WAVE OPTICS

HUYGENS PRINCIPLE

INTRODUCTION OF ELECTRIC CHARGE AND FIELD

Wave Optics Theories

Wave optics is a field of study that holds a significant place in the history of science, marking a notable disagreement between two influential scientific communities. This disagreement revolves around the fundamental nature of light, with one side advocating for the particle-like characteristics of light, while the other side champions the wave-like nature of light.

In this intellectual battle, Sir Isaac Newton emerges as a prominent advocate of the particle theory of light. He proposed a theory known as the corpuscular theory, which posited that "light is composed of minuscule and lightweight particles called corpuscles." According to this theory, these corpuscles travel at incredibly high speeds from a light source, and when they strike the retina of the eye, they create the sensation of vision. This theory, put forth by Newton, contributed to the ongoing discourse surrounding the nature of light.

Huygens Wave Theory

For a significant period of time, Sir Isaac Newton's corpuscular theory of light went unchallenged. However, it wasn't until the early 18th century that Christopher Huygens boldly presented his wave theory of light. According to Huygens, light is comprised of waves that traverse through an exceedingly sparse and highly elastic material medium, which is believed to permeate all of space. This intangible medium is referred to as ether.

In Huygens's theory, this ether is envisioned as having an extremely low density but an exceptionally high modulus of elasticity, which results in light traveling at considerable speeds.

Huygens's wave theory offered explanations for various optical phenomena, including the behavior of light in terms of reflection, refraction, interference, and diffraction. However, it faced challenges when it came to elucidating:

1. Polarization: Huygens's theory considered light waves to be mechanical disturbances, which were thought to be of a longitudinal nature, and this couldn't account for the polarization of light.

2. Black Body Radiation, Photoelectric Effect, and Compton Effect: These significant phenomena remained unexplained by Huygens's theory.

It's worth noting that the hypothetical medium known as ether, which Huygens postulated, was never discovered. Furthermore, our modern understanding of light acknowledges its ability to propagate even in a vacuum, a fact that was not known during the era of these early light theories.

Maxwell Electromagnetic Theory

Maxwell's groundbreaking insights led to a paradigm shift in our understanding of light. He asserted that light is not a mechanical wave, as Huygens had postulated, but rather an electromagnetic wave. These electromagnetic waves have distinctive characteristics; they are transverse in nature, which means the oscillations of the electric and magnetic fields occur perpendicular to the direction of wave propagation. This revelation fundamentally transformed our comprehension of light and its behavior.

Maxwell's work also provided a fundamental relationship that governs the speed of electromagnetic waves, including light. This speed, denoted as C, is a constant and is equal to approximately $3 \times 10^{8m/s}$ meters per second. Maxwell's equations defined the speed of light as a function of two fundamental constants:

1. Permeability (μ_0): A physical constant with a value of approximately $4\pi \times 10^{-7}$, which characterizes the behavior of magnetic fields in a vacuum.

2. Permittivity (ε_0): Another fundamental constant, approximately equal to 8.854×10^{-12}, which characterizes the behavior of electric fields in a vacuum.

The relationship between these constants, permeability (μ_0) and permittivity (ε_0), along with the speed of light (C), is encapsulated in the equation:

$$C = \frac{1}{\sqrt{(\mu_0 \varepsilon_0)}}$$

This equation, derived from Maxwell's work, not only solidified the understanding of light as an electromagnetic wave but also provided an exact numerical value for the speed of light, which is now a fundamental constant in physics. Maxwell's theory paved the way for further advancements in electromagnetism and the unification of various phenomena under a single framework.

Wave front and Wave Normal

Wave front

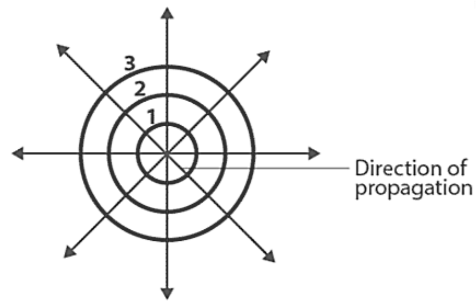
A wave front is a concept that describes a specific region within a wave where all points are in phase, meaning they are at the same stage of their oscillatory motion. When considering wave fronts in the context of light, they reveal how the light wave propagates and interacts with its surroundings. The shape and characteristics of wave fronts can vary depending on the nature of the light source, resulting in three primary types of wave fronts.

Spherical Wave Front

When light emanates from a singular point source, the configuration of the wave fronts takes on a spherical shape. This means that the wave fronts represent concentric spheres originating from the point source of light. Imagine the way ripples expand when you drop a stone into a calm pond. Similarly, when light radiates from a single point, it propagates outward in all directions, forming successive spherical surfaces of light waves.

Each sphere represents the continuous outward movement of light from the source, and these spherical wave fronts characterize the behavior of light emitted from a point source.

In spherical wave front,



Amplitude of light waves,

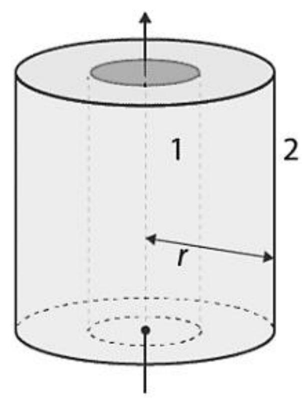
$$A \alpha \frac{1}{r}$$

And, Intensity of light waves,

$$I \alpha \frac{1}{r^2}$$

Cylindrical Wave Front

When the source of light takes on a linear form, the resulting wave fronts exhibit a cylindrical shape. In this context, it means that all points along these wave fronts are at an equal distance from the linear source of light. Imagine a long, straight light source, like a fluorescent tube or a laser beam. The wave fronts that form under such conditions appear as a series of parallel, flat, and elongated surfaces, similar to the shape of a cylinder. This signifies that the light waves are propagating uniformly in a direction perpendicular to the linear source, creating a cylindrical pattern of wave fronts extending infinitely along the length of the source.



In this case, Amplitude of light waves,

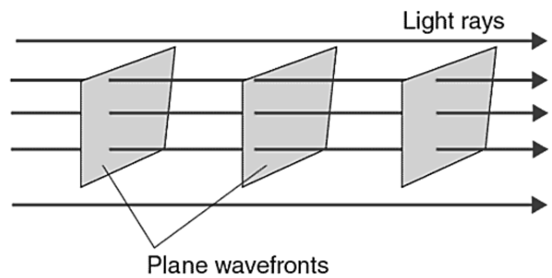
$$A \alpha \frac{1}{\sqrt{r}}$$

Intensity of light waves

$$I \alpha \frac{1}{r}$$

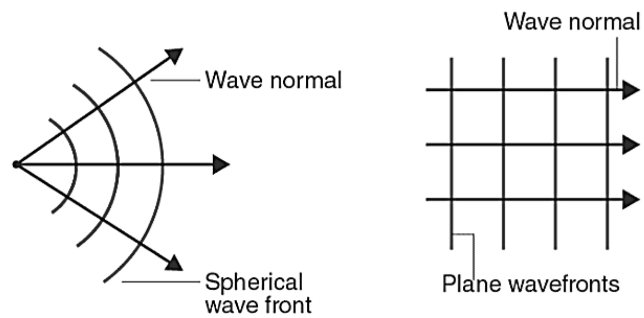
Plane Wave Front

In cases where the source of light is extremely distant, the wave fronts take on a planar or flat shape. This means that the wave fronts appear as flat, parallel surfaces that extend indefinitely. Unlike spherical or cylindrical wave fronts, the plane wave fronts have the unique characteristic of maintaining a constant amplitude. As a result of this constancy, the intensity of the light also remains consistent. In other words, when light emanates from a remote source and forms planar wave fronts, it retains its strength and doesn't exhibit variations in intensity as it travels through space. This property of plane wave fronts is particularly useful for various applications in optics and wave optics.



Wave Normal

A "wave normal" is a term used in the context of wave optics to describe a line that is drawn perpendicular to a wave front’s surface at a specific point. This line is oriented in the direction in which light propagates. In simpler terms, it represents the direction in which the light is moving and is therefore referred to as a "ray" of light. Hence, the wave normal and the ray of light are essentially one and the same, both denoting the path that light takes as it travels through space. This concept is fundamental in understanding how light behaves and interacts with various optical elements and surfaces.



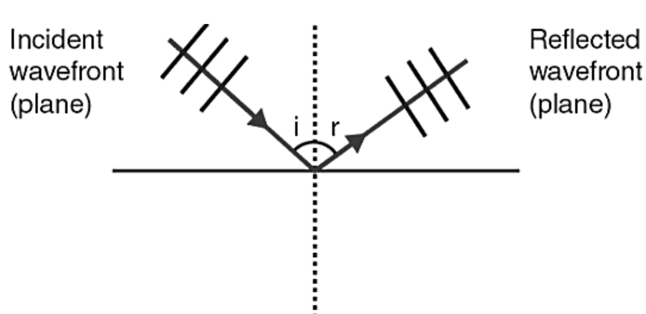
Shape of Wave fronts

A lens possesses the ability to alter the curvature and shape of wave fronts. This concept of wave fronts, particularly in relation to reflection and refraction, can be described as follows:

Wave fronts for Reflection

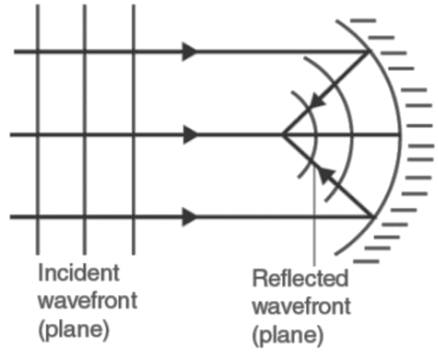
If light falls on a plane mirror:

When plane wave fronts are incident upon a plane mirror and get reflected, the shape of the wave front for the reflected light remains planar.

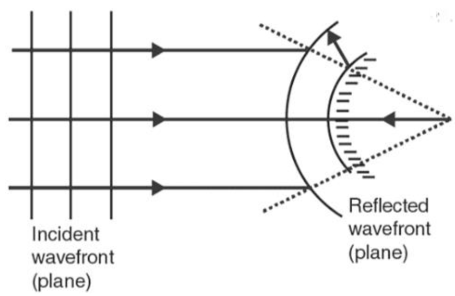


If light falls on a concave mirror; convex mirror:

When a plane wave front strikes a concave mirror, the reflected light takes on a spherical wave front shape.



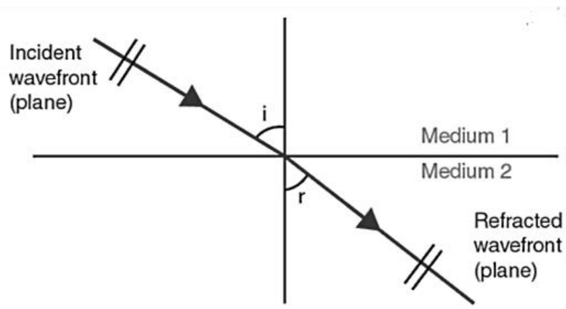
When a plane wave front is incident on a convex mirror, the shape of the reflected light wave front becomes spherical.



Wave fronts for Refraction

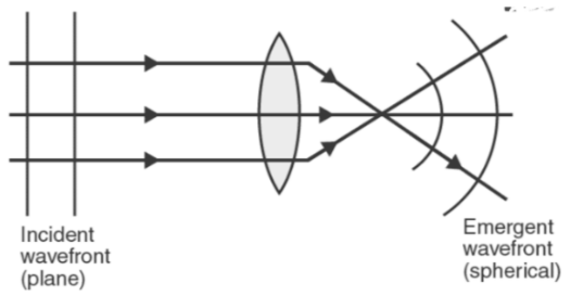
If light falls on plane surfaces:

When a plane wave front is incident on a plane surface, the refracted ray will also exhibit a plane wave front.



If light falls on curved surfaces:

When a plane wave front strikes a converging or diverging lens, the light emerging from the lens will exhibit a spherical wave front.



A wave front is typically depicted as a flat or planar surface.

$y = 8\sqrt{3x}$

Determine the path along which the wave travels.

Solution:

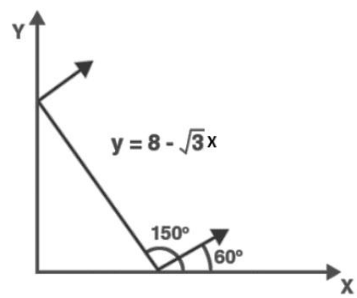
Given,

$y = 8 - \sqrt{3x}$

This implies that the wave front can be depicted as a straight line characterized by a specific slope.

$\tan\theta = -\sqrt{3}$

As it has a negative slope, the wave front is represented like

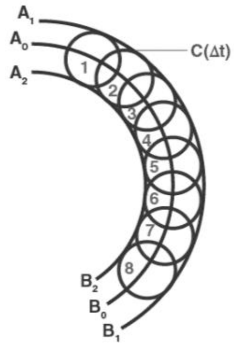


The wave front is inclined at an angle of 150° with respect to the x-axis. Consequently, the wave must be oriented perpendicular to the wave front, which means it forms an angle of 60° with the x-axis.

Huygens's Principle

Following Huygens's principle, each point on an existing wave front can be considered as a point source of fresh disturbance, emitting spherical wavelets referred to as secondary wavelets. These secondary wavelets expand outward in all directions at the wave's velocity.

A surface that just grazes these secondary wavelets, touching them tangentially in the forward direction at any given moment (Δt), delineates the position and configuration of the new wave front at that instant. This is termed the "secondary wave front."



As introduced earlier, Huygens's principle involving secondary wavelets was successful in elucidating various optical phenomena, including reflection, refraction, interference, and diffraction. However, it did not provide an explanation for the formation of wave fronts of secondary wavelets primarily in the forward direction rather than the backward direction.

Interference of Light

The phenomenon that arises from the non-uniform distribution of energy in a medium when two light waves overlap is referred to as interference.

Coherent and Incoherent Source

Coherent sources are defined as two sources that emit monochromatic light continuously and maintain a constant (or zero) phase difference between them.

HUYGEN'S PRINCIPLE:

The principles of wave optics are as follows:

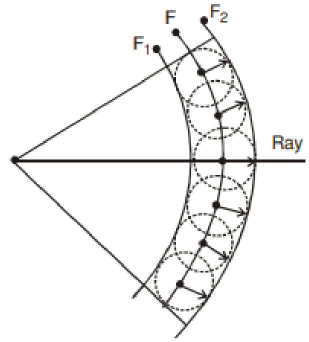
1. Each source of light serves as a point of origin for waves that spread in all directions. Particles that are equidistant from the source and vibrate in the same phase collectively form a surface known as a wave front.

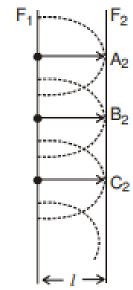
2. Waves propagate perpendicular to the wave front.

3. Rays originating from the same source take the same amount of time to reach from one wave front to another.

4. Every point on a wave front acts as a source of new disturbances, generating spherical secondary wavelets that travel at the speed of light in all directions within that medium.

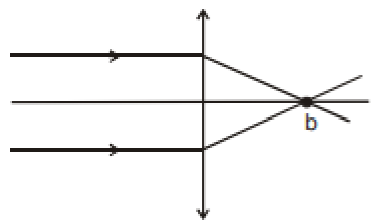
5. The forward envelope that encloses the tangents at the secondary wavelets at any given moment defines the new position of the wave front. Energy is not propagated backward when a wave travels in the forward direction.





Example.

For the given ray diagram, draw the wave front



Solution.