

# Fiber Optics Communications

**Week 2**

**Optical Fiber and Light Guiding Principle**

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# Topics of Previous (Week-1) Lecture

- Overview of Optical Fiber Communication
- Historical Perspectives of Fiber Optics Communications
- Optical Fiber Communication Main System components
- Overview of WDM System
- Major Applications Fiber Optic Communication

# Week-2: Lecture Learning Outcomes

1. Explain the main historical and modern theories of light (corpuscular, wave, electromagnetic, and quantum theories).
2. Compare and contrast the contributions of different theories of light to understanding the nature of light
3. Differentiate between different theories of optics (ray optics, wave optics, electromagnetic optics, and quantum optics).
4. Identify the limitations and applications of each theories of optics
5. Define polarization and describe different polarization states (linear, circular, elliptical).
6. Identify the main components of an optical fiber (core, cladding, jacket).
7. Explain the principle of light propagation in fiber optics.
8. Define optical modes and differentiate between single-mode and multimode fibers

# Week-2: Optical Fiber and Light Guiding Principle

## Outline

- Theories of Light
- Theories of Optics
- Polarization of Light
- Wave Fronts
- Light Intensity and Power Flow
- Optical Fiber structure and Light Propagation
- Optical modes in optical fiber

# Introduction: Physics of Light

- Fiber optics communication technology relies on emission, transmission, and detection of light
- Understanding fundamental nature of light and light-matter interaction is desirable to fully understand how light signals travel along an optical fiber
- Different **Theories of Light** had been proposed at different times to explain the **Nature of Light**
- Different **Theories of Optics** are also developed based on Those theories of light to explain **Light-Matter Interactions**

## Theories of Light

- Newton's Corpuscular Theory
- Huygene's Wave Theory
- Maxwell's Electromagnetic Theory
- Planck's Quantum theory

## Theories of Optics

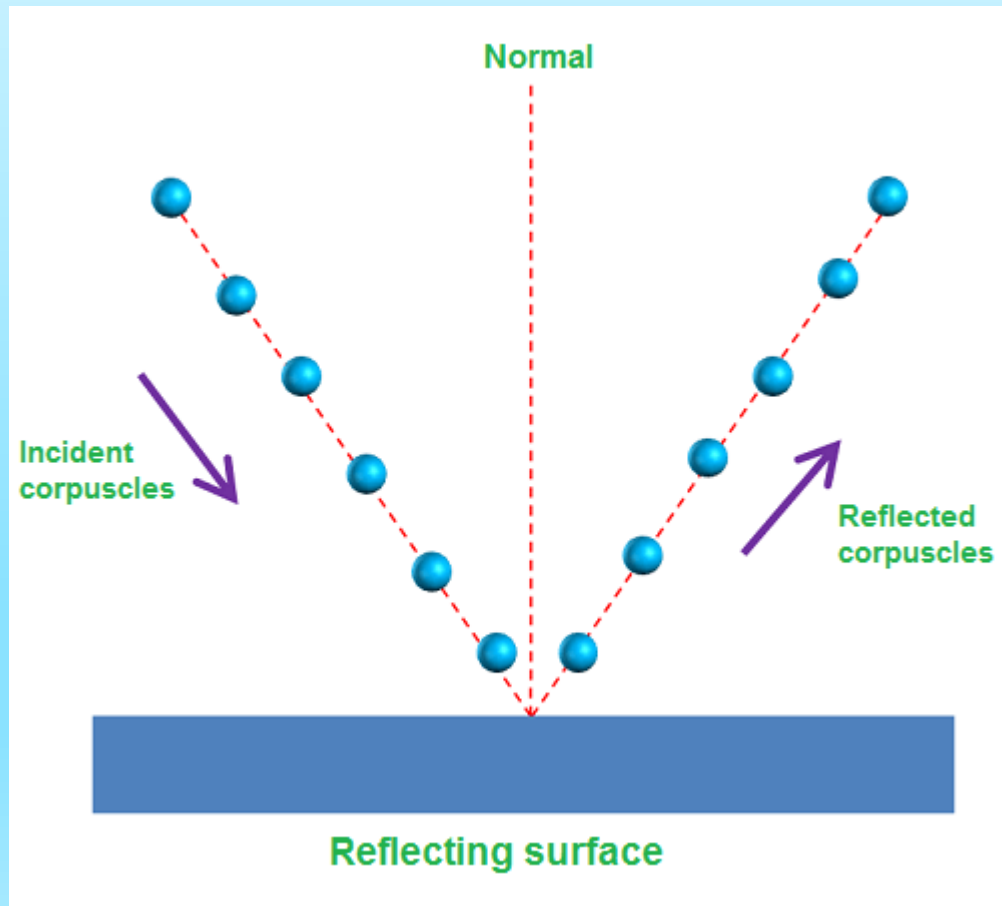
- Geometrical or Ray Optics
- Wave Optics
- Electromagnetic Optics
- Quantum Optics



# Theories of Light

# Newton's Corpuscular Theory

- Proposed by **Newton in 1704**, it was the first scientific attempt to explain the nature of light
- States Light as stream of **minute particles** traveling in straight lines called **Corpuscles**
- **Light reflects** because corpuscles striking a surface are pushed back by a **Repulsive force**

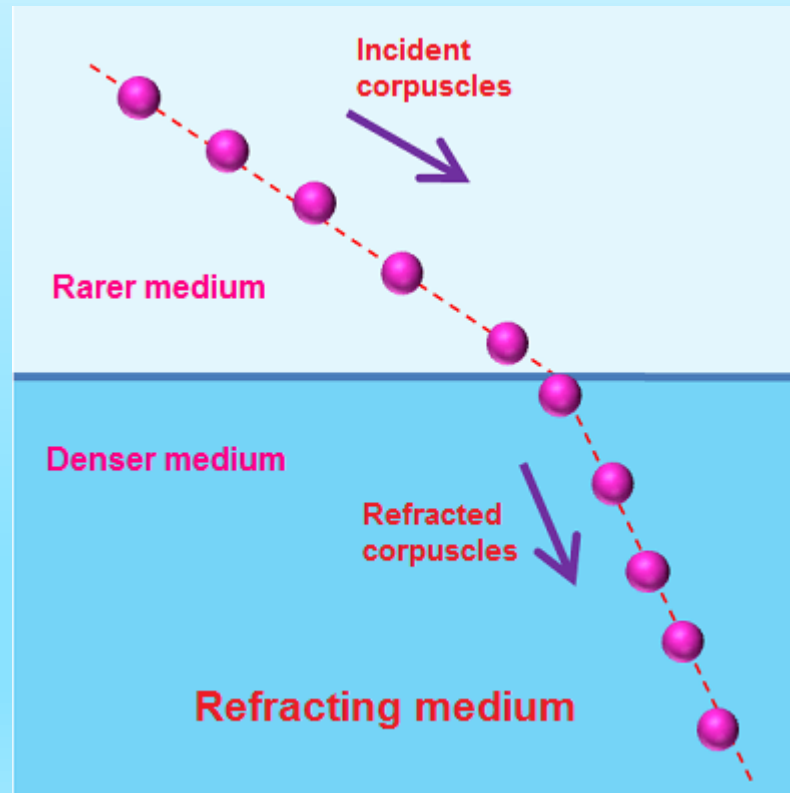


**Figure 1: Light Reflection**

**Source:** "Corpuscular Theory of Light", Physics and Radio Electronics. <https://www.physics-and-radio-electronics.com/blog/wp-content/uploads/2016/11/reflectionoflightcorpuscletheory.png>

# Newton's Corpuscular Theory Cont..

- **Light refracts** because corpuscles approaching refractive surface are attracted to the surface by an **Attractive force**
- Their speed increases and change their direction while entering to denser medium from rare medium



**Figure 2: Light Refraction**

**Source:** "Corpuscular Theory of Light", Physics and Radio Electronics. <https://www.physics-and-radio-electronics.com/blog/wp-content/uploads/2016/11/corpuscular-theoryrefractionoflight-1.png>

# Newton's Corpuscular Theory Cont..

## Corpuscles Properties

- Emitted from the luminous bodies
- Possess elastic nature
- Carries kinetic energy while travelling
- Travel at high velocity in straight lines
- Different size of Corpuscles leads to different color of light
- Travels faster in the denser medium than in the rarer medium

## Weakness of the theory

### 1. Wrong Assumptions By Newton

- Different size of Corpuscles leads to different color of light
- Travels faster in the denser medium than in the rarer medium
- Attractive and repulsive force assumptions

### 2. Incompleteness of the Theory

- Unable to explain diffraction, interference, and polarization of light

# Huygene's Wave Theory

- Proposed by **Christian Huygens** in 1670
- States Light as a **Longitudinal Wave**
- The waves emitted by the source move in a straight line in a homogeneous medium
- Various colors of light are due to **different wavelengths** of the light waves.
- Velocity of light in an optically denser medium is less than that in a rarer medium

## Strength of the Theory

- Able to explain reflection, refraction, interference, and diffraction

## Weakness of the Theory

### 1. Wrong assumption

- **Wrongly Considering Light as Longitudinal Wave rather than Transverse wave**

### 2. Incompleteness

- **Fails to explain the polarization of light**

# Maxwell's Electromagnetic Theory

- Proposed by **Maxwell** in ninth Century
- Light waves are **electromagnetic waves** with mutually coupled electric and magnetic fields
- This theory proves that light waves are **Transverse Waves**
- Confirms Light wave does not require medium for propagation and can travel through Vacuum

## Strength of the Theory

- Able to explain reflection, refraction, interference, diffraction, and **polarization**

## Weakness of the Theory

- Fails to explain Photo Electric Effect

# Planck's Quantum theory

- Proposed by **Max plank**
- Stated Light wave is discrete packets of energy called **Quanta** or **Photons**
- The photons are travels with velocity of light

## Strength of the Theory

- Able to explain **Photo Electric Effect**

## Weakness of the Theory

- Fails to explain interference, diffraction and polarization

## Wave - Particle Duality

- Proposed by **Albert Einstein** and Extended by **De-Broglie**
- Stated Light as having both particle and wave nature
- With this introduction of **dual nature**, **Quantum Theory** able to explain photo-electric effect and all optical phenomena.



# Theories of Optics

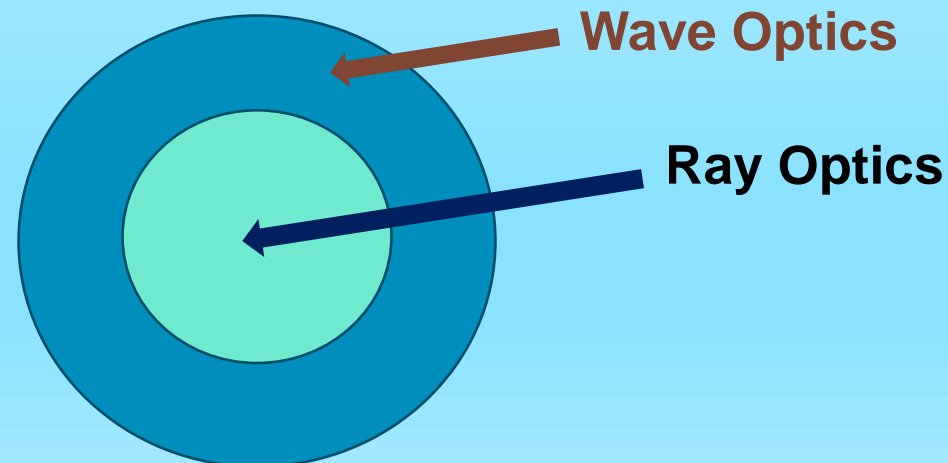
# Geometrical or Ray Optics

- Different Optics theories had been developed to explain different optical phenomena occurred during light-matter interactions
- Ray optics is the simplest widely used theory of Optics.
- Light is modeled as rays that follow geometric laws in various media
- In homogeneous media (e.g., glass or air), light rays travel in straight lines.
- Ray optics can explain optical phenomena when the wavelength of light is very small compared to the objects through or around which light is passing.
- This theory adequately described large-scale optical effects such as **reflection** and **refraction** of Light.
- Ray optics is enough theory to determine the conditions under which light is guided within a given medium, such as a glass optical fiber.

# Wave Optics

- Wave optics is modeled based on wave nature of light
- In Wave Optics, light is described by a scalar function, called the wavefunction.
- Ray optics represents the limit of wave optics in the case of infinitesimally short wavelengths
- Ray theory is a subset of the broader wave theory of Optics
- Wave optics able to describe optical phenomena occurred when light interact with a matter having comparable dimension with the wavelength of light.
- Wave optics explains phenomena which are beyond the reach of ray optics, such as interference and diffraction of Light.
- Wave optics has a limitation to describe Polarization of Light

**Figure 3: Wave optics encompasses ray optics**



# Wave Optics: Wave Equation

- Light propagates in the form of waves.
- Speed of light in a vacuum and in a material having refractive index,  $n$ , is related by:

$$c = \frac{c_0}{n} \quad (1)$$

**Where:**

$c_0$  Speed of light in a vacuum

$c$  Speed of light in a material having refractive index  $n$

- An optical wave is described mathematically by a real function of position,  $r = (x,y,z)$  and time,  $t$ , as  $u(r,t)$  called **wave function**.
- The wave function,  $u(r,t)$ , should satisfy the following partial differential equation called the

**wave equation:**

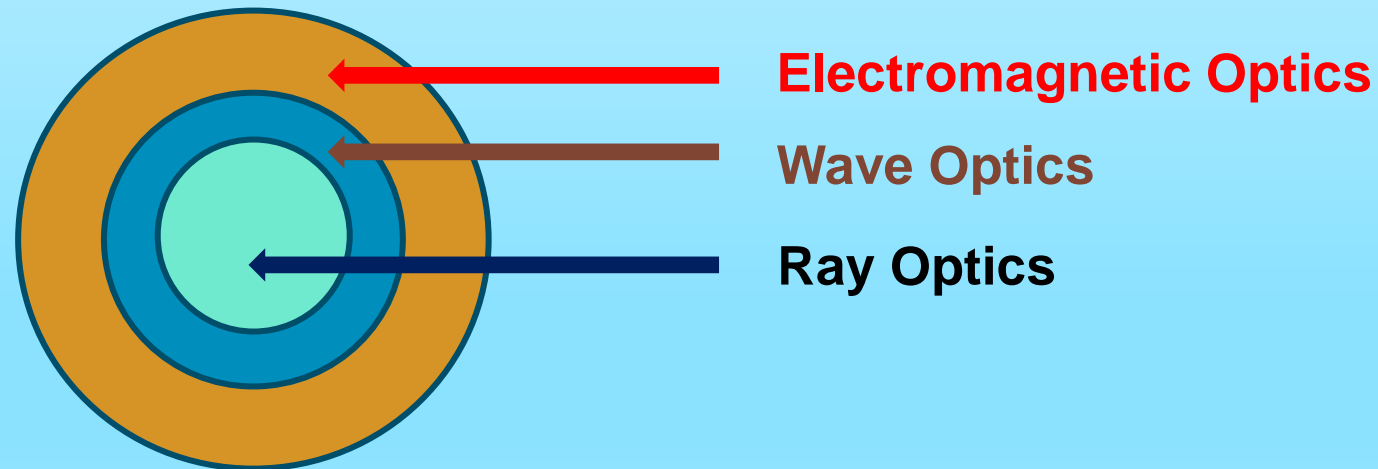
$$\nabla^2 u - \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} = 0 \quad (2)$$

**Where:**

$\nabla^2$  The Laplacian operator

# Electromagnetic Optics

- In Electromagnetic optics, light is an electromagnetic phenomenon that is described by a vector wave theory.
- Light is treated as Electromagnetic radiation propagates in the form of two mutually coupled vector waves, an electric-field wave and a magnetic-field wave.
- Electromagnetic optics thus encompasses wave optics, which in turn reduces to ray optics in the limit of short wavelengths [1]



**Figure 4: Electromagnetic optics encompasses wave optics**

# Electromagnetic Optics

- Maxwell's equations can successfully describe light propagation
- Electromagnetic optics gives the most complete classical description of light phenomena
- Maxwell's Equations of source-free, linear, homogeneous, isotropic & non-dispersive media :

$$\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} \quad (3a)$$

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (3b)$$

$$\nabla \cdot \vec{E} = 0 \quad (3c)$$

$$\nabla \cdot \vec{H} = 0 \quad (3d)$$

**Where:**

$\vec{E}$  Electric Field

$\vec{H}$  Magnetic Field

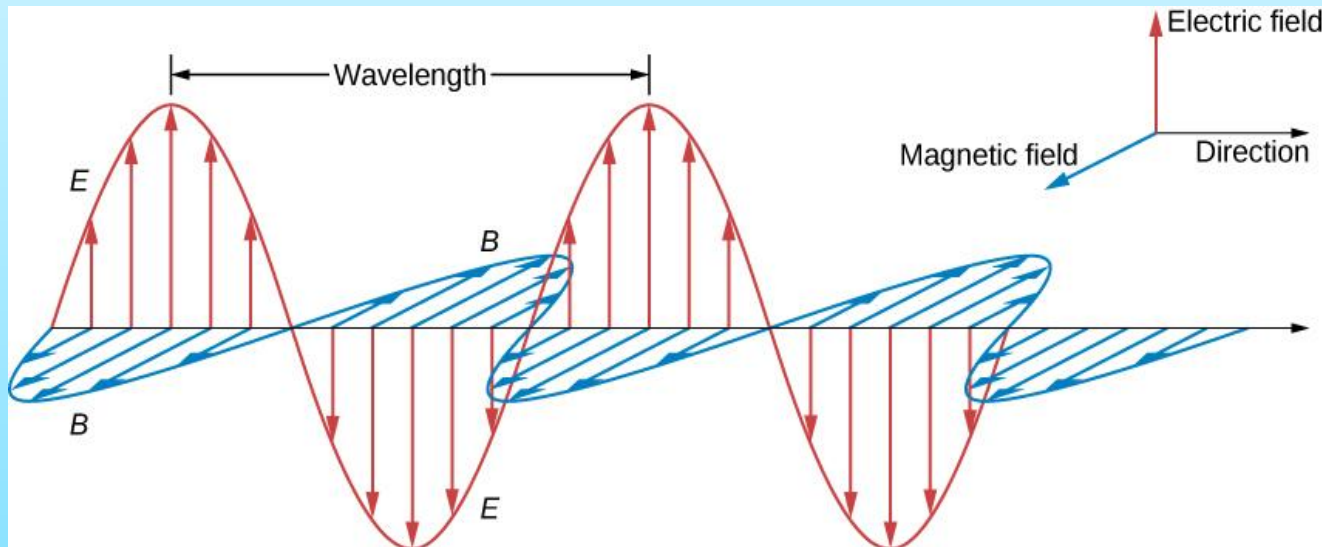
$\varepsilon$  Electric permittivity

$\mu$  Magnetic Permeability

- Electromagnetic Optics can describe Light Polarization and all phenomena involving the transmission of light through modeling of light as a vector function of waves.

# Electromagnetic Optics

- All electric and magnetic fields are harmonic functions of time of the same frequency.
- Light is a Transverse Electromagnetic wave; Electric and magnetic fields are perpendicular to each other and both perpendicular to the direction of propagation.



**Figure 5: Transverse Electromagnetic wave**

**Source:** R. Kotha, "Electromagnetic Waves," Notes, Jan. 21, 2025.

<https://www.rkotha.com/Notes/Physics-1C/Media/Pasted-image-20230830124246.png>

# Electromagnetic Optics: Wave Equation

- The necessary condition for electric and magnetic field to satisfy Maxwell's equations is each of their component **in x, y, and z direction** satisfy the wave equation (free space):

$$\nabla^2 u - \frac{1}{c_0^2} \frac{\partial^2 u}{\partial t^2} = 0 \quad (4)$$

- $c_0$  the speed of light in the vacuum which is given by:

$$c_0 = \frac{1}{\sqrt{\epsilon_0 \mu_0}} \approx 3 \times 10^8 \text{ m/s} \quad (5)$$

- The scalar function  $u(r, t)$  represents any of the three of Electric field or Magnetic field:

**Electric field components**

$$E_x, E_y, E_z$$

**Magnetic field components**

$$H_x, H_y, H_z$$

# Polarization of Light

- Sunlight and incandescent light are electromagnetic waves vibrating in many directions—this is called **unpolarized light**
- In **polarized light**, electromagnetic waves vibrations occur in a single plane
- There are different types of Polarizations.

## Types of Polarizations

- Linear Polarization
- Elliptical Polarization
- Circular Polarization

# Linear Polarization

- The electric field of linearly polarized plane waves traveling in a direction  $\mathbf{k}$  can be represented as:

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{e}_i E_0 e^{j(\omega t - \mathbf{k} \cdot \mathbf{r})} \quad (6)$$

**Where:**

$\mathbf{r} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z$  represents the position vector

$\mathbf{k} = k_x\mathbf{e}_x + k_y\mathbf{e}_y + k_z\mathbf{e}_z$  represents the wave propagation vector

$\mathbf{e}_i$  is a unit vector parallel to an axis  $i$

$E_0$  is the maximum amplitude of the electric field

# Linear Polarization

- The actual measurable value of electric field obtained by taking the real part of eq (6):

$$\text{Re}\{E(r,t) = e_i E_0 e^{j(\omega t - \mathbf{k} \cdot \mathbf{r})}\} \quad (7)$$

- For the light wave propagating in z-direction:

$$\mathbf{k} = k_z \mathbf{e}_z \quad (8)$$

- The electric field oscillating in x-direction with  $e_i = e_x$  is given by:

$$E_x(z,t) = e_x E_{0x} (\cos(\omega t - kz)) = e_x E_x \quad (9)$$

**Where:**

$E_0$  is the maximum amplitude along x axis

$E_x$  is the amplitude at a given value of z

# Linear Polarization

- The light wave given in eq (9) is a linearly polarized wave with polarization vector  $e_x$
- Considering another linearly polarized wave that is independent and orthogonal to the wave given in eq(9) as:

$$E_y(z, t) = e_y E_{0y} (\cos(\omega t - kz + \delta)) = e_y E_y \quad (10)$$

**Where:**

$\delta$  is the relative phase difference between x and y polarized wave

- The resultant wave becomes:

$$E(z, t) = E_x(z, t) + E_y(z, t) \quad (11)$$

# Linear Polarization

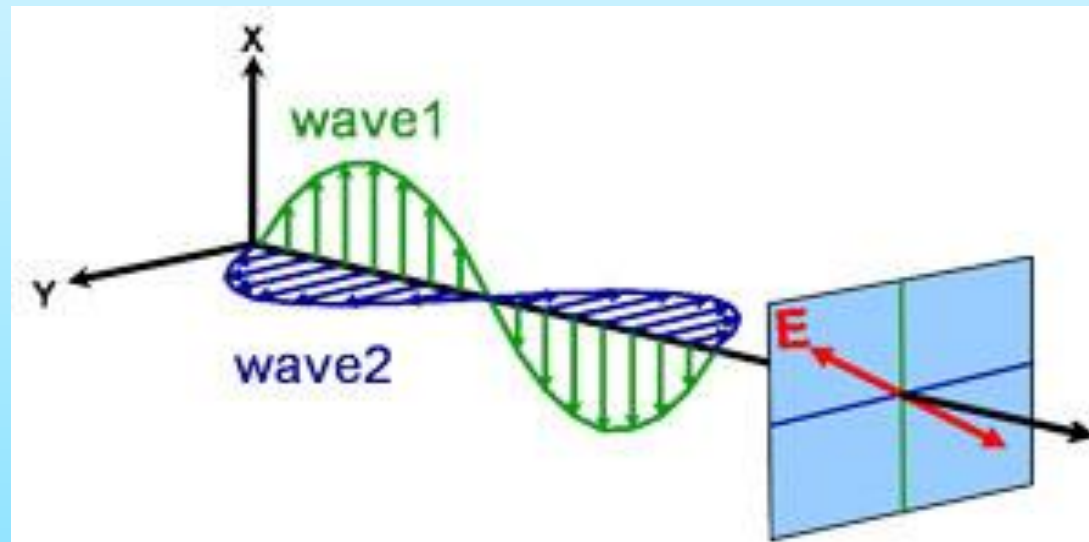
- If  $\delta$  is zero or multiple of  $2\pi$  the resultant wave becomes linearly polarized wave with polarization vector having:

**Angle with respect to  $e_x$**

$$\theta = \arctan\left(\frac{E_{0y}}{E_{0x}}\right) \quad (12)$$

**Magnitude**

$$E = \sqrt{E_{0x}^2 + E_{0y}^2} \quad (13)$$



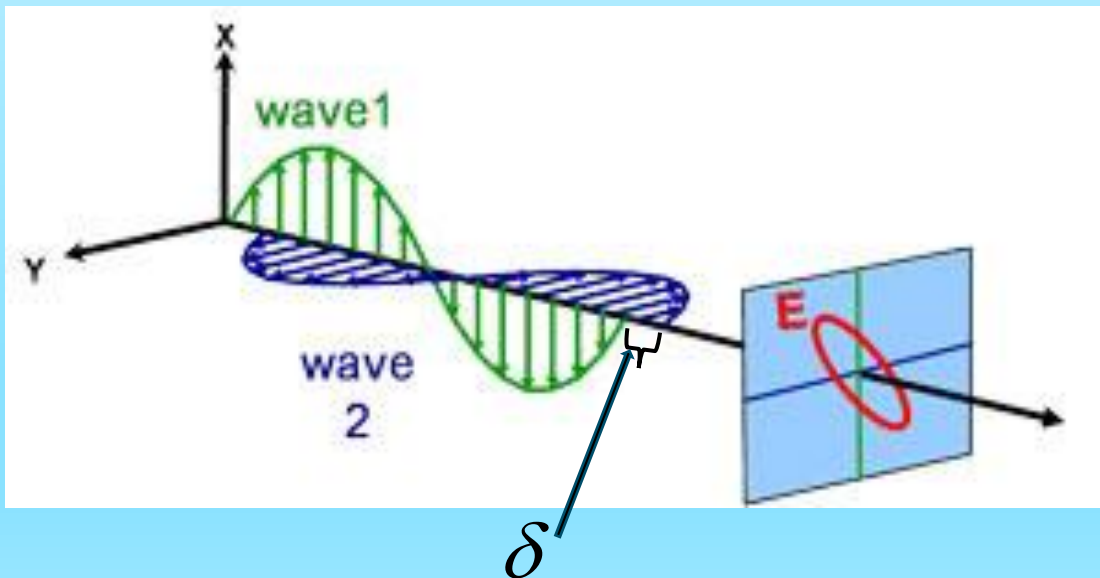
**Figure 6: Linear Polarization**

**Source:** J.A. Woollam, "Polarized Light," Ellipsometry Tutorial. <https://www.jawoollam.com/wp-content/uploads/linear-polarized-light.jpg>

# Elliptical Polarization

- For general value of  $\delta$ , the resultant field trace an ellipse given by:

$$\left(\frac{E_x}{E_{0x}}\right)^2 + \left(\frac{E_y}{E_{0y}}\right)^2 - 2\left(\frac{E_x}{E_{0x}}\right)\left(\frac{E_y}{E_{0y}}\right)\cos\delta = \sin^2(\delta) \quad (14)$$



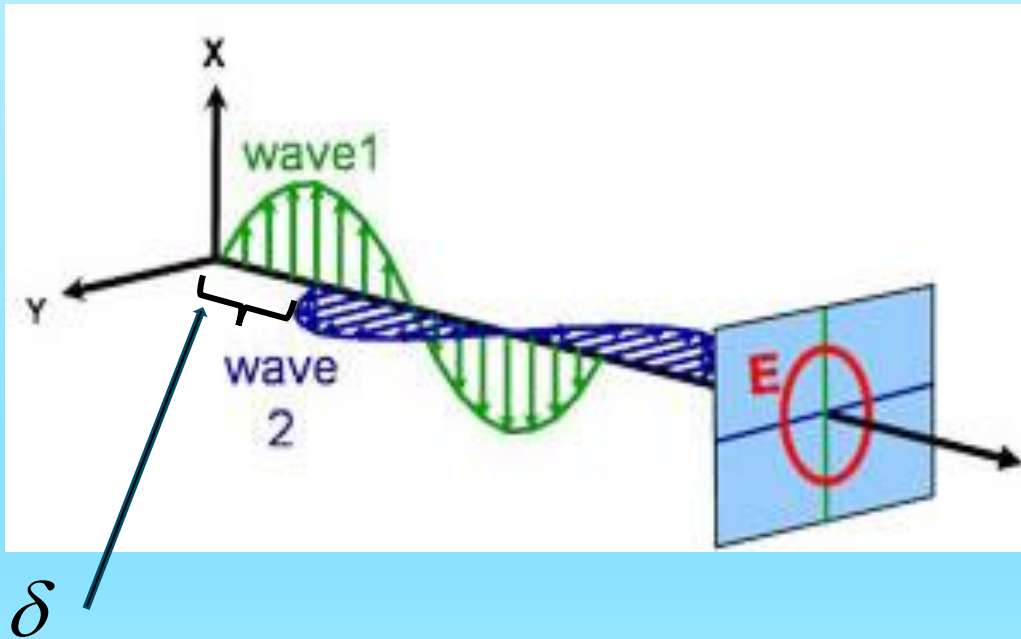
**Figure 7: Elliptical Polarization**

**Source:** J.A. Woollam, "Polarized Light," Ellipsometry Tutorial. <https://www.jawoollam.com/wp-content/uploads/elliptical-polarized-light.jpg>

# Circular Polarization

- When  $E_{0x} = E_{0y}$  and  $\delta = \pm\pi/2 + 2m\pi$  for  $m = 0, \pm 1, \pm 2, \dots$ , the light becomes circularly polarized and the resultant field trace a circle given by:

$$E_x^2 + E_y^2 = E_0^2 \quad (15)$$

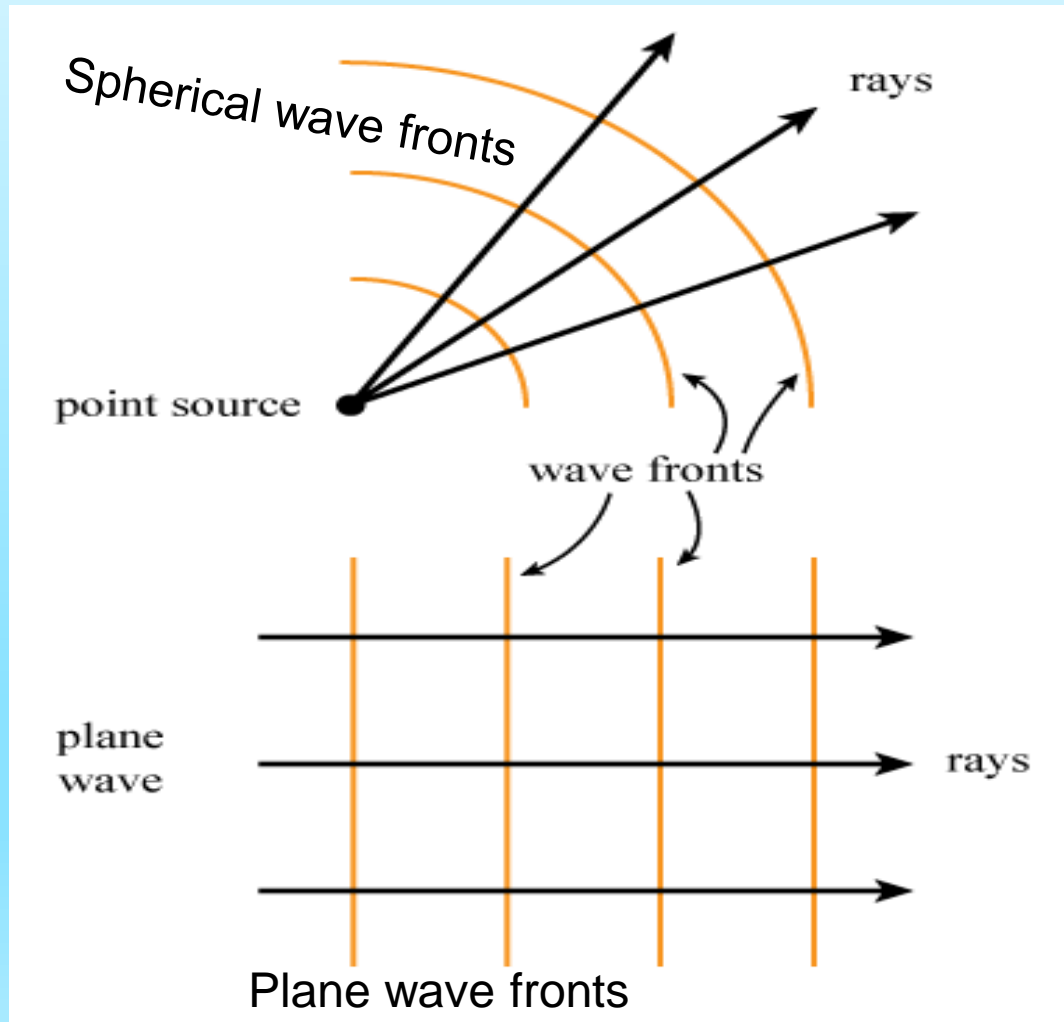


**Figure 8: Circular Polarization**

**Source:** J.A. Woollam, "Polarized Light," Ellipsometry Tutorial. <https://www.jawoollam.com/wp-content/uploads/circular-polarized-light.jpg>

# Wavefronts

- A wavefront is the set of all locations in a medium where the wave is at the same phase.



**Figure 9:Wavefronts**

**Source:** "Geometrical Optics," Geometrical Optics Lab Manual, Physics EM Lab 1, Texas A&M University, WebAssign.

[https://www.webassign.net/question\\_assets/tamucalcphysem1/lab\\_10/images/figure10-2.png](https://www.webassign.net/question_assets/tamucalcphysem1/lab_10/images/figure10-2.png)

# Intensity and power flow of TEM Wave

- The Poynting vector,  $S$  , describes the direction and rate of power flow of an electromagnetic wave.

$$S = \frac{1}{2} \vec{E} \times \vec{H}^* \quad (16)$$

- $S$  is parallel to the wave vector  $k$  and perpendicular to wave fronts.
- For TEM wave propagating in  $z$  - direction, the Intensity at a given point  $z$ ,  $I(z)$  , is given by magnitude of the Poynting vector as:

$$I(z) = \frac{(E(z))^2}{2\eta} \quad (17)$$

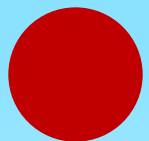
**Where:**

$E(z)$  Is the magnitude of electric field at point  $z$

$\eta = \sqrt{\frac{\mu}{\epsilon}}$  Is intrinsic or wave impedance

# Quantum Optics

- Electromagnetic optics offers the most comprehensive description of light in classical optics
- However, Electromagnetic optics is short to explain optical phenomena such as emission and absorption of light.
- Quantum optics steps in to explain such Optical phenomena which have quantum mechanical nature.
- Quantum optics models optical phenomena occurred during light-matter interaction considering both particle and wave nature of light.
- **Particle Nature:** Light energy is emitted or absorbed in discrete units called quanta (photons).
- **Wave Nature:** Photon energy depends on frequency and Frequency,  $\nu$ , is determined by measuring a wave property of light, i.e.  $E_p = h\nu$



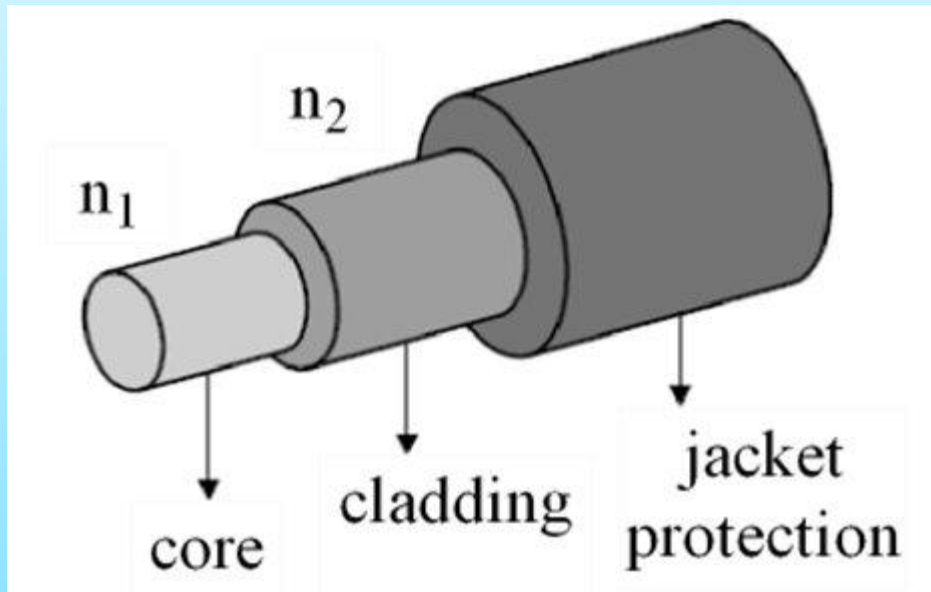
**Therefore, Both particle and wave natures are required to explain light absorption and Emission**



# Light Propagation in Glass Optical Fibers

# Optical Fiber structure

- An optical fiber is a cylindrical dielectric waveguide that operates at optical frequencies
- The Conventional optical fiber has the following structure:



**Figure 10: Structure of Glass Fiber**

**Source:** J. Militký, D. Křemenáková, and J. Šašková, "Optical Attenuation of Linear Composites Containing SEPOF," IOP Conference Series: Materials Science and Engineering, vol. 460, 2018.

[https://www.researchgate.net/publication/329895661/figure/fig1/AS:707416106745856@1545672551267/Typical-structure-of-optical-fiber\\_W640.jpg](https://www.researchgate.net/publication/329895661/figure/fig1/AS:707416106745856@1545672551267/Typical-structure-of-optical-fiber_W640.jpg)

## Fiber Core:

- High-purity silica
- High refractive index compared to cladding
- Main media for optical energy transmission

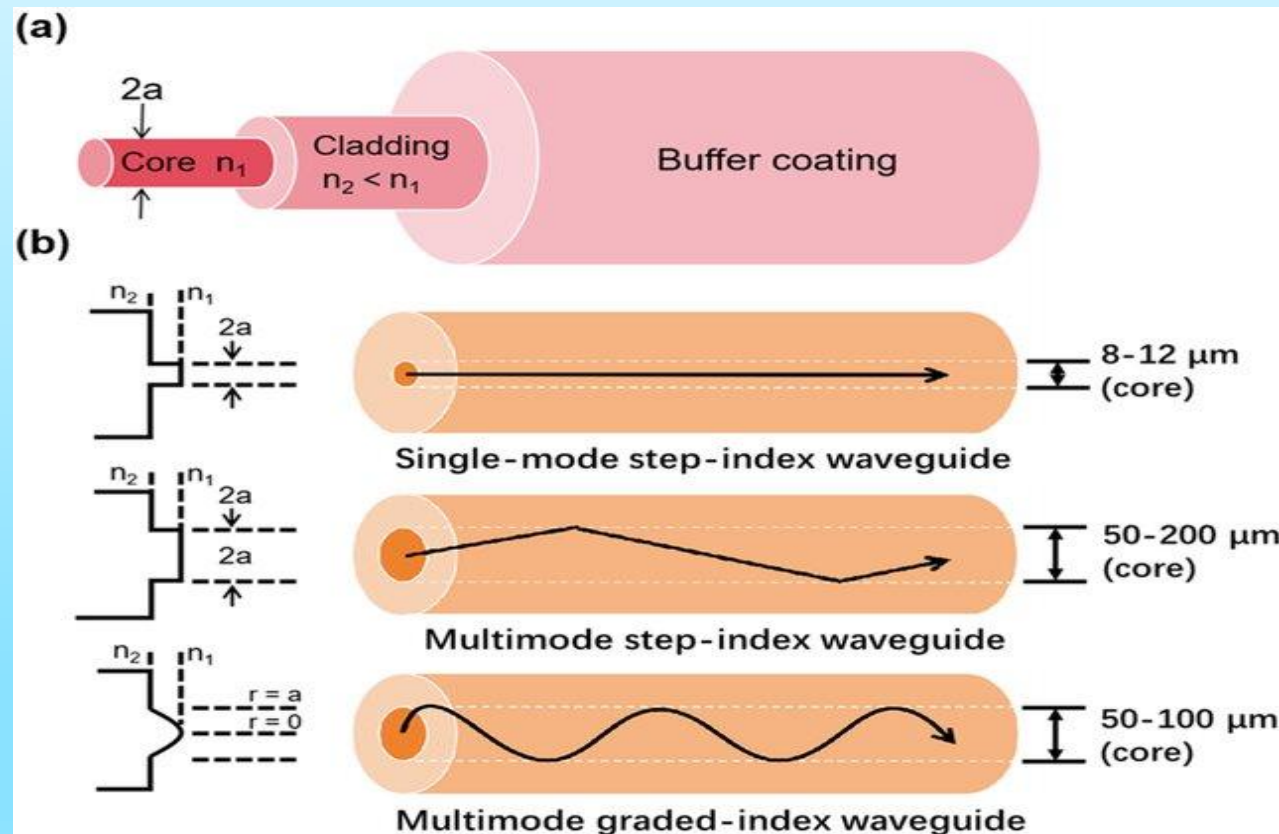
## Cladding:

- High-purity silica with little dopant
- Provides a reflective surface and optical isolation for the transmission of light

**Jacket:** made of plastic for mechanical and moisture protection

# Light Guiding by Total Internal Reflection

- Light signal propagation inside different optical fibers using total internal reflection as a physical mechanism



**Figure 11: Signal propagation in Fiber**

**Source:** D. Křemenáková, J. Militký, and J. Šašková, "Optical attenuation of linear composites containing SEPOF," IOP Conference Series Materials Science and Engineering, 2018.  
[https://www.researchgate.net/publication/380791404/figure/fig1/AS:11431281250304608@1717805490365/a-Schematic-of-a-conventional-silica-fibre-structure-bComparison-of-conventional\\_W640.jpg](https://www.researchgate.net/publication/380791404/figure/fig1/AS:11431281250304608@1717805490365/a-Schematic-of-a-conventional-silica-fibre-structure-bComparison-of-conventional_W640.jpg)

# Optical Modes in Optical Fiber

- The Light field that is guided in optical fiber can be represented by the superposition of trapped modes inside the optical fiber.
- Considering a monochromatic light, the time (t) and z dependence of a mode traveling in z direction is given by [2]:

$$e^{j(\omega t - \beta z)} \quad (18)$$

**Where:**

$\omega$  is the angular or radian frequency

$\beta$  is the z component of the propagation constant

- Optical modes become guided only for certain discrete value of  $\beta$
- For circular optical waveguide a mode remains guided as long as it satisfies the following condition [3]:

$$n_2 k < \beta < n_1 k \quad (19)$$

**Where:**

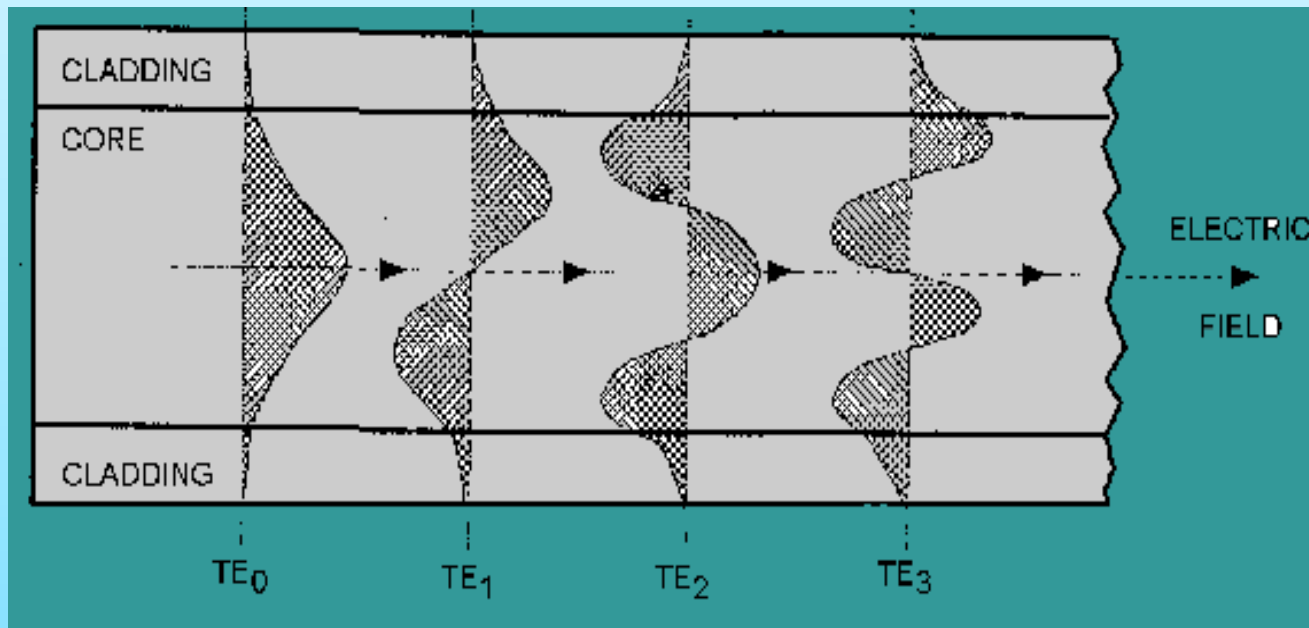
$n_1$  Core refractive index

$n_2$  Cladding refractive index

$$k = \frac{2\pi}{\lambda}$$

# Optical Modes in Optical Fiber

- Different Order Transverse electric field (TE) modes will be propagating in the waveguide
- The order of a mode is determined by the number of field maxima within the core of the fiber



**Figure 12: Field pattern of TE optical Modes**

**Source:** "Mode Theory," NEETS Module 10, Tpub.  
<https://www.tpub.com/neets/tm/30NVM018.GIF>

# Cutoff Wavelength and V Number

- When  $\beta = n_2k$ , a mode is no longer properly guided and is called being **cut off**
- Unguided radiation modes appear for frequencies below the cutoff point where  $\beta < n_2k$
- V number or normalized frequency is an important parameter connected with the cutoff condition, it is given by

$$V = \frac{2\pi a \sqrt{n_1^2 - n_2^2}}{\lambda_c} \quad (20)$$

**For single-mode fiber**  
 $V \leq 2.405$

- Cut off wavelength,  $\lambda_c$ , is the wavelength at which higher order modes are cut off
- The Number of Mode, M, supported in Step Index and Graded index Multimode fiber given by:

**Step-index multi-mode fiber**

$$M = \frac{V^2}{2} \quad (21)$$

**Graded index multi-mode fiber**

$$M = \frac{V^2}{4} \quad (22)$$

# Summary

- Different types of light and optics theories had been developed to explain the nature of light and different optical phenomena
- Electromagnetic optics is the most complete optics theory to explain different optical phenomena compared to other classical optics theory such as ray and wave optics.
- Quantum optics is the only optics theory which can explain photoelectric effect using the Wave - Particle Duality nature of light.
- Polarization is an important parameter to understand the interference of light and there are Linear, Elliptical and Circular type of polarizations.
- Glass Optical Fiber has three parts: Core, Cladding, and Plastic jacket and each part serves different purpose.
- Total Internal Reflection is an important physical mechanism to guide the light in the fiber optic
- Different optical modes which have different field pattern are propagating in multi-mode fiber optic

# References

- [1] E. A. Saleh and M. C. Teich, "Fundamentals of Photonics", Wiley, 3<sup>rd</sup> ed., Pp.161, 2019.
- [2] Gerd Keiser, "Fiber Optic Communications", Springer, Pp.18, 2021.
- [3] Le Nguyen Binh, "Optical Fiber Communication Systems with MATLAB® and Simulink® Models", CRC Press, Pp.19, 2015.



**Thank You !**