Experiment A-1, Part II. Compare those results with the observations of this experiment.

1. When light passes through narrow slits, do you think it is behaving as particles or waves?

2. Why? (For example, compare the relative intensities of laser light at and near the center of a screen for a double-slit pattern with your answers to Question 2, Part I, and Question 3, Part II. Or compare the way the width of the central light band in a single-slit pattern varies with slit width and your answers to Question 7, Part I and Question 11, Part II of Experiment B-1.)

WHICH MODEL ACCOUNTS FOR INTERFERENCE?

If you now compare observations of Experiment B-1 with those from Experiment A-1, you should be able to decide whether the wave model or the particle model best explains interference. Your experience with water waves in the second experiment indicates that an interference pattern is formed when waves pass through two small openings. This pattern is formed by the overlapping of the two sets of waves created by the two slits. The interference pattern spreads out when the two slits are moved closer together. This same behavior was observed with laser light in Experiment A-1. On the other hand, the particle model predicts that just two spots of light would be produced by the particles coming through the two slits. We may therefore conclude that the double-slit experiment strongly supports the idea of a wave model of light.

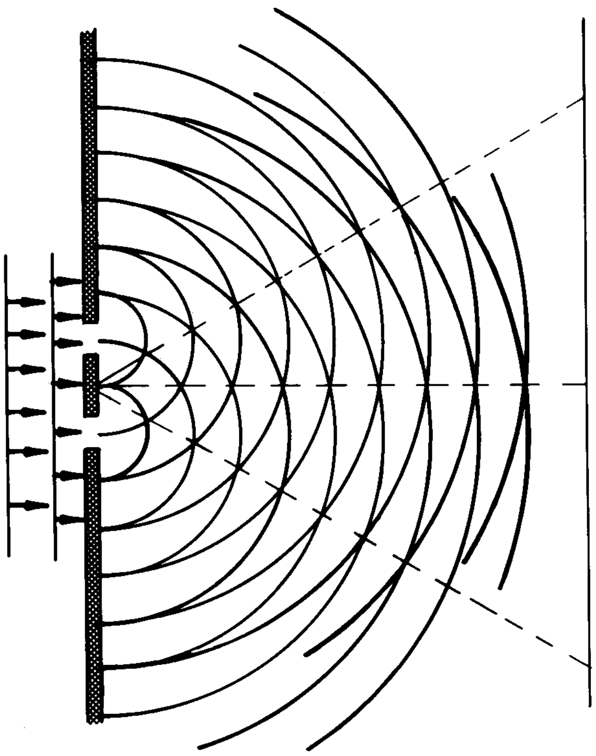

Figure 15.

YOUNG'S DOUBLE-SLIT EXPERIMENT

The double-slit experiment was one of the critical experiments which led to the acceptance of the wave model of light. All through the eighteenth century, a particle model of light was widely accepted, primarily because of the great influence of Newton. However, early in the nineteenth century, a number of interference experiments and calculations by the English scientist Thomas Young (1773-1829), and the French scientist Augustin Fresnel (1788-1827), changed the opinions of many. The double-slit experiment, first performed by Young, is often called Young's experiment.

CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

Young's explanation of the double-slit interference pattern can be understood with the aid of Figure 15.

In this figure, the straight lines to the left of the slits represent wave crests as viewed from the top. As the straight waves strike the double slits, the waves *diffract* and spread out from one slit as semicircular waves. This picture is much like the water-wave pattern obtained in Experiment B-1. In Figure 15, we are assuming that a straight-wave crest (or trough) hits both openings at the same time and that the two circular waves which form then spread out in the region beyond the slits. That is, each opening acts as a new source of circular waves. A circular-wave crest emerges from the upper slit at the same time that another circular-wave crest emerges from the lower slit. As these waves move away from the slits, they overlap everywhere. The overlapping waves from the two slits *interfere* with each other to produce a characteristic pattern. Where crest and crest (or trough and trough) meet, *constructive interference* produces a larger crest (or a deeper trough). Correspondingly, where crest and trough meet, *destructive interference* produces cancellation of the wave. Although the waves are continuously moving through the ripple tank, the *pattern* of destructive and constructive interference does not move. (For example, there is always constructive interference along the perpendicular bisector of the line connecting the two slits.) As you noticed in Experiment B-1, increasing the wavelength of the waves spreads out the interference pattern.

Question 6. Using the particle model, would you expect the center of the double-slit pattern to be brighter or darker than the places immediately to each side of the center? What does the wave model predict? Does the particle model predict more than two maxima? What about the wave model? How do these predictions compare with your observations of light made in Experiment A-1?

WAVELENGTH AND COLOR

The results of Experiment A-1 and Experiment B-1 have a number of implications for light. The appearance of an interference pattern, when light passes through two slits, rather than two spots of light, indicates that light is behaving like waves instead of like particles. The bright spots in the pattern occur at positions of constructive interference, where the resultant wave is large, and the dark spots are at the positions of destructive interference, where the resultant waves are very small. The interference pattern observed in Experiment A-1 for blue light, where the bright spots were closer together than for red light, suggests that blue light has a shorter wavelength than red light. Let us assume that different wavelengths of light give rise to different color sensations. Since red and blue are at the two ends of the visible spectrum, it is logical that the color red is caused by the longest wavelength we can see, and the color violet by the shortest. All the other spectral colors perceived are then produced by intermediate wavelengths. Then a prism separates white light, which is a mixture of all visible wavelengths, into all the spectral colors where each color corresponds to a certain wavelength of light. A non-spectral color is one that does not correspond to a single wavelength (actually a "single wavelength" is always a small interval of adjacent wavelengths). Non-spectral colors are mixtures of somewhat widely separated wavelengths.

Question 7. Would you expect light of a single wavelength to give rise to the sensation of brown? Why or why not?

HOW THE SLIT SEPARATION AFFECTS AN INTERFERENCE PATTERN

You have already seen that changing the separation between two slits affects an interference pattern. You can discover the relationship between slit separation and the angles between a maximum and the central maximum in an interference pattern by doing Experiment B-2.

EXPERIMENT B-2. The Interference of Light

For this experiment you will need the glass slide containing different single and double slits which you used in Experiment A-1. The slide contains a number of double slits; the separation between the two slits of each pair is different. You will need to know the separation in each case. This information may be given to you by your instructor, or he may ask you to measure slit separations with an appropriate instrument, such as a traveling microscope.

Place the narrowest set of slits in a laser beam and observe the pattern on a screen placed two meters from the slits. Figure 16 shows this arrangement as seen from above.

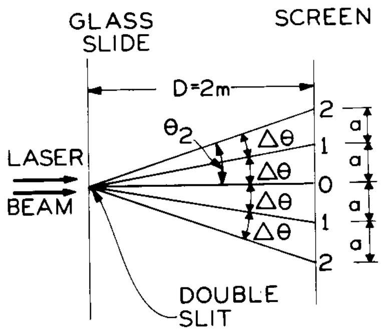

Figure 16.

The lines from the double slit represent the light paths leading to bright spots in the interference pattern. The numbers 0, 1, and 2 are placed where the various spots appear on the screen. The Greek letter *theta* (θ) is used to represent the angle between the line to the central bright spot, labeled 0 on the screen, and the line for any other bright spot in the pattern. For example, the angle θ_2 is shown for the second bright band from the center of the screen. The angle between lines corresponding to each of the bright bands is labeled $\Delta\theta$. The Greek letter *delta* (Δ) is used to represent "a change in" some quantity; in this case, in an angle.

Since the angular separations, $\Delta\theta$, are quite small, the angle (in radians) may be calculated by dividing the distance a (in meters) between the bright bands on the screen by the distance D from the slits to the screen (2 m).

1. What is the distance between bands?

2. Find $\Delta\theta$ in radians.

3. What is the distance d between the slits in meters?

Repeat the above procedure for three more pairs of slits with different values of d. Record your data in the table in the work sheets at the end of the module.

4. How does $\Delta\theta$ change as d increases?

If $\Delta\theta$ decreases as d increases, one *possible* relationship is that $\Delta\theta$ is proportional to $1/d$. To test for this relationship calculate the values of $1/d$ and record them in the table in the work sheets. (From now on we will use the symbol "m" to represent "meter" and "m^{-1}" to represent "reciprocal meter" (1/meter).

Plot a graph of $\Delta\theta$ on the vertical axis and $1/d$ on the horizontal axis.

5. Is this graph a straight line?

6. Draw the best straight line through your points which passes through the origin. (If this relationship is really a proportionality, the line must go through the origin.) Calculate the slope of the line.

7. What are the units of the slope?

CONCLUSIONS BASED ON EXPERIMENTAL RESULTS

In Experiment B-2 you discovered the relationship between the angular separation, $\Delta\theta$, of two adjacent spots in an interference pattern (diffraction pattern), and the separation between the slits, d. This relationship, *for small angles,* is expressed as

$$\Delta\theta \approx (\text{constant}) \times 1/d \qquad (1)$$

where $\Delta\theta$ is the radians and d is in meters. The constant in Equation (1) is a very small length, about 6×10^{-7} m. Since increasing the wavelength in a double-slit experiment spreads out the interference pattern (increases $\Delta\theta$), then the constant must have something to do with wavelength. As a matter of fact, the constant *is* the wavelength. Equation (1) can be used as a definition of wavelength. If we let the Greek letter *lambda* (λ) stand for the wavelength, and substitute λ for the constant in Equation (1), we obtain

$$\Delta\theta \approx \lambda/d \qquad (2)$$

This formula is valid for small angles ($\Delta\theta$ less than about 10°).

Problem 1. When a light source which emits violet light is used to produce a double-slit pattern, the bright bands are found to be separated by 0.40 cm. If the screen is 2.00 m from the slits, and the slit separation is 0.20 mm, what is the wavelength of this violet light? (Note that we can calculate very small wavelengths from measurements of the much larger distances of interference patterns.)

WHAT ABOUT LARGE ANGLES? (Optional)

What is the correct equation for the separation of bands when the angle θ is large? Although we do not have time in this section of the module to examine the case experimentally for larger angles, we can describe the results of such experiments. For any double-slit interference pattern, the relationship between wavelength slit separation and angle of "spread" is found to be given by

$$\sin\theta = \lambda/d \qquad (3)$$

Here the angle θ is measured from the central bright spot to the first adjacent bright spot. The correct relationship for the sixth, seventh, or Nth bright spots, for instance, would be

$$\sin\theta = N\lambda/d$$

$N = 0$ refers to the central bright spot, $N = 1$ refers to the first adjacent bright spot on either side of the central spot, $N = 2$ refers to the next spot, and so forth.

This equation may be represented in a different form by multiplying both sides by d, giving

$$N\lambda = d\sin\theta \qquad (4)$$

λ, d, and θ have already been defined, and N, the number associated with each bright spot, counting from the central bright spot, is called the *order* of that spot.

Problem 2. Sound is a wave which travels through air and other materials. Suppose that the wavelength of a certain pitch of sound is 80 cm. What separation would you need between two "slits" to produce an interference pattern of sound with a first order maximum at an angle of 30° with respect to the central maximum?

LIGHT WAVES HAVE SHORT WAVELENGTHS

We conclude that light behaves like waves, and that this behavior is clearly shown by the formation of interference patterns. What sort of wave is light? For example, what is it that causes the light to move from one place to another? Such questions are very puzzling. For now, we simply note that no material seems to be necessary, since light crosses the empty regions of outer space.

Different wavelengths of visible light are seen as different spectral colors. The wavelengths for visible light are quite small, for example, about 6.5×10^{-7} m for red light, and the wavelength of blue light is about 4.5×10^{-7} m.

Problem 3. The prefix *nano* means 10^{-9}. Express the wavelength of violet light in nanometers (nm). Do the same for the wavelength of red light.

LIGHT WAVES HAVE HIGH FREQUENCY

The small wavelength of light and its high speed imply a very high frequency for the light waves. The speed of light in empty space is about 3×10^8 m/s. We can use the wave relationship which connects the speed, wavelength, and frequency of *any* wave, to find the frequency ν of a light wave*

$$\lambda\nu = c \tag{5}$$

For green light, with $\lambda = 500$ nm, solving Equation (5) for ν

$$\nu = c/\lambda \tag{6}$$

$$\nu = \frac{3 \times 10^8 \text{ m/s}}{0.5 \times 10^{-6} \text{ m}} = 6 \times 10^{14} \text{Hz}$$

This result means that six hundred trillion waves per second are emitted by the source and, correspondingly, six hundred trillion waves pass a given point in the path of this light every second.

Problem 4. Find the frequency of deep violet light. Which has the higher frequency, red light or violet light?

THE ELECTROMAGNETIC SPECTRUM

The small wavelength of light was an important reason why its wave properties were not discovered for a long time. The visible spectrum ranges from about 700 nm (red) to 400 nm (violet) in wavelength. Actually, we know now that the visible spectrum is just a small part of a much larger *electromagnetic spectrum.* Light is one type of *electromagnetic wave*; all electromagnetic waves travel at the same speed in empty space, $c \approx 3 \times 10^8$ m/s, and they are identical except for wavelength. Our eyes respond only to those wavelengths we call light. Figure 17 is a diagram of the electromagnetic spectrum.

The wavelengths of light from available lasers extend into the ultraviolet and infrared portions of the spectrum. Table 1 is a short listing of the more common laser materials and wavelengths.

Table I.
Laser Materials and Wavelengths

Active Material	λ(nm)
Ruby	694.3
Helium-Neon	632.8
Neodymium in glass	1060
Gallium Arsenide	840
Carbon Dioxide	10,600
Argon	488
Argon	514.5
Helium-Cadmium	442

MONOCHROMATICITY AND TEMPORAL COHERENCE

Any laser produces light which is very nearly a single wavelength. Light of a single wavelength is called *monochromatic* light. Truly monochromatic light does not exist. However, the term is also applied to light which has a very narrow spread of wavelengths. In this sense, laser light is monochromatic. Ordinary light sources may be made nearly monochromatic by using good filters. However, the filtering of such a source reduces the useable light output to a level which is extremely low. Laser light does not require filtering; it is nearly monochromatic and very intense.

The *monochromaticity* of laser light is closely related to another important property

*The Greek letter *nu* (ν) is commonly used for frequency.

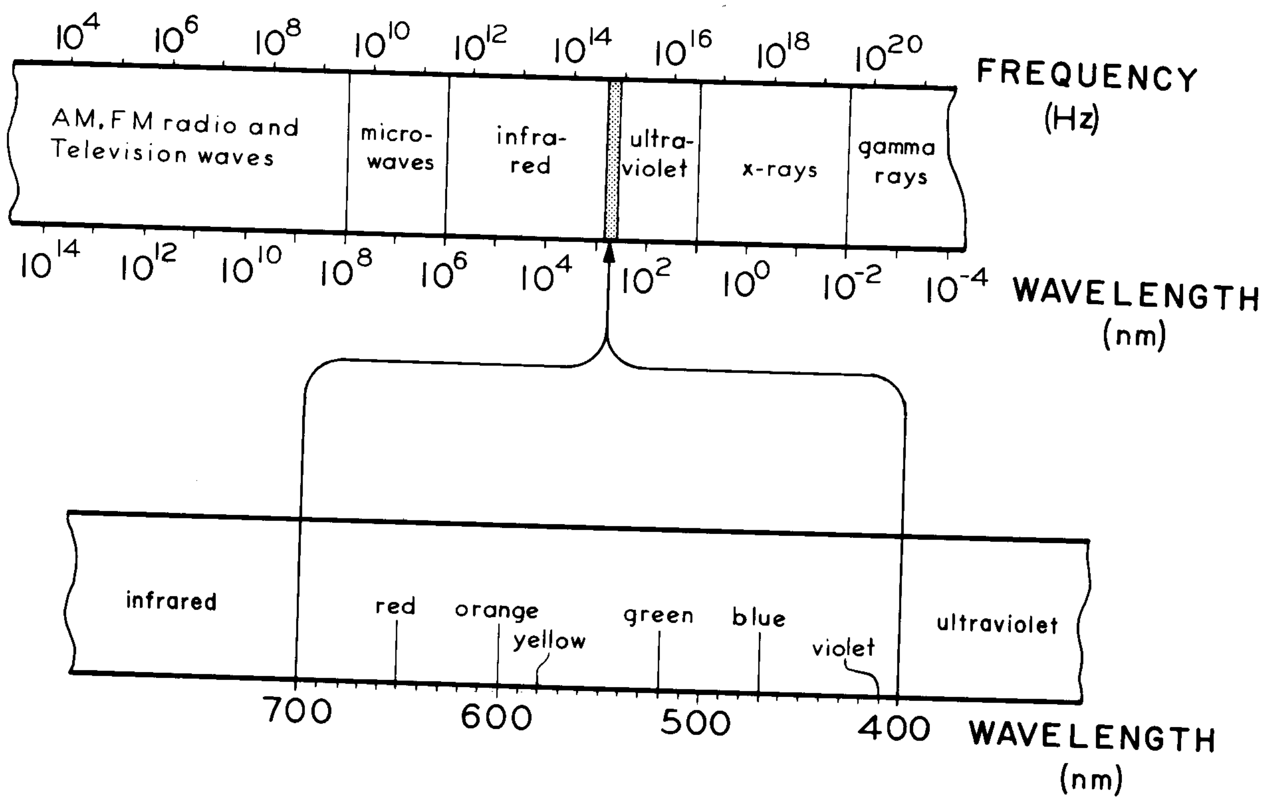

Figure 17.

called *temporal (time) coherence.* To say that light has *temporal coherence* means that the light waves emitted by a source at one time have a fixed relation to the waves emitted at a later time. As indicated in Figure 18, temporally coherent light is in the form of long wave *trains*, instead of shorter, unrelated wave *pulses*.

Suppose, for example, that you could sit and watch waves move past some point in space. If the waves possess temporal coherence, then the time between passage of successive wave crests is always the same. A similar statement can be made about the time of passage of any other part of the wave, such as wave troughs. If the waves do not have temporal coherence, the time from crest to crest will vary. If we could start at a crest with light which does not possess temporal coherence, and wait a whole number of periods as the wave passes by, we would be as likely to arrive at a trough or any other point on the wave as we would a crest.

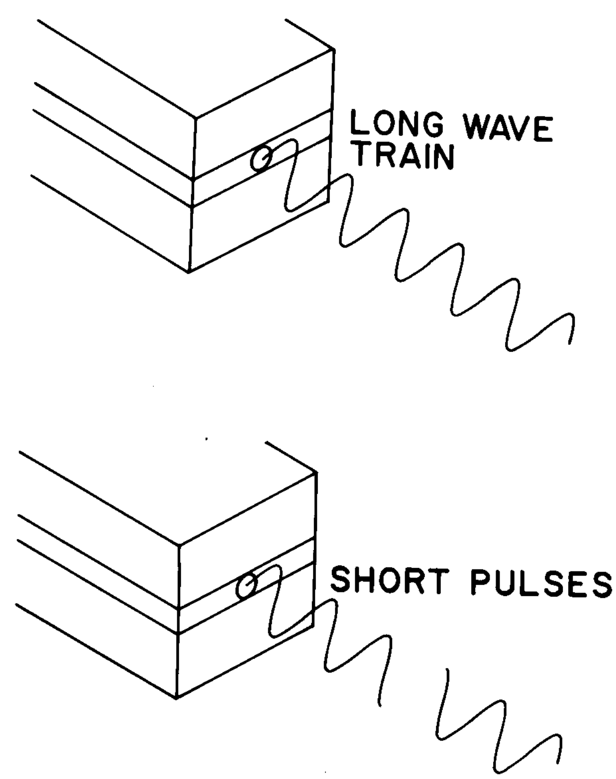

Figure 18.

SPATIAL COHERENCE

Laser light possesses another kind of coherence which light from an ordinary source does not have. It is called *spatial coherence* (coherence in space). Spatial coherence means a fixed relationship between waves that are in different regions of space. For example, one might imagine two parts of a laser beam as they pass through different points of a plane which is perpendicular to the beam. Then, the two parts of the beam may pass through the plane in such a way that both have crests (or troughs) at the plane at the same time. In that case, the two waves are said to be *in phase*, and spatially coherent. If the crest of one wave passes the plane every time a trough of the other wave passes, the two waves are said to be *out of phase*. They are still spatially coherent. If the *phase relationship* (relationship between the crests and troughs of one part of the wave and those of the other part) remains the same for some period of time, the waves are said to possess temporal coherence for that period of time. The period of time during which the wave is temporally coherent is called the *coherence time*.

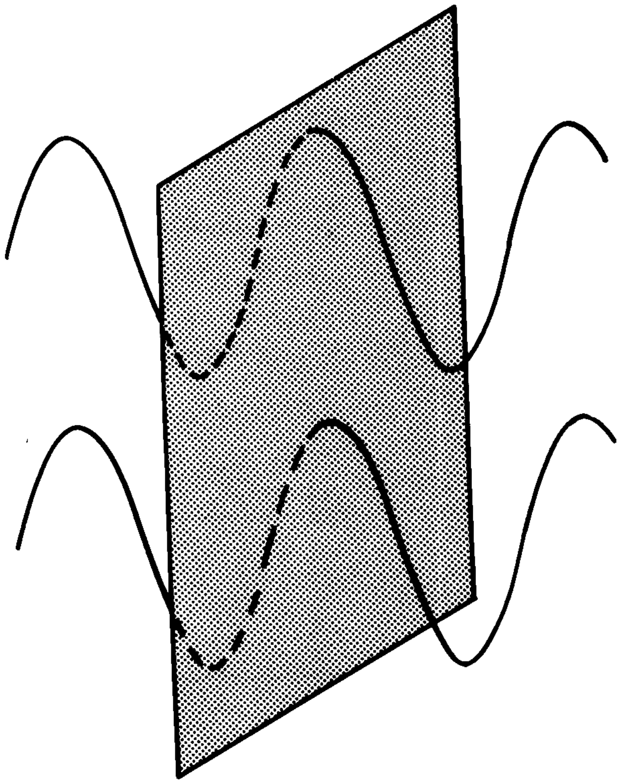

Figure 19A.

Figure 19A shows two waves which have both temporal and spatial coherence passing through a plane in phase.

Figure 19B shows two waves which have both temporal and spatial coherence passing through a plane out of phase.

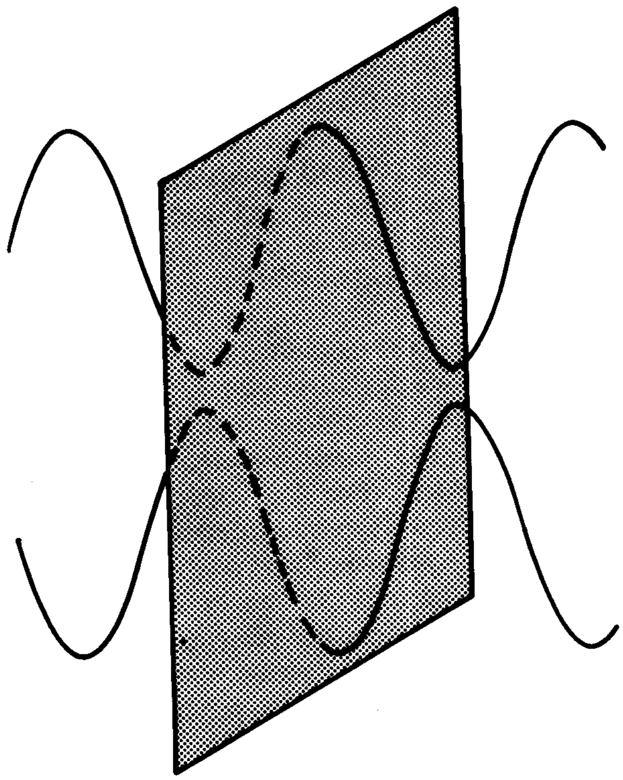

Figure 19B.

If there is no fixed relationship between the light at two separate points of the plane (i.e., no relationship that persists for longer than the time of a simple wave cycle), the light is spatially incoherent. However, incoherent light tends to "smooth out" as it moves away from the source. This can be understood by considering the *wavefronts* of the light. For a wave which consists of many small pieces, the adjacent crests (or troughs) can be connected together to form a surface, as indicated in Figure 20A. If this surface is a plane, the wave is called a plane wave. If wavefronts are constructed through successive crests, the result is a set of parallel surfaces separated by one wavelength and moving together, as shown in Figure 20B. To make the drawing easier, lines are customarily drawn to represent cross sections of the wavefronts, as shown in Figure 20C. For a small source, the wavefronts are spherical. Figure 21A represents a portion of spherical wavefronts for a coherent source. In the ripple tank, the wavefronts were seen as straight lines (on the source side of the slits) or as semicircles (on the other side of the slits). If the light is incoherent, the wavefronts are "wrinkled" in random ways, as shown in Figure 21B.

You can also use a small *aperture* (opening) to obtain spatially coherent light without the inconvenience of moving so far away from the source. By allowing only a small portion of the wavefront to come through the opening, a smoother portion of wavefront is obtained, which then spreads out as shown in Figure 22. At a great distance from the source this "wrinkling" becomes relatively less important because one uses only a small fraction of the whole wavefront. But the improved coherence at great distances is at the expense of decreased intensity. The smoothing action of the small aperture can

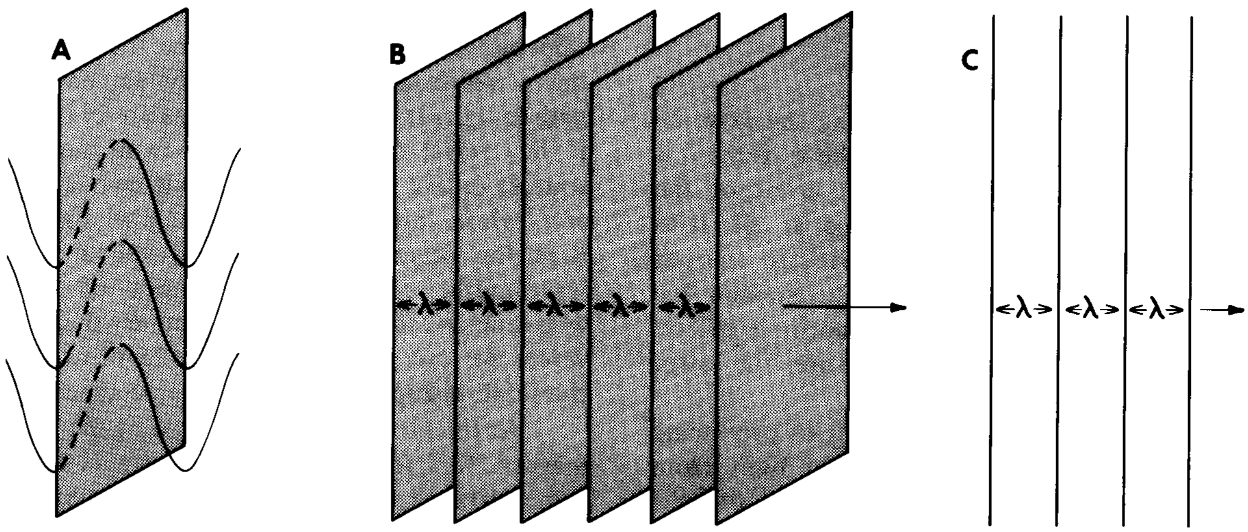

Figure 20A, B, and C.

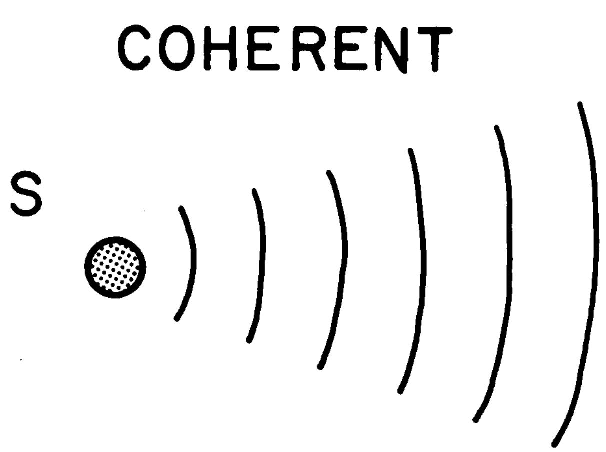

Figure 21A.

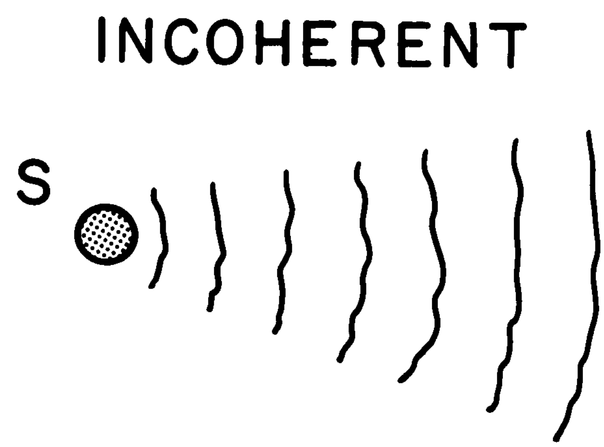

Figure 21B.

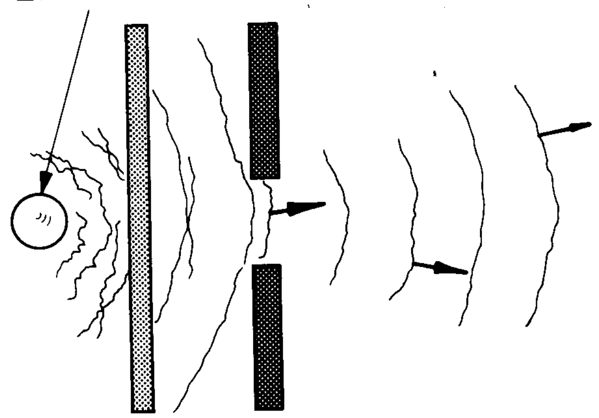

Figure 22.

best be explained by considering the extreme case where only one point of the wavefront is allowed to pass through. One point of the wavefront has no irregularities at all. It is exactly the same as if a perfectly smooth wavefront hit the opening. The smaller the aperture, the better the smoothing effect. However, the smaller the aperture, the lower the light intensity.

All of the various methods of producing spatially or temporally coherent light from *ordinary* sources reduce the amount of light available. The better the coherence obtained, the less light there is to work with. *Lasers* produce light which is spatially and temporally coherent and quite intense.

Question 8. Explain how you would obtain light that is both spatially and temporally coherent from an incandescent lamp.

INTERFERENCE

When two waves of the same kind meet in space, they add together. This basic property of all waves is called *superposition.*

Imagine that you have two identical light sources, such as two lasers, which produce light beams which are perfectly coherent with each other (this is theoretically possible, but very difficult to do in practice). You could then aim the two beams at the same point on a screen. If the two waves were in phase, they would add up to create a bright spot on the screen. Such "adding up" of waves is called *constructive interference.* If the two beams were completely out of phase, they would cancel each other out and produce a dark spot (no light). This process is called *destructive interference.*

In the ripple-tank experiments, the two slits serve as sources of two coherent waves whose crests and troughs you can actually see. Further, you can see that the two waves show constructive interference at some points, and destructive interference at other points. At still other points, there are various mixtures of the two types of interference. The relationship between phase and distance traveled by the waves from the source to the screen (the path length) is that the two waves are in phase if they travel the same distance from the two sources (equal path lengths), or if one travels any whole number of wavelengths further than the other. If one wave travels a half-wavelength, or any odd number of half-wavelengths, farther than the other, the two waves are out of phase. Figure 23 illustrates the relationship for waves in a ripple tank.

At the point on the right side of the tank marked "0," the two waves have traveled the same distance from the slits and are in phase, producing constructive interference. At the points labeled "½," one wave has traveled a half-wavelength farther than the other, so they are out of phase. At the points marked "1," the two waves are in phase again because one of the waves has traveled a full wavelength farther than the other, and so on.

The double-slit experiments with light are slightly more subtle. Since laser light has both temporal and spatial coherence, an interference pattern is created whenever a laser beam passes through two closely spaced slits. The light diffracts and spreads out as it passes through each slit, causing two coherent waves which then interfere in the same way as do water waves. The bright spots in the interference pattern are points of constructive interference, and the dark spots are points of destructive interference. Interference patterns

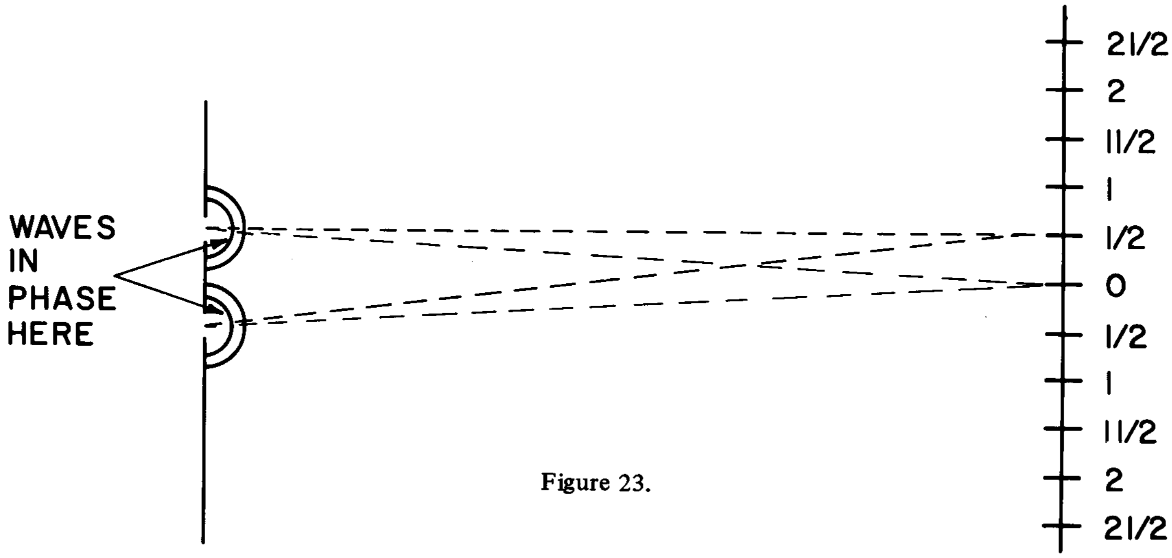

Figure 23.

are more difficult to obtain with ordinary light because it lacks coherence. More will be said about the relationship between the number of interference spots observed and the coherence of the light in Section C of the module.

In Experiment A-1, you observed another type of interference. The interference bands seen with the two optical flats are caused by interference between light beams reflected from the glass on the top and bottom surfaces of the "sandwich" of air between the flats. Referring to Figure 24, the light entering the eye from point A reaches the eye by two different paths. One of these is a path which is reflected from point A. The other is light which has been reflected from point B through point A to the eye. Since the two light beams reaching the eye from point A have traveled different distances, they may not be in phase. Whether or not they are in phase depends on the difference in path length of the two light beams, and on the wavelength of the light. The dark bands are caused by destructive interference, while the light bands are caused by constructive interference. The fact that the bands you observed were parallel is an indication that the glass surfaces of the optical flats are really "flat." The interference patterns created by an optical flat on a non-flat surface are complex swirls of light and dark bands, instead of parallel, straight bands.

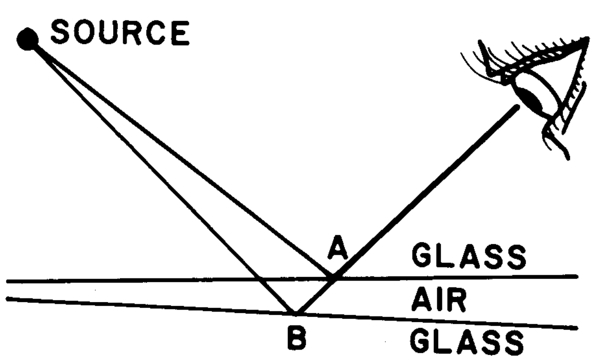

Figure 24.

WAVES AND HOLOGRAPHY

With the aid of the wave theory of light, we can study some of the applications of the laser in more detail. For instance, the theory of holography was worked out, using the idea that light is a wave, before lasers were invented. Coherent light is necessary to make holograms, therefore they were very difficult to make before laser light was available. The hologram does not have to be made with the same wavelength light as is used to view the image. In terrain-mapping radar systems, for example, holograms are made from the reflected radar wave information. The holograms are then viewed with visible light.

Holograms can also be made by using a combination of sound and light waves. Such *acoustic* holograms are then viewed with light. This technique has promising medical applications because sound waves can penetrate the body. Someday this technique may surpass the x-ray in importance for viewing internal organs. The advantages of holography over x-ray include the possibility of a much more detailed picture, particularly of soft tissues, and the absence of radiation danger.

WAVES AND COMMUNICATIONS

Light can be used to transmit information. Radio and television broadcasting are examples of the use of other electromagnetic waves for the transmission of information. Before lasers, there were no powerful sources of coherent light waves that could be used for communication. The advantage of using light frequencies for communication lies in the high frequency that is available. The higher the frequency of the wave, the greater the amount of information which can be carried by it. Presently available radio, television, and microwave broadcast bands cover a range of about 9.5×10^9 Hz, but the visible and near-by infrared frequencies cover a range of about 9×10^{14} Hz. This great frequency range implies that a great deal of information could be carried by light waves, at least theoretically. The problem is that an effective way must be found to *modulate* and *demodulate* light waves. Modulation means varying the wave in some manner in order to have it carry information. Correspondingly, demodulation means translating the modulated wave back into the desired information at the receiving end. These techniques are not nearly so well developed at optical frequencies as they are at lower frequencies. Still, we might expect that telephone conversations will at some future date be carried on laser light beams propagating down long, evacuated tubes.

SUMMARY

The following statements summarize the concepts, definitions and principles you have learned in this part of the module.

Light travels from its *source* at an extremely great speed: 1.86×10^5 mi/s or 3×10^8 m/s in empty space.

A *model* for the behavior of light is a mental picture that can be used to visualize the effects and processes that light exhibits.

Macroscopic refers to objects of substantial size, usually large enough to be seen with the eye.

Microscopic refers to objects the size of atoms or molecules.

The *color* of a light wave as seen by the eye corresponds to the wavelength of that light wave.

The angular separation of the bright bands in an interference pattern (diffraction pattern) is inversely proportional to the separation between the slits. In equation form, for small angles, this relationship is

$$\Delta\theta = \lambda/d$$

The quantity λ is the wavelength and d is the separation of the slits.

The number of bright bands (maxima) from the central maximum in an interference pattern to another given maximum is called the *order* of that maximum.

(Optional) For all angles of separation, and for all orders *(N)*, the relationship among angular separation, wavelength, slit separation, and order number is

$$N\lambda = d(\sin\theta)$$

The wavelengths of the visible spectrum vary continuously from about 7×10^{-7} m for the longest visible wave (*red*), down to about 4×10^{-7} m for the shortest visible wave (*violet*).

The frequencies of the visible spectrum range from about 4×10^{14} Hz to 7.5×10^{14} Hz.

Monochromatic light refers to light that is very nearly a single color, or likewise a single wavelength.

Temporal coherence (coherence in time) is a measure of the extent to which light waves are continuous and uninterrupted in time.

Spatial coherence (coherence in space) is a measure of the extent to which wavefronts are smooth and coordinated.

Laser light has a high degree of spatial and temporal coherence in a beam which diverges only slightly.

White light (from an incandescent source) is highly incoherent, both spatially and temporally. It can be made more coherent by means of a filter and a slit. To bring it to a high degree of coherence requires a great loss of intensity of light.

GOALS FOR SECTION C (OPTIONAL)

The following goals state what you should be able to do after you have completed this section of the module.

1. *Goal:* Understand the concepts of bandwidth and fractional bandwidth.

   Item: A filter is centered at 500 nm and has a 10-nm linewidth. What is the frequency bandwidth of the light it passes?

2. *Goal:* Understand the concepts of coherence time and coherence length.

   Item: A laser emits wave trains 100 waves long with a wavelength of 442 nm. What is the coherence time of this source?

3. *Goal:* Understand the nature of spatial and temporal coherence required for interference experiments.

   Item: The air film between two optical flats is 0.03 mm thick. What is the maximum bandwidth of sodium light ($\lambda = 589$ nm) that would give good interference fringes?

4. *Goal:* Understand how the concepts of atomic energy levels and photons are related to the emission and absorption of light.

   Item: What frequency of light would be emitted by a hydrogen atom when it falls from the fifth to the third energy level?

5. *Goal:* Understand the terms spontaneous emission, stimulated emission, natural linewidth, and Doppler linewidth.

   Item: Which of the previous four terms best fits the description "it can be roughly calculated from the lifetime of the excited state?"

6. *Goal:* Understand the concept of population inversion and the methods for achieving it.

   Item: In the ruby laser how short would the lifetime of the intermediate state need to become before an inverted population would be impossible?

7. *Goal:* Understand how the end mirrors of a laser produce a narrow bandwidth.

   Item: How long should the resonant cavity of a He-Ne laser be in order to produce ten axial modes within the Doppler broadened line with $\Delta\nu_D / \approx 10^{-5}$?

Answers to Items Accompanying Previous Goals

1. 1.2×10^{13} Hz
2. 1.47×10^{-13} s
3. 5×10^{12} Hz
4. 2.34×10^{14} Hz
5. Natural linewidth
6. About 10^{-9} s
7. 0.317 m

SECTION C (OPTIONAL)

An Analysis of Laser Light

BANDWIDTH

The monochromaticity of light can be related mathematically to its temporal coherence. To do this we need a quantitative measure of monochromaticity. The range of frequencies emitted by any light source is usually referred to as the *bandwidth* or *linewidth*. Laser light has a spread of frequencies (a non-zero bandwidth) although it is usually small compared to light from other sources. It is important to remember that bandwidth refers to a *range* of frequencies, not to the actual frequencies. For example, we might speak of the "bandwidth" of heights of people in a classroom: such a "bandwidth" might be 1 foot, the difference between the tallest and shortest persons in the room, whereas the average height itself might be 5 feet 9 inches. Similarly, the bandwidth of laser light may be about 10^8 Hz, spread about a central light frequency of more than 10^{14} Hz. If we use $\Delta\nu$ to represent bandwidth and ν to represent frequency, then for a typical helium-neon (He-Ne) laser the ratio of bandwidth to central frequency is

$$\Delta\nu/\nu \approx 10^8/5 \times 10^{14} \approx 2 \times 10^{-7}$$

The bandwidth of laser light may be only about 0.0001% of the average frequency, whereas in the previous example of heights the "height bandwidth" was about 15% of the average value.

The ratio of the bandwidth to the average frequency, called the *fractional bandwidth,* is a common way of expressing how monochromatic a source is. A small range of frequencies, $\Delta\nu$, implies a small range of wavelengths, $\Delta\lambda$, because wavelength and frequency are related through Equation (5), and the fractional ranges are equal.

$$\Delta\nu/\nu = \Delta\lambda/\lambda \qquad (7)$$

The small bandwidth of laser light is one of the things that distinguishes the laser from all other light sources and leads to the very pure color of laser light.

Problem 5. About what range of wavelengths would be expected from the typical He-Ne laser if the center wavelength is 633 nm?

COHERENCE LENGTH

The fractional bandwidth is a measure of the monochromaticity of a source; the length of an emitted wave train, ΔL, is a measure of the temporal coherence of the source. This length is called the *coherence length*. Because the wave travels at a constant speed, the coherence length can be written in terms of the time interval, Δt, during which the wave train is emitted (also called *coherence time*).

$$\Delta L = c\Delta t \qquad (8)$$

It turns out that we can relate, in an approximate manner, the time of emission to the bandwidth of frequencies emitted. Since the relationship is simple, while the derivation of it is not, we shall just state it for use at this time:

$$\Delta t \approx 1/\Delta\nu \qquad (9)$$

where Δt is in seconds (s) and $\Delta\nu$ is in hertz (Hz). Combining Equations (8) and (9), we obtain a relationship between coherence length and bandwidth

$$\Delta L \approx c/\Delta\nu \qquad (10)$$

Equation (10) states that a small bandwidth (highly monochromatic light) means a large coherence length (high temporal coherence), and vice versa. The temporal coherence of laser light is another aspect of its monochromaticity.

Example Problem. What is the coherence length of a He-Ne laser whose bandwidth is 10^8 Hz?

Solution. Given is $\Delta\nu = 10^8$ Hz, and we know already that $c = 3 \times 10^8$ m/s. These values may be substituted directly into Equation (10).

$$\Delta L = \frac{3 \times 10^8 \text{ m/s}}{10^8 \text{ Hz}}$$

Since $\quad 1 \text{ Hz} = 1/\text{s}$

$$\Delta L = 3 \text{ m}$$

Problem 6. What is the coherence length of a ruby laser with bandwidth 2×10^9 Hz?

Problem 7. If the ruby laser of the above problem has an average wavelength of 694 nm, what range of wavelengths is emitted?

Problem 8. If white light is passed through a filter with center wavelength of 500 nm and a bandwidth of 1 nm, what is the resulting coherence length of the light?

INTERFERENCE REQUIRES COHERENCE

Considerable spatial coherence and some temporal coherence are required to produce a double-slit interference pattern. Spatial coherence is the major factor because the interference is between different parts of wavefronts emitted at the same, or very nearly the same, time. In other words, the interference is between different portions of the same or nearby wavefronts, and these portions must have a fixed relationship with each other to produce a stationary interference pattern.

In Figure 25, the points a and b represent the portions of the wavefronts which will pass through the two slits and spread out into new coherent wavefronts. After passing through the slits the wave from point a on wavefront 1 will add constructively with that

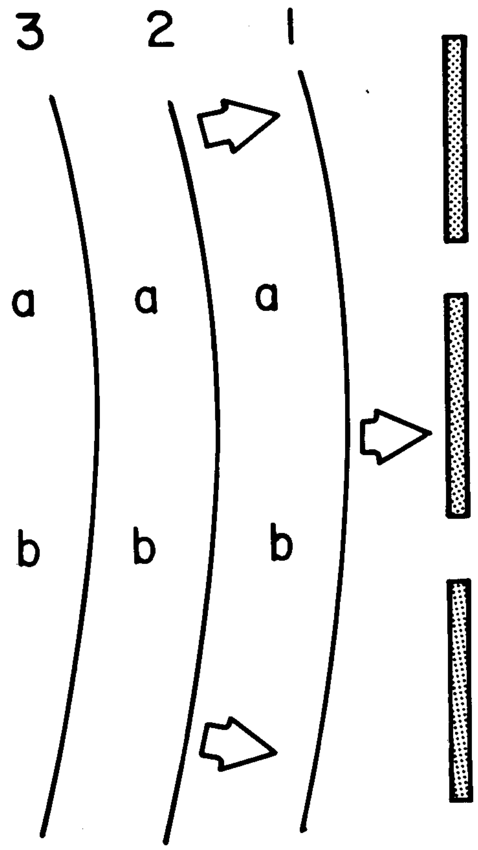

Figure 25.

from point b of the same wavefront in the center of the screen. This produces the central maximum of the interference pattern. (This is also called the zeroth-*order* maximum.) Similarly, the waves produced from points a and b of wavefronts 2 and 3 will add at later times to produce the same central maximum. To produce an adjacent maximum, called the first-order, the wave from point 1a interferes constructively with that from point 2b, 2a with 3b, etc. This maximum is at an off-center position which must be closer to the lower slit in the figure, for the two waves to arrive in phase. The next, second-order, maximum is produced by constructive interference between points 1a and 3b, 2a and 4b, etc. Thus we can conclude that very little *temporal* coherence is required for the center of the interference pattern, but more temporal coherence is required for the edges of the pattern where wavefronts are interfering with others several wavelengths away.

For an interference pattern containing ten orders, besides the central one, the wave train must contain at least eleven equally spaced wavefronts. The tenth-order maximum is produced by constructive interference of the first wavefront passing through one slit with the eleventh wavefront through the other slit.

The time required for eleven wavefronts to pass through the slits is very short. For light having an average wavelength of 6×10^{-7} m, the coherence time Δt required is given by the equation

Total length of wavetrain
= speed × coherence time

or for n waves, measuring from the first to the nth wavefront

$$(n - 1)\lambda = c\Delta t \qquad (11)$$

or, where there are 11 wavefronts

$$10 \times 6 \times 10^{-7} \text{ m} = 3 \times 10^{8} \text{ m/s} \times \Delta t$$

Solving for Δt, this gives

$$\Delta t = \frac{6 \times 10^{-6}}{3 \times 10^{8}} = 2 \times 10^{-14} \text{ s}$$

This temporal-coherence time corresponds to a coherence length of 6×10^{-6} m or ten wavelengths. The slit separation you have used in the laboratory is about 0.1 mm, or about 100 wavelengths. In order to get a stationary interference pattern, the waves must be spatially coherent for about this distance along the wavefronts. Thus even if temporal coherence is poor, compared with the spatial coherence, we can still get double-slit interference with several orders.

You should now do Experiment C-1.

EXPERIMENT C-1. Spatial and Temporal Coherence

Part I: Spatial Coherence

Suppose two beams of light leaving a single source in different directions pass through slits, diffract, and thus overlap in the space beyond the slits. They will form interference patterns only if the light is spatially coherent over the distance separating the slits.

Place an incandescent lamp at one end of an optical bench. Immediately in front of the lamp place a piece of frosted glass that has been masked except for a strip two or three millimeters wide running vertically down the center. From a distance of about two meters, look at the frosted glass through a pair of closely spaced slits. With the slits parallel to the unmasked strip of the frosted glass, look for an interference pattern of bright and dark fringes.

1. Is there evidence of interference?

While looking through the slits, move closer to the frosted glass.

2. Do you observe any change in the interference pattern?

Continue moving closer to the frosted glass until the slits are just a few centimeters from the frosted glass.

3. Is there now evidence of interference? How would you explain this?

> CAUTION: Never look directly into laser light.

Now place a white screen at the end of the optical bench and a pair of slits about 10 cm in front of the screen. Mount the laser at the other end of the optical bench and illuminate the pair of slits with the laser beam. Look for an interference pattern on the screen.

4. Is there evidence of interference?

Move the laser toward the slits until it is as close as possible while still illuminating both slits.

5. Do you observe any change in the interference pattern?

6. From these observations, what can you say about the spatial coherence of laser light compared with that from the incandescent lamp?

Part II: Temporal Coherence (Coherence Length)

The purpose of this experiment is to compare the coherence length of two kinds of single-color light: the almost "pure" (narrow bandwidth) light from a laser, and the less "pure" (wider bandwidth) light from a filtered mercury lamp. To do this you will compare the quality of different interference fringes obtained with a *Michelson interferometer*. An *interferometer* is a device which uses the phenomenon of interference to measure very small distances. In the Michelson version, a beam of light from the source shines on a special mirror (*beamsplitter*) which transmits half of the light beam and reflects the other half of the light beam. The transmitted part of the beam travels to a regular mirror and is reflected back. The reflected half of the original beam travels (in a direction perpendicular to that of the transmitted beam) to another mirror and is also reflected back. These two parts of the original beam are then recombined by the beamsplitter to produce interference fringes similar to those you saw in Experiment A-1. These interference fringes arise because the two parts of the beam travel slightly different distances between the point where the beam is split and the point where the two beams recombine. The interference pattern is determined by this path difference.

Set up the interferometer and mercury light source with a green filter (Figure 26).

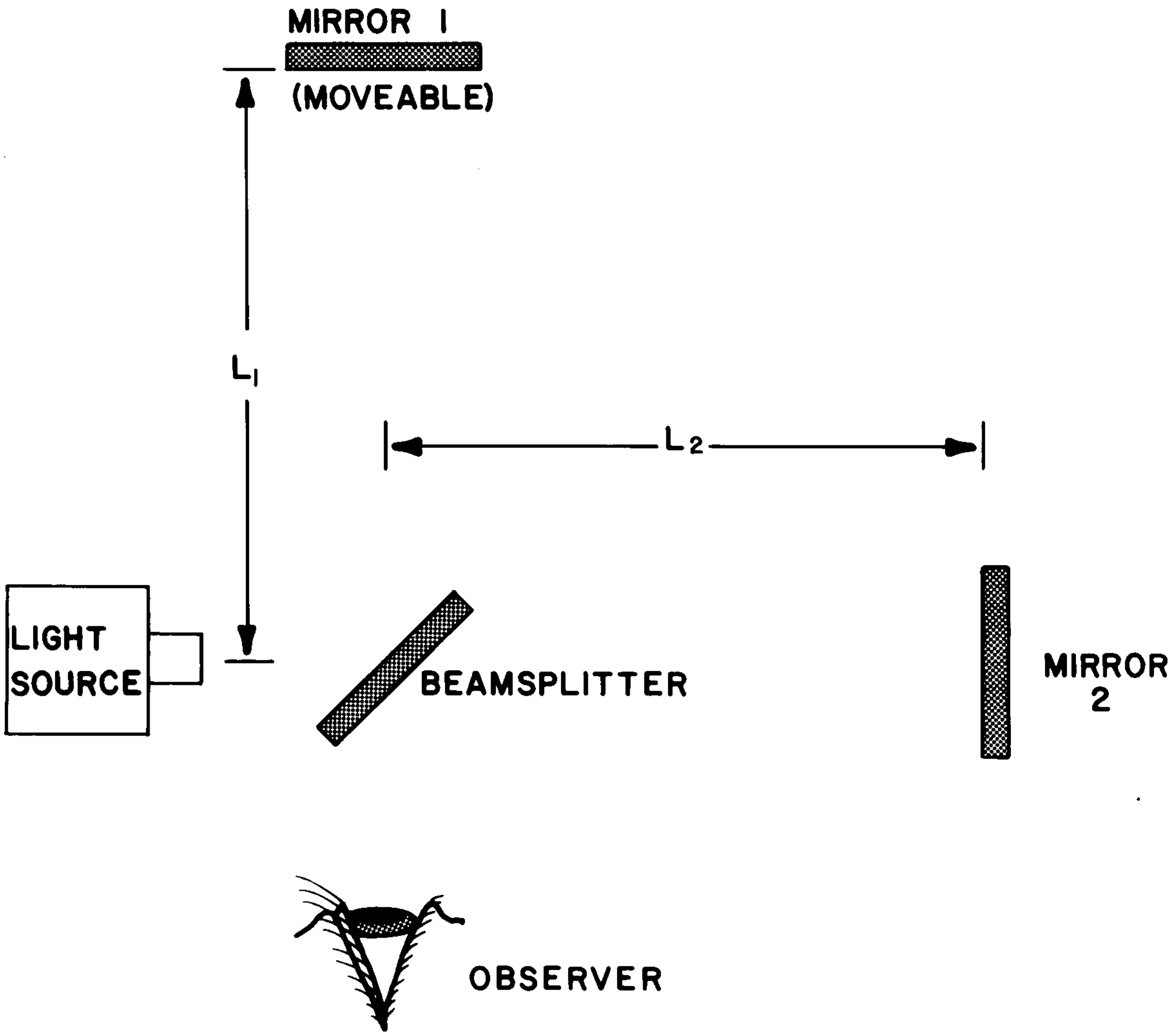

Figure 26.

On your interferometer one of the mirrors is moveable along the light path and one or both of the mirrors can be tilted. Adjust the moveable mirror so that the two light paths are as nearly equal as you can get them by measuring with a meter stick. Hold the point of a pencil just in front of the light source and look through the beamsplitter at the images of the source. If you see more than one image of the pencil point, one or both of the mirrors is tilted. Adjust the tilt of the mirrors to merge the images of the pencil point into one image. As the images merge exactly, a pattern of *interference fringes*, alternate light and dark bands, should pop into view. You can then further adjust the tilt of the mirrors to get a circular pattern of fringes similar to that shown in Figure 27.

Now change the distance L_1 by moving the moveable mirror slowly and observe what happens to the fringes. Continue this until the fringes disappear. Then move the mirror in the other direction until the fringes disappear again.

1. What happens to the fringes as you move the mirror? About how far can you move the mirror and still see fringes?

In order to produce interference fringes, the path difference, $2|L_1 - L_2|$, must be less than the coherence length.

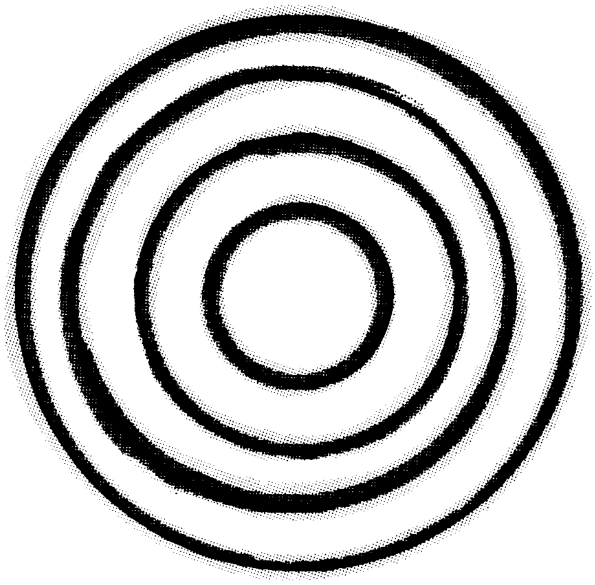

Figure 27.

2. What can you conclude about the coherence length of the filtered mercury-vapor light?

Replace the mercury-vapor light and filter with the laser. Use a lens to expand the beam and direct it into the interferometer. Place a white screen in front of the beam-splitter and adjust the mirrors to give an interference pattern on the screen.

3. How does this pattern compare with that of the previous light source?

4. By changing the path difference, what can you determine about the coherence length of the laser light?

5. Compare the coherence lengths of the filtered mercury-vapor light and the laser light.

LINE SPECTRA OF GASES

In Experiment C-1 you saw that the coherence length of a He-Ne laser is much longer than that of a filtered mercury-vapor source. The filtered mercury-vapor light, in turn, has a longer coherence length than light from an incandescent lamp, because the green light from a filtered mercury-vapor source has a much smaller bandwidth than that produced by allowing light from an incandescent lamp to pass through the same filter. This smaller bandwidth is related to the group of wavelengths, called the *spectrum*, emitted by a hot gas such as mercury vapor. Light from a hot solid, such as that from the filament of an incandescent lamp, contains all visible wavelengths from 400 nm to 700 nm. But when a gas is heated or electrically caused to emit light, only certain wavelengths are emitted. This kind of spectrum is called a *line spectrum* because it appears as a set of colored lines when viewed through a wavelength-measuring instrument such as a *spectrometer.* Each colored line corresponds to a different emitted wavelength (and frequency).

The green filter used with the mercury-vapor source passes only the green line and absorbs the other lines in the mercury spectrum. The wavelengths of the absorbed lines are not too close to the wavelength of the green line. The green light emitted by mercury vapor has a much narrower bandwidth than the bandwidth passed by the filter if "white light" is used.

ATOMS AND LIGHT

To understand how gases emit line spectra and how laser light has a narrower bandwidth than the lines emitted by a gas, we need to study the interaction of light with atoms.

How the atoms of a substance emit and absorb light has been of great interest to scientists for many years. The optical properties of gases depend strongly on the structure of the individual atoms or molecules of the gas. This is true because particles in a gas are relatively independent of one another. But in solids, interactions between atoms occur, resulting in more complex optical properties.

A MODEL OF AN ATOM

The idea that all matter might be constructed of large numbers of very small building blocks, called *atoms*, occurred to the Greeks several thousand years ago. A more refined version of this concept was developed in the wake of experiments performed by Dalton and others early in the nineteenth century. Originally the atom was thought to be indivisible. Late in the nineteenth century evidence accumulated to indicate that atoms have internal parts and that these parts show electrical properties. Pieces of atoms, called *electrons*, can easily be separated from the remaining portions of the atoms. The separated parts are called *ions*; the electron is a negative ion and the remainder of the atom is a positive ion. All electrons appear to be identical, regardless of their origins. An electron has a mass which is less than 0.1% of the mass of small atoms, and a negative electrical charge. When an electron is removed from a neutral atom, the charge of the positive ion left behind is equal and opposite to that of the electron. The number of electrons in an atom varies from element to element.

Questions arose about the internal structure of atoms. For example, what is the nature of the massive positive ions? How are electrons arranged within an atom?

A number of "models" for the structure of atoms have been proposed, with varying degrees of success in predicting atomic behavior. The structure of atoms is still not fully known, but, as a result of many experiments, organized with the help of theories, we now know a great deal about how atoms are put together and why they behave as they do. One well-established fact is that most of the mass of an atom is in the *nucleus*, a tiny core that occupies only a small fraction of the volume of the atom. Surrounding this nucleus are electrons, which are constantly in high-speed motion. Each nucleus, which has a positive charge, tends to attract and hold just enough electrons so that their total negative charge is equal in size to the charge of the nucleus. The surrounding electrons determine the chemical properties of the atom; when an electron is removed from an atom, the resulting ion has different chemical properties.

For the purposes of this module, the most important characteristic of atoms is that each atom possesses a certain energy which is internal to the atom. This energy is due to the arrangement of the nucleus and the electrons and has nothing to do with any other energy the atom may have because of its motion or its interactions with other atoms. Further, this "internal" energy, which we shall simply call the "energy of the atom," has the rather surprising property that, for a given atom, it can have only certain values, called *energy levels*.

The lowest energy level is called the *ground state,* and atoms are normally found in the ground state. An atom can absorb energy in various ways provided just enough energy is available to cause the atom to "jump up" to a higher energy level, called an *excited state*. If left alone long enough, the atom returns to its ground state. When it does so, it emits the radiation we see as a particular colored line (or lines) in the spectrum of a gas.

Analysis of the spectrum of a gas can lead to knowledge of the energy structure. A diagram showing the energy levels of the hydrogen atom is shown in Figure 28.

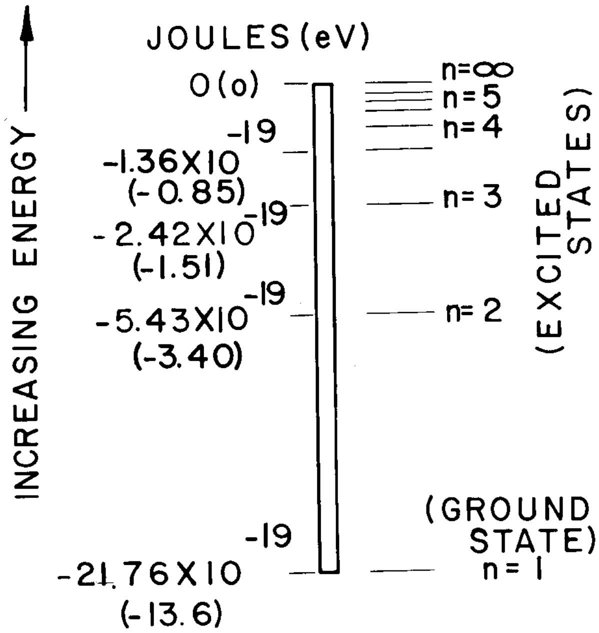

Figure 28.

PHOTONS

What happens when atoms in an excited state "drop" to the ground state? We know that the atom emits radiation of a particular color. It is this radiation phenomenon that led to the idea of energy levels in the first place. A complete theory must include a model for the atoms that emit the radiation and also a model for the radiation itself. In the earlier sections of this module, we discussed a wave model for light, which successfully explained phenomena such as interference and diffraction. However, the wave model previously discussed does not adequately explain other phenomena such as the spectrum of radiation emitted by glowing gases.

Historically, an important clue to another aspect of light came from experiments involving the *photoelectric effect.** When light falls on certain materials under the right circumstances, electrons are ejected. A close examination of this phenomenon showed that a wave model of light cannot account for the observations. For example, the kinetic energy of the electrons which are kicked out of the material does not depend upon the intensity of the light, but it does depend upon the wavelength. Also, physicists expected that a bright light would cause the first electrons to come out of the surface sooner than would a dim light, and this proved not to be the case. In 1905, Albert Einstein showed that the characteristics of the photoelectric effect support a *photon model* for light. He argued that the light consists of tiny bundles of energy, called *photons*, and that these photons have the characteristics of particles. (Nearly twenty years passed before Einstein's strange idea was generally

*This effect is made use of in photocells, which are used in some kinds of exposure meters, automatic door openers, and burglar alarms, among other things.

accepted.) If one measures the frequency of light, the energy of each photon is given by the formula

$$E = h\nu \qquad (12)$$

where $h = 6.63 \times 10^{-34}$ joule-second (J·s). The constant h is known as Planck's constant. The very small value of Planck's constant implies a small energy for one photon, even at the very high frequency of visible light.

Question 9. Which have higher energy, photons of red light or photons of blue light?

Problem 9. What is the energy of a photon of green light with frequency $\nu = 6 \times 10^{14}$ Hz?

THE WAVE AND PARTICLE NATURE OF LIGHT

We have just stated that one gets the energy of a photon, which has *particle* properties, by measuring the frequency of the light, which is a *wave* property. Is light a wave? Is light a particle? By now you may be thoroughly confused. Interference, diffraction, and refraction, as well as effects not mentioned in this module, are *wave* phenomena. The photoelectric effect and the emission of light from an atom, as well as other effects, are *particle* phenomena.

An experiment using light of extremely low intensity has helped to resolve this apparent dual character of light. It is possible to make the intensity of light so low that only one photon of light can pass through one or the other of a pair of slits. When we do this experiment, a photographic plate registers single particles of light, one after the other. Thus, as the light strikes the film, the interaction is particle behavior. After a large number of particles have passed through the slits, we find that they have formed an interference pattern on the film. This statistical behavior of large numbers of photons can be explained using a wave model.

This dilemma illustrates the basic problem of "model building" in modern science. Scientists, as well as others, prefer models that can readily be visualized, models that correspond to everyday things in the world around us (a light wave is "like" a water wave; a photon is "like" a marble). Unfortunately, the models that seem to be forced upon us by the facts of modern physics are not like this. Some of our modern models mix seemingly incompatible ideas and defy simple visualization.

The important point is that, for light, both models are needed. In the case of particle interactions you need the energy or momentum of a photon; but to get these quantities, you need the frequency or wavelength associated with the photons' statistical behavior. In the case of interference, you need the accumulation of individual photon collisions with a photographic plate or screen.

INTERACTION OF ELECTRONS AND PHOTONS

When an atom absorbs light, the energy of the atom changes to a higher energy level. When the atom emits light, it jumps to a lower energy level. Each such jump or *transition* is associated with the absorption or emission of a single photon. If no energy is lost, then the change in energy of the atom must equal the energy of the photon absorbed or emitted

$$E_n - E_m = h\nu \qquad (13)$$

where E_n and E_m refer to the higher and lower energy levels, respectively.

Example Problem. What is the energy of a photon emitted by a hydrogen atom, when the atom jumps from the third to the first energy level?

Solution. You are only given the numbers of the energy levels involved in the transition. Use Figure 28 to find

$$E_3 = -2.42 \times 10^{-19} \text{ J}$$

and

$$E_1 = -21.76 \times 10^{19} \text{ J}$$

Substituting into Equation (13),

$$E_3 - E_1 = -2.42 \times 10^{-19}\ \mathrm{J} - (-21.76 \times 10^{-19})\ \mathrm{J}$$

$$= 21.76 \times 10^{-19}\ \mathrm{J} - 2.42 \times 10^{-19}\ \mathrm{J}$$

$$= 19.34 \times 10^{-19}\ \mathrm{J}$$

Problem 10. What is the energy of a photon emitted from a hydrogen atom, when the energy of the atom falls from the second to the first level?

Problem 11. What frequency light will cause the hydrogen atom to jump from the second to the third energy level?

Question 10. In a certain atom, green light will cause an atom to jump from the first to the third energy level. Would a shorter or a longer wavelength be required to produce a transition from the first to the second energy level?

SPONTANEOUS EMISSION

If an atom is *excited* (raised to a higher energy) by some outside source of energy, such as by the absorption of a photon, the atom eventually gives up that energy and falls back to the ground state. The energy thus lost by the atom may appear as light or as other forms of energy. For a given excited atom, it is impossible to tell exactly when such a transition will take place, but there is some average time for a large collection of identical atoms. This average length of time that an atom spends in the excited state before emitting a photon and returning to a lower state is called the *lifetime* of the excited state. Atomic lifetimes are usually very short, on the order of 10^{-8} s for the excited states that produce visible light. The emission of radiation by a group of excited atoms which undergo transitions to the ground state, with no outside influence, is called *spontaneous emission*. Ordinary light sources emit their light by spontaneous emission.

STIMULATED EMISSION

Excited atoms can also emit light and return to the ground state by another process called *stimulated emission*. If a photon of the correct frequency passes close enough to an excited atom, it can "stimulate" the atom to emit its excitation energy in the form of another photon corresponding to exactly the same frequency. Stimulated emission is possible only when the incoming photon has energy (frequency) exactly equal to the difference in energy between the excited energy level and a lower energy level. This process is the inverse of *absorption*, in which a photon corresponding to just the right frequency is absorbed by an atom in the ground state, thereby raising the atom to an excited state. A light wave can cause each of a certain number of atoms in the ground state to absorb a photon. The same light wave can cause each of the *same* number of atoms in the excited state to emit a photon. That means that if there were only the ground-state and one excited-state level, as many atoms would lose energy as would gain energy. This is the reason why lasers must be made with materials having more than two energy levels.

The interesting feature of the stimulated-emission process for the study of lasers is that the emitted light wave is exactly aligned crest-to-crest with the stimulating wave, is exactly the same frequency, and is traveling in exactly the same direction. The two waves are *coherent*. Lasers emit their light by stimulated emission. The three processes – absorption, spontaneous emission, and stimulated emission – are illustrated in Figure 29A, B, and C.

NATURAL LINEWIDTH

You might wonder why laser light has a narrower linewidth than the light emitted by glowing gases. The spectrum of the light from a gas does contain narrow lines of color, but each line contains not just one frequency, but rather a small spread of frequencies. If for a

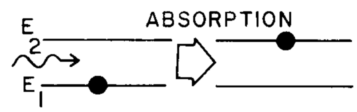

Figure 29A. For absorption the atom absorbs a photon of just the right energy and jumps to a higher energy level.

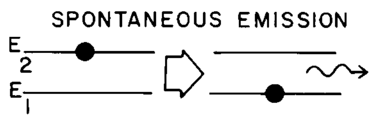

Figure 29B. In spontaneous emission, the excited atom simply drops to a lower energy state.

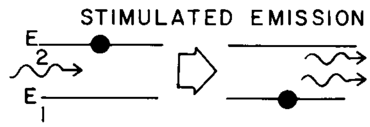

Figure 29C. In stimulated emission the excited atom is affected by a photon of just the right energy and two identical photons go off together.

particular excited state, Δt is the time during which light is emitted, we can use Equation (9) to find the bandwidth of the spontaneously emitted light. This bandwidth is called the *natural linewidth,* $\Delta\nu_N$.

$$\Delta\nu_N \approx 1/\Delta t \approx 1/10^{-8}\,\mathrm{s}$$

$$\Delta\nu_N \approx 10^8\ \mathrm{Hz}$$

The natural linewidth of an optical transition is roughly the same as the linewidth of a helium-neon laser.

DOPPLER LINEWIDTH

Since the natural linewidth of a spectral line is about the same as the linewidth of laser light, you might wonder why laser light is so much more nearly monochromatic than light of a single color emitted by a gas discharge. The reason is that there are other processes in a gas discharge that tend to spread out, or *broaden,* spectral lines. The most important of these, called *Doppler broadening*, is caused by the motion of the atoms or molecules which emit the light. The particles in a gas have sufficient *thermal* (heat) energy at room temperature to be moving at fairly high speeds. But a motion of the source of a wave affects the wave frequency observed. Motion of the source toward the observer causes an increase in the frequency observed, while motion away from the observer leads to a decrease in the frequency observed. You may have noticed this effect in connection with sound waves; when a car is approaching its horn sounds higher-pitched than when it is leaving.

In a gas, the sources of the light waves, the atoms or molecules, are moving at different speeds and in random directions, some toward and some away from the observer. Since each line we see results from the same transition in many of these moving atoms, the frequencies are spread out, some higher and some lower than that from a stationary atom. This results in a general broadening of the line over a range of frequencies, as indicated in Figure 30. At room temperature, this *Doppler*

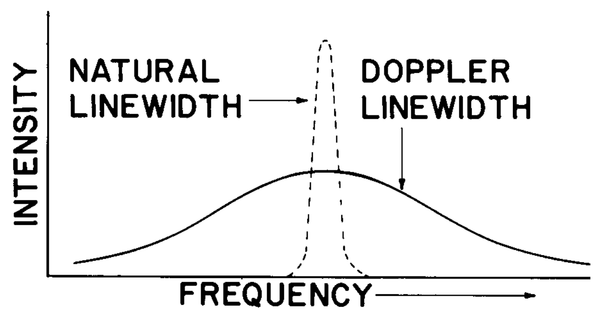

Figure 30. The graph is badly distorted since the broadened linewidth is about 100 times the natural linewidth and, for the same number of atoms, the natural linewidth peak is much higher.

linewidth, $\Delta\nu_D$, is on the order of ten to one hundred times the natural linewidth. Thus:

$$\Delta\nu_D \approx 10^9\ \mathrm{Hz}$$

$$\Delta\nu_D/\nu \approx 10^{-5}$$

The green light from the mercury-vapor lamp may have a linewidth this large or larger. Laser light is considerably more monochromatic.

INVERTED POPULATION NEEDED FOR LASER ACTION

The light in a laser originates in the atoms of the *active material.* In the first operational laser, the material used was a piece of ruby. Ruby is aluminum oxide with chromium ions in it. Although they compose only about 0.05% of the ruby, the chromium ions are the active material and they emit the laser light. Lasers with many other active materials have been built since the ruby laser, but we shall confine our attention primarily to the ruby laser and the helium-neon laser since they are still the most common.

The chromium in ruby is in the form of positive ions with three electrons missing. These ions take the place of some aluminum ions in the crystalline structure of the solid aluminum oxide. The energy levels of the chromium ions in the aluminum oxide crystal are similar to those of the simple atoms. However, some energy levels are spread into "bands" as a result of the electrical forces which hold the solid together. An *energy band* can be thought of as a great many closely spaced energy levels, and an ion can have essentially any energy within the band. This is indicated in the energy-level diagram of Figure 31.

To achieve laser action there must be more ions in the right excited state than in the ground state. Otherwise more photons are lost in exciting ground-state ions than are gained by stimulated emission. A *population inversion* exists when there are more excited- than ground-state ions.

OPTICAL PUMPING IN RUBY LASER

Various methods of adding energy to the active materials are used to obtain population inversions. One of the most straightforward, called *optical pumping*, is used to excite the ruby laser. The chromium ions are excited by absorbing photons from an initial burst of light supplied by a flashlamp. The flashlamps used are similar to the electronic flashlamps used by photographers. However, an inverted population cannot be obtained simply by adding energy to ions in the ground state and thereby raising them to a single excited state. If the atom had only two energy levels, it would be impossible to get an inverted population by optical pumping. Once half of the atoms were excited, as many would be stimulated to emit as would be excited by the pumping radiation, and a balance would be achieved that would involve no gain in the number of photons. In the ruby laser, there are actually two levels and two bands involved in the population inversion. In the energy-level diagram of Figure 31, only the single band and the single energy level which are involved in the laser action are shown. Light from the flash tube excites chromium ions to an energy band. These excited ions lose some of their energy by collisions within the crystal and thus fall to the excited-state energy level, as shown in Figure 31.

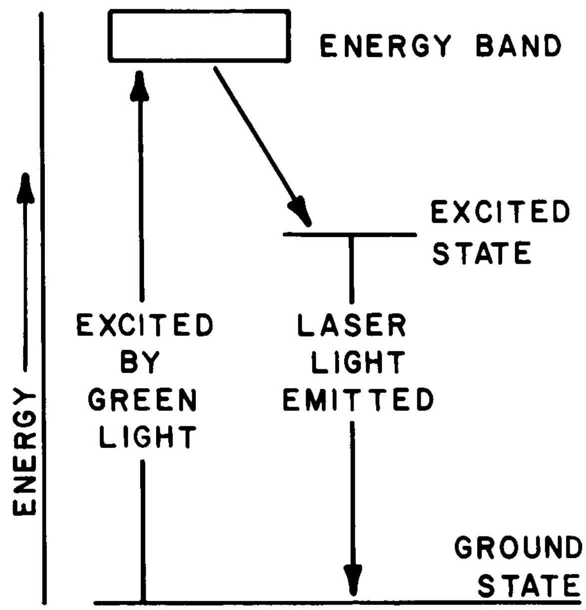

Figure 31. A simplified energy-level diagram of chromium ions in a ruby. The excited-state level has been moved to the right just to make room on the diagram.

The process of losing energy by collisions without emitting a photon is called *thermal relaxation*. Thermal relaxation proceeds very rapidly (10^{-9} s), transferring energy to the ruby in the form of heat. On the other hand, the excited-state energy level is relatively long-lived, with a lifetime on the order of 10^{-3} s; and this energy level is therefore called *metastable*. The net result is that ions "pile up" in the metastable energy level. Thus an inverted population is achieved. The transition between the metastable state and the ground state will then occur. The first few photons, which are produced by spontaneous emissions, stimulate more ions to emit, and the result is a laser beam at a wavelength of 694.3 nm.

PUMPING SCHEME FOR HE-NE LASER

A completely different scheme is used to energize the atoms in a He-Ne laser. The energy originates in an electric discharge through the gas which is about six parts helium to one part neon. The discharge is started by accelerating electrons through the gas toward a positive electrode.

The free electrons moving through the gas collide violently with the atoms and give them the energy to jump to excited energy levels. Although neon is the active material of the laser, a fortunate closeness of energy levels makes it helpful to use a mixture of helium and neon. As shown in Figure 32, helium happens to have an excited energy level which has just the same energy as one of the neon levels.

Neon can be made to "lase" by itself, but it turns out to be easier and much more efficient to excite the helium atoms in the discharge; those excited helium atoms give energy to the neon atoms in collisions. This can happen because the energy levels of the two gases are so nearly the same.

Although, with a great deal of effort, ruby lasers can be run continuously, they are usually pulsed. Helium-neon lasers are usually run continuously. A comparison of Figures 31 and 32 indicates why this is the case. For the ruby laser to work, it is necessary to produce a population inversion between an excited energy level and the ground-state level. However, at room temperature most of the ions tend to be in the ground state and well over half of them must be raised to the excited state. On the other hand, the helium-neon

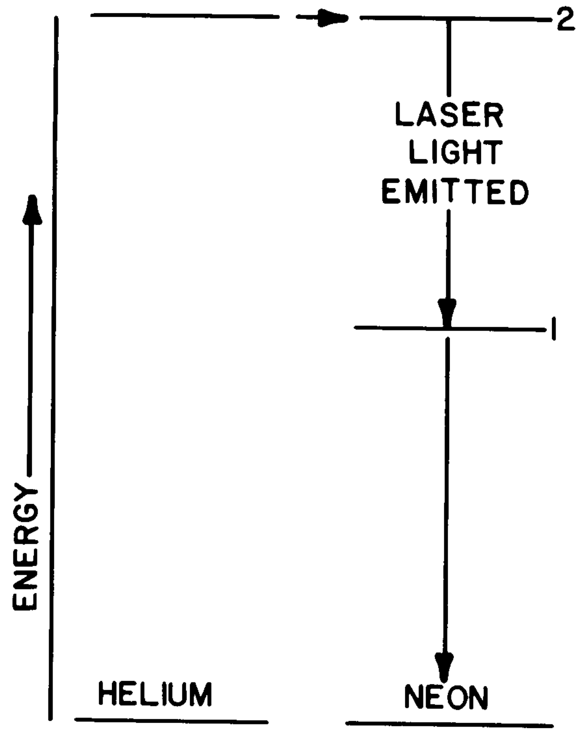

Figure 32. A simplified energy-level diagram for helium and neon. The first excited level of neon really consists of 10 closely spaced levels, and level 2 is really 4 levels. Other multiple levels are omitted.

laser requires only a population inversion between level 2 and level 1. Fortunately, level 1 has almost no atoms in it at room temperature. This means that only a relatively few atoms need be in level 2 for a population inversion to occur. Also, spontaneous transitions from level 1 to the ground state occur very rapidly, so it is easy to maintain the population inversion continuously. The stimulated transitions from level 2 to level 1 produce visible laser light at a wavelength of 632.8 nm, but by using other transitions helium-neon lasers have been made to produce laser light at many different wavelengths, especially in the infrared.

AMPLIFICATION BETWEEN END MIRRORS

Once a population inversion has been created in the active material, laser action starts with a spontaneous emission. Any photon emitted spontaneously by an atom may pass close enough to an excited atom to cause a stimulated emission. The two coherent photons resulting may then cause stimulated emissions in other atoms which are still in the excited state, and a kind of "chain reaction" may occur, building up the number of mutually coherent photons as it proceeds. This is indicated in Figure 33, where a single photon starts the process in a number of excited atoms.

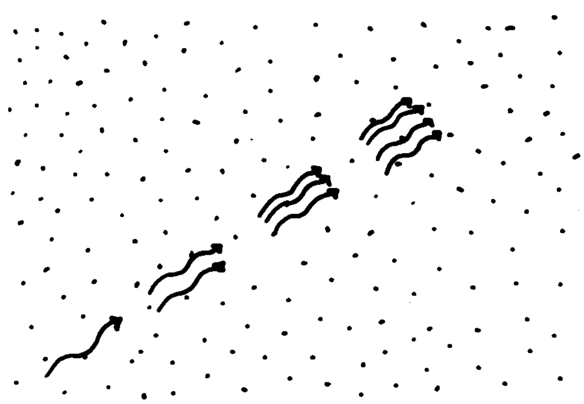

Figure 33. In a group of excited atoms a spontaneous emission starts a "chain reaction" of stimulated emissions and a coherent beam of light emerges.

In the usual case, the active medium is contained in a cylindrical shape, as indicated in Figure 34A. Then when a spontaneous emission occurs and produces some stimulated emissions, the resultant wave is likely to simply escape out the side, as in Figure 34B. However, occasionally a spontaneous emission will start out exactly along the length of the cylinder and, after having a long distance to build up, the wave will emerge out the end, as in Figure 34C. However, even though it has built up a great deal the coherent wave is still very tiny. To build it up even more, a mirror is placed so that the wave goes back through the active material and causes many more stimulated emissions, as in Figure 34D. Finally, a second mirror is placed on the other end, so that the wave makes repeated passes through the medium, gaining intensity with each pass. The region between the two mirrors is called the *laser cavity*. One of the mirrors is made only partially reflecting so that a small fraction of the light passes through it. We see this fraction as laser light.

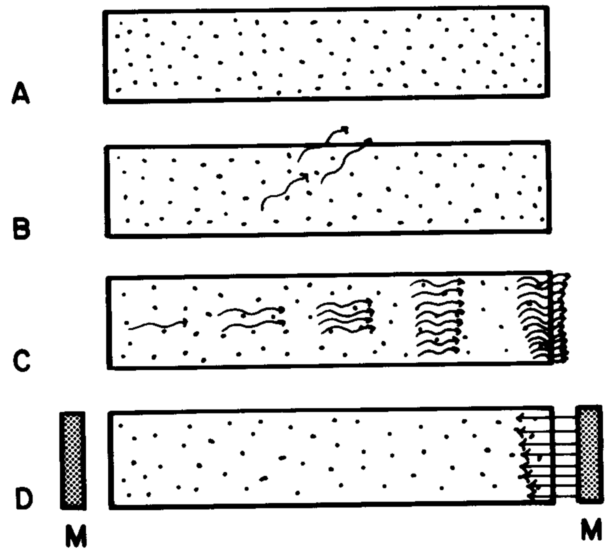

Figure 34.

STANDING WAVES IN THE LASER (OPTIONAL)

Actually, the role of the end mirrors is more important than indicated above. To see why, we can consider the light as a wave reflecting back and forth between the mirrors. At each mirror surface the wave is reflected. Inside the laser then, a *standing wave* pattern is created.

Some points on a standing wave never move at all and are called *nodes*. Halfway between successive nodes are positions of maximum variation called *antinodes*. For a guitar string the variation is the transverse displacement of the string. In the laser the variation involves changes in the electrical and magnetic forces that charged particles would feel if put at these points in space. The mirrors guarantee that the *electromagnetic waves* will have nodes at some particular points in space near the mirror surfaces. This is analogous to the guitar string which, because of being clamped at its ends, has nodes there.

Thus, the end mirrors will pick out wavelengths such that a standing wave just fits in with nodes at the right places; all other wavelengths die out rapidly. For this reason the region between the end mirrors is said to form a *resonant cavity*. The internal laser light can be thought of as a standing wave that grows rapidly as more and more excited atoms are stimulated to emit photons.

For a guitar string, some possible standing waves are shown in Figure 35. Each

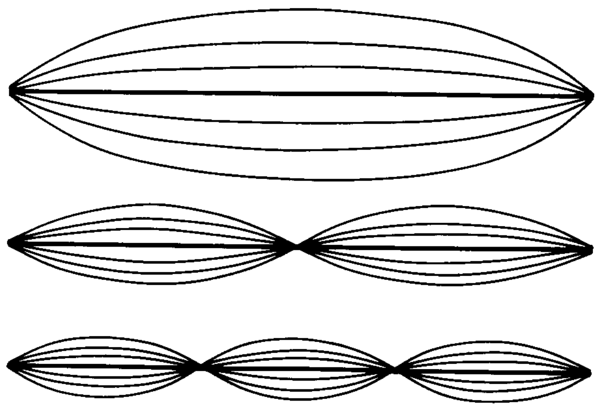

Figure 35.

different standing wave is called a *mode of oscillation*. The distance between adjacent nodes is ½ λ. Thus, the possible wavelengths can be seen from this figure to be

$$\lambda_1 = 2L$$

$$\lambda_2 = L$$

$$\lambda_3 = \frac{2L}{3}$$

$$\vdots$$

$$\lambda_n = \frac{2L}{n} \qquad (14)$$

Here L is the length of the string and n is the number of half-waves which exactly fit in.

For a laser, we can make the approximate assumption that there is a node at each mirror. However, because the wavelength of light is so small, there will always be a very large number of nodes in the laser cavity.

Problem 12. What is the longest wavelength of a standing wave, with nodes at both ends, that will fit into a 10-cm cavity? Could this be a light wave?

Problem 13. Assuming nodes at both ends, how many half-waves of green light (λ = 500 nm) will fit in a 50-cm resonant cavity?

AXIAL AND NON-AXIAL MODES (OPTIONAL)

There is one complication to this analysis that should be considered. Standing waves that are slightly inclined with respect to the axis are also possible, as indicated in Figure 36. This fact would allow many more possible

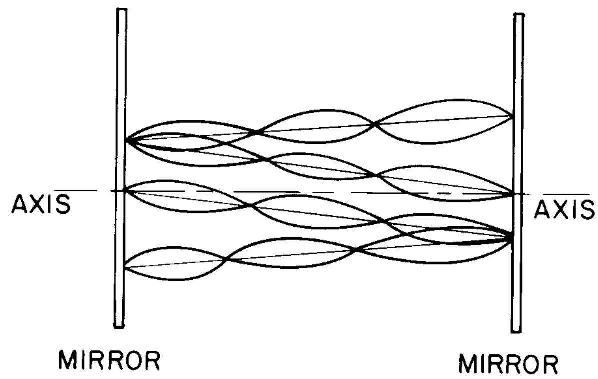

Figure 36.

wavelengths to be supported in the laser if there were not some way to keep these modes from gaining too much energy. To distinguish between these standing waves and the ones parallel to the axis, we shall call the latter *axial modes* and the former *non-axial modes*. As noted earlier, the non-axial modes will tend to "walk off" the mirrors after a few passes, and so do not get a chance to build up by stimulated emission. By making the resonant cavity long with respect to the size of the end mirrors, the non-axial modes are eliminated.

COEXISTING AXIAL MODES (OPTIONAL)

Even when the non-axial modes are eliminated, several different axial modes can compete for the energy stored in the inverted population. This competition arises because several axial mode frequencies usually fall within the Doppler-broadened emission linewidth of the active material. We calculate the separation between two successive axial mode frequencies using Equations (14) and (6).

$$\nu_n = c/\lambda_n = nc/2L$$

$$\nu_{n+1} = (n+1)c/2L$$

The frequency difference between these two modes is

$$\nu_{n+1} - \nu_n = (c/2L)\,(n+1-n) = c/2L$$

The fractional frequency separation is then given by

$$\frac{\nu_{n+1} - \nu_n}{\nu_n} = \frac{c/2L}{nc/2L} = \frac{1}{n} \qquad (15)$$

The number n is the number of half wavelengths that fit in the resonant cavity. For light it is quite large, say

$$n \approx 10^{+6}$$

Then

$$\frac{\nu_{n+1} - \nu_n}{\nu_n} \approx 10^{-6}$$

This last figure may be compared with the Doppler linewidth noted earlier

$$\frac{\Delta\nu_D}{\nu} \approx 10^{-5}$$

This implies that one can expect up to ten axial modes within the Doppler-broadened emission line of the active material. A typical situation is shown in Figure 37. As a population inversion is created in the active material, the axial mode closest to the center of the Doppler linewidth begins to oscillate. If the pumping process is powerful enough to overcome the loss of excited atoms due to this mode, then the next closest modes also begin to oscillate. The final laser spectrum may appear as several "sharp spikes" which are much closer together than the Doppler linewidth of the active material.

LINE NARROWING (OPTIONAL)

This process of producing "sharp spikes" which are much narrower than the Doppler linewidth is called *line narrowing*. This line narrowing occurs automatically within the laser cavity.

One way of understanding this is

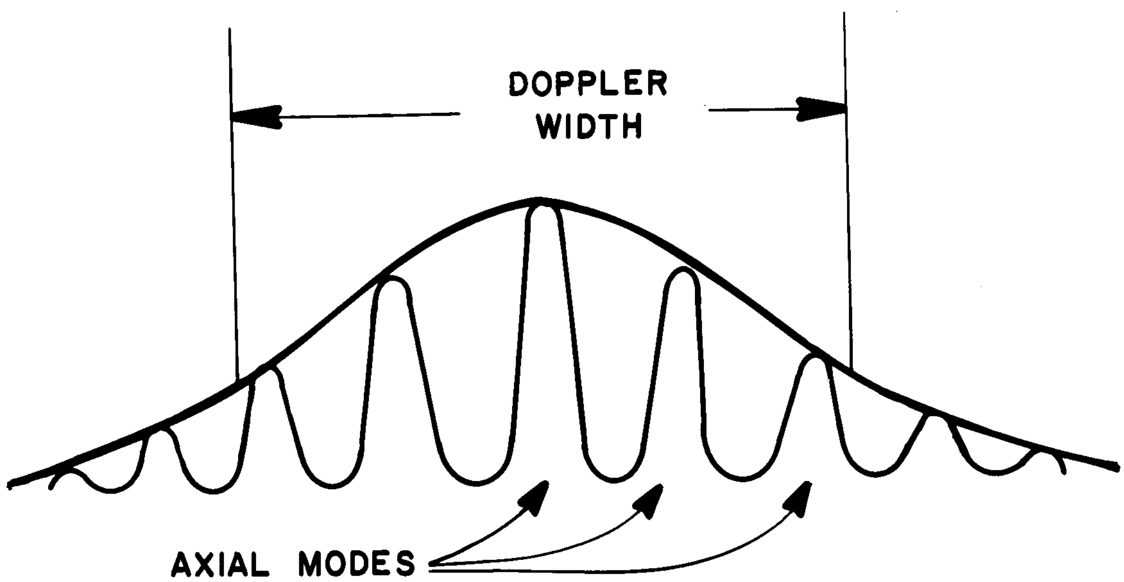

Figure 37.

through the standing wave discussion of the preceding section. But the same phenomenon may be looked at in a somewhat different way. First, a given wave in the cavity stimulates emissions of those atoms which are moving at just the proper speed so that their photons have exactly the same frequency as the stimulating wave. Each wave which gets started picks out the right atoms to add coherent radiation to itself. Secondly, after a number of passes between the mirrors, only those waves which reinforce themselves grow and the others destroy themselves. Saying this another way, if a portion of the wave has made two passes through the cavity, it adds to portions which have made four passes, or ten, or twenty, *only* if all of the portions are in phase. Since the waves all travel at the same speed, for a given cavity length only waves of the right wavelength reinforce themselves. Other waves will arrive at the same spot out of phase with themselves and die out. This is indicated in Figure 38.

(A)

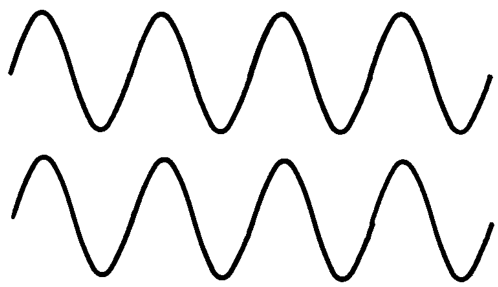

Figure 38A. Two portions of a wave which happens to have the right wavelength for a particular cavity reinforce because they are in phase.

(B)

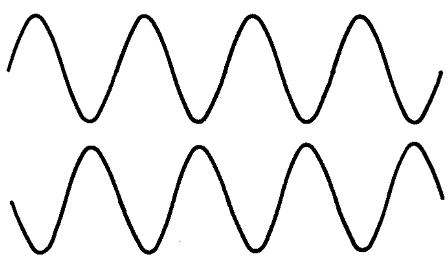

Figure 38B. In the same cavity, a wave of another wavelength destroys itself by destructive interference because its two parts are out of phase.

OTHER LASERS

Since the development of the first ruby and helium-neon lasers, a great many other materials, including even a gelatin dessert, have been made to undergo laser action. Some of these other lasers are important because of some properties not possible with the first two types. For example, argon lasers produce green light and cadmium (metal-vapor) lasers produce blue light. A carbon dioxide (molecular) laser can produce extremely powerful infrared radiation. Diode lasers, which use the same kinds of semiconductors as do transistors, produce only a small amount of light, but they are very small and easy to power; they may have application in super fast computers. Organic-dye lasers have relatively very large linewidths, but they can easily be *tuned* to produce a wide range of colors of light.

SUMMARY

The monochromaticity of any light source can be measured by its bandwidth, $\Delta\nu$, or fractional bandwidth $\Delta\nu/\nu$.

For the very monochromatic light of a laser the fractional bandwidth might be $\Delta\nu/\nu = \Delta\lambda/\lambda \approx 10^{-6}$.

The temporal coherence of any source is measured by the coherence length, ΔL, which is directly related to bandwidth

$$\Delta L = c/\Delta\nu$$

Monochromatic light is temporally coherent and vice versa. The two terms mean exactly the same thing.

Light has both wave and particle properties. A photon (light particle) has an energy

$$E = h\nu$$

where $h = 6.63 \times 10^{-34}$ J·s (Planck's constant) and ν is the frequency of the associated wave.

Gases emit light only at certain frequencies or wavelengths. The resulting spectrum is called a line spectrum. A gas will absorb just those frequencies it emits. The frequencies absorbed or emitted by a gas depend on the energy levels of its atoms.

An atom can absorb one photon and jump to a higher energy level, or it can emit one photon and jump to a lower energy level. In either case, the change in the energy of the atom will equal the energy of the photon:

$$E_n - E_m = h\nu$$

When an atom falls to the ground state from an excited state without any outside influence, the process is called spontaneous emission. Spontaneous emission accounts for most of the light from ordinary sources.

When an excited atom is stimulated to emit by a light wave of just the right frequency, the process is called stimulated emission. In stimulated emission, the emitted light is of the same wavelength and exactly in phase with the stimulating light. Laser light is produced by stimulated emission from the atoms of the active material.

The natural linewidth, $\Delta\nu_N$, of a spectral line depends on the lifetime of the excited state. Thus, it is usually quite narrow: $\Delta\nu_N/\nu_N \approx 10^{-6}$. However, Doppler broadening can increase this value by a factor of ten or more so that $\Delta\nu_D/\nu \approx 10^{-5}$.

To make a laser work, there must be more excited atoms than ground-state atoms. This condition is known as inversion. A ruby laser uses the energy from a flashlamp to produce population inversion in a process called optical pumping. In a helium-neon laser, an electric discharge excites the helium atoms, which transfer their energy to neon atoms by collisions, producing the required population inversion.

Because of the way they build up in the laser cavity, the resulting waves are highly coherent (monochromatic) and well collimated (non-diverging).

Work Sheets
Experiment A-1

Name____________________________

Part I:

1. ____

2. ____

3.

4.

5. ____

6. ____

7. ____

8. ____

9.

10.

11.

Part II:

1.

2.

3.

4.

5.

6.

7.

8.

9.

10.

11. ______________________________
____
____
____
____
____

Part III:

1. Diameter = __________ cm
2. Diameter = __________ cm
3. Difference = __________ cm
4. Diameter = __________ cm
5. Diameter = __________ cm
6. Difference = __________ cm
7. ______________________________
____
____
____
____
____
____
____
____

COMPUTATION SHEET

Work Sheets
Experiment B-1

Name____________________________

Part I:

1.

3.

5.

7. __________________________________
____

Part II

1.

2. __________________________________
____
____

3. __________________________________

4. __________________________________
____

5. __________________________________
____
____
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6. __________________________________
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7. __________________________________
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8. ______________________________

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9.

10.

11. ______________________________

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12.

13. ______________________________

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Part III:

1. ______________________________

____

____

2. ______________________________

____

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____

____

Work Sheet
Experiment B-2

Name____________________________

1. $a =$ ______________ m

2. $\Delta\theta = a/D =$ ______________ radians

3. $d =$ ______________ m

Trial	$\Delta\theta$	d (m)
1		
2		
3		
4		

4. ______________________________
____

Trial	$\Delta\theta$	d (m)	$1/d$ (m^{-1})
1			
2			
3			
4			

5. ______________________________

6. ______________________________
____
____
____

slope = ________________________

7. ______________________________

Work Sheet
Experiment C-1

Name________________________

Part I:

1. ________________________
2. ________________________
3. ________________________
4. ________________________
5. ________________________
6. ________________________

Part II:

1. ________________________
2. ________________________
3. ________________________
4. ________________________
5. ________________________