Diffraction of Visible Light

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Lab 8

Visible light has an intriguing property: it behaves as both a wave and a particle. This property confused many scientists and theorists back during the advent of optics, or the section of physics that accounts for the behavior of light. The particle theory of light was developed first on a timeline, before the wave theory. This split in the genius minds of that time resulted in multiple methods of dealing with this wave-particle duality. Geometric optics is used when modeling light as a ray of particles – rays are represented as straight lines that are reflected or refracted through surfaces. Physical optics, on the other hand, deals with optics issues that are dependent on the wave behavior of light.

Pierre Gassendi originally suggested the particle theory of light. This theory (also referred to as corpuscular theory, for light was figured to be made up of little particles called "corpuscles") was expanded and developed extensively by Sir Isaac Newton. Newton dealt heavily with geometric optics, therefore, because the particle theory of light governs the effects of reflection and refraction (Sabra 1981, 209).

Later scientists found exceptions to this theory, however. According to geometric optics, when a ray of light encounters an obstacle, a shadow with sharp edges should be observed. Francesco Maria Grimaldi first observed and recorded evidence contrary to this notion. His optics experiments yielded shadows that were fuzzy around the edges. Upon closer inspection, alternating dark and light bands around the perimeter caused this fuzziness. He studied these banded patterns and coined the term diffraction, and the patterns he observed diffraction effects (Sabra 1981, 185).

Rene Descartes, another notable theorist, also attempted to support geometric optics in his day, like Newton. His ideas, termed Cartesian theory, were the basis of many notable physicists at that time, because he initiated clear mechanical pictures as the most productive way to solve physical problems. He particularly sought to understand rectilinear propagation, or the idea that rays of light may cross with no effect to each other. This concept worked with his theories of reflection and refraction, two concepts that depend solely on geometric optics, but he could not explain diffraction effects with the mechanical pictures he had conceptualized (Sabra 1981, 186).

Robert Hooke was one of the first theorists to venture towards wave theory with concern to light. In his study of colored light with the basis of Cartesian theory, he proposed the concept of a wave front, illustrated by water waves. He defines this wave front as a sphere whose surface is perpendicular to the direction of propagation, or travel, at all points (Sabra 1981, 192).

Ignace-Gaston Pardies and Pierre Ango took this idea of a wave front a little further in their separate research. The work of these two physicists was the basis for Christiaan Huygens' wave theory of light.

Huygens introduced light as a wave by drawing an analogy between light and sound. Much like sound waves, light waves can turn corners. Even though his theory still depended heavily on geometric Cartesian theory, he did formulate the idea of secondary waves, which are central to the phenomena of diffraction. By his definition, each point on a wave surface is considered the potential center of a secondary wave, which also travels at the same velocity as the wave front (Sabra1981, 212). These potential secondary waves are referred to as Huygens' wavelets.

Several other physicists expounded on Huygens' principle until it became the modern wave theory that physical optics depends on today, in conjunction with particle theory to form the wave-particle duality of light. Different optical singularities still rely on one theory over the other, however, in order for the outcomes and mathematics to make sense.

Interference is one optical phenomenon that relies solely on the wave property of light. It is defined as any situation in which two or more waves overlap in space. Whenever this happens, the overall wave is subject to the principle of superposition; that is, the displacement of the wave at any point or instant may be found by adding the displacements that would have been formed by the individual waves at that point or instant (Young and Freedman 2004, 1339). Superposition is a linear concept, which is highly convenient when simplifying optical problems in a plane. It is what allows for the simple addition or subtraction of multiple wave displacements when they cross.

There are different instances of interference, most commonly constructive or destructive interference. Constructive interference of light occurs when two waves are in phase and the amplitudes of the waves are added, resulting in a larger wave, or brighter illumination. Destructive interference is the opposite: when the amplitudes partially cancel each other out, the result is a smaller wave, or less illumination (Francon 1979, 9). This difference in illumination can also be referred to as intensity, or the energy of the wave crossing an area in a unit of time. The intensity changes as a result of the electric and magnetic fields oscillating and producing different wave amplitudes (Stewart 2012, 413). These instances of interference generally only involve the crossing of waves from a small number of sources.

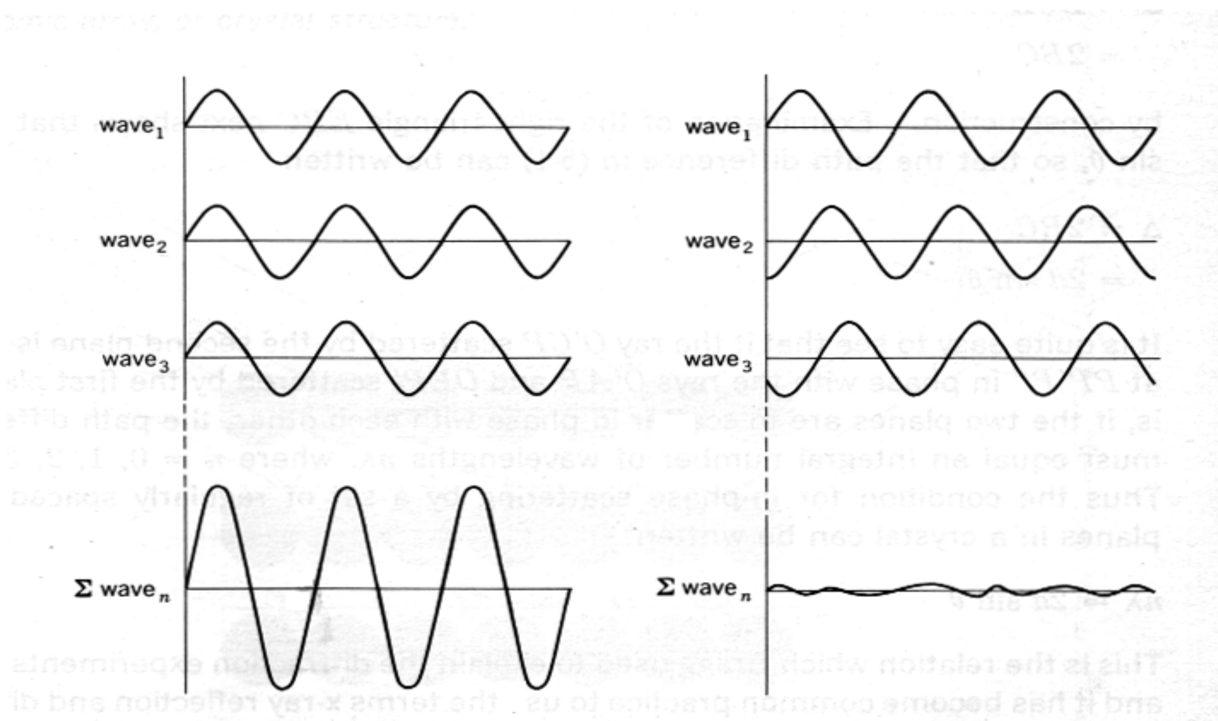


Figure 1 – Constructive and Destructive Interference

Diffraction is now considered another term for interference, usually in reference to a continuous distribution of light waves. It refers to the observable effect when these light waves are combined, generally because of an encounter with an obstacle. The obstacle cuts off part of the wave, and the remaining parts of the wave front interact (Young and Freedman 2004, 1369), causing an alternating pattern of constructive and destructive interference. Diffraction patterns refer to the arrangement of light and dark bands around the edge of the shadow produced when the light waves hit the obstacle. The light bands are due to constructive interference, and the dark bands are due to destructive interference (Francon 1979, 9). These patterns may also be referred to as fringes (Baldock 1981, 171).

Figure 2 – Edge Diffraction Fringe

Augustin Jean Fresnel hypothesized that each of the wavelets on a wave front is subject to interference from other wavelets. This idea, combined with Huygens' principle, is the basis of diffraction – that a wave propagating linearly can experience interference, resulting in changes in intensity that then result in diffraction fringes. This notion, named the Huygens-Fresnel principle, predicts the amplitude of a wave in the direction of propagation (Francon 1979, 26).

Light as used in the following optical experiments is considered as plane waves, or parallel rays. Light is physically caused by the propagation of an electric field and magnetic field simultaneously, according to electromagnetic theory (Francon 1979, 1). Solving Maxwell's Equations, a set of differential equations that governs the relationship between electric and magnetic fields, demonstrates this ideal – the end result is that a wave must travel at a velocity equal to the speed of light in order to be an electromagnetic wave (Stewart 2012, 407). Therefore, light waves are solutions to Maxwell's Equations, and because these equations are linear, a superposition of plane waves also solves the equations (Mansuripur 2002, 26).

A point light source provides light by emitting vibrations of the electric field. The consequent rays of light are parallel, because they originate from the same point; hence, they are considered plane waves. Because the vibrations have the same origin, the plane waves have the same frequency, which contributes to the interference patterns when the waves interact in the plane (Francon 1979, 9). There is no fundamental difference between interference and diffraction, however – both rely on the concepts of superposition of plane waves and Huygens' principle (Young and Freedman 2004 , 1369, 1378).

Most instances of diffraction as studied in the world of physics are produced using a point light source, an obstacle with an aperture, and a simple screen on which to observe diffraction effects. The aperture is said to diffract the light that passes through it, or spread out the light beyond the aperture's geometric shape onto the screen (Francon 1979, 25). Another term for this action is scattering (Baldock 1981, 171).

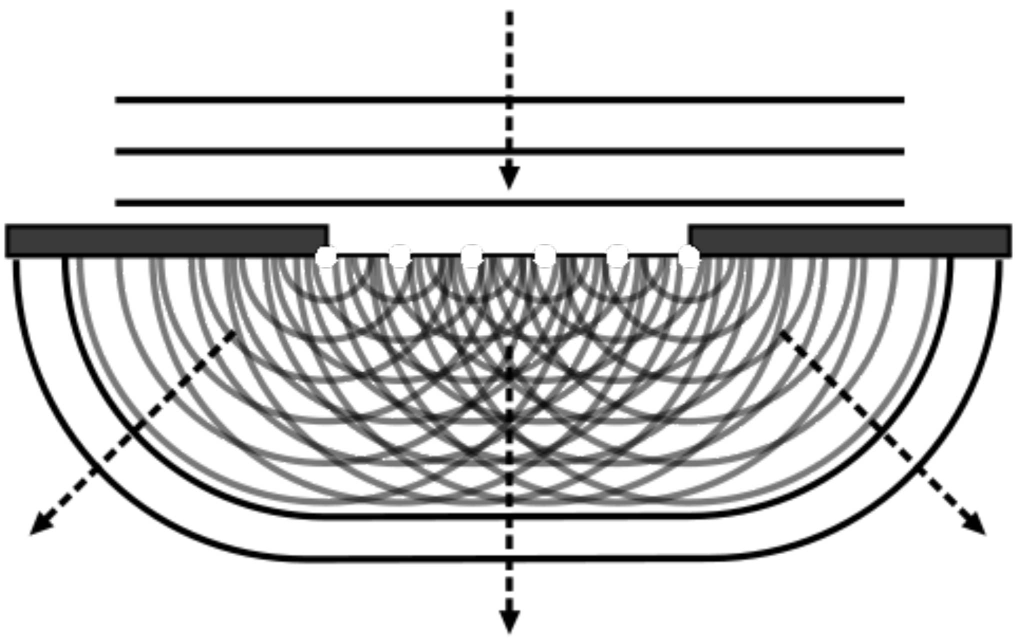
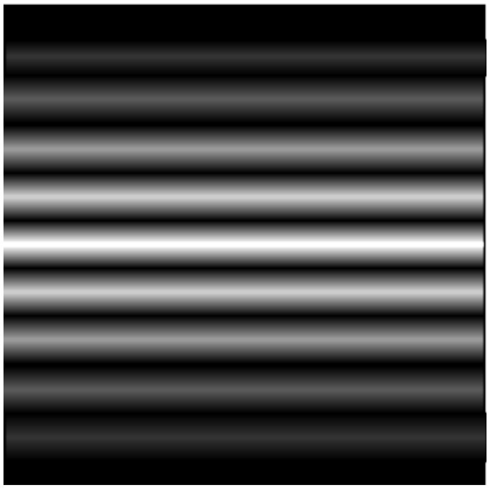
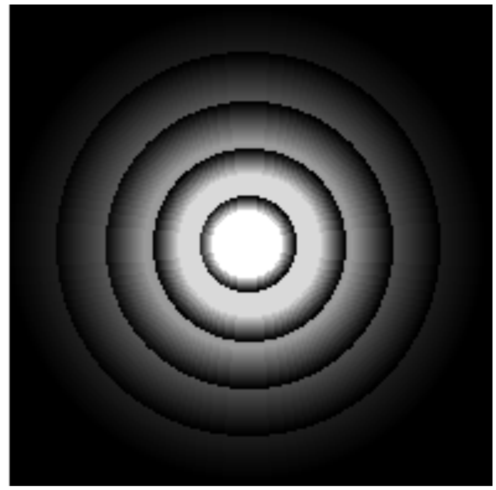


Figure 3 – Diffraction Through an Aperture, Huygens-Fresnel Principle

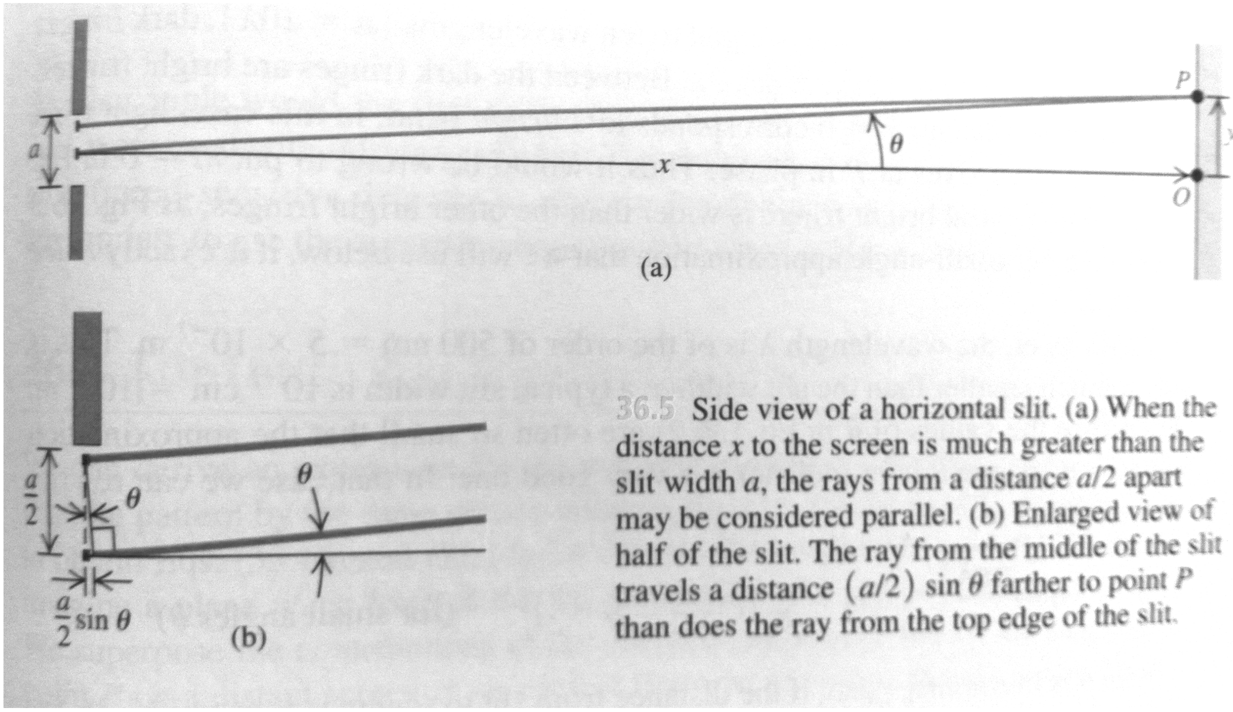
Diffraction patterns rely mainly on the size and geometry of the aperture through which light is transmitted. The smaller the aperture, the more light will spread out across the screen (Francon 1979, 25). The amplitude of the wave at any position on the screen is directly proportional to the surface area of the aperture. Also, the intensity of the light wave is directly proportional to the surface area of the aperture squared (Francon 1979, 32). Geometrically, for example, if the aperture is rectangular, it will spread out the light vertically into a pattern consisting of alternating horizontal light and dark bands. If the aperture is circular, a central bright spot will be transmitted with alternating light and dark rings surrounding it.

Figures 4 and 5 – Diffraction Patterns of Rectangular and Circular Apertures

The analysis of diffraction thence splits into two modes: Fresnel or Fraunhofer diffraction. In Fresnel diffraction (named for Augustin Jean Fresnel, who also built on Huygens' principle to form the aptly named Huygens-Fresnel principle), or near-field diffraction, the point light source and obstacle are at a finite distance from the screen. In Fraunhofer diffraction (named for Joseph von Fraunhofer), or far-field diffraction, the diffraction patterns are analyzed at infinity - to qualify, the point light source, obstacle, and screen must be far enough away from each other so that all light rays can be considered parallel (Young and Freedman 2004, 1369). Most mathematical interpretation of diffraction is done via Fraunhofer diffraction, which makes analysis simpler.

The Fraunhofer diffraction formulas can be figured by studying the fringes of an optical system with an obstacle with a single slit. In this single-slit experiment, the pattern can be mathematically explained by determining where the dark fringes occur on the screen – that is, where two light rays out of phase cross to cancel each other out.



36.5 Side view of a horizontal slit. (a) When the distance x to the screen is much greater than the slit width a, the rays from a distance $a/2$ apart may be considered parallel. (b) Enlarged view of half of the slit. The ray from the middle of the slit travels a distance $(a/2)\sin\theta$ farther to point P than does the ray from the top edge of the slit.

Figure 6 – Diffraction of a Single Slit

Suppose the vertical slit width is a, and the wavelength of light is λ. Consider θ to be the angle a light ray makes with the incident (the center of the central bright band) when it leaves the aperture at a distance $a/2$. This light ray will converge with another ray that leaves the aperture at a distance a at a point above (or below) the center. We can conveniently set the difference of path of these two rays to $\lambda/2$ because of infinity, so the two waves cancel each other out when they reach the screen, resulting in a dark fringe. Using basic trigonometry, the location of a dark band is given by the following:

$$\frac{a}{2}\sin\theta = \pm\frac{\lambda}{2} \qquad \text{or} \qquad \sin\theta = \pm\frac{\lambda}{a}$$

The location has a plus-or-minus sign because of symmetry in the scattering of light. This formula is extended for different path differences in relation to the wavelength, and so the location of all dark fringes in a single-slit diffraction is given by:

$$\sin\theta = \frac{m\lambda}{a} \qquad (m = \pm1, \pm2, \ldots)$$

Assuming the slit width a is significantly smaller than the distance x between the obstacle and the screen, resulting in a small enough θ to make trigonometric approximations, this formula can be rewritten in a more measurable form using x and the vertical distance of the mth dark fringe y_m (Young and Freedman 2004, 1371-72):

$$y_m = x\frac{m\lambda}{a}$$

Thomas Young was another physicist who adopted the wave theory of light, and proposed his double-slit experiment as further proof. In this setup, light from a point light source is first transmitted through an obstacle with a single slit, and then through an obstacle with two equal side-by-side slits. The resultant waves are superimposed in the middle of the system in a different way than single-slit diffraction patterns. If the slits are a finite distance apart, the constructive interference of the wave front from one slit will combine with the destructive interference of the other slit to produce a consistent pattern in the middle of the screen (Young and Freedman 2004, 1377). The farther from the center the secondary wave fronts are, the less interference is observed between the two, and the pattern dissolves into standard bands of high intensity and low intensity.

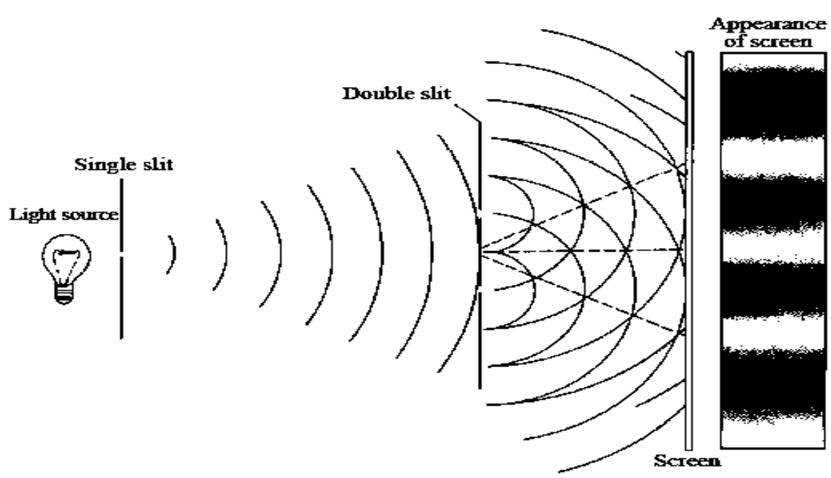


Figure 7 – Young's Double-Slit Experiment

Diffraction grating, or an array of a large number of parallel slits with equal dimension and spacing, is also highly useful in observing the behavior of visible light waves when they encounter obstacles. The variety of materials that can be used for diffraction grating, along with the freedom of slit size and spacing, makes for a wide range of interesting results when studying the diffraction patterns. For example, a diffraction grating can be constructed from fine wire mesh, or by using a diamond to scratch grooves on a glass surface. The latter is considered reflection grating, which is a specific kind of grating that reflects light instead of transmitting it. When the grating is viewed at different angles, the wavelength and therefore color of the light varies depending on the angle of reflection in the eye of the viewer (Young and Freedman 2004, 1379-80).

Diffraction of visible light is most useful when verifying basic optics equations with respect to the wave theory of light or, say, disproving Sir Isaac Newton in the late 1600s. The aforementioned experiments and calculations are generally carried out using a point white light source or laser. However, diffraction can be applied to different sorts of waves, such as sound or water, as analogized by early physicists when attempting to prove the wave theory of light, or other electromagnetic waves, such as x-rays. Diffraction of any of these waves serves as a model to understand linear propagation and interference of waves.

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Figure 1: http://capsicum.me.utexas.edu/ChE386K/html/wave_interference.htm

Figure 2: http://spiff.rit.edu/richmond/occult/bessel/bessel.html

Figure 3: http://en.wikipedia.org/wiki/File:Refraction_on_an_aperture_-_Huygens-Fresnel_principle.svg

Figures 4 and 5: http://www.pages.drexel.edu/~garfinkm/Scope.html

Figure 6: *University Physics with Modern Physics, 11th Edition.*

Figure 7: http://www.askamathematician.com/2011/06/q-what-is-a-measurement-in-quantum-mechanics/