Chapter One

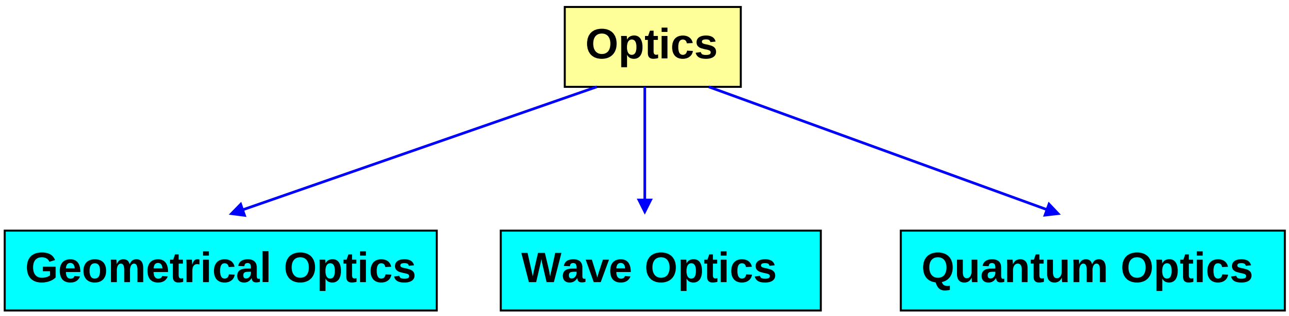
1.1 Introduction to Optics

What dose optics mean?

Optics is the branch of physics, which deals with such questions and describes about the phenomena and laws associated with the generation, and propagation of light and its interaction with matter.

These are some of the many questions that arise in our mind:

- What is light?
- How is it generated?
- How fast does it travel?
- How does it propagate across empty space?
- How does it behave when it comes across an object?
- How does it interact with matter?



1.2 BRIEF HISTORY

(A) **Development of Geometric Optics:**

(B) **Development of Wave Optics:**

(C) **Development of Quantum Optics:**

(D) **Nature of light:**

(A) Development of Geometric Optics:

- The Greeks were aware of the rectilinear propagation of light. They knew that when light is reflected from a mirror, the angle of incidence is equal to the angle of reflection. This was stated by **Euclid** (300 B.C.) in his book **Catoptrics**.

- Alexandria suggested that light travel the shortest path between two points. They were also aware of refraction of light as it passes from one transparent medium to another.

- Claudius (130 A.D.) measured the angles of incidence and refraction for several media.

- Francis Bacon (1215-1294) suggested the idea of using lenses.

- In 1609 Galileo (1564-1642) devised a practical telescope.

- Van Leeuwenhoek (1632-1723) developed the first microscope.

- John Kepler discovered the phenomenon of total internal reflection.

- In 1621 Willebrod Snell (1591-1626) and independently in 1637 Rene Descartes (1596-1650) discovered the law of refraction.

- In 1658, Fermat (1601-1655) discovered the principle of least time.
- In 1660 the phenomenon of diffraction was noticed by Grimaldi (1618-1663).
- In 1667 Newton established that white light is composed of seven independent colors.

- In 1670, Bartholinus (1625-1698) discovered the phenomenon of double refraction.

- In 1675 Isaac Newton (1642-1727) put forward the ***corpuscular theory***. According to this theory, a luminous body emits in all directions streams of extremely minute particles, called *corpuscles*. The particle theory of Newton could explain:

1- The straight line propagation of light and that an object casts a sharp shadow.

2- The theory could prove the laws of reflection and refraction of light.

Newton predicted that **light should travel faster in a denser medium than in a rarer medium.**

However, the phenomenon of diffraction and Newton's rings could not be explained on the basis of corpuscular theory.

- In 1676, Romer (1644-1710) proved that light travels with a finite velocity.

- Robert Hooke (1635-1703) studied the colored patterns formed due to thin film interference.

(B) Development of Wave Optics:

In 1678 Huygens (1629-1695), a contemporary of Newton, proposed wave theory of light. According to this theory, light energy is supposed to be transferred from one point to another in the form of waves. Huygens was able to:

1- Prove the ordinary laws of reflection and refraction.

2- Light should travel slower in a denser medium than in a rarer medium.

3- He explained the phenomenon of double refraction by assuming two types of waves.

The wave theory was not accepted immediately. The main reason was that a wave motion needs a medium; but light could travel to us from the sun through the vacuum of space.

- In 1803, Thomas Young (1773-1829) demonstrated for the first time the interference of light beams. He also explained Newton's rings and the colors of thin films on the basis of interference of light waves. Thomas Young provided strong support to the wave theory.

- In 1808, Malus (1775-1812) discovered the polarization of light.

- In 1815, Augustin Fresnel (1788-1827) further developed the wave theory and explained the rectilinear propagation of light which has been the way of accepting wave theory. He provided a satisfactory explanation of the diffraction phenomenon.

Following Huygens, both Young and Fresnel assumed that light waves are **longitudinal**. Young and Fresnel conceived of an elastic medium, which was assumed to exist pervading the entire universe, and it was named ***ether***. The vibrations of the ether propagated as light, just as longitudinal vibrations in air propagate as sound. But the longitudinal wave theory of light could not explain polarization, a property exhibited by **transverse waves** but not by longitudinal waves.

- Fresnel and Arago (1786-1853) conducted experiments on superposition of linearly polarized light.

- Young eventually realized that light is a transverse wave and in 1817 explained the results of Fresnel and Arago's experiments.

- In 1850, Jean Foucault (1791-1868) established that light travels slower in liquids than in air. This is just opposite to the prediction of Newton's theory.

(C) Nature of light:

- Around 1836, Faraday (1791-1867) showed that a varying magnetic field induces an electromotive force and thus established the connection between electricity and magnetism. Further, Faraday showed that the polarization of light was affected by a strong magnetic field, which was the first hint as to the electromagnetic nature of light.
- Clerk Maxwell (1831-1879) unified the empirical laws of electricity and magnetism into a coherent theory of electromagnetism. In 1873, Maxwell showed that the **speed of electromagnetic waves equals the speed of light**. He made the prediction that light is a

high frequency electromagnetic wave.

- In 1887, Hertz (1857-1894) confirmed Maxwell's theoretical prediction by producing and detecting electromagnetic waves. The electromagnetic waves were initially supposed to be supported by the ether medium. Though electromagnetic theory is capable of explaining the phenomena connected with the propagation of light, **it fails to explain the processes of emission and absorption**.
- In 1887, Michelson-Morley performed the famous ether-drift experiment and found that light travels at the same speed irrespective of the position of the earth in its orbit. It led to the conclusion that ether does not exist. Hence, ***light is a self-sustaining high frequency electromagnetic wave***. This theory is known as the ***Field Theory***.

(D) Development of Quantum Optics:
- In 1814 Franhofer discovered dark lines in the solar spectrum.

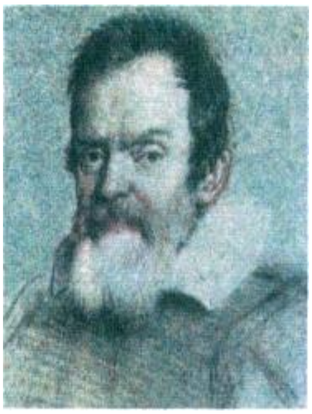
- In 1861 Kirchhoff found that every gaseous chemical element possesses a characteristic line spectrum.

- In 1900, in order to obtain a correct theoretical expression for the **black body radiation**, Max Planck (1858-1947) found it necessary to suppose that **light is absorbed or emitted in the form of elementary quanta**.

- In 1905, Einstein (1879-1955) made use of the quantum concept to successfully **explain the photoelectric emission**. According to him, **light is a stream of photons**.

- Niels Bohr (1885-1962) devised an atomic model for the emission and absorption of light. It successfully explained the **simple laws of line spectra of gases**.
- The first coherent source of light, namely **laser was built in 1960**.
- Quick developments in **holography and fiber optics** followed the discovery of lasers.

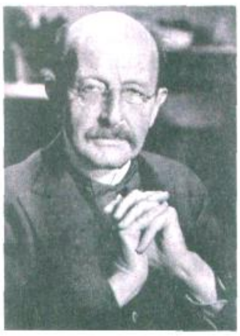
We now visualize a photon as a bundle of electromagnetic radiation that oscillates with a definite frequency and travels through free space with the speed of light. Individual photons carry energy and momentum, so light has particle-like properties. When the number of identical photons is very large, they exhibit the properties of a continuous wave with the same definite frequency and propagation speed as the quantum. The phenomena of interference, diffraction and polarization and propagation of light in space explained by classical electromagnetic wave theory, whereas the experiments involving interaction of light with matter, such as photoelectric effect are best explained by assuming that light is a particle.



In 1609, Galileo devised a practical telescope.

Isaac Newton (1642-1727)

Thomas Young (1773-1829)



Max Planck (1858-1947)

1.3 THE FOUR IMPORTANT THEORIES

Various theories have been put forward about the nature of light. We will make a brief survey of the four important theories which guided the evolution of our understanding of the nature of light. The theories are known as:

1. Corpuscular theory
2. Wave theory
3. Electromagnetic theory and
4. Quantum theory.

1.3.1. CORPUSCULAR THEORY

The corpuscular theory was postulated by ancient Greeks and was favored by Sir Isaac Newton. **According to this theory, a luminous body continuously emits tiny, light and elastic particles called *corpuscles* in all directions**. These particles or corpuscles are so small that they can readily travel through the interstices of the particles of matter with the velocity of light and they possess the property of reflection from a polished surface or transmission through a transparent medium. When these particles fall on the retina of the eye, they produce the sensation of vision. On the basis of this theory, phenomena like rectilinear propagation, reflection and refraction could be accounted for, satisfactorily.

1.3.2. WAVE THEORY

In seventeenth century, while the corpuscular theory was accepted, the idea that light might be some sort of wave motion had begun to gain ground. In 1679, Christian Huygens proposed the wave theory of light. **According to this, a luminous body is a source of disturbance in hypothetical medium called ether.** Huygens assumed these waves to be longitudinal, in which the vibration of the particles is parallel to the direction of propagation of the wave.

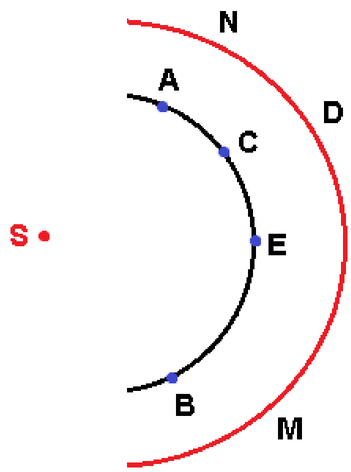
Huygens could satisfactorily explain reflection, refraction and double refraction. However, the phenomenon of polarization discovered by him could not be explained. Rectilinear propagation of light also could not be explained on the basis of wave theory. The difficulties mentioned above were overcome, when **Fresnel and Young suggested that light wave is transverse and not longitudinal as suggested by Huygens**. In a transverse wave, the vibrations of the ether particles take place in a direction perpendicular to the direction of propagation. Fresnel could also explain successfully the rectilinear propagation of light by combining the effect of all the secondary waves starting from the different points of a primary wave front.

1.3.2.1. Huygens Principle

Huygens ' construction is based on the following two fundamental postulates:

(i) **Every point on a wave front acts as a 'secondary' source. Secondary wavelets spread in all directions from these new sources. The secondary wavelets are spherical and have the same frequency and velocity as the original wave.**

(ii) **The surface, which touches all the wavelets from the secondary sources, gives the new position of the wave front.**



Huygens ' Principle served as very useful guide in explaining the phenomena of interference, diffraction and polarization.

1.3.3. ELECTROMAGNETIC THEORY

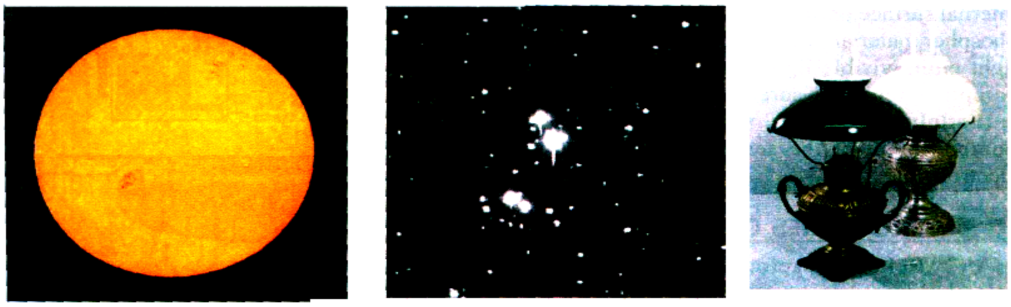
In 1862 Maxwell synthesized electricity and magnetism. He showed that electromagnetic waves travel with the speed of light and hence drawn the most important conclusion that light wave itself is an electromagnetic wave. Ultimately, in 1887 Michelson and Morley proved conclusively that there was no ether surrounding the earth or elsewhere.

1.3.4. QUANTUM THEORY

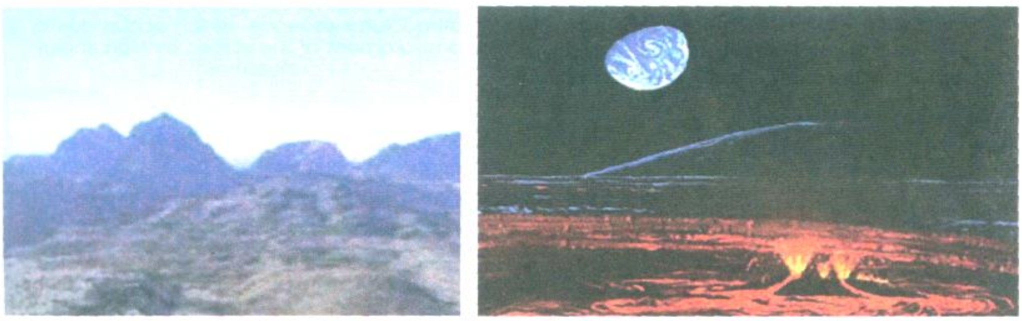
While experimenting on the black body radiation, Max Planck had come to the conclusion that the absorption or radiation of energy is not a continuous process and the energy called ***quantum***. Each quantum carries an energy $h\nu$ where h is a constant now called Planck's constant. Einstein elaborated the quantum concept of photoelectric emission. The quanta are named as photons and it travel with a speed of light. In 1923 Compton found that when x-rays interact inside matter, the scattered rays contained not only the original x-rays but also x-rays of wavelengths longer than the original. Though the quantum theory explains successfully the interaction of radiation with matter, it cannot account for the phenomenon of polarization, interference and diffraction.

1.4 THE SOURCES OF LIGHT

The sun, the stars, lamps give off light. They are called luminous bodies. Other objects moon, mountains, trees etc. are non-luminous. They are visible only when they receive light from some luminous source and they send the light to our eyes.



Luminous bodies: Sun, star and lamp.



Non-luminous bodies: Mountain and moon.

Types of Luminescence Sours

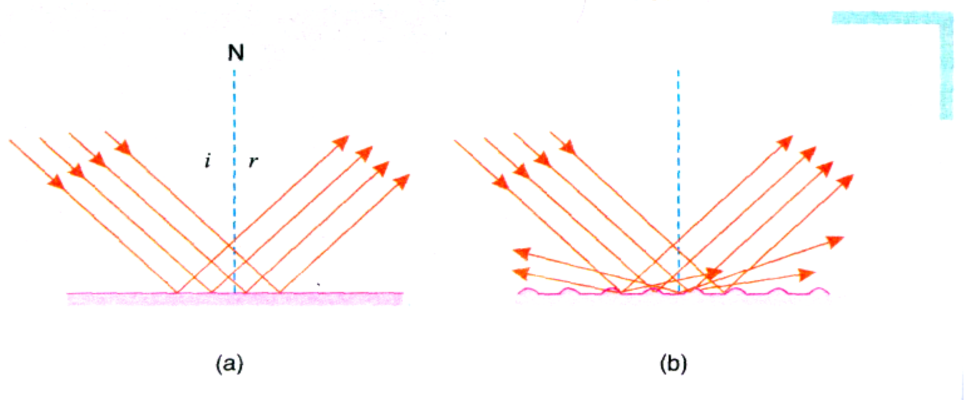
-Thermalluminescence
-Electroluminescence
-Chemiluminescence
-Photoluminescence
-Cathodoluminescence

1.5 PROPERTIES OF LIGHT

Reflection and refraction are the important properties of light. We briefly discuss about them here.

1.5.1. REFLECTION OF LIGHT

When light travelling in a medium encounters a boundary leading to a second medium part of the incident light is returned to the first medium from which it came. This phenomenon is called reflection. Reflection of light from a smooth surface is called **regular reflection**. Reflection from a rough surface is known as **diffuse reflection**. The difference between diffuse and regular reflection is a matter of surface roughness.

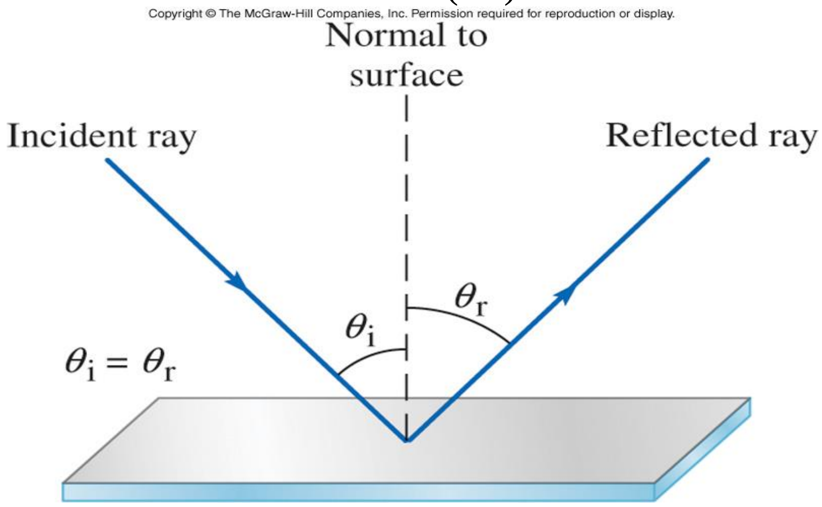


1.5.1.1. Laws of reflection

<u>First Law:</u> The incident ray, the reflected ray and the normal at the point of incidence are in the same plane. This plane is called the plane of incidence.

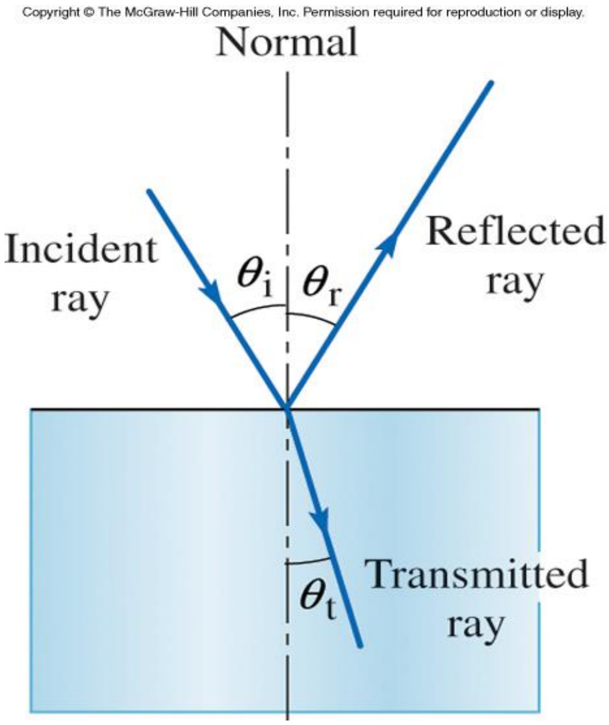
<u>Second Law:</u> The angle of reflection is equal to the angle of incidence.

$$i = r \qquad (1.1)$$



1.5.2. REFRACTION OF LIGHT

When a ray of light travelling through a transparent medium encounters a boundary leading into another transparent medium, part of the ray is reflected and part of it enters the second medium. The ray that enters the second medium is bent at the boundary and is said to be refracted. Thus, refraction means that the light ray follows in the second medium a direction different from its direction in the first medium.



$$\mu_1 \sin\theta_1 = \mu_2 \sin\theta_2 \qquad \text{Snell's Law}$$

1.5.2.1. Laws of refraction

First Law: The incident ray, the refracted ray and the normal at the point of incidence lie in the same plane.

Second Law: The ratio of the sine of the angle of incidence to the sine of the angle of refraction for any two given media is constant.

$$\frac{\sin i}{\sin r} = \mu \quad \text{...........(1.2)}$$

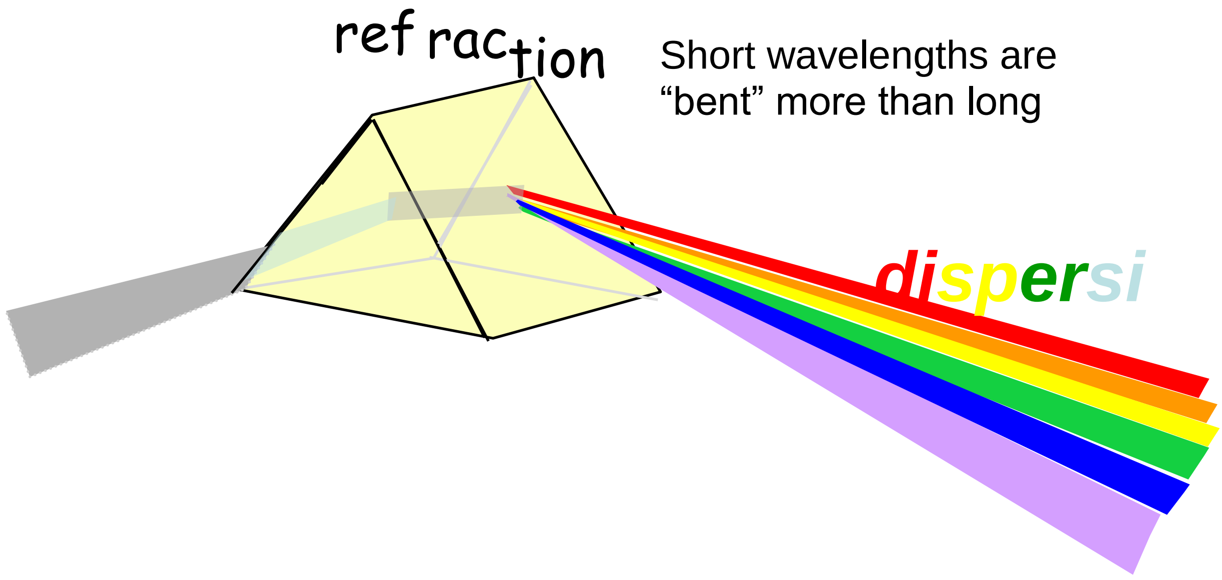
REFRACTIVE INDEX

The refractive index of a medium is defined as the ratio of velocity of light in a vacuum to the velocity of light in the medium.

$$\mu = \frac{c}{v} \quad \text{.....................(1.3)}$$

The absolute refractive index for air under standard conditions is **1.0002918** for light having wavelength of the sodium (589.3 nm).

Note: The refractive index depends not only on the substance but also on the wavelength of the light. The dependence on wavelength is called dispersion.



Light is “bent” and the resultant colors separate (dispersion).
Red is least refracted, violet most refracted.

Indices of Refraction[a]

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

1.6 OPTICAL PATH

The shortest distance, L between two points A and B is called the geometric path.

From equation (1.3)

$$\mu = \frac{c}{v} = \frac{AB/t}{AB/T} = \frac{T}{t}$$

Where t and T are the time taken by the light ray in air and in a medium respectively and AB is the optical path.

$$T = \mu t \quad \text{..................(1.4)}$$

The above relation means that a light ray takes μ times more time to cover the distance AB in a medium.

If a ray of light travels a distance L in a medium of refractive index μ . In a certain interval of time, then it would travel a greater distance Δ in air during the same interval of time. Therefore,

$$\frac{\Delta}{L} = \frac{ct}{vT} = \mu \quad \text{............(1.5)}$$

Or

$$\Delta = \mu L$$

i.e., **Optical path length = (Refractive index)*(Geometric path length)**

Thus, the **optical path length is defined as the product of refractive index and the geometric path length.**

1.6 VISIBLE RANGE

The arrangement of the various electromagnetic waves in a continuous sequence of frequencies and wavelengths is called an **electromagnetic spectrum**.

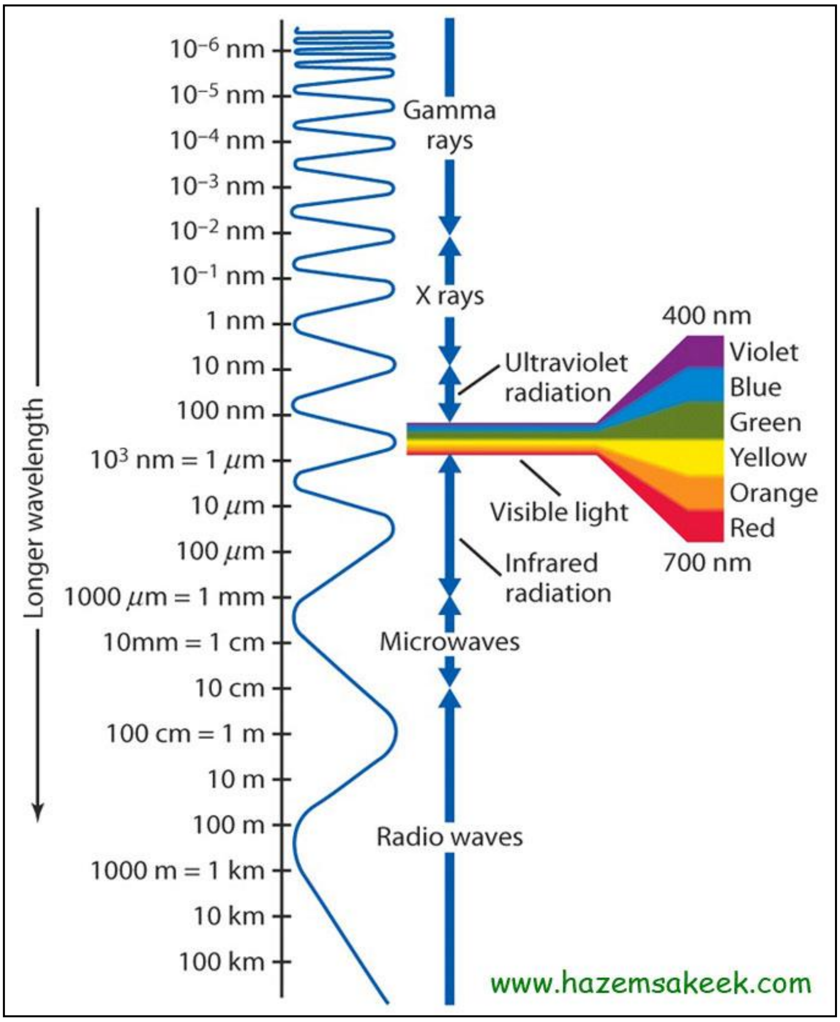


TABLE-1

Colour	*Vacuum wavelength* (*Å*)	*Frequency* (10^{14}*Hertz*)
Red	7800 - 6200	3.84 - 4.82
Orange	6220 - 5970	4.82 - 5.03
Yellow	5970 - 5770	5.03 - 5.20
Green	5770 - 4920	5.20 - 6.10
Blue	4920 - 4550	6.10 - 6.59
Violet	4550 - 3990	6.59 - 7.69

1 angstrom (Å) $= 10^{-10}$ m = 0.1 nm
1 nanometre (nm) $= 10^{-9}$ m = 10 Å
1 micrometre (μm) $= 10^{-6}$ m = 10,000 Å = 1000 nm

1.7 PHOTONS

According to quantum theory, light is considered as a stream of special particles, namely photons. Photons do not have rest mass and travel with a velocity equal to the speed of light in a vacuum. The fundamental characteristics of a photon are its energy E and momentum p.

$$E = h\nu \quad \text{.....................(1.6)}$$

$$p = \frac{h\nu}{c} = \hbar k \quad \text{..........(1.7)}$$

k is a wave vector has a magnitude $2\pi/\lambda$ and a direction coinciding with that of wave velocity.

Photon mass $m = \frac{h\nu}{c^2}$ is the mass of the electromagnetic field.

1.8 THE DUAL NATURE

In view of these developments, light must be regarded as having a dual nature Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations.

We use all the three descriptions namely **rays, waves and photons** appropriately to describe the behavior of light.

- When light is refracted or reflected by optical elements such as lenses, we mostly use the ray description.
- When light propagates through space or any medium, we use the electromagnetic wave description.
- Whenever light interacts with matter, we make use of the photon description.

QUESTIONS

1. What is meant by reflection?
2. State and explain the law of reflection.
3. What do you mean by refraction of light?
4. What is absolute refractive index of a medium?
5. What is Snell's law?
6. What is meant by optical path? How is it different from geometrical path length?
7. What are the four important theories of light?
8. Explain briefly the corpuscular theory and its limitations?
9. Describe the Huygens' wave theory?
10. Why light is classified in the category of electromagnetic waves?
11. Explain what the visible region means?
12. What is photon theory of light?
13. Explain the dual nature of light?