Chapter 10
Reflection, Refraction, Diffraction and Interference

Overview
When waves are incident at a boundary between media (such as water waves on shallow water encountering a sudden change in depth of the water or light passing either from air to glass or glass to air), part of the wave energy is reflected and part is transmitted. Some of the wave energy is absorbed as it travels in either medium. The following figure shows a boundary (represented by the horizontal line) between media and “rays” representing the paths and directions of incident, reflected and refracted waves.

![Diagram of wave reflection with angles labeled](image)

Reflection
Waves can be reflected at boundaries between media. The reflection occurs because of interactions between the waves and the media. For example, electromagnetic waves interact with atoms or molecules in a substance. In the case of visible light, the light interacts directly with the electrons and
the electrons can be viewed as either replacing photons with new photons or as a source of new waves which are the reflected waves. The reflected waves have the same frequency, wavelength and speed as the original incident waves since the reflected waves are in the same medium.

Consider waves incident on a boundary surface at an angle $\theta$ from the normal (the line perpendicular to the surface). This angle is called the “angle of incidence.” Mathematicians, wanting to be precise, say that $\theta$ is the “measure” of the angle of incidence because the measure is a quantity but an angle is really a geometrical construction or a shape. The reflected waves travel at the same angle $\theta$ from the normal but on the opposite side of the normal from the incident waves. This angle for the reflected waves is called the “angle of reflection.” Both angles have the same measure.

**Law of Reflection:** The angle of reflection has the same measure as the angle of incidence, the incident and reflected rays lie in the same plane and the reflected and incident rays are on opposite sides of the normal.

This Law of Reflection is often stated in an abbreviated form as “the angle of reflection has the same measure as the angle of incidence.” This concept is easy to visualize when the boundary surface is smooth. However, if the boundary surface is composed of many component surfaces, which are little surfaces that differ in orientation and have normals in different directions, visualization of the situation can become complicated. If these component surfaces are significantly larger than the wavelength of the waves, the reflection is said to be “diffuse” reflection because the rays are reflected through many angles. You see effects of diffuse reflection when you look at the surface ordinary paper. Light incident on the paper is reflected at many angles.

**Refraction**

Waves transmitted from one medium to another retain their frequency, but may change speed and wavelength. Refraction is the bending of transmitted waves, at the boundary between media, due to the changing of the speed of the waves at the boundary. We have already been introduced to the angle of incidence and the angle of reflection. The angle $\theta_r$ of the transmitted wave from the normal is called the “angle of refraction.” Physicists and engineers specify the “index of refraction” as a measure of the speed of light in a medium. The index of refraction $n$ of a medium is the ratio of the speed of light in vacuum $c$ to the speed of light in the medium $v$.

\[
n = \frac{\text{speed of light in vacuum}}{\text{speed of light in the medium}} = \frac{c}{v}
\]
\[ v = \frac{c}{n} \]

The index of refraction is never less than unity. \( n \geq 1 \). The larger the index of refraction \( n \) is, the slower light is in the medium \((v=c/n)\). When light passes from a medium into a medium of larger index of refraction, the light slows and bends toward the normal (and away the surface). When light passes from a medium into a medium of smaller index of refraction, the light increases speed and bends away from the normal (and toward the surface).

Water has a larger index of refraction than air does. When a fish in a pond sees a human standing in or at the edge of the pond, refraction causes the human to appear near the fish. Thus, fishers like to stand in shade to prevent fish from spotting them. When a person watches a fish swimming in the pond, refraction makes the fish appear farther out in the pond than the fish really is. Thus, people often don't realize that the fish are close enough to hear them talking.

A law of optics known as “Snell's Law” gives the relations between indexes of refraction and the angles of incidence and refraction at the boundary between two media. The line perpendicular to a boundary between two media is called the “normal line” or simply the “normal.” Consider light in a medium with index of refraction \( n_1 \) incident at the boundary at angle \( \theta_1 \) from the normal to the boundary between two media and entering the second medium with index of refraction \( n_2 \) at refracted angle \( \theta_2 \) from the normal. Snell's Law states that the indexes of refraction and angles are related as follows.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

**Images**

When we look at an object, we see the object because the light rays from each point of the object travel in all directions. Reflections and refractions can form an “image” of a point or an object by making rays from that point or object to appear to be coming from another location. In lecture, I like to show a real image formed by a lens. The image is called a “real image” because light rays actually pass through the image to form the image. When we look in a mirror and see an image of ourselves that appears to be behind the mirror, that image is a “virtual” image because the light rays don't really go behind the mirror to form the image even though the image is behind the mirror. Since light rays actually go to a real image to form it, we can place a screen at the real image so the image is projected onto the screen. However, we cannot place a screen behind a mirror to project the virtual image onto the screen. When you stand before a plane mirror and look at your reflection, you can lift your right
hand and notice that the image is lifting its left hand. The top-to-bottom and left-to-right axes have not been altered in the reflection, but the front-to-back axis has been reversed.

Concave and convex mirrors form images that may appear as distorted representations of the original object. Convex mirrors form virtual images that appear close to the mirror and smaller than the original object. The human brain can trick humans: some people see the small images and assume the object is far even though the image is close to the mirror. This is why convex mirrors on vehicles often are accompanied by a warning sign suggesting that objects may be closer than they appear. Concave mirrors form real or virtual images depending on whether the object is close to or far from the mirror. A virtual image formed by a concave mirror appear larger than the original object and farther away from the mirror than the object.

We see how light can form an image of an object. I should mention that we can also form an image of an image. For example, a reflection from a mirror is a virtual image can be formed into another image by use of a lens. Formation of images from images is done in the compound lenses of cameras, in binoculars, in optical microscopes and in optical telescopes.

**Fermat's Principle of Least Time**

Fermat's Principle of Least Time provides another viewpoint of reflection and refraction.

**Fermat’s Principle of Least Time:** When light passes between two points, the light takes the path of least travel time between the points.

Thus, light takes the path of least travel time in media. This principle is consistent with other laws regarding reflection and refraction. For example, the Law of Reflection can be shown to provide the path of least travel time for light being reflected. Some scientists and engineers consider Fermat's Principle of Least Time to be the reason for the Law of Reflection. Fermat's principle can also be shown to lead to Snell's Law. This leading to other laws of optics is one of the reasons Fermat's Principle of Least Time is viewed as an important law of optics.
Dispersion and Rainbows

Dispersion is the property of different treatment of light of different frequencies. It is a common property of refraction. Glass has a higher index of refraction than air does. On entering glass from air, light of higher frequencies (lower wavelengths) bends more toward the normal than light of lower frequencies (higher wavelengths) does. On exiting the glass back into air, the light of higher frequencies bends more away from the normal than light of lower frequencies does. Thus, dispersion separates various frequencies of light. The effects of dispersion are seen in leaded glass, clear gemstones (such as diamonds for example) and in rainbows. A rainbow is the result of dispersion by many drops of water in the sky. Often, two rainbows—a primary bow and a secondary bow—are formed. The secondary bow is formed when light is reflected one additional time in the water drops. It is fainter than the primary bow because of the longer path through the water drops, and has the order of colors reversed because of the additional reflection. The inside of the primary bow is the lower-frequency “red” side of the visible spectrum and the outside has the higher-frequency “violet” side.

Total Internal Reflection

When light crosses a boundary between media and goes from one index of refraction to a lower index of refraction, the light rays bend away from the normal and toward the surface of the boundary. The angle of refraction is greater when the angle of incidence is greater. That is, the light bends closer to the surface when the angle of incidence is greater. Also, the refracted light is dimmer—less light is refracted and more light is reflected—when the angle of incidence increases. At a particular angle of incidence, called the “critical angle,” the refracted light becomes parallel to the surface. At angles of incidence greater than the critical angle, no light is transmitted and all of it is reflected (as though the surface was a perfect mirror). This phenomenon of all the light being reflected is called “total internal reflection.” Such total reflection is useful for making media for transmission of light from a source to a destination. This is the main useful property of “fiber optics” that transmit light. This type of reflection is also a main reason you often cannot see a fish in a lake unless the fish is closer to you. Total internal reflection is used in optical fibers used in communications, the optics in binoculars and light pipes used by artists.

Lenses and Aberrations

Lenses are optics that use refraction, especially optics that use refraction to form images. For most types of lens, refraction occurs at each of two surfaces of the lens. Converging lenses concentrate light
rays, and can form real or virtual images. Diverging lenses spread the light rays and can form virtual images. Typical converging lenses are convex on both sides (they seem to bulge at the center) but typical diverging lenses are concave on both sides. The “principal axis” of a lens is the line about which the lens has rotational symmetry (that is, has the same features on opposite sides of the line). This axis typically passes through the center of a lens and is perpendicular to the two faces. It joins the centers of curvature of the lens faces. The “focal plane” of the lens is the plane in which the lens forms an image of an object that is at infinite distance from the lens. For some thick lenses, this focal plane may actually be a focal surface which is not totally flat. The focal point is the intersection of this focal plane with the principal axis. The focal length is the distance from the center of the lens on the principal axis to the focal point. There are actually two focal points, one on each side of the lens, but they both have the same focal length for a typical thin lens. For a converging lens to form a real image, the object should be at a distance from the lens of more than the focal length. For the converging lens to form a virtual image, the object should be closer to the lens than a focal length. This relation of images also applies to concave mirrors: the mirror produces a real image if the object is farther from the mirror than the focal length of the mirror, but a virtual image if the object is closer than the focal length.

People easily confuse the focal plane and focal point with the “image plane” and “image point.” The image plane for any given distance of the object from the lens is the plane in which the lens forms the image of the object. This plane is the focal plane if the object is at infinite distance from the lens. The image point is the intersection of the image plane with the principal axis. The image point is the focal point if the object is at infinite distance from the lens. For an object closer to the lens, the image point is further from the lens and continues moving away from the lens as the object comes closer.

An aberration is a distortion of the image. Lenses are usually of the “spherical” type in which either face of a lens is part of the surface of a sphere. These kinds of lenses are fairly easy to make. The two easiest shapes of optics to make are flat (as in windows) and spherical. However, the laws of physics (the laws of optics) can be applied to show this is not exactly the correct shape to form a sharp image. Thus, a distortion of the image results from using spherical lenses, and this aberration is called “spherical aberration.” Military projects and astronomy often use lenses that are not of the spherical type in order to avoid spherical aberration, but such optics are difficult to make and have a higher cost than ordinary spherical lenses.

Dispersion occurs in lenses. Different colors of light are focused differently by a lens. Thus, a colored image is distorted because of this dispersion and the aberration is called “chromatic aberration.” Engineers use special coatings on lenses in an attempt to counter chromatic aberrations. Another
approach used by astronomers and some photographers is to replace lenses by mirrors since mirrors can form images without dispersion.

Astigmatism is an aberration in which rays of light in two perpendicular planes have different image planes. That is, the focusing in the vertical direction is different from the focusing in the horizontal direction. The image is blurred either in the vertical or in the horizontal direction. Such aberration can be caused by a lens or mirror that is curved differently in the vertical direction than in the horizontal direction.

**Huygens' Principle and Diffraction**

Huygens lived about the same time as Newton. Huygens studied waves and developed an early version of a physical law that is called “Huygens' Principle.” The calculus Newton developed was later used to precisely express this principle mathematically. However, mathematical expression of Huygens' Principle is beyond this textbook. In our class, we use terminology similar to that used by Huygens. Thus, we start as Huygens did by considering the beginning formation of a wave.

A disturbance or oscillation can be a source of waves. If you drop a pebble in a pond, the disturbance of the surface causes water waves to form on the surface. If you pluck a string on a musical instrument, the oscillation of the string causes sound waves to travel in the air around the string. Consider the action of the waves: they also cause disturbances and oscillations. Thus, Huygens reasoned, each point of a wave should be able to act as a source of waves. Every point of a wave can produce “secondary” waves. Thus, he formed a physical law that expresses this idea.

**Huygens' Principle:** Every point of a wave acts as source of “secondary” waves.

However, if every point acts as a source, you may wonder why we don't see several additional waves. Huygens realized that there are many additional waves but they superpose in a way that hides the individual secondary waves but maintains the original wave. (You can think of this type of superposition as constructive interference maintaining the motion of the wave and destructive interference hiding the individual secondary waves.) If these little sources of secondary waves were not present, a wave would not continue to travel.
Most of the waves we encounter in nature are two-dimensional or three-dimensional. For example, water waves on the surface of water can be considered two-dimensional waves because they travel on a two-dimensional surface. Huygens and other people often drew the crests of two-dimensional waves as lines or curves. These curves are called “wavefronts.” This concept of wavefronts can also be applied to waves in three dimensions (such as, for example, the cases of sound waves and light waves). (Physicists generalize the meaning of this term so it can be applied to any “in-phase” part of the wave rather than just the crest. Thus, the valleys of water waves could be considered wavefronts rather than the crests.) People often rephrase Huygens' Principle replacing “wave” with “wavefront” so the principle says “every point of a wavefront acts as source of secondary waves.”

A simple experiment to show the effect of Huygens' Principle involves eliminating part or most of the wavefront so the remaining part can be seen generating secondary waves. A firm boundary with a small slit can be used to block most of the wavefront. This eliminates most of the secondary waves that would have been generated by many points of the wavefront. The slit, which allows waves to pass through its small opening in the boundary, appears to be a source of waves and secondary waves radiate radially out from the slit. The oscillation in the slit acts as a source of these secondary waves. If the slit is widened, the secondary waves superimpose and interfere with each other, and they thus hide each other so only the forward moving waves are noticeable.

Diffraction

Diffraction is changing the direction of waves by eliminating part of the wavefront. Diffraction is an effect caused by Huygens' Principle or a combination of Huygens' Principle and interference between the waves that remain after part of the wavefront is blocked. People often say diffraction “bends” the waves. The slit experiment used to demonstrate Huygens' Principle exhibits diffraction. The wavefront was moving forward before the slit is encountered but most of the waves coming through the narrow slit go in other directions rather than just forward.

Another example of diffraction is found when waves pass by a boundary. Waves can diffract as they pass the boundary and change direction because the boundary blocks part of the wavefront. For example, water waves on the surface of the ocean come toward the beaches. To make an artificial harbor for boats, construction crews build a “breakwater” which is a barrier to block part of the wavefront of the water waves. The plan is to make the water surface smoother behind the breakwater. When a narrow breakwater is perpendicular to the direction the waves are traveling, part of the waves
turn near the end of the breakwater and enter the artificial harbor. The water may be smoother behind
the breakwater, but the artificial harbor still has waves entering it.

The effects of diffraction depend on wavelength and the sizes of regions of the wavefront eliminated
and the regions retained. Diffraction effects with slits are more noticeable when the slits are not too
large compared to the wavelengths of the waves. For a fixed slit size, waves with longer wavelengths
tend to change direction through wider angles than waves with small wavelengths. With the smaller
wavelengths, the secondary waves tend to interfere in a way that hides them and prevents the effects of
diffraction. (Some people call this dependence on wavelength a type of dispersion, but other people
reserve the term “dispersion” for bending waves by changes in speed of the waves.) Since diffraction
depends on wavelength, diffraction is often used to separate various frequencies of waves. For
example, “diffraction gratings” are arrays of tiny lines with tiny spacings, and are used to separate
colors of light passing through the gratings.

To cause diffraction, part of the wavefront is eliminated. One way to eliminate part of a wavefront is to
block part of the wavefront. Another way involves reflection and absorption. A surface can reflect part
of a wavefront and absorb the other part. For example, people notice colors in reflections from a
compact disk (CD) or DVD illuminated by white light. The disks have thin tracks separated by small
distances. The thin areas between tracks reflect light but parts of the tracks absorb light. Thus, part of
the wavefront is eliminated and diffraction occurs. Since the diffraction depends on the wavelengths of
light, separation of colors of light can be expected. However, much of the separation of the reflected
light is due to interference. By the combination of diffraction and interference, the reflected colors are
separated so that various colors of light travel from the disks at different angles.

**Superposition and Interference**

We now return to the subjects of superposition and interference. Earlier chapters focused on
interference with one-dimensional waves (such as transverse waves on a string or spring) but now we
focus on two-dimensional and three-dimensional waves (such as water waves or light). The effects of
interference depend on the wavelengths of waves. An example situation in which superposition and
interference is important is the example of waves passing through a linear array of slits. Such arrays are
often used to separate waves of different wavelengths. Regions where maximal constructive
interference occurs are antinodes and regions where maximal destructive interference occurs are called
nodes. At nodes, the interfering waves cancel each other out so minimal amplitude occurs.
Interference effects are seen in thin films in which light is reflected from the front and back faces of the films. The waves reflected from the back interfere with waves reflected from the front. This interference causes various colors of reflections from the thin films. Engineers use such thin films in design special filters to eliminate a wavelength of light. Thinner films are used to eliminate shorter wavelengths. However, the films can also be tilted so the light travels a longer distance in the film and a longer wavelength is canceled. Interference is involved in the separation of colors in reflections from CD and DVD disks. Interference is used by engineers designing radio and radar systems. Engineers design arrays of antennas that use interference to direct and sweep a beam of radio waves or microwaves.

Polarization

Electromagnetic radiation, including radio waves and light, is composed of electromagnetic waves that are transverse waves with electric and magnetic fields oscillating in directions perpendicular to the direction of wave travel. The directions in which the electric field and magnetic field are pointing is the subject of “polarization” of the waves. In most light we encounter, the directions of the electric and magnetic fields are random but still perpendicular to the direction of travel. Suppose electromagnetic radiation is traveling forward toward us as we observe it. At one moment the electric field may be oscillating vertically with the oscillations between up and down, but at another moment the electric field may be oscillating horizontally with the electric field vector oscillating between left and right. Such random directions of oscillation is common in ordinary electromagnetic radiation, but “polarized” radiation (discussed next) is less random.

In “linearly polarized” electromagnetic radiation, the line along which the electric field oscillates, as the radiation passes an observation point, is constant. For example, for electromagnetic radiation traveling forward toward us, the electric field may be oscillating vertically. People often speak of the “direction of polarization” as being the two directions (up and down in the present example) of the line along which the electric field oscillates. In our example, they can say the direction of polarization is vertical because the electric field oscillates vertically. The magnetic field will be perpendicular to the electric field but still perpendicular to the direction of travel. Thus, if the electric field oscillates vertically, the magnetic field will be oscillating horizontally.

© Copyright 2015, 2016 and 2017 by Ron Ferril. All rights reserved.
Circularly polarized electromagnetic radiation has constant magnitude of electric field but the electric field is turning in one direction at a constant rate for each frequency present in the radiation. The electric field is a vector and this turning constitutes a changing electric field. With such circular polarization, the magnetic field also has a constant magnitude (proportional to the magnitude of the electric field) but the magnetic field turns its direction at the same rate as the electric field for each frequency. If two beams of circularly polarized electromagnetic radiation have the same magnitudes of electric fields and are traveling in the same direction, but have their electric fields turning in opposite directions, then the two beams can be superimposed to form linearly polarized radiation. (There is also a way to superimpose linearly polarized beams to form a circularly polarized beam, but this situation is more complicated.) Elliptical polarization is intermediate between linear and circular polarization because the direction of the electric field turns but the magnitude also oscillates. Radiation that is elliptically polarized can be regarded as a superposition of linearly and circularly polarized radiation.

Linearly polarized light is formed from ordinary unpolarized light by special filters. These filters suppress oscillation of the electric field in one direction and allow oscillation in the direction that may be called the “polarization axis” of the filter. If you pass light through one of these filters to polarize it vertically (so the electric field is oscillating vertically), the filter suppresses oscillation of the electric field in the horizontal direction so the light is polarized vertically. If you then pass the resulting polarized light through another such filter but with its polarization axis turned perpendicular to that of the first filter, then little or no light passes since the second filter suppresses oscillation in the vertical direction. However, if you turned the second filter midway between the vertical and horizontal orientations (45 degrees from either vertical or horizontal), the second filter will pass some light through but it will emerge from the second filter linearly polarized in the direction midway between vertical and horizontal (that is, in other words, at 45 degrees from either vertical or horizontal).

Light becomes partially linearly polarized when it reflects off surfaces at some angles of incidence. The reflections partially suppress oscillations of the electric field in one direction. Polarized filters for cameras or sunglasses suppress glare by having their polarization axes perpendicular to the expected polarization of the reflected light. Since glare off of surfaces parallel to the ground are often partially polarized in a horizontal direction, the polarization axis is often turned vertical to suppress transmission of the reflected light through the filter.
Holography

In a previous chapter, we were introduced to images formed by lenses and mirrors. In class, I demonstrated some real images that appeared to be the actual three-dimensional objects of which they were images. Real and virtual images can also be formed by diffraction. Holography is a type of photography that uses a two-dimensional pattern to diffract light to form images. The images formed by holography usually are three-dimensional so a person can move to view one part of an image behind another part of the image. Making a hologram of an object involves light coming from every point of the object to every point of the surface of a photographic plate, with exceptions where light is blocked because of the shape of the object. In old methods, a single frequency of light was used from a “coherent” source. Newer methods and film emulsions can use more than one frequency.

Light Emission

For a substance to emit light, the electrons are excited to states of higher energy so the transition back to the states of lower energy will cause energy to be converted to electromagnetic radiation which is emitted. Some details of this emission can be understood from the fundamental physical laws we have already learned. Those fundamental laws are

- Newton's laws (three laws of motion and one law of gravity)
- the Law of Conservation of Charge and
- Maxwell's (four) equations.

However, some details are explained by fundamental physical laws that were not discovered until the twentieth century. For example, quantum physics determines the rules regarding which frequencies of light are emitted. One result of quantum physics is that light is composed of particles called photons. Another result of quantum physics is that the energy of photons of light are proportional to the frequency of the light. A consequence of modern physics is that gases of chemical elements emit a “discrete” spectrum which means they emit light of only certain frequencies.

A spectroscope is an instrument that measures the frequencies of light in a beam of light. The spectroscope represents discrete frequencies as short lines called “spectral lines.” Atoms and molecules absorb the same frequencies they emit. Thus, when astronomers used spectrosopes and other spectrometers, they noticed that large bodies of gas in outer space absorb the same spectral lines they emit when excited.

© Copyright 2015, 2016 and 2017 by Ron Ferril. All rights reserved.
A blackbody is a body which absorbs all light incident on it. A good absorber of light is also a good emitter of light. (This can be shown from the Law of Conservation of Energy.) Thus, a blackbody should be the best emitter. The concept of a blackbody was theoretical and early attempts to make or simulate a blackbody involved black paint or “lampblack.” These attempts yielded fairly good results. Eventually, the best physical representation of a blackbody was made by painting the inside of a large chamber black and then drilling a small hole in one wall of the chamber. Then the hole was taken to be the blackbody or at least the best approximation of a blackbody available. Studies were made of the spectrum of colors of light emitted when a blackbody was heated. The average frequencies emitted by blackbodies and other hot glowing bodies were found to be roughly proportional to the absolute temperature of the blackbody.

The filaments of incandescent lamps and other hot glowing bodies (such as the Sun) were found to have roughly the same characteristics as blackbodies. Since the operation of incandescent lamps involves generation of much heat, such lamps are known to be inefficient. Some modern light sources—fluorescent lamps and LED lights for example—involve less heat production and are considered to be more efficient. However, many modern sources of light lack some characteristics of blackbodies.

**Fluorescence and Phosphorescence**

Fluorescence is the behavior of electrons in an atom being excited to states of a higher energy but then emitting photons of lower energy when they transition back to the states of lower energy. The fluorescent material glows as the electrons transition back to their original states. This is different from reflection of light in which the photon of reflected light has the same energy as the photon of incident light. The reason the emitted photon has lower energy than was needed to excite the electron is that the electron transitions back to its original state in two or more steps. The energy released cannot be more than the energy received. Some transition steps may not emit any visible light. Thus, the step that emits a phone cannot emit a photon with as high a frequency as the original absorbed photon had. In fluorescence, the time between excitation and emission is short. Humans cannot notice any delay between excitation and emission.

Phosphorescence is the same process as fluorescence except the electrons remain in excited states for a significantly long time. Thus, humans notice the material is still glowing when the source of excitation has been removed. Usually, the source of excitation in fluorescence and phosphorescence is incident
light and some people specifically mean excitation by light when they use the terms “fluorescence” and “phosphorescence.” A major point is that the emitted light must not be of higher frequency than the incident light. (Since the energy of a photon is proportional to the frequency of the light, the Law of Conservation of Energy can be used to verify that the frequency of emission cannot be higher.)

**Lamps**

There are several types of lamps for emitting light.

- **Incandescent lamp**: The electrons in a “filament” are excited by heat, and the heat is generated by passing an electric current through the filament.

- **Fluorescent lamp**: Electrons are emitted by a filament (or other device) and strike gas to produce ultraviolet electromagnetic radiation. This radiation excites electrons in a fluorescent material causing fluorescence. The frequencies emitted by the fluorescent material cannot be higher than the frequency of the radiation produced by the gas.

- **Light-emitting diode (LED)**: This is an electronic device that easily allows current to flow in one direction but resists current flow in the opposite direction, and current flow excites electrons by making them pass from one energy band into another band of lower energy. The transition emits light.

**Laser**

A laser is a device that emits light of one or a few frequencies, but emits this light so the waves are “in phase” which means their crests are all aligned so there is constructive interference rather the random combination of constructive and destructive interference present in ordinary light. In ordinary “spontaneous emission” of light, electrons are excited and spontaneously transition back to their original states. In “stimulated emission,” electrons are excited but remain in the excited state long enough for photons passing these excited electrons to cause them to transition to lower energies and emit photons in phase with the passing photons. These new photons emitted by stimulated emission can join the other photons in causing more stimulated emission of photons. (This concept caused people to invent the term “laser” originally as an acronym which labeled the laser process as “Light Amplification by Stimulated Emission of Radiation.” The term “amplification” was considered improper by some scientists and engineers so the term “laser” is normally used without reference to its acronym history.) The designs of the original lasers included attempts to have only one frequency in
order to help keep the waves in phase. Some lasers emit multiple frequencies but keep waves in phase for each frequency.

**Example Calculations**

**Example 01.** Suppose waves pass from one medium into a second medium and travel slower in the second medium. Part of the waves are reflected and part is transmitted through the boundary surface between media. We know the part transmitted is refracted toward the normal to the surface because the speed is slower in the second medium. The reflected part travels at the same angle with respect to the normal as the incident waves traveled. Thus we know this information—characteristics of the angles of incident, reflected and refracted waves—about the waves.

**Example 02.** Suppose light travels through a medium with index of refraction $n = 2$. We can calculate the speed $v$ of light in that medium.

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

$$v = \frac{c}{n} = \frac{3 \times 10^8 \text{ m/s}}{2} = 1.5 \times 10^8 \text{ m/s}$$

Thus, light travels in the medium at half the speed $c$ it travels in vacuum.