18ECO1077- Fiber optics and opto electronics. ①-①.

Unit-I: Introduction to optical fibers

Syllabus

Evolution of fiber optic system - elements of an optical fiber transmission link - Advantages of fiber optic system - Characteristics and behavior of light - Total internal reflection - Acceptance angle - Numerical aperture, Critical angle - Solving problems - Ray optics - types of rays - optical fiber modes - optical fiber configurations - single mode fiber - Multimode fibers - Step index fibers - Graded index fibers.

① Evolution of Communication system:

1. principle interest of human beings has been to devise communication systems for sending message from one distant place to another. The fundamental element of any such communication system is shown in fig 1.

Message source → Transmitter → Transmission channel → Receiver → Message destination

Fig 1-1 Fundamental elements of Communication system.

- Information source - inputs message to transmitter.
- Transmitter - couple message to transmission channel (channel - medium bridging distance between transmitter and receiver)

Types → guided - core / waveguide
Types → unguided - atmospheric / space channel.

- Signal - while travelling through channel, it may be attenuated and distorted with distance.
- Receiver - Extract weak and distorted signal from channel, amplify and restore to original form.

② Forms of communication system:

Motive :

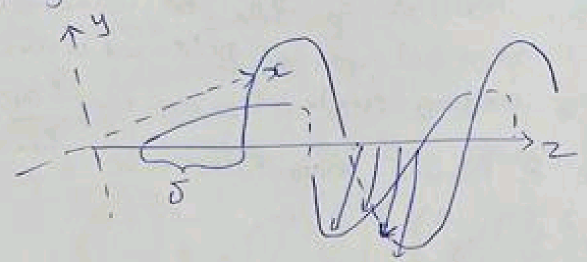
- To improve fidelity
- To increase data rate so more information could be send.
- Increase transmission distance between relay stations.

Elliptical and circular polarization.

→ for general value of δ, the wave given by pre equation is elliptically polarized.

→ for circular polarization, $E_{0x} = E_{0y} = E_0$ & relative phase difference $\delta = \pm \pi/2 + 2m\pi$ where $m = 0, \pm1, \pm2 ...$ whereas linear polarization is equal to zero.

→ Resultant vector E will both rotate and change in magnitude as a function of angular frequency ω.



Quantum nature of light:

1. In dealing with interaction of light & matter, such as occurs in dispersion & in emission and absorption of light, neither particle theory, nor wave theory of light is appropriate.

Quantum Theory:-

1. Consider particle as well as wave properties. (particle nature arises from observation that light energy is always emitted or absorbed in discrete units called quanta / photons).

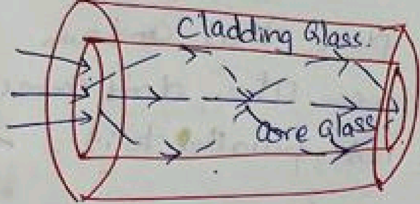
2. Photon energy depend only on frequency, which inturn must be measure by observing wave property of light.

Relation b/w E (energy) & frequency ν of photon:

$\boxed{E = h\nu}$ $\quad h = 6.625 \times 10^{-34}$ J/s → plancks constant.

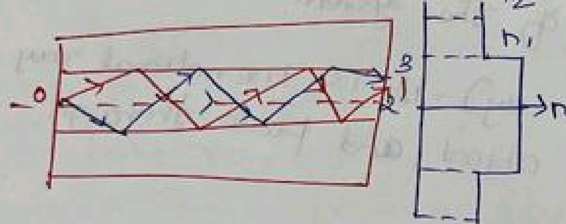
3. Refractive index difference b/w core & cladding is small.
4. Neither dispersion nor degradation. ∴ It suitable for long distance communication.
5. Laser diode is used to pass light through SMF.

Multimode fiber:

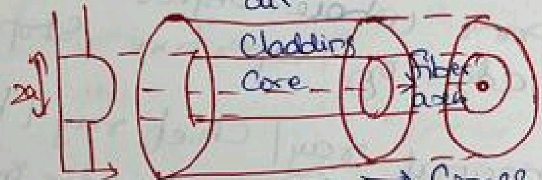


1. Allow large no. of modes of light ray to travel.
2. Core diameter = 40 μm
   Cladding diameter = 70 μm.
3. R.I difference Larger than SMF.
4. Due to multimode, dispersion, signal degradation takes place.
5. Not suitable for long distance due to dispersion & attenuation.

Step index.



Graded index fiber.



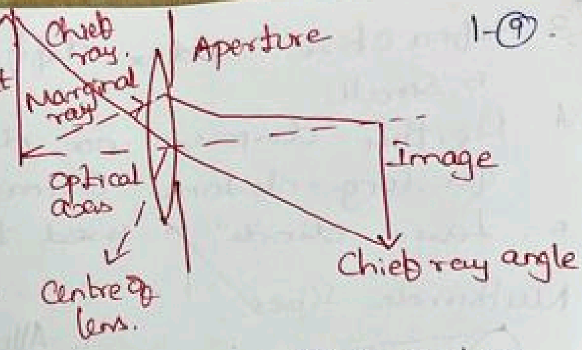
1. Refractive index of core & cladding are constant.
2. Light ray propogate through it in form of Meridional rays which cross fiber axis during every reflection at core-cladding boundary.
3. diameter = 50-200 μm (Core) (MMF)
   for SMF = 10 μm
* light travel in zig-zag manner.

Attenuation is more in MMF than SMF.

1. Core has non-uniform refractive index that gradually decreases from center towards core cladding interface
2. Cladding has uniform refractive index.
3. Light rays propagate through it in form of helical rays.
* path of light is helical.
4. Core diameter = 50 μm (MMF)
5. Attenuation is less

1-(9).

...g rays:



1. ...ridional ray | tangential ray - Confined to plane containing System optical axis & object point from which ray originated.

2. Skew ray. - don't propagate in plane that contains both object point & optical axis. They don't cross optical axis anywhere and are not parallel to it.

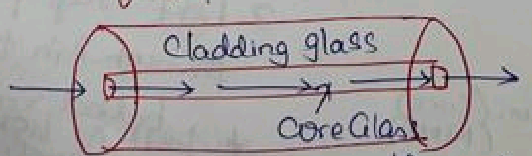
3. Marginal ray. (ray (or marginal axis ray).
- It is the meridional ray that starts at point where object crosses optical axis, touches the edge of aperture stop of the system.

- Principal ray | Chief ray [b-ray] - it is meridional ray that starts at edge of object, and passes through centre of aperture stop.
- sagittal (or) transverse ray
- paraxial ray
- parabasal ray.

Modes of fiber → No. of Modes → Single mode fiber (SMF); Multimode fiber (MMF)

Modes of fiber → Refractive index → Step index. (Single/multi mode); Graded index.

Single Mode fiber:



1. only mode propagate through fiber.
2. Core diameter (5 µm), Cladding diameter (70 µm)

Postulates of Ray optics:

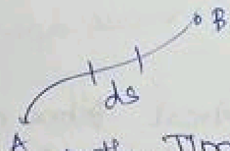
1. light travels in the form of rays. Rays are emitted by light source, observed by light detector.

2. optical medium (through which ray propagates) characterized by real scalar quantity $n \geq 1$ called refractive index. speed of light in vacuum is $C = 3\times10^8$ m/s. speed of light in medium is $v = c/n$. time taken by light to cover a distance d is

$t = nd/c$ [$\because nd \to$ optical length].

3. In homogenous medium, refractive index $n(r)$ varies with position, optical path length opl b/w 2 points A & B is

$$\text{opl} = \int_A^B n(r)\,ds.$$



ds → Element of length along path. Time taken by light to go from A to B is $t = \text{opl}/c$.

4. light ray b/w A & B follow path such that the time of travel relative to neighboring paths, is an extremum (minimum). This means that the variation in travel time / equivalently in the optical path length is zero. that is,

$$\delta \int_A^B n(r)\,ds = 0.$$

Types of ray:

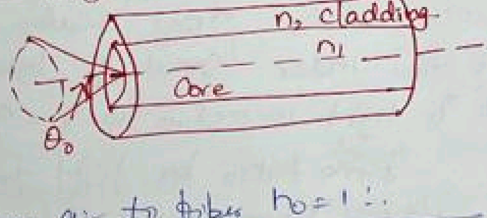
① Incident ray. – light strikes surface

② reflected ray – light reflected by surface.
$\theta_r \to$ angle b/w surface normal & reflected ray.

③ refracted ray / transmitted ray.
- light transmitted through surface.
- θ b/w this ray & normal is angle of refraction.

1-8.

R.I of core and cladding are 1.50 & 1.48 respectively in an optical fiber. Find the numerical aperture and acceptance angle.



$n_1 = 1.5 \quad n_2 = 1.48$

$NA = ? \quad \theta_0 = ?$

$\theta_0 = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$

For light travelling from air to fiber $n_0 = 1$ ∴

$\theta_0 = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right) = \sin^{-1}\sqrt{1.5^2 - 1.48^2}$

$\boxed{\theta_0 = 14.1^\circ}$

Numerical aperture $NA = \sin\theta_0 \Rightarrow \sin(14.1^\circ) = 0.244$

2. NA of an optical fibre is 0.2 when surrounded by air. Find the refractive index of its core given the R.I of cladding is 1.59. Find Acceptance angle when fibre is in water. Assume refractive index of water is 1.33.

$NA = \sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$ for air; $n_0 = 1$

$NA = \sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

$0.2 = \sqrt{n_1^2 - 1.59^2} \Rightarrow n_1 = 1.6.$

While in water; $n_0 = 1.33$.

$(NA)_{water} = \frac{\sqrt{1.6^2 - 1.59^2}}{1.33} \quad \theta_0 = \sin^{-1}(0.1504)$

$\boxed{\theta_0 = 8.65^\circ}$

Ray optics:

- Study of light and its interaction with matter.
- Simplest theory of light. Rays travel in optical media according to a set of geometrical rules. Hence ray optics is also called geometrical optics.
- Its concerned with location & direction of light rays

Evolution:

∘ Before 19^{th} century - use of fire signal by Greek, century B.C for sending alarms, calls for help (or announce) certain event.

∘ 150 BC - optical signals were encoded relation to alphabet so any message could be sent.

Limitations:

∘ eye used as receiver, line of sight (LOS) transmission paths required.

∘ Telegraph - Samuel F.B Morse in 1838 (in 1844 commercial telegraph implemented)

∘ Used ~~wire~~ wire cables for information transmission - High frequency carriers used - bandwidth increased so as information capacity.

Applications: Television, Radar, Microwave link.

∘ Transmission media used: millimeter & microwave waveguide, metallic wires.

∘ Another part of EM spectrum is optical range 50 nm (UV) to 100 µm (far infrared), visible spectrum (400nm - 700nm) band.

③ Evolution of fiber optic system.

1. Advent of laser (coherent source) in 1960 paved way for this system. optical frequency 5×10^{14} Hz information capacity is 10^5 times greater than microwave system (~10 million TV channels).

2. Unguided medium limitations:

1. atmospheric channel by rain, fog, snow and dust make high speed carrier system economically unattractive in view of present demand of channel capacity.

2. Cover only short distance (upto 1km)

3. optical fiber - More reliable and versatile than atmosphere, but extremely large loss (more than 1000 dB/km) made them impractical

1. This is the expression for acceptance angle. The light rays contained within core having the angle $2\theta_{max}$ are accepted in to core of fibre & propagation. Such a cone is therefore known as acceptance cone.

2. Fractional refractive index change / relative refractive index is the ratio of difference between refractive index of core and cladding to refractive index of core. It is denoted by Δ i.e. $\Delta = \frac{n_1 - n_2}{n_1}$

Δ is always positive, generally of order of $1/100$.

Numerical aperture:

- light gathering (collecting) capacity of an optical fibre. Numerical aperture provides important relationship between acceptance angle and the refractive index of core and cladding.

- It is defined as the sine of acceptance angle i.e.,

$$NA = \sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

for air; $n_0 = 1$ $NA = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$

$$n_1^2 - n_2^2 = (n_1 - n_2)(n_1 + n_2) = \frac{(n_1 + n_2)}{2n_1}(n_1 - n_2) 2n_1.$$

Let $\frac{n_1 + n_2}{2} \approx n_1$; $\Delta = \frac{n_1 - n_2}{n_1}$

$$\therefore n_1^2 - n_2^2 = 2\Delta n_1^2$$

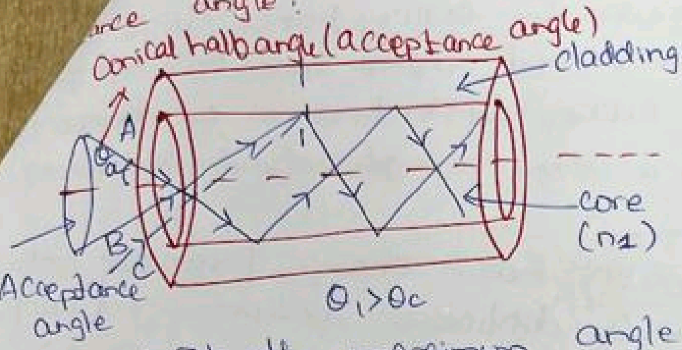
$$\therefore NA = \sqrt{n_1^2 - n_2^2} = \sqrt{2\Delta}\, n_1$$

Value of NA typically from $\boxed{0.1 \text{ to } 0.5}$

Problem 1:

Refractive index.

...nce angle:



1. It is the maximum angle with the axis of the optical fiber at which the light can enter into the optical fiber in order to be propagated through it.

2. Let us consider an optical fibre having core with refractive index n_1 & cladding refractive index n_2 such that $n_1 > n_2$. Refractive index of launching medium is n_0. Let us consider light ray AO enters fiber making an angle θ_i with axis.

3. OB is refracted ray that makes an angle θ_r with axis and strikes core-cladding interface at an angle, which is greater than critical angle. Thus it undergoes total internal reflection at the interface.

$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0}$ in Δ OBL, $\sin\theta_r = \sin(90° - \phi) = \cos\phi$

$\sin\theta_i = \frac{n_1}{n_0}\cos\phi$

when $\phi = \phi_c$, $\theta_i = \theta_{max}$

$\sin\theta_{max} = \frac{n_1}{n_0}\cos\phi_c$

Apply, Snell's law at core-cladding interface; $\frac{\sin\phi_c}{\sin 90°} = \frac{n_2}{n_1}$ cos.

$\sin\phi_c = \frac{n_2}{n_1}$

$\sqrt{1-\cos^2\phi_c} = \frac{n_2}{n_1}$

$1-\cos^2\phi_c = \frac{n_2^2}{n_1^2}$

$\cos\phi_c = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$

$\sin\theta_{max} = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$

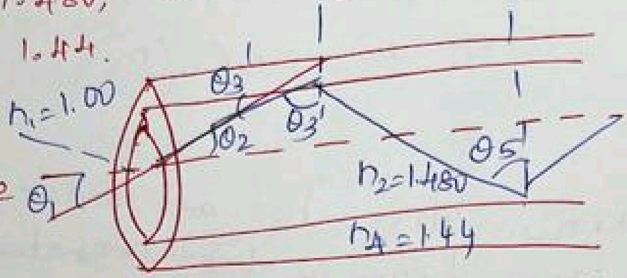
$\therefore$ $\theta_{acceptance\ angle}$

$\theta_{max} = \sin^{-1}\frac{\sqrt{n_1^2-n_2^2}}{n_0}$

for air, $n_0 = 1$

$\theta_{max} = \sin^{-1}\sqrt{n_1^2-n_2^2}$.

3. Consider fiber shown below. The index of refraction of inner core is 1.480, index of refraction of outer cladding is 1.44.



A) What is critical angle of core-cladding interface?

$$\theta_c = \sin^{-1}(n_4/n_2) = \sin^{-1}\left(\frac{1.44}{1.480}\right) = \sin^{-1}(0.9729)$$

$$\boxed{\theta_c = 76.6^\circ}$$

b) For what range of angles in the core at the entrance of fiber (θ_2) will be light be completely internally reflected at core cladding interface?

$$\boxed{\theta_2 = \theta_3' = 90 - \theta_3}$$

Snells law at entrance; $n_1 \sin\theta_1 = n_2 \sin\theta_2$

θ_3, θ_5 are alternate angles of parallel lines.

Therefore, 2 angles are equal; $\boxed{\theta_5 = \theta_3}$

For internal reflection to occur, $\theta_3 >> \theta_c$;

$$\theta_3 = 90^\circ - \theta_2 > \theta_c.$$

$$90^\circ - \theta_c > \theta_2$$

$$\therefore 90^\circ - 76.65^\circ = 13.35^\circ > \theta_2$$

→ So angle of refraction at entrance must be less than 13.4°. if total internal reflection is to occur at upper edge of fiber.

c) What range of incidence angle in air does this corresponds to:

by Snells law; $\sin\theta_1 = (n_2/n_1)\sin\theta_2 < \left(\frac{n_2}{n_1}\right)\sin(13.40^\circ)$

$$\sin\theta_1 = \left(\frac{n_2}{n_1}\right)\sin\theta_2 < \left(\frac{n_2}{n_1}\right)\sin(13.40^\circ)$$

$$\theta_1 < \sin^{-1}\left[(1.48/1)\sin(13.40)\right] \quad \boxed{\theta_1 < 20.0^\circ}$$

critical angle, $\theta_2 = 90^\circ$

$$n_1 \sin\theta_1 = n_2 \sin 90^\circ = n_2 \times 1$$

$$\theta_1 = \theta_c = \arcsin\left(\frac{n_2}{n_1}\right).$$

Problem:

1. An unknown glass has an index of refraction of $n=1.5$. For a beam of light originated in the glass, at which angle the light 100% reflected back in to the glass [R.I of air is $n_{air} = 1.00$].

Total internal reflection occur at θ_c

$$\boxed{\sin\theta_c = n_2/n_1}$$

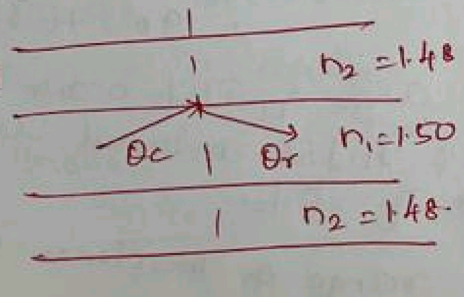
→ If incident ray equals the critical angle, then the angle of refracted ray exit along boundary at 90°.

$$\sin\theta_c = \frac{n_{air}}{n_{glass}} = 1/1.5$$

$$\theta_c = \sin^{-1}(1/1.5) = 41.8^\circ.$$

→ Hence if $\theta_{incidence} > 42^\circ$, then all incident ray completely return back into same medium.

2. The core of optical fiber has R.I of 1.50 & the cladding surrounding core has R.I of 1.48. The physical construction of this fiber is shown in the fig. below.



• Calculate critical angle (θ_c) that will just confine the signal in optical fiber.

$$\sin\theta_c = \left(\frac{n_2}{n_1}\right)$$

$$\theta_c = \sin^{-1}\left(\frac{1.48}{1.5}\right) = 80.63.$$

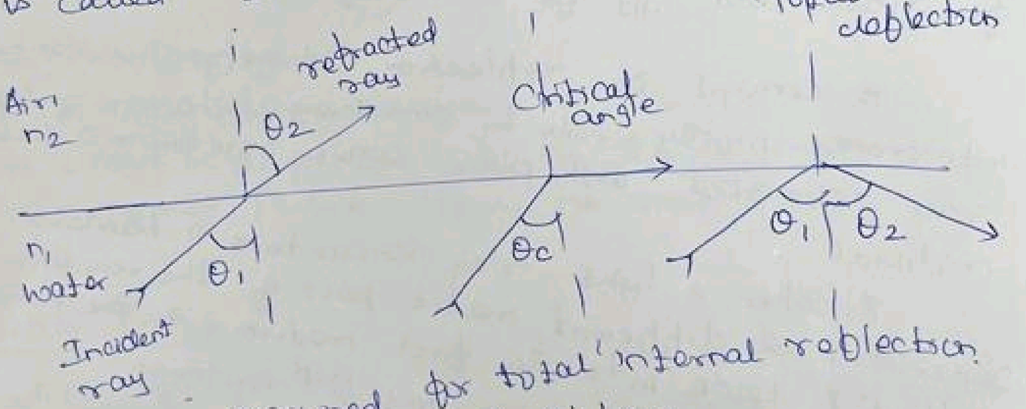
$$\boxed{\theta_c = 80.63^\circ}$$

1. According to law of reflection the angle a[illegible] incident ray strike interface is exactly equal [illegible] the angle the reflected ray makes with same interf[ace]

2. Incident ray, normal to the interface reflec[ted] ray all lie in the same plane, which is perpendicu[lar] to the interface plane between 2 materials.

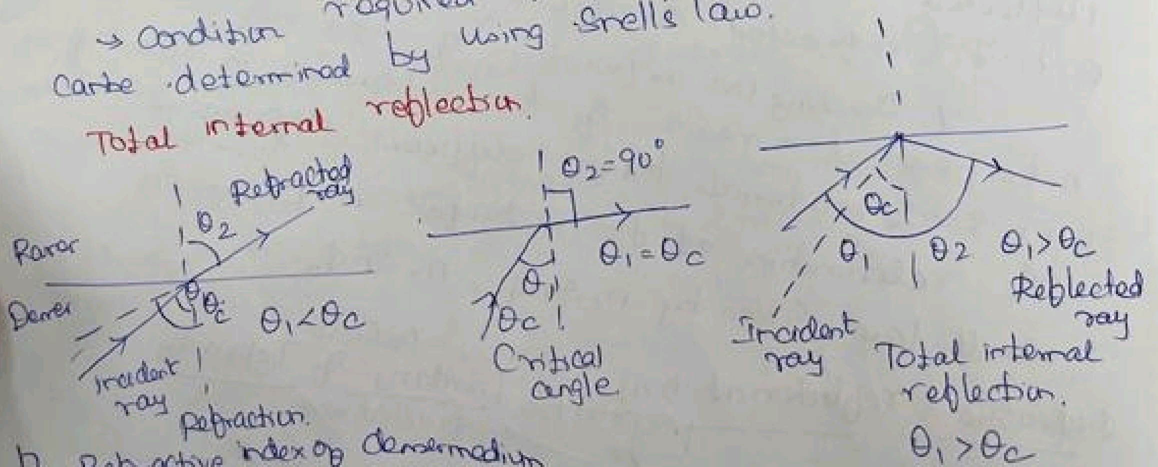
3. When light travelling in certain medium is reflected off an optically denser material (one with high refractive index) its called external reflection.

4. Conversely, reflection of light off of less optically densematerial (such as light travelling in glass being reflected at glass-to-air interface) is called Internal reflection.



→ Condition required for total internal reflection can be determined by using Snell's law.

Total internal reflection.



n_1 - Refractive index of densermedium

n_2 - Refractive index of rarermedium

θ_1 = angle of incidence ; θ_2 = angle of refraction

θ_c = Critical angle.

Optical Laws & definitions:

Fundamental optical parameter of material is refractive index / index of refraction.

2. In free space, light travels at a speed of $C = 3\times10^8$ m/s. speed of light related to frequency ν & wavelength λ by $C = \nu\lambda$.

3. upon entering a dielectric / non conducting medium the wave now travels at a speed, v. which is characteristics of material & less than c.

4. The ratio of speed of light in vacuum to that in matter is index of refraction n of the material & is given by $\boxed{n = c/v}$

values of n are [1.00 for air, 1.33 for water, 1.50 for glass, and 2.42 for diamond].

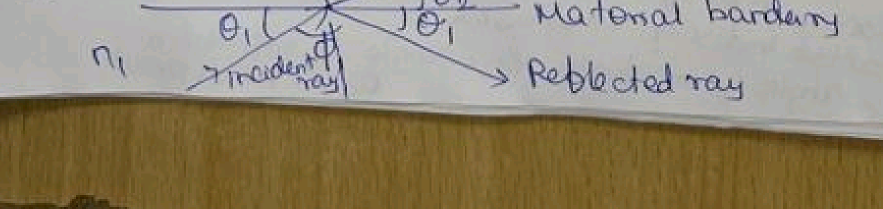
5. concept of reflection and refraction can be interpreted mostly easily by considering behavior of light rays associated with plane waves travelling in a dielectric material.

6. when a light ray encounters a boundary separating 2 different media, part of the ray is reflected back into the first medium & the remainder is bent (refracted) as it enters 2nd material.

7. Bending (or) refraction of light ray at the interface is a result of the difference in speed of light in 2 materials having different refractive indices. The relationship at the interface is known as Snell's law, given by $n_1 \sin\phi_1 = n_2 \sin\phi_2$

$n_1 \cos\theta_1 = n_2 \cos\theta_2$

Refraction & reflection at material boundary of light ray



1-6.

$$\boxed{(z,t) = Re(E) = e_x E_{ox} \cos(\omega t - kz)}$$

The above eqn for x-polarized light, for another orthogonal y-polarized light is.,

$$\boxed{E_y(z,t) = e_y E_{oy} \cos(\omega t - kz + \delta)}$$

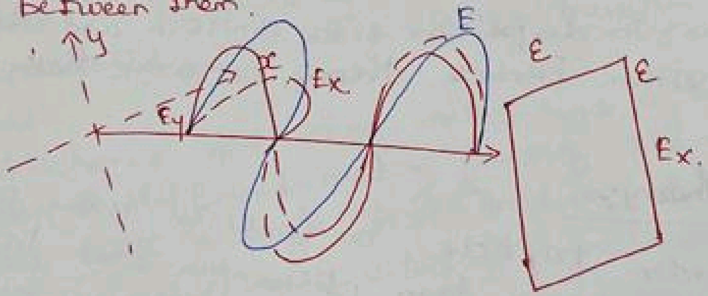
$\delta \rightarrow$ relative phase diff b/w waves. Resultant waves is then simply.

$$E(z,t) = E_x(z,t) + E_y(z,t)$$

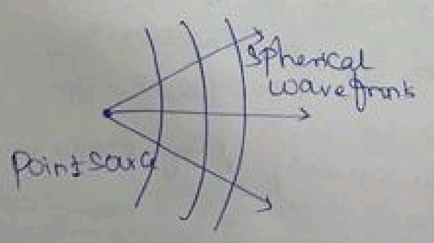
If δ is zero | an integer multiple of 2π, the waves are in phase. Eqn., is then also a linearly polarized wave with polarization vector making angle; $\theta = \arctan\left(\frac{E_{oy}}{E_{ox}}\right)$ with respect to e_x & having magnitude

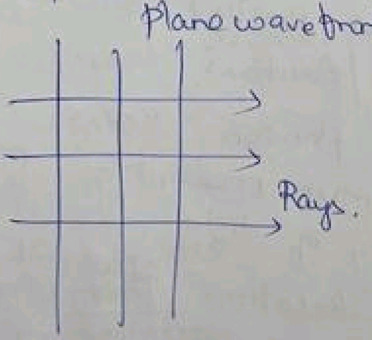
$$E = \left(E_{ox}^2 + E_{oy}^2\right)^{1/2}$$

Addition of 2 linearly polarized wave with zero relative phase between them.



Representation of spherical and plane wavefront & their associated rays.



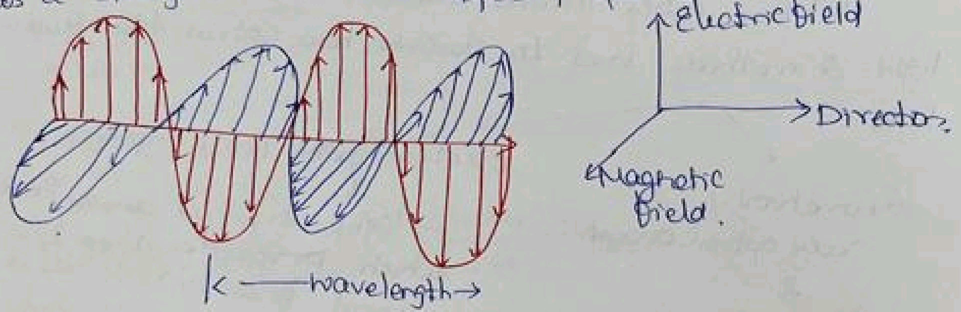


could be interpreted on assumption that light was wave motion. In 1864, maxwell theorized. light wave must be Electromagnetic in nature.

→ light wave are transverse [wave motion is perpendicular to direction in which wave travels].

→ In wave / physical optical viewpoint EM waves. radiated by small optical source canbe represented by train of spherical wave fronts (locus of all points in wave train which have same phase).

→ if wavelength of light is smaller than object (or opening) which it encounters, the wavefront appears as a straightline to this object / opening.



Linear polarization:

→ train of plane / linearly polarized waves travelling in K-direction be

$$\boxed{A(x,t) = e_i A_0 \exp[j(\omega t - kx)]}$$

$x = xe_x + ye_y + ze_z$ [general position vector]

$k = k_x e_x + k_y e_y + k_z e_z$ [wave propagation vector].

A_0 = max. amplitude of wave

$\omega = 2\pi\nu$, ν → frequency of light;

magnitude of wave vector, $\boxed{K = \frac{2\pi}{\lambda}}$ called as wave propagation constant;

λ → wavelength of light;

e_i → unit vector lying parallel to axis designated by i.

Figure of merit of receiver: minimum optical power necessary at desired data rate to attain either a given probability for digital systems or a specified SNR for a analog system.

9. Repeater: need in transmission line to amplify and reshape the signal. (it consists of receiver and transmitter placed back to back).

Receiver detect optical signal and converts to electrical signal, which is amplified, reshaped & sent to electrical input of transmitter section.

⑥ Characteristics and behavior of light:

1. Fiber optics involves emission, transmission, detection of light. 2 methods used to describe how optical fiber guides light.

Geometrical / ray optics concept
⇓
→ reflection & refraction to provide an intuitive picture of the propagation mechanisms

Electromagnetic wave approach.
⇓
→ light treated as an EM wave which propagates along the optical fiber waveguide (it involve maxwell's eqn subject to cylindrical boundary conditions of fiber)

Nature of light.

→ In 17th century, light consists of stream of minute particle that are emitted by luminous sources.

• Particle travel in straight line, assumed to be penetrating transparent but deflected from opaque ones.

• Described large-scale optical effects like reflection, refraction, but failed to explain interference & diffraction.

• Diffraction was explained by Fresnel in 1815

Major elements of an optical fiber transmission link. basic components are the transmitter, cable and receiver. Additional elements include fiber and cable splices, repeaters beam splitters, and optical amplifiers.

1. Transmitter - Consists of light source & its associated drive circuitry.

2. Cable - offering mechanical and environmental protection to optical fibers inside.

3. Receiver - Consists of photodetector plus amplification and signal restoring circuitry.

4. Optical fiber is one of the most important elements in optical fiber link. Installation can be done either aerial, inducts undersea or buried directly in ground.

5. Length : Several hundred meters to several km for long-distance applications.

6. Light source : LED / LASER - light ouput modulated rapidly by varying bias current. electrical input to transmitter can be analog / digital.

- Optical source is a square-law device, that a linear variation in drive current results in linear change in optical output power.

⇒ for 800-900nm, light source alloys are GaAlAs.
⇒ for 1100-1600nm, InGaAsP.

7. photodiode : progressively attenuated and distorted signal because of scattering, absorption and dispersion mechanisms in waveguided will be detected by this. It's also a square-law device.
⇒ Analagous to source, (Convert received. Optical power to electric current output).

Types: ① PIN
② Avalanche photodiode (APDs) for low-power signal.
Both exhibit high efficiency and response speed.

⑧. Receiver: More complex than transmitter, since it has to both amplify and reshape degraded signal received by photodetector.

4. Losses due to impurities in fiber material. 1-②.
1970, Silica fiber having 20 dB/km attenuation was fabricated.
Later attenuation reduced to 0.16 dB/km at 1550nm.

5. Development of optical fiber system grew from combination of Semiconductor Technology (give light source, photodetectors) and optical waveguide technology.

fiber optics
Narinder S. Kapany
father of fiber optics
india.

④ Advantages over conventional copper systems:
1) Low transmission loss and wide bandwidth
→ carry more data over long distance.
→ Decreased no. of wires
→ Reduced no. of repeaters, this inturn decreases system cost and complexity.

Charles Kuen Kao
father of fiber optic communication
1960 (glass)
1977 - Turn

2) Small size and weight.
→ Low weight, small (hair-sized)
3) Advantages in aircraft, satellites and ships.
4) Immunity to interference.
→ fibers are dielectric in nature, so they are immune to EMI (Electromagnetic interference) like inductive pickup from signal-carrying wires and lightning. And EMP (pulse) effects which is useful in military applications.
5) Electrical isolation: fibers made of glass (insulator) enable them to be attractive in hazardous environments as it creates no arcing or sparking.
6) Signal security: opaque jacketing around fiber make optical signal well confined in waveguide. Can be used in banking, computer networks and military systems.
7) Abundant raw material: Silica is abundant and inexpensive.

⑤ Elements of optical fiber transmission link.