Lightwave fundamental: Light has a dual nature. Two complementary theories have been proposed to explain how light behaves and the form by which it travels.

1. Particle theory: Light consists of a stream of small particles, because it travels in straight lines at great speed speed. And it is reflected from mirror in a predictible way.

2. Wave theory: Light is a wave, because it undergoes diffraction and interference (Young's double-slit experiment). Light behaves as an electromagnetic wave.

Particle theory:

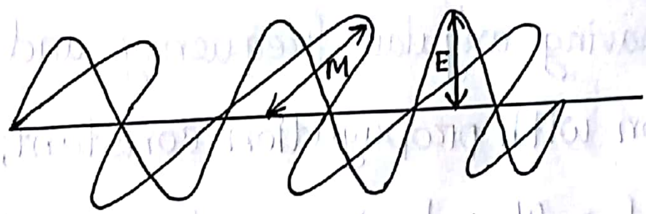
$\Delta E = h\nu$

Photon (particles) carry the energy of light.

Photon energy, $E = h\nu = \frac{hc}{\lambda}$ where, $c = \nu\lambda$

$h = 6.626 \times 10^{-34}\ m^2\ kg/s$

Wave nature:



velocity of propagation, $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$

$\mu_0 = 4\pi \times 10^{-7}\ TmA^{-1}$

$\epsilon_0 = 8.854 \times 10^{-12}\ C^2 N^{-1} m^{-2}$

A simple plane wave is given by, $E = \hat{x}\ E_m \cos(\omega t - kz)$

where, $k = \frac{\omega}{c}$

In a medium other than free space,

$$K = \frac{\omega}{v} = \frac{\omega n}{c}$$ [in terms of refractive index n, the velocity is $v = \frac{c}{n}$]

□ Wave Equation: Maxwell's equations in a homogeneous and lossless dielectric medium are written in terms of the electric field E and magnetic field M as,

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = -\epsilon \frac{\partial E}{\partial t} = -\frac{\partial D}{\partial t}$$

B = magnetic flux density $[B = \mu H]$

D = electric flux density $[D = \epsilon E]$

where,

$$\epsilon = \epsilon_0 n^2$$

$$\mu = \mu_0$$

$$\text{wave number} = \frac{\omega}{v} = \frac{\omega}{\sqrt{\mu\epsilon}} = Kn \text{ ; where, } K = \frac{\omega}{c}$$

$$\text{wavelength, } \lambda = \frac{c}{f} = \frac{\omega/K}{f} = \frac{2\pi}{K}$$

EMW having angular frequency and propagating in the z direction with propagation constant, the electric and magnetic fields of a fiber having axial symmetry can be expressed as:

$$\tilde{E} = E(r,\theta)\, e^{j(\omega t - \beta z)}$$

$$\tilde{H} = H(r,\theta)\, e^{j(\omega t - \beta z)}$$

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \theta^2} + \left[k^2 n(r,\theta)^2 - \beta^2\right] E_z = 0$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \theta^2} + \left[k^2 n(r,\theta)^2 - \beta^2\right] H_z = 0$$

In axially symmmetric optical fibers, the refractive index distribution is not dependent on θ and is expressed by n_r.

Modes in an optical fiber consits of

- TE modes $(E_z = 0)$
- TM modes $(H_z = 0)$
- Hybrid modes $(E_z \neq 0,\ H_z \neq 0)$

Group and Phase Velocity:

The phase velocity of a wave is the rate at which the phase of the wave propagates in space.

A plane wave is given by, $E_x = E_m \cos(\omega t - kz)$

Velocity for which phase $(\omega t - kz)$ is constant → phase velocity

$\omega t - kz = 0$

or, $kz = \omega t$

or, $\frac{\omega}{k} = \frac{z}{t}$

Phase velocity, $V_p = \frac{\partial z}{\partial t}$

$= \frac{\omega}{k}$

$= f\lambda$

$$V_p = \frac{\omega}{k}$$

ω = angular frequency

The group velocity of a wave is the velocity with which the overall shape of the wave's amplitudes propagates through space.

group velocity, $V_g = \frac{d\omega}{dk}$

Note: group velocity = phase velocity [when, RI = (C)]

refractive index, $RI = \frac{c}{V_p}$

Polarization:

- Describes the direction of the electric field oscillations.
- Induced by preferential reflection, transmission, scattering, or passing light through a birefringent material.
- Light is an EMW, and the electric field of this wave oscillates perpendicularly to the direction of propagation.
- If the direction of the electric field of light is well defined, it is called polarized light.
- Most common source of polarized light is a LASER.

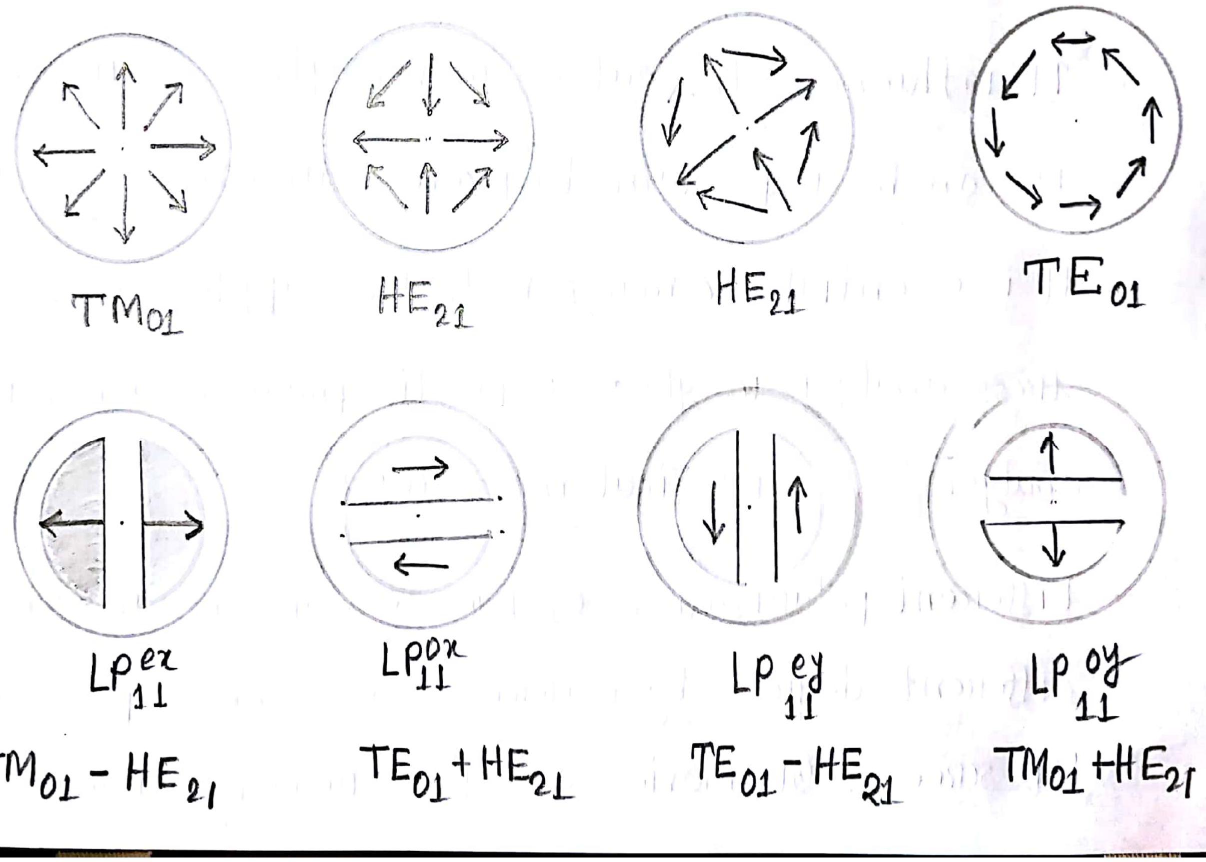
Importance of polarization:

- The polarization of light affects the focus of laser beams.
- It influences the cut-off wavelengths of filters.
- It can be important to prevent unwanted back reflections
- It is essential for many metrology applications such as stress analysis in glass or plastic, pharmaceutical ingrediant analysis, and biological microscopy.
- Different polarizations of light can also be absorbed to different degrees by materials, an essential property for LCD screens, 3D movies, and glare-reducing sunglasses.

(i) Linear Polarization: the electric field of light is confined to a single plane along the direction of propagation

(ii) Circular Polarization: the electric field of the light consists of two linear components that are perpendicular to each other, equal in amplitude, but has a phase diff. of $\pi/2$. The resulting electric-field rotates in a circle around the direction of propagation.

(iii) Elleptical Polarization: The electric field of light describes an ellipse. This results from the combination of two linear components that are different in amplitudes and phase difference is not equal to $\pi/2$.



- EH : strong electric E_z field compared to the magnetic H_z field.
- HE : strong magnetic H_z field compared to the electric E_z field.

six field components (3 electric, 3 magnetic)

- Propagation modes are discrete and require two indexes (l, p) to be identified: HE_{lp}, EH_{lp}

- For $l=0$, the hybrid modes (EH and HE) are analogous to TE and TM modes of planar waveguides.
  - two linearly polarized sets of modes circulary symmetric with vanishing either the E or H: TE_{op} $(E_z = 0)$
    TM_{op} $(H_z = 0)$

- The lowest order transverse modes: TE_{01}, TM_{01}

Cutoff frequency, $V = V_c = 2.405$

where, V = normalized frequency $= \frac{2\pi}{\lambda} a \sqrt{n_{co}^2 - n_{cl}^2}$

a = core radius

λ = free-space wavelength

n_{co} = RI of core

n_{cl} = RI of cladding

NA = Numerical Aperture $= \sqrt{n_{co}^2 - n_{cl}^2}$