Applied Physics

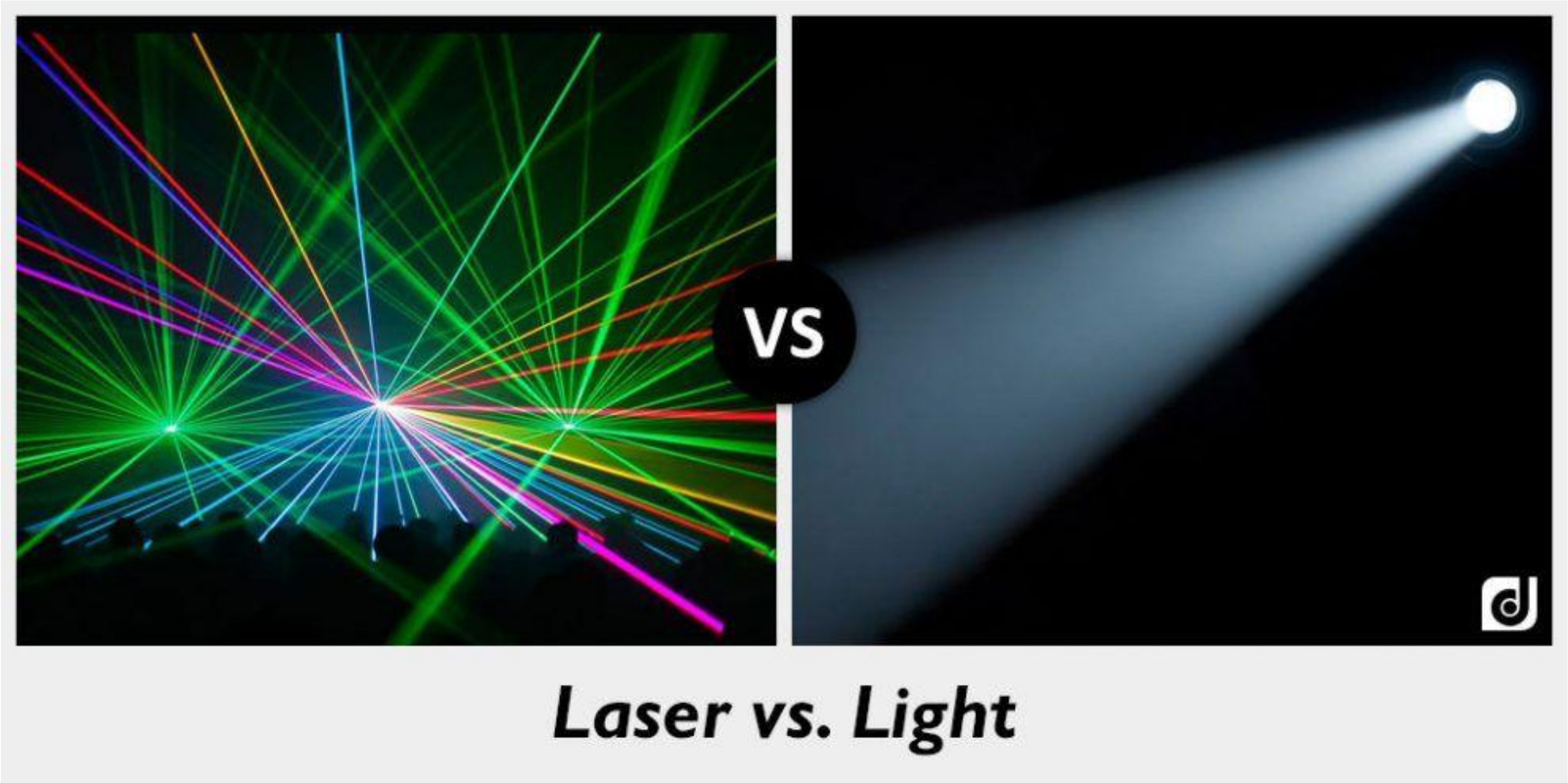
Unit 4: LASERS AND FIBER OPTICS

Dr. G. Patrick

Lasers: Introduction, Characteristics of lasers, Einstein coefficients, Resonating cavity, Active medium-Meta stable state, Pumping, Population inversion, Construction and working of Ruby laser and He-Ne laser, Applications of lasers.

Fiber Optics: Introduction, Principle and Structure of an optical fiber, Basic components in optical fiber communication system, Comparison of optical fibers over conventional cables, Acceptance angle-Numerical aperture, Types of optical fibers, Losses associated with optical fibers, Applications of optical fibers.

Laser (Light Amplification by Stimulated Emission of Radiation)



Ordinary light and Laser light

Ordinary Light	Laser Light
• Spontaneous emission	• Stimulated emission
• Incoherent	• Coherent
• Divergent	• Highly directional
• Polychromatic	• Monochromatic
• Cannot be focused to a sharp focus	• Can be focused to a very sharp spot

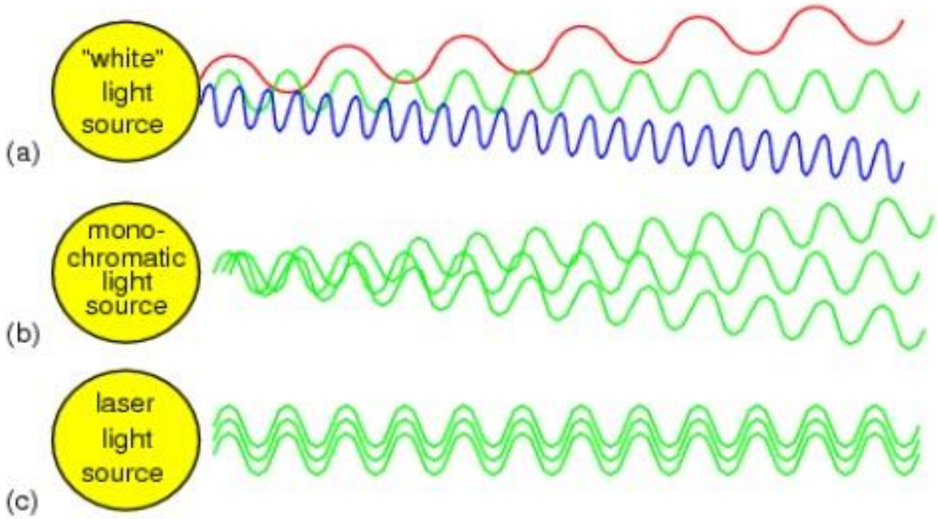
LASER: **Characteristics**

Some of the special properties which distinguish lasers from ordinary light sources are characterized by:

1. Directionality
2. High Intensity
3. Mono- chromaticity
4. Coherent

LASER: **Characteristics**

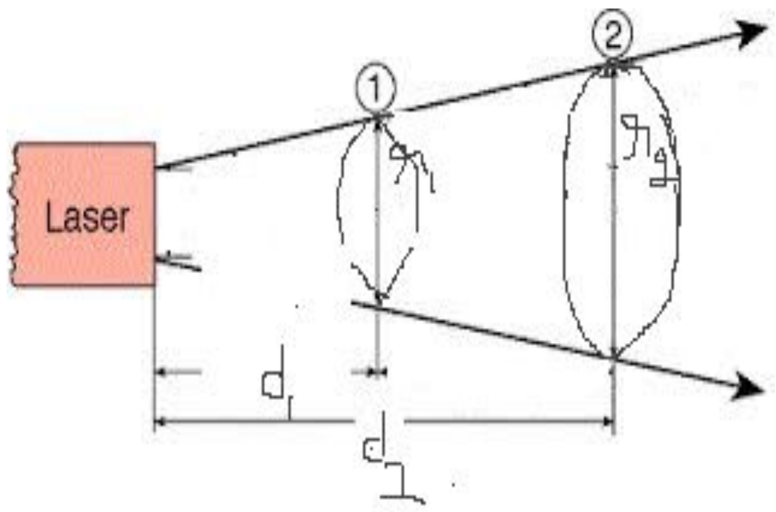
- Directionality



LASER: **Characteristics**

Directionality

- A very tight beam which is very strong and concentrated
- The directionality of laser beam is expressed in terms of angle of divergence (Φ)



LASER: **Characteristics**

- Divergence or Angular Spread is given by $\boldsymbol{\Phi = r_2 - r_1 / d_2 - d_1}$
- Where d_1, d_2 are any two distances from the laser source and r_1, r_2 are the radii of beam spots at distance d_1 and d_2 respectively as shown in the figure.
- Laser light has less divergence, which means that laser light has more directionality.

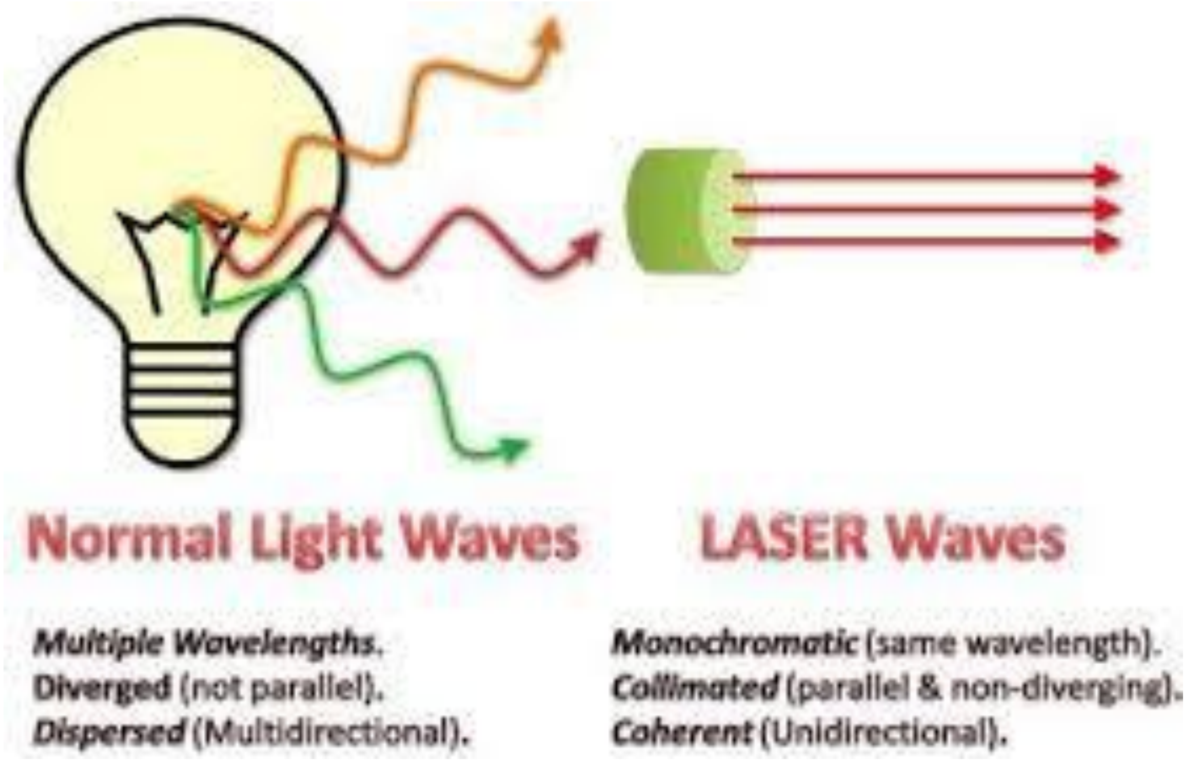
LASER: **Characteristics**

High Intensity

- In case of lasers, light is a narrow beam and its energy is concentrated within the small region.
- The concentration of energy accounts for greater intensity of lasers.

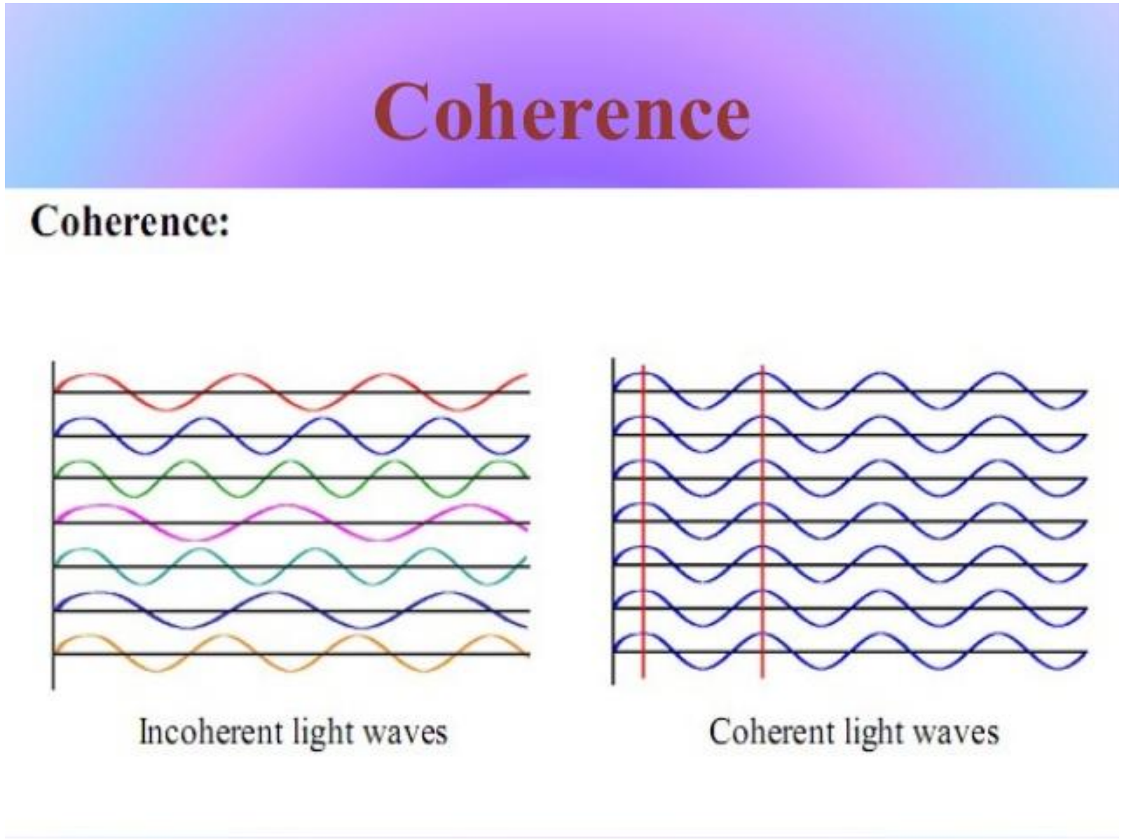
LASER: **Characteristics**

- Mono- chromaticity: one specific colour

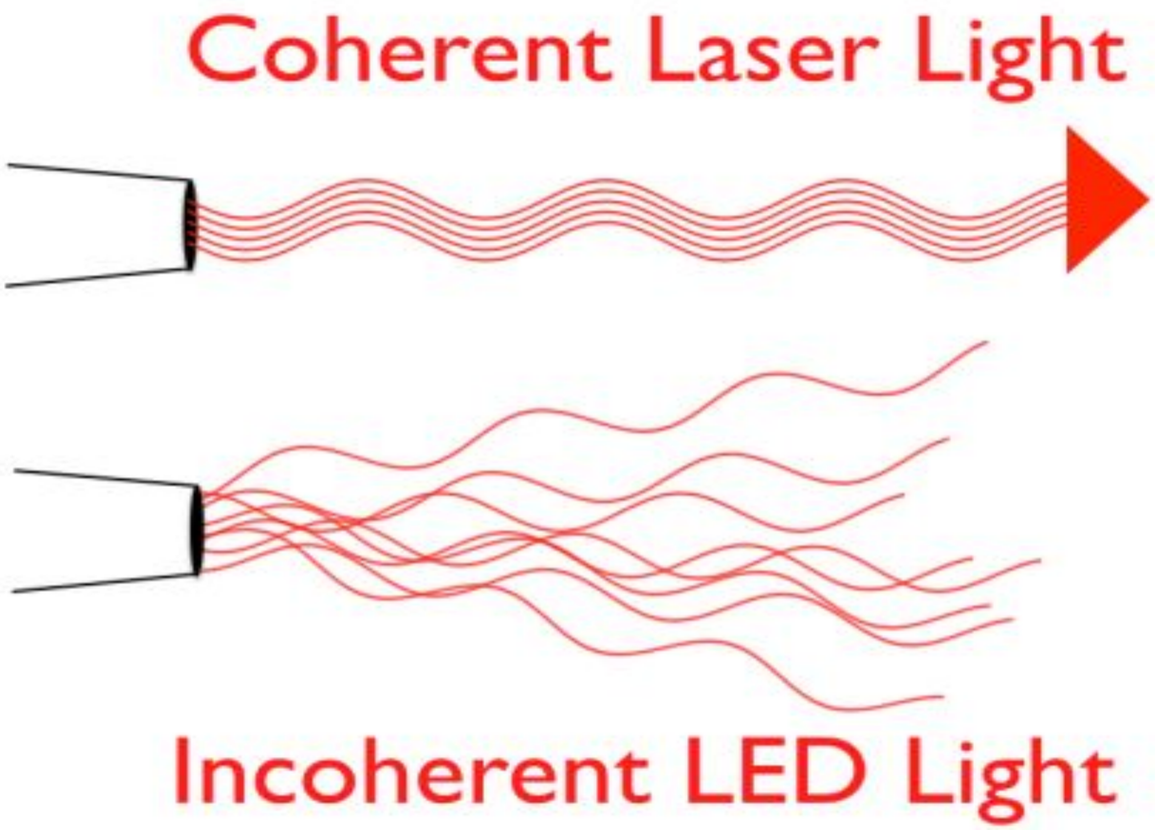


LASER: **Characteristics**

- Coherent



LASER: **Characteristics**

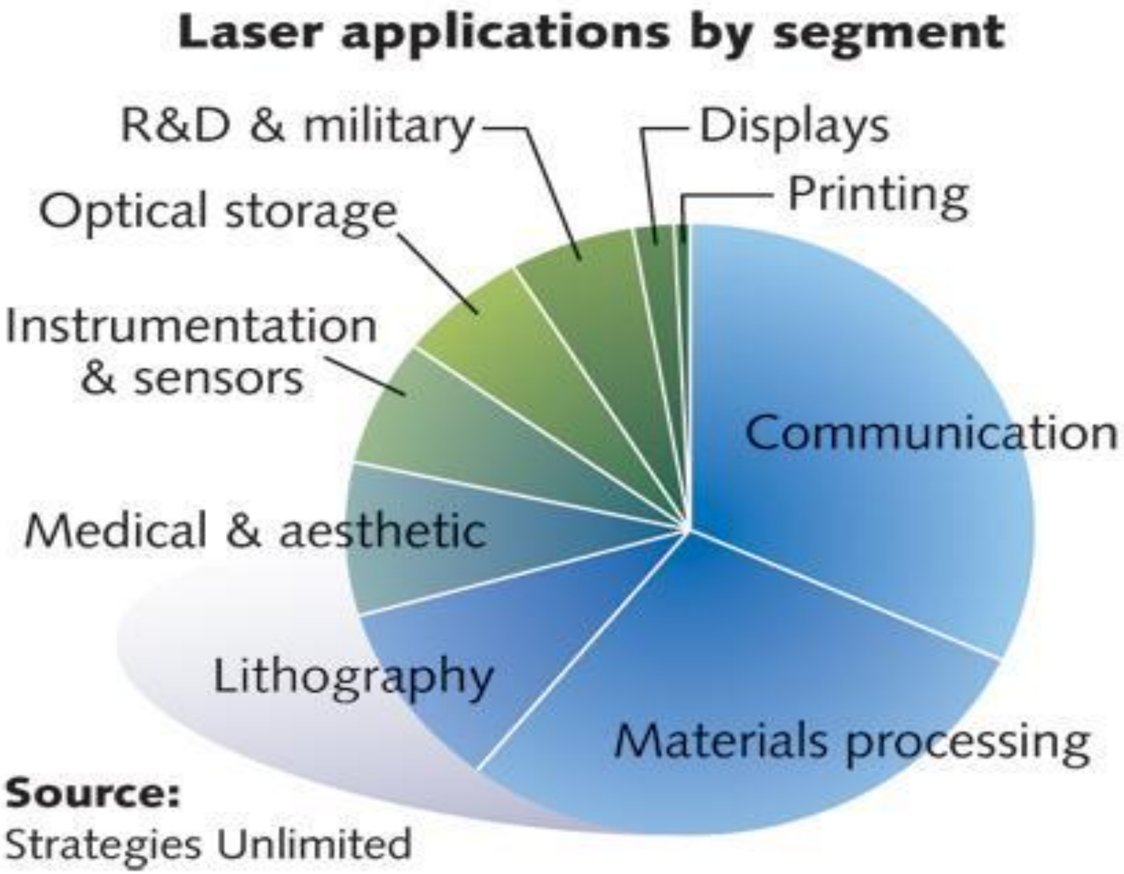


LASER: **Characteristics**

Coherence

- If any wave appears as pure sine wave for longtime and infinite space, then it is said to be perfectly coherent.
- Practically, no wave is perfectly coherent including lasers. But compared to other light sources, lasers have high degree of coherence because all the energy is concentrated within the small region. There are two independent concepts of coherence.
- i) Temporal coherence (criteria of time)
- ii) Spatial coherence (criteria of space)

Applications of Laser



Applications of Laser

Communication:

- Lasers are used in optical communications, due to large band width.
- The laser beam can be used for the communication between earth & moon (or) other satellites due to the narrow angular spread.
- Used to establish communication between submarines i.e. under water communication.

Medical:

- For removal of Cataract.
- Used to detect and remove stones in kidneys.
- Used to detect tumors in brain.

Applications of Laser

Industry:

- Welding
- Cutting
- Drilling

Einstein's Coefficients

In a collection of atoms, all three transition processes occur simultaneously:

Transitions:

- Absorption or Stimulated absorption(upward transition)
- Spontaneous emission (downward transition)
- Stimulated emission (downward transition)

Einstein's Coefficients

Let

- N_1 = number of atoms per unit volume with energy $E_{1.}$
- N_2 = number of atoms per unit volume with energy $E_{2.}$
- $u(\upsilon)$ = energy density of interacting photons.

When these photons interact with atoms both upward(absorption) and downward (stimulated emission) transition occur.

Einstein's Coefficients

- **Upward transition**

Stimulated absorption rate $= N_1\, u(\upsilon)\, B_{12}$

Where B_{12} is the Einstein coefficient of stimulated absorption.

- **Downward transition**

The excited atoms may come down either by spontaneous emission or stimulated emission.

Einstein's Coefficients

Downward transition

- By spontaneous emission

Spontaneous emission rate = $N_2 A_{21}$

Where A_{21} is the Einstein coefficient for spontaneous emission.

- By Stimulated emission

Stimulated emission rate = $N_2 u(\upsilon) B_{21}$

Where B_{21} is the Einstein coefficient for Stimulated emission

Einstein's Coefficients

- Under thermal equilibrium number of upward transitions = number of downward transitions per unit volume per second.
- $N_2 A_{21} + N_2 u(\upsilon) B_{21} = N_1 u(\upsilon) B_{12}$ □ 1
- $u(\upsilon) = A_{21}N_2 / B_{12}N_1 - B_{21}N_2$ ----------------> 2
- Dividing all terms by $B_{21}N_2$,
- $u(\upsilon) = (A_{21}/ B_{21}) \times 1 /[(B_{12}N_1 / B_{21}N_2) – 1]$ --------> 3
- By substituting $N_1/N_2 = \exp (h\upsilon/kT)$ from Boltzmann Distribution law,
- $u(\upsilon) = (A_{21}/ B_{21}) \times 1/[(B_{12} / B_{21}) \exp (h\upsilon/kT) – 1]$ -----> 4

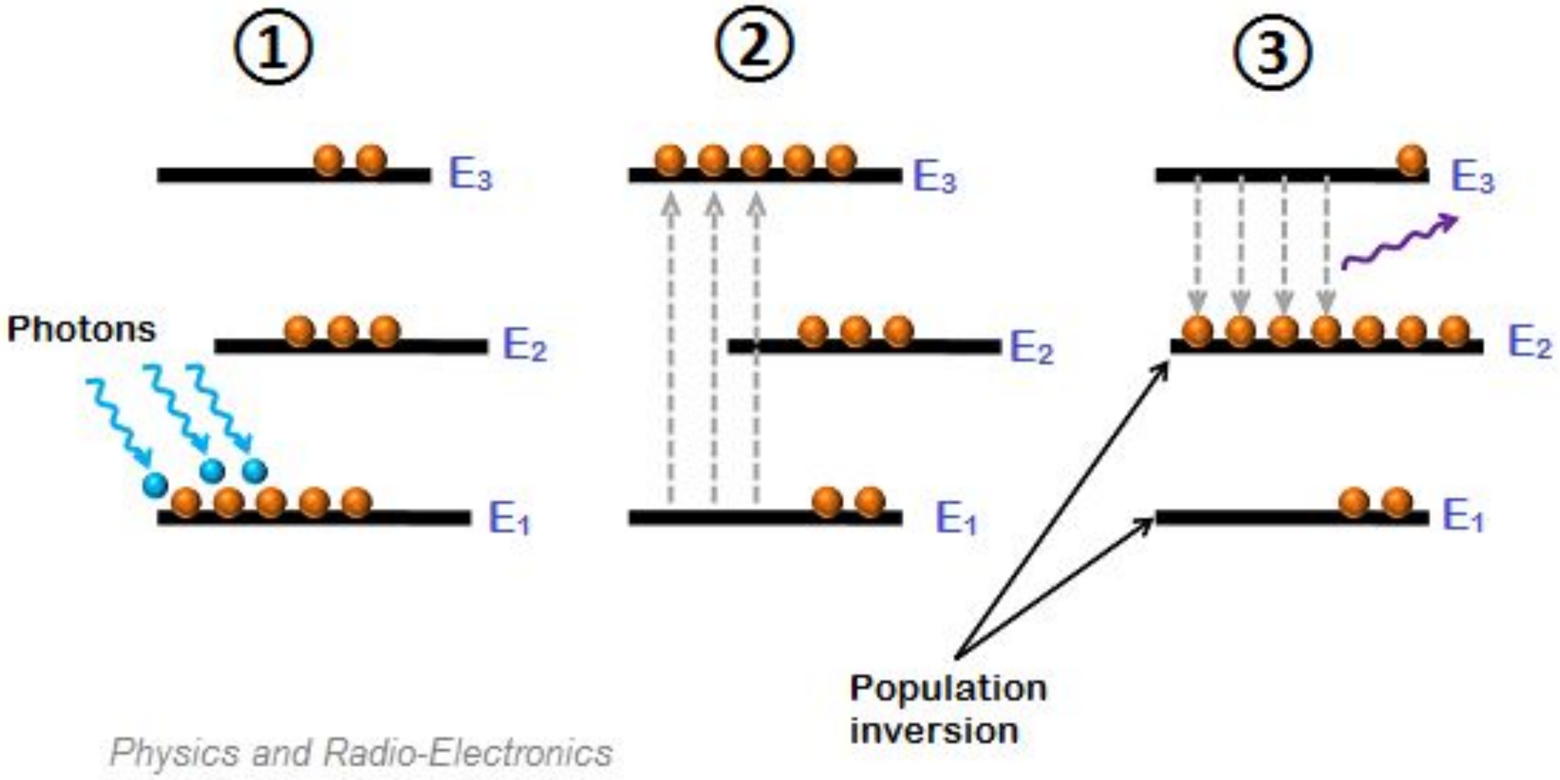
Einstein's Coefficients

- Above equation must agree with planks energy distribution – radiation formula.
- $u(\upsilon) = 8\,\pi\, h\upsilon^3/C^3\ [1/\exp\,(h\upsilon/kT)\ -1]$ ----> 5
- Comparing equations 4 & 5
- $B_{12} = B_{21}$ and get $A_{21}/\,B_{21} = 8\,\pi\, h\upsilon^3/C^3$
- The co-efficients A_{21}, B_{12} and B_{21} are known as Einstein coefficients.

Requirements for Laser action/Components of Laser

- Population inversion
- Metastable state
- Active medium
- Resonating cavity
- Pumping

Population inversion



Population inversion

- Assume there are a group of N atoms, each of which is capable of being in one of the two energy states.

Let

N_1 = no of atoms in the state E_1

N_2 = no of atoms in the excited state E_2

$E_2 > E_1$ and $N = N_0 \exp(-h\upsilon/kT)$

where N_0 is the number of atoms in the ground state.

Population inversion

- Under thermal equilibrium condition

  $N_1 >> N_2$ and Population inversion is not achieved.
- Population inversion is a condition in which

  $N_2 >> N_1$

This is a non equilibrium state and exists only for a short time.

- Population inversion can be achieved by pumping techniques, which transfers large number of atoms from lower energy state to higher energy state.

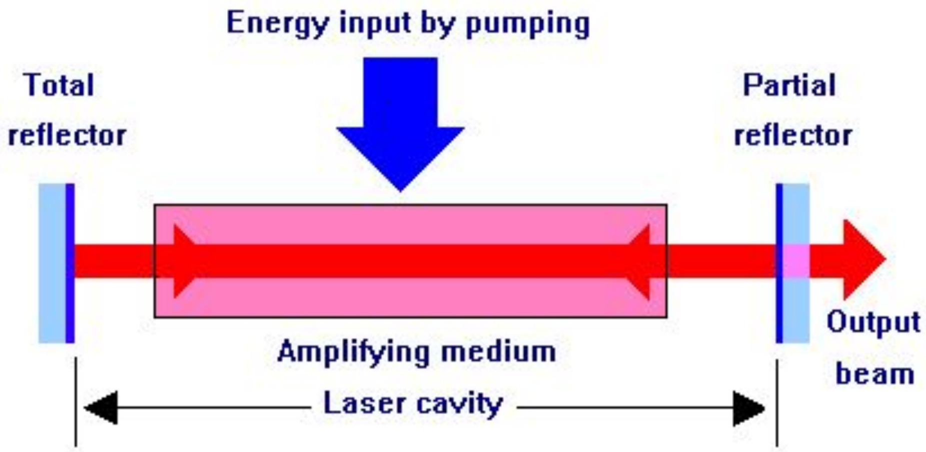
Metastable state

- Atoms excited to higher levels have a short life time (10^{-9} s) and drop to lower state by spontaneous emission.
- For population inversion to take place atoms should wait in the excited state for some time (10^{-6} s to 10^{-3} s). Such an energy state is called metastable state.

Active medium

- Active medium is the material in which laser action takes place.
- It is a medium in which population inversion has been achieved.

Resonating cavity



- A pair of optically plane parallel mirrors, enclosing laser medium in between them is known as optical resonant cavity.
- One mirror is fully reflecting and the other partially reflecting.

Role of optical resonator

- To provide positive feedback of photons into the medium so that stimulated emission is sustained and the laser acts as a generator of light.
- It selects the direction in which light is to be amplified i.e. in the direction of optical axis of the mirror. Optical cavity makes the laser beam directional.
- It increases photon density through multiple reflections.
- It selects and amplifies only certain frequencies causing laser output to be monochromatic.

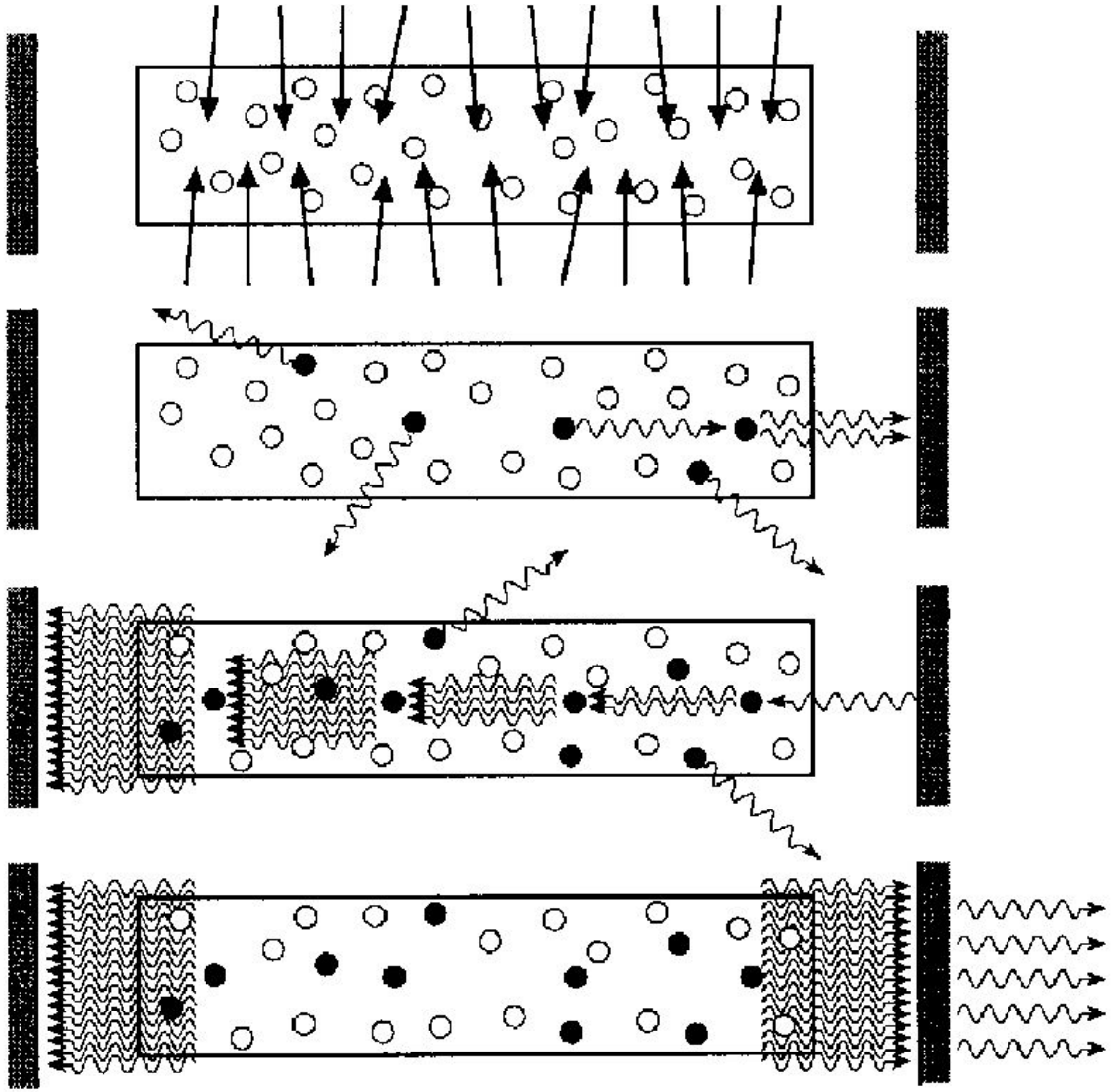
Pumping

- Pumping is the process of supplying energy to laser system to achieve population inversion.

Methods of pumping

- Optical pumping
- Electrical discharge

How a Laser Works



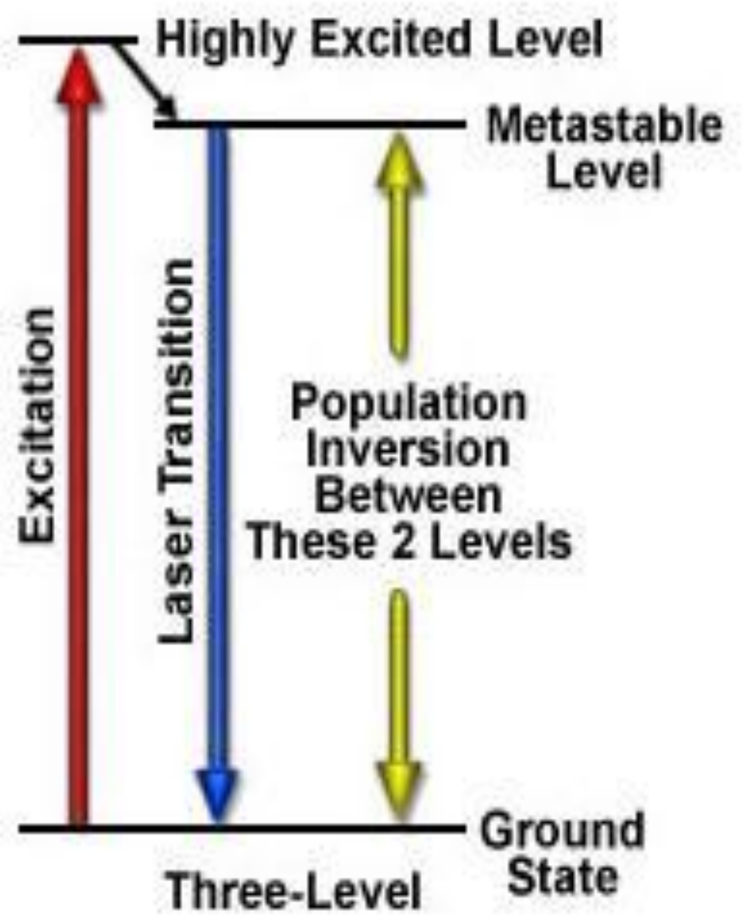
pump on
○ = atoms in excited state

spontaneous emission &
rare stimulated emission

stimulated emission of
light along the laser axis

steady-state
laser operation

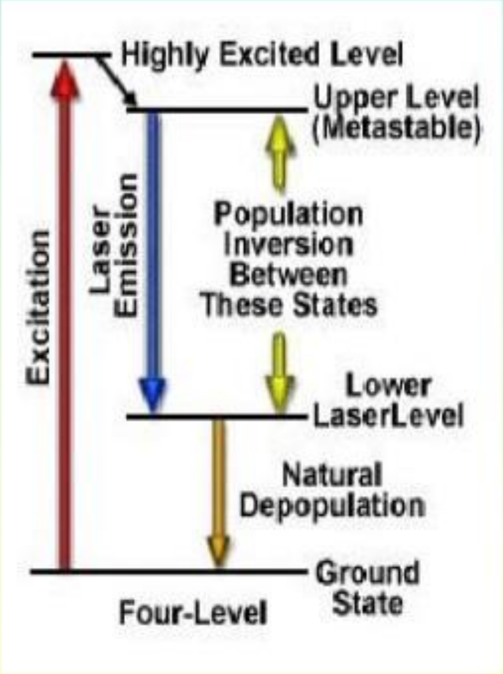
Three-level Laser System



- Initially excited to a short-lived high-energy state .
- Then quickly decay to the intermediate metastable level.
- Population inversion is created between lower ground state and a higher-energy metastable state.

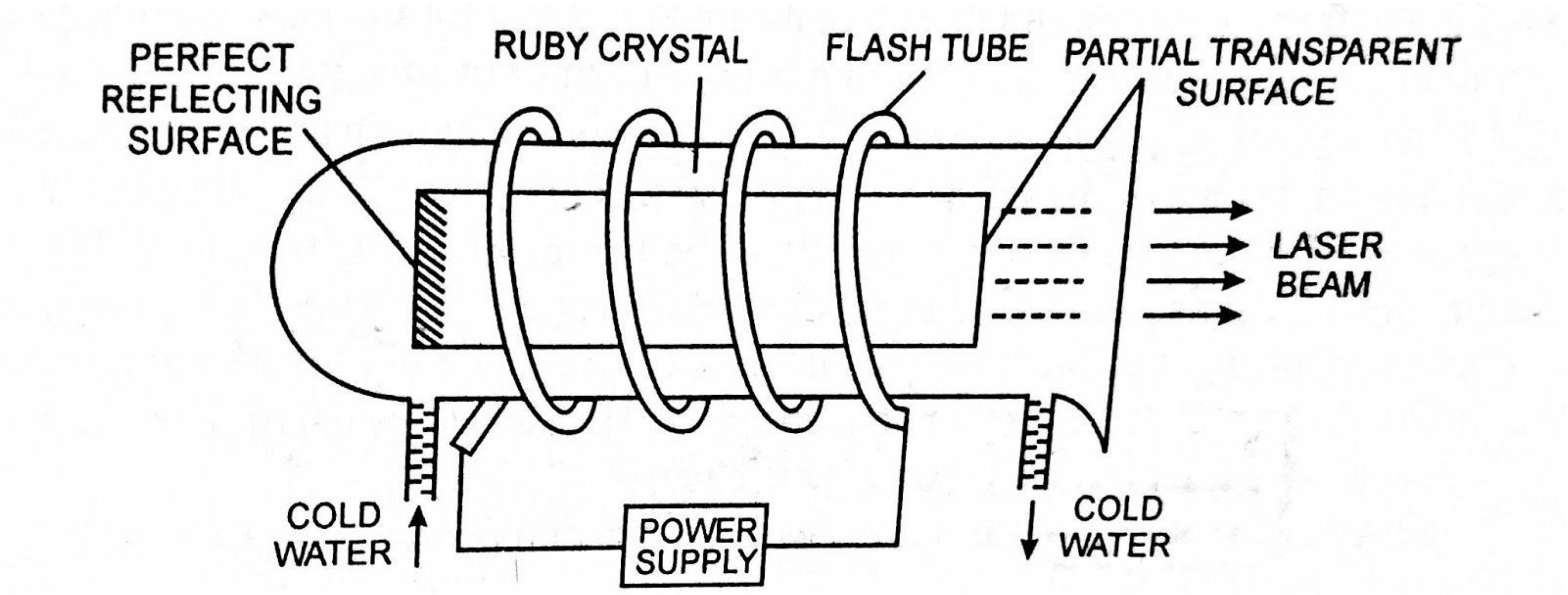
Four level Laser system

Four-level Laser System



- Laser transition takes place between the third and second excited states.
- Rapid depopulation of the lower laser level.

Solid-state Laser : Ruby laser



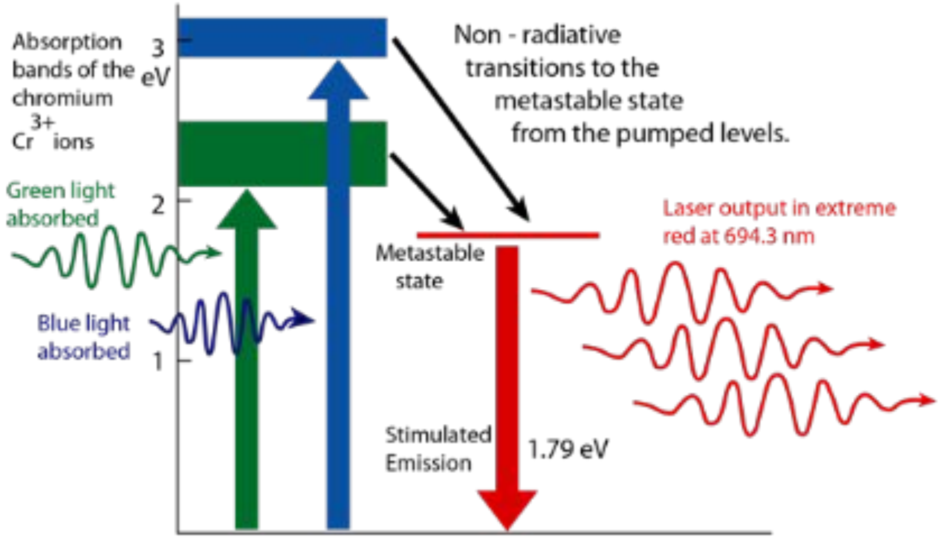
Ruby Laser

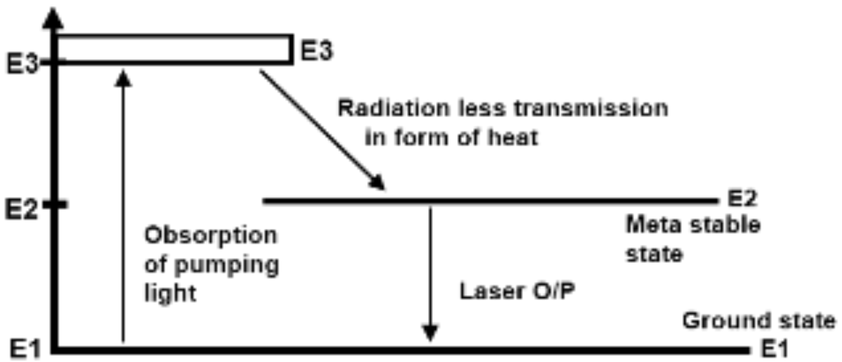
- It is a solid state laser.
- Ruby is aluminum oxide (Al_2O_3) crystal containing 0.05% of chromium atoms.
- Cr^{3+} ions are active material where as aluminum and oxygen are inert.
- Ruby rod is cylindrical in shape of length 4 cm and diameter 1 cm.
- Its ends are polished (silvered) and parallel to each other.

Ruby Laser

- One end of the rod is fully reflecting and the other end partially reflecting. Ruby rod acts as an optical resonator.
- Ruby rod is surrounded by a helical Xenon flash lamp which is used for pumping.

Ruby Laser: energy levels





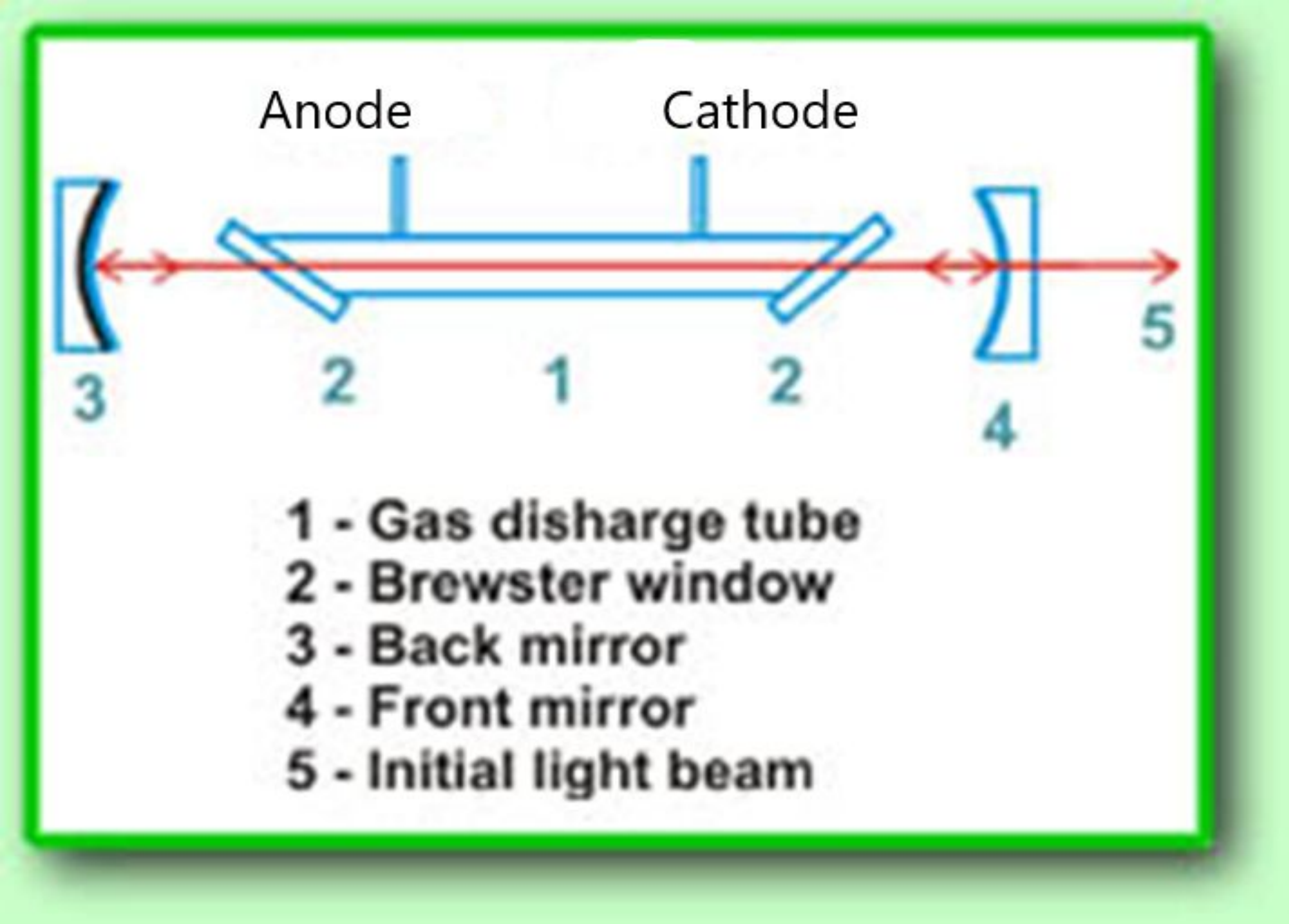
Ruby Laser

- When Xenon flash lamp is switched on, Cr^{3+} ions are excited to state E_3 and E_3^I by the green and blue components of white light.
- Cr^{3+} ions undergo nonradiative transition from E_3 and E_3^I to E_2 .
- E_2 is a metastable state and Cr^{3+} ions accumulate in E_2 state.
- Population inversion of E_2 w.r. to E_1 occurs.
- The process starts when a photon is produced by transition of Cr^{3+} ion from E_2 to E_1 . This is spontaneous emission.

Ruby Laser

- This spontaneous photon stimulates another excited ion to downward transition.
- This process continues and many photons are released.
- Red photons of wavelength 6943 Å are given out.
- The output is not continues but pulsed.

Gas Laser: Helium - Neon



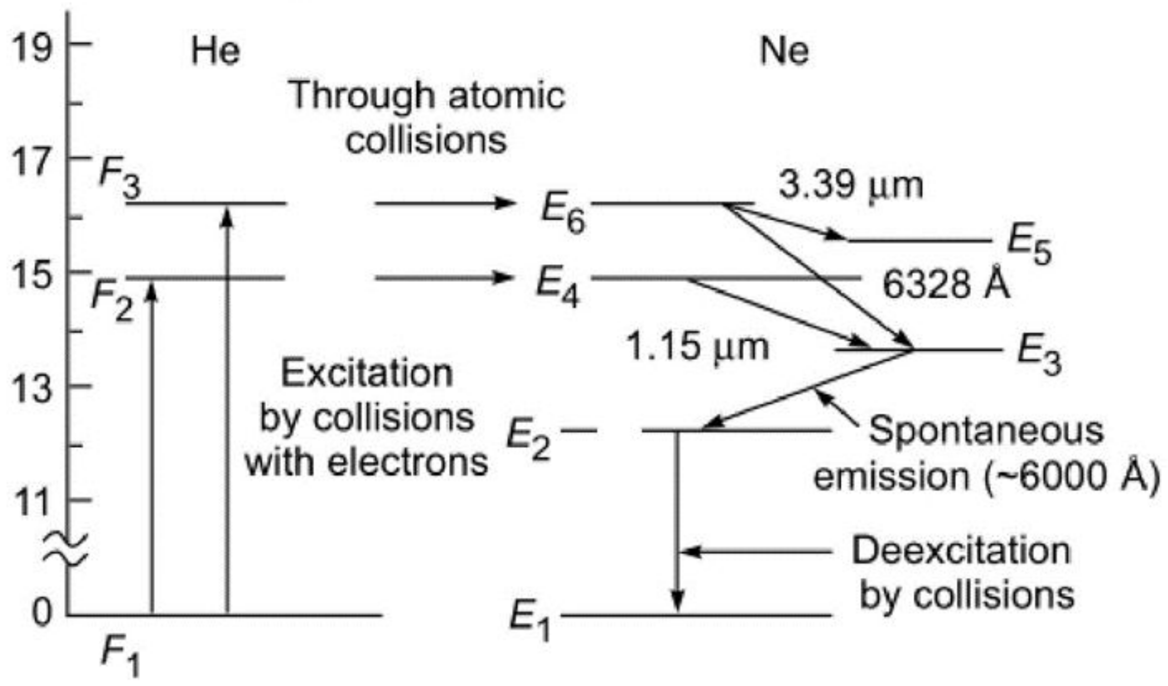
Helium – Neon Laser

- In gas lasers such as helium – neon the atoms are characterized by sharp energy levels as compared to those in solids which have broad absorption bands.
- Helium – neon laser consists of long discharge tube filled with a mixture of helium and neon gases in the ratio 10 : 1
- Electrodes are connected to high voltage source(10 KV).

Helium – Neon Laser

- Laser action is due to neon gas. Helium atoms help to excite neon atoms.
- The discharge tube contains windows placed at Brewster's angle.
- Two mirrors are also present. One mirror is fully reflecting and the other partially reflecting.

Energy diagram



Helium – Neon Laser

- When power is switched on, electrons and ions produced in the discharge tube collide with helium and neon atoms.
- Helium being lighter gets excited more readily compared to neon.
- Energy levels F_2 and F_3 of helium is close to energy levels E_4 and E_6 of neon atom.
- When helium atoms collide with neon atoms they transfer their energy. This is known as resonant energy transfer.

Helium – Neon Laser

- E_6 is a metastable state. Transitions from E_6 to E_3 produces the characteristic wavelength of 6328 Å .
- Other two wavelengths produced are 3.39 μm and 1.15 μm. They are eliminated.
- Brewster's window made of glass or quartz, absorb 3.39 μm and 1.15 μm wavelength and allow 6328 Å to pas through.
- Mirrors provide optical feedback. They are coated with multilayer dielectric material which only reflects back 6328 Å .

Application of Lasers

- Ruby Laser: Measurement of distance using pulse echo technique, drilling of high quality holes.
- Helium – neon Laser: Metrological application, bar code reading.
- Carbon dioxide Laser: Welding, cutting
- Argon ion Laser: Welding retinal detachment
- Semiconductor Laser: Laser printer

Introduction to Fiber Optics

Fiber Optics

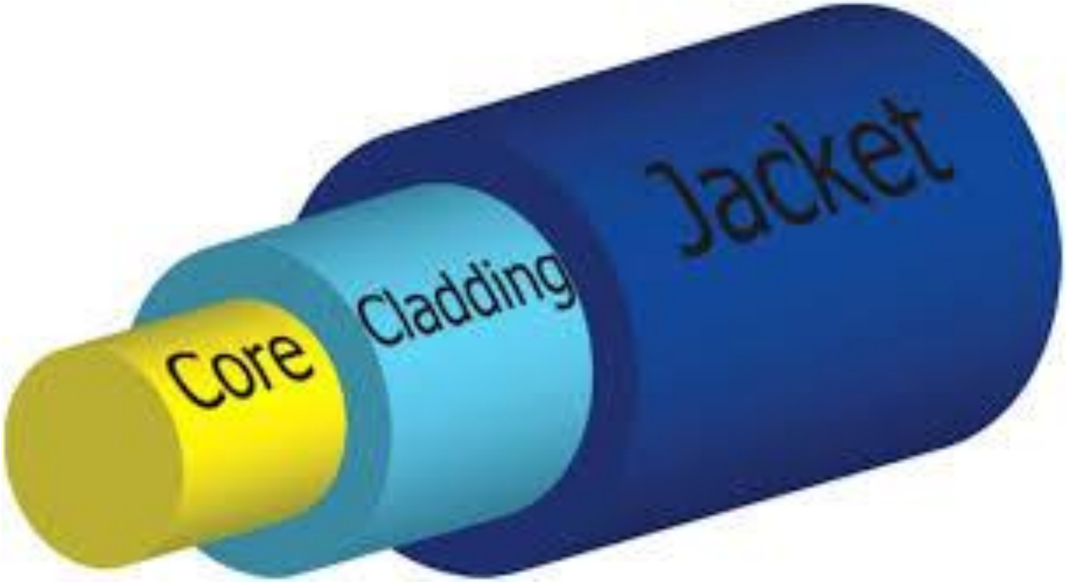
- Definition of Optical Fiber:

An optical fiber is a cylindrical wave guide made of transparent dielectric (glass or plastic) which guides light waves along its length by total internal reflection.

- Principle: The propagation of light in an optical fiber is based on the principle of total internal reflection.
- Conditions for TIR:

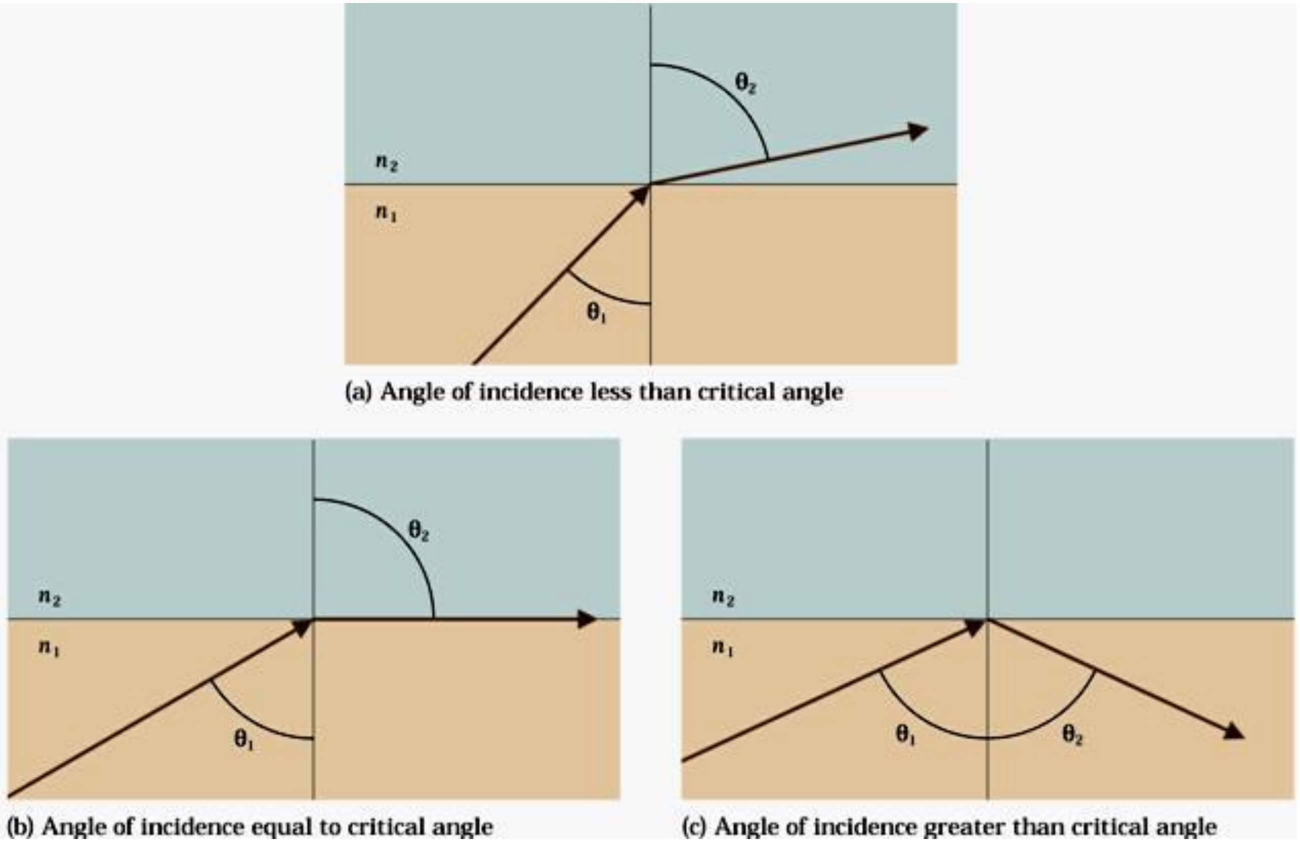
1. Light should be passing from a denser medium to rarer medium.
2. The angle of incidence in the denser medium should be greater than the critical angle.

Structure of Optical Fiber



- It has three coaxial regions i.e. the core, cladding and outer jacket.
- Core: It is the innermost cylindrical region. It is also the light guiding region.
- Cladding: The core is surrounded by the cladding.
- Outer jacket: It is a plastic coating to protect the cladding.

Total internal reflection



(a) Angle of incidence less than critical angle

(b) Angle of incidence equal to critical angle

(c) Angle of incidence greater than critical angle

Principle

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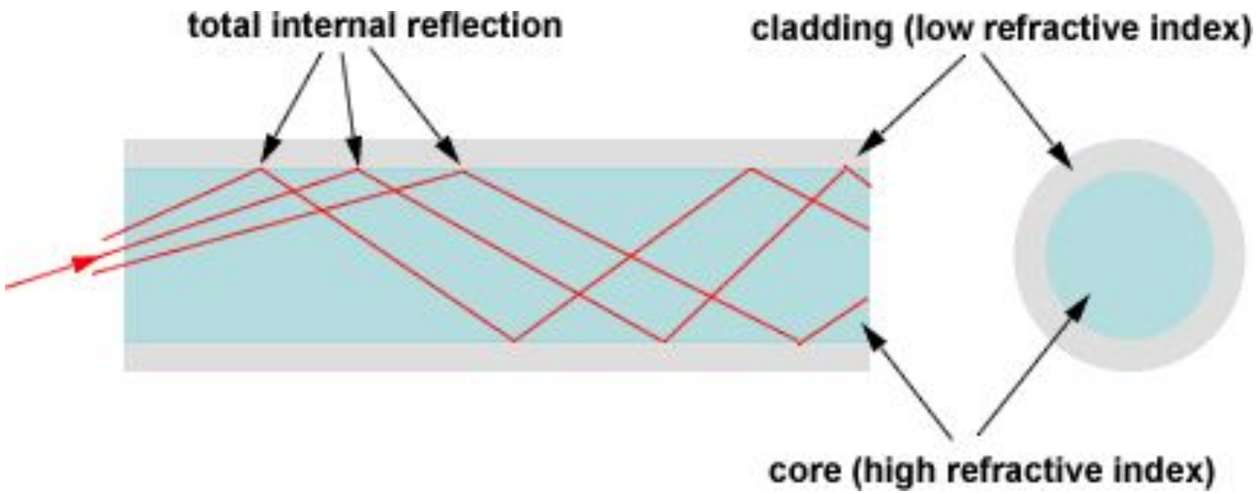
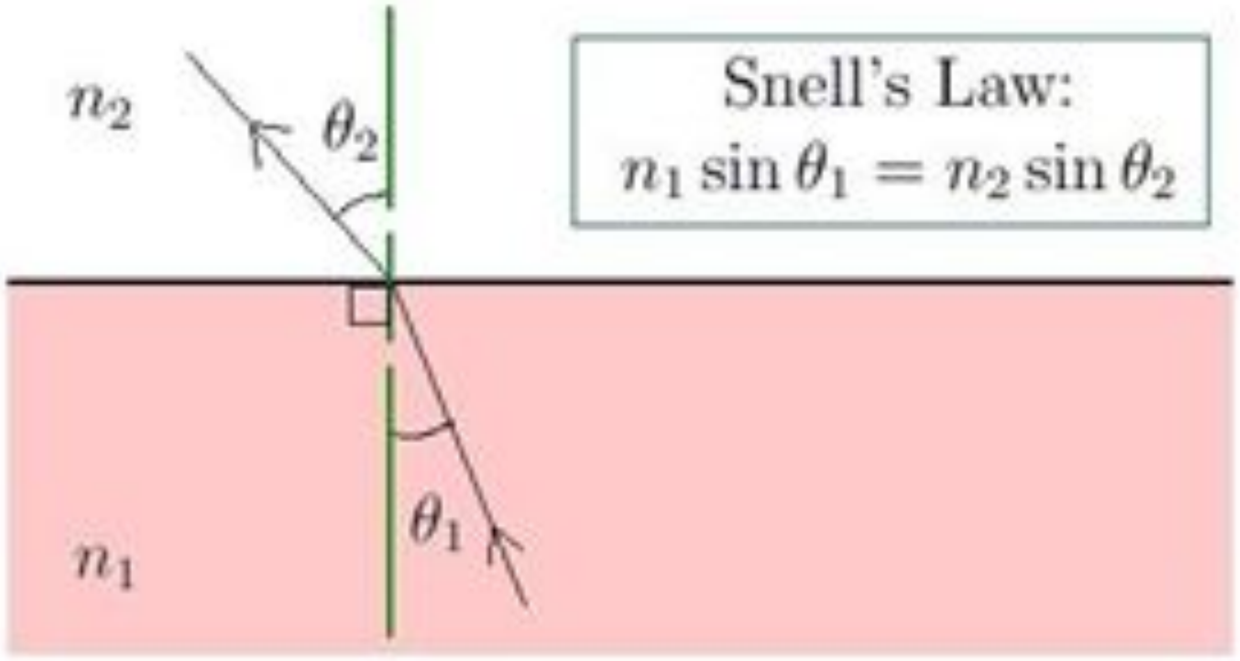


total internal reflection
cladding (low refractive index)
core (high refractive index)

Snell's Law



Snell's law

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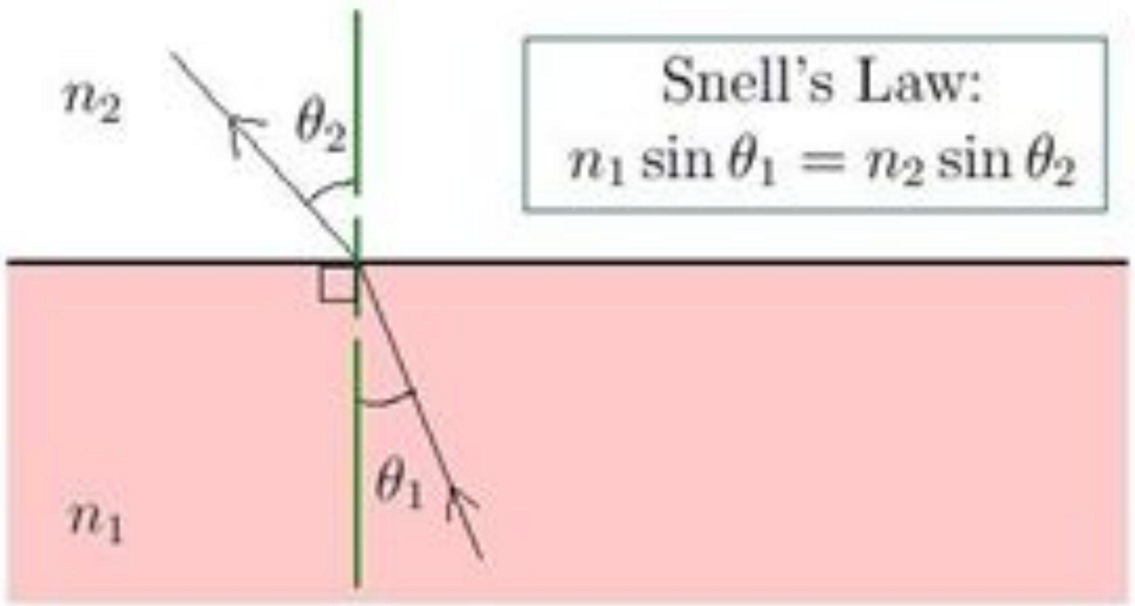


Application of Optical Fibers

Optical Fibers have many applications, some of them are:

- They are used for illumination and short distance transmission of images.
- They are used as wave guides in telecommunications.
- They are used in fabricating sensors.

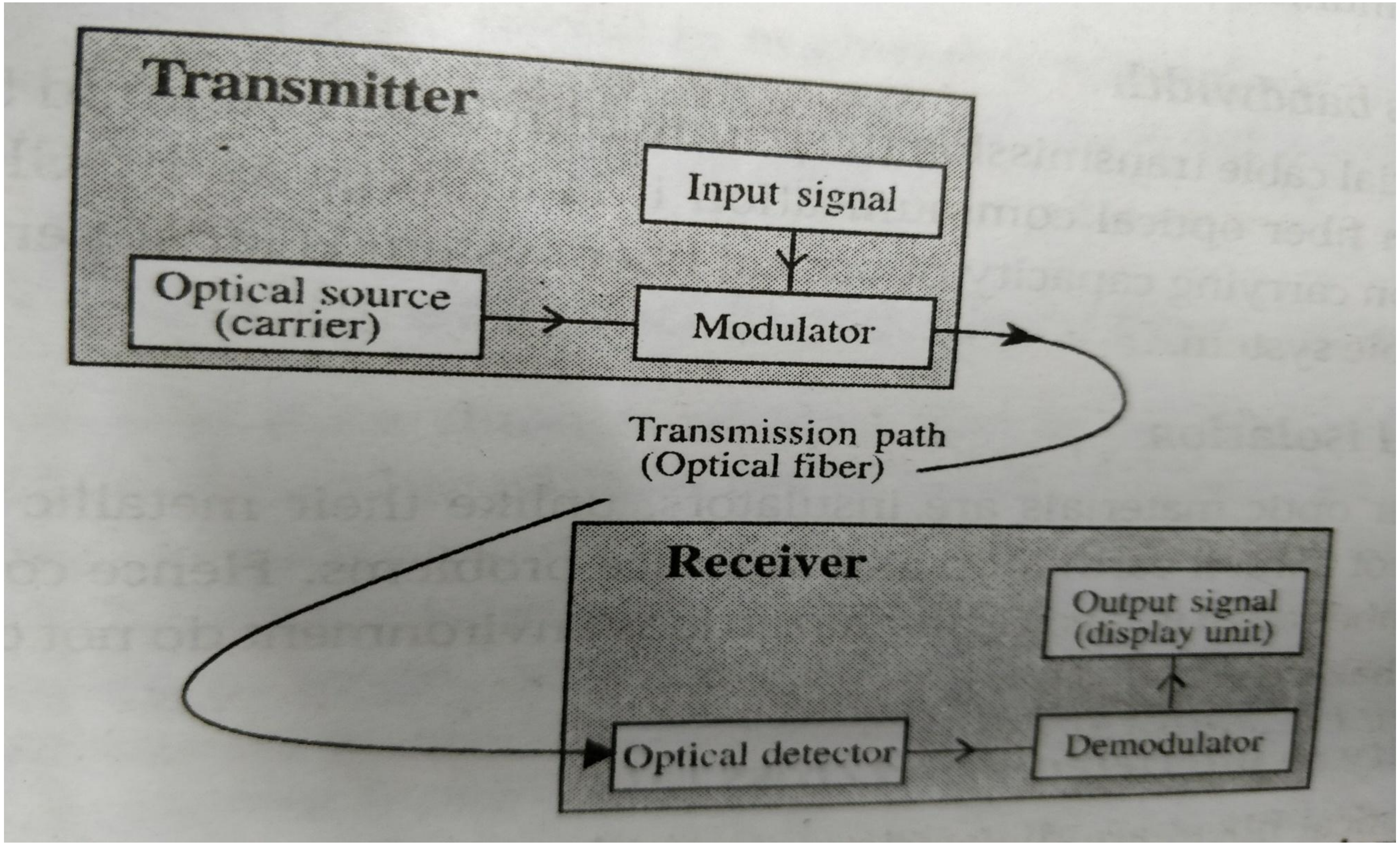
Optical fiber communication system

- Fiber optic communication system comprises of:

1. Transmitter
2. Receiver

- Transmitter consists of light source and input signal modulator.
- Receiver consists of optical detector, signal demodulator and output signal display unit such as CRO.
- Optical fiber acts as transmission path. It carries the modulated output light signal from the transmitter to the receiver.

Optical fiber communication system



Optical fiber communication system

- Information that is to be transmitted is first converted into an optical signal from an electrical signal
- The signal is then modulated using a optical source (carrier) by a modulator. The carrier wave is generated using a LED or Laser diode.
- The carrier source output into the fiber is represented by a single pulse.
- Optical fiber carriers the pulse.
- In the fiber the pulse is attenuated and distorted and hence repeaters are used to regenerate the signal.

Optical fiber communication system

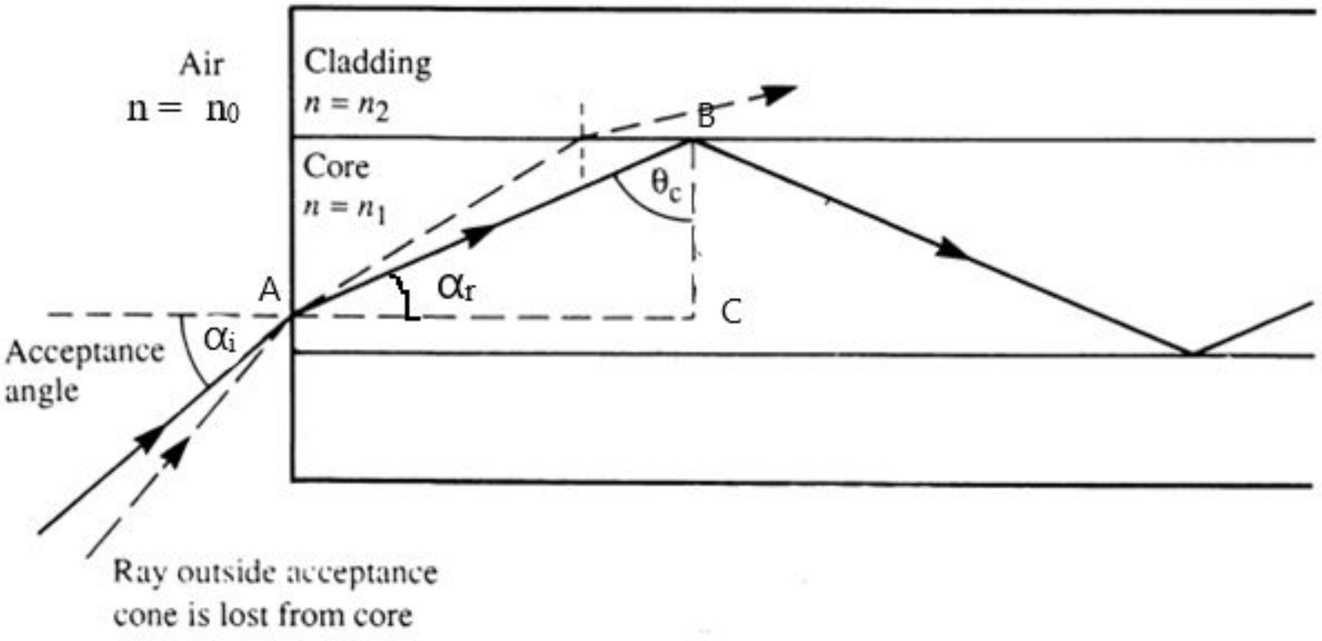
- At the receiver the optical signal is converted to electrical signal using a PIN diode.
- The signal is then demodulated and the original information is obtained.
- Couplers are used to couple the modulated light signal to be transmitted with the fiber.
- Connectors are used to increase the length of the fiber.
- Repeaters are used to reshape, retime and retransmit the signal.

Comparison of Optical fiber and conventional cables

- Large bandwidth: Optical fiber BW = 10^{15} GHz, metallic wires = 500 MHz
- Electric isolation: Optical fibers are insulators where as metallic wires are conductors. Hence optical fibers can be laid even in electrically hazardous environment.
- Optical fibers are immune to EM interference since in optical fibers information is carried by photons which are neutral and cannot be disturbed by high voltage fields.
- No cross talk in optical fibers since it works on the principle of total internal reflection.
- Small size and weight.
- Low transmission loss: The transmission loss per unit length of an optical fiber is about 4 dB/km. Hence for Optical fibers repeaters are spaced at a distance of 100 km where as for copper cables it is at a distance of 2 km.
- Low cost: Optical fibers are made of silica which is abundant on earth.

Acceptance angle

- Acceptance Angle: The maximum angle of incidence to the axis of optical fiber at which the light ray may enter the fiber so that it can be propagated through TIR.



Acceptance angle

- The light is launched from a medium of refractive index n_0 (n_0 = 1 for air) into core of refractive index $n_{1.}$
- The ray enters the fiber from air medium at an angle of incidence of α_i at the point A. The angle of refraction at A is α_r .
- This ray undergoes total internal reflection at B (core-cladding interface) at an angle θ. The minimum angle for TIR is $\theta = \theta_c$ (critical angle).

Acceptance angle

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Acceptance angle

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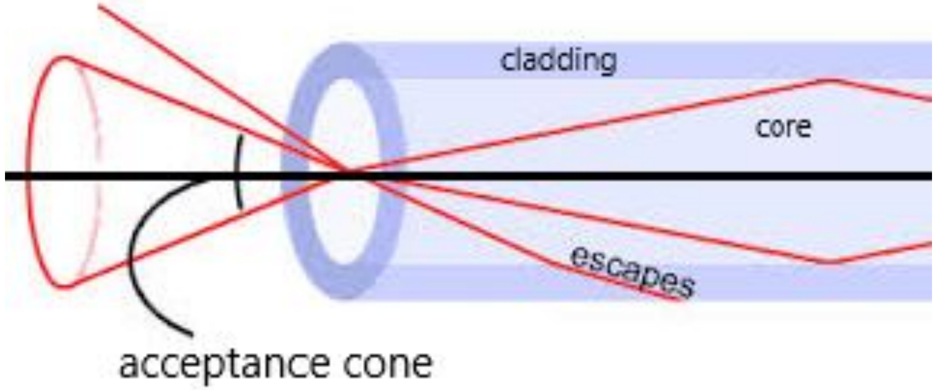
Acceptance angle

- This maximum angle is called acceptance angle or acceptance cone half angle.
- Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection.



Numerical aperture

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Numerical aperture

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Types of Optical Fiber

- Based on mode of propagation, fibers are classified in to

  1. Single mode propagation and 2. Multi mode propagation

- Based on variation in the core refractive index (n_1), optical fibers are divided in to two types

  1. Step index fiber and 2. Graded index fiber

- Based on material, fibers are classified as

  1. Plastic and 2. Glass

Types of Optical Fiber

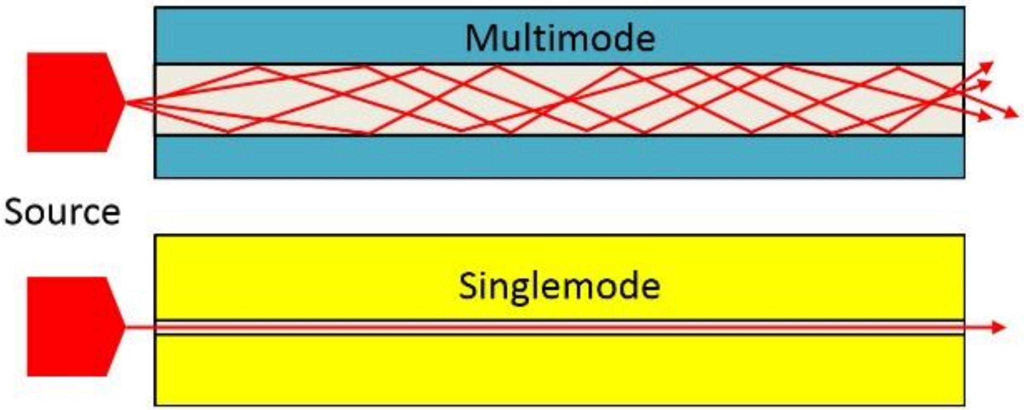
- Based on mode of propagation, fibers are classified in to

1. Single mode propagation and 2. Multi mode propagation

Modes: Light launched in to the fiber within the acceptance cone, propagates through it by total internal reflection. But only light which travel through the fiber in a particular direction are allowed, which satisfy the condition of constructive interference. The light rays travelling in these specified directions are called modes.

Single mode and Multimode Fiber

- If the thickness of the fiber is small that it supports only one mode then the fiber is called monomode or single mode fiber.
- If the fiber supports more than one mode then it is called multimode fiber.



Single mode and Multimode Fiber

Single mode	Multimode
• Has a small core diameter (2 to 8 µm) and can support only one mode of propagation.	• Has a large core diameter (about 50 µm) and can support a number of modes.
• Launching of light in to the fiber is difficult.	• Launching of light in to the fiber is easy.
• Fiber can carry information to longer distance since dispersion of signal is less.	• Fiber can carry information to short distance only since dispersion of signal is more.

Step index and Graded index Fiber

- Step index fiber

In these fibers the refractive index of core is uniform and is slightly more than that of the cladding.

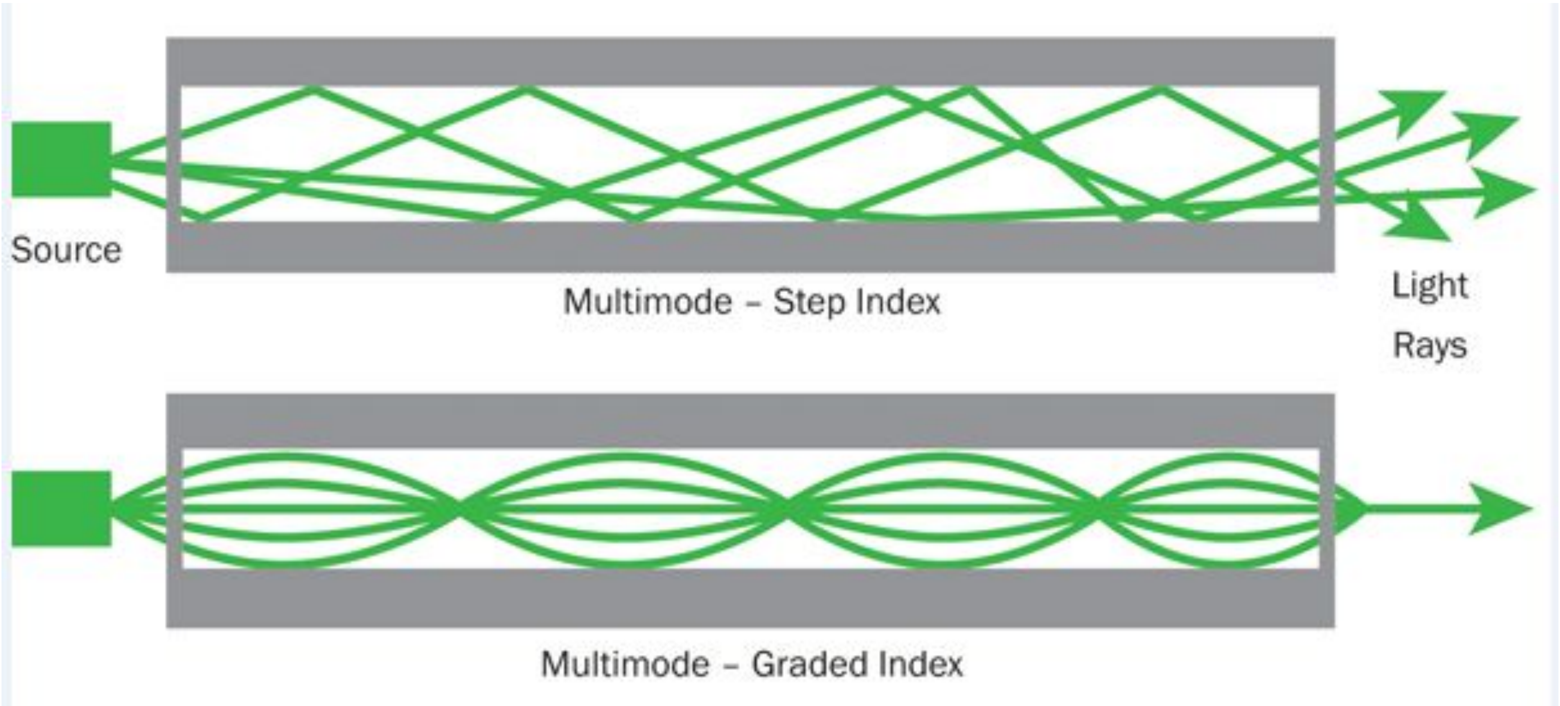
Intermodal dispersion or pulse broadening occurs.

- Graded index fiber

In graded index multimode fiber the refractive index of the core varies radially. It has maximum refractive index at its center which gradually decreases with increase of radius. At the core – cladding interface the refractive index of core and cladding are the same.

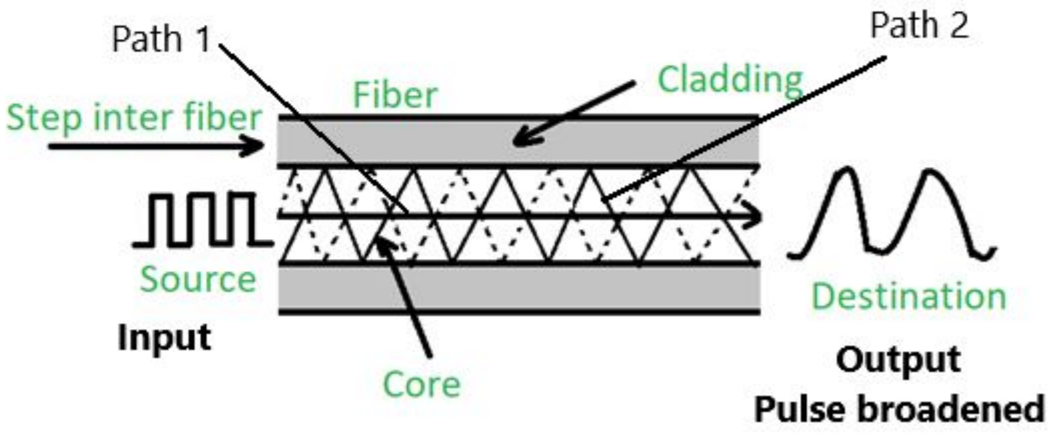
Pulse broadening is overcome in graded index fiber.

Step index and Graded index Fiber



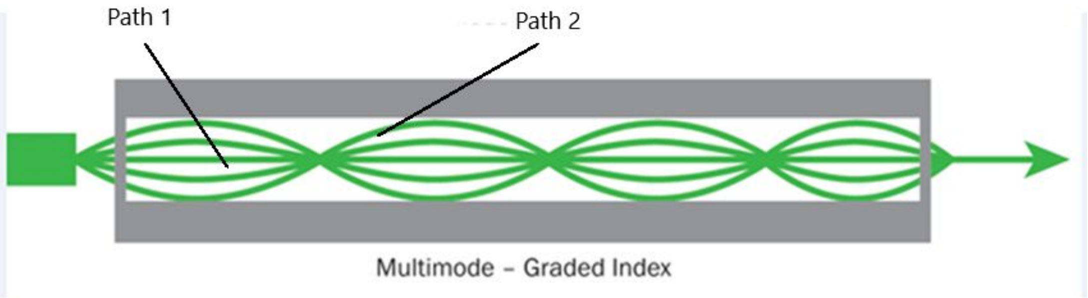
Transmission of signal in step index fiber

- Let a pulse travel through the step index multimode fiber.
- The pulsed signal travels in different paths(path 1 and path 2).
- At the receiving end the ray travelling along path 1 reach first while the ray travelling along path 2 reaches after some time delay.
- Hence the pulsed signal received at the destination is broadened and is called intermodal dispersion.
- Intermodel dispersion can be overcome by using graded index fiber.



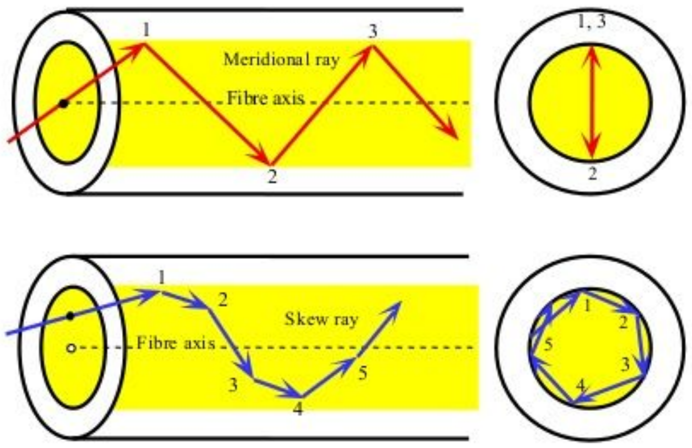
Transmission of signal in graded index fiber

- Let a signal pulse travel in two different paths 1 and 2.
- The Pulse travelling along path 1, travels less distance but in a medium of higher refractive index.
- The pulse travelling along path 2, travels more distance but in a medium of lesser refractive index.
- Hence both the pulse reach the destination at the same time and pulse broadening is overcome.



Meridional ray and skew ray

- A ray that propagates through the core of a fiber undergoing total internal reflection is called meridional ray. A meridional ray always crosses the fiber axis.
- Skew rays describe angular helical path as they travel along the fiber. A skew ray does not cross the fiber axis.



(a) A meridional ray always crosses the fiber axis.

(b) A skew ray does not have to cross the fiber axis. It zigzags around the fiber axis.

Difference between step index and Graded index fiber

Step Index	Graded Index
1. RI of core is uniform throughout except at one stage.	1. Refractive index varies gradually with radial distance.
2. Single & multimode propagations exist.	2. It is a multi mode fiber.
3. Used for short distance applications.	3. Used for long distance applications.
4. Attenuation losses are of the order 100 dB/km.	4. Attenuation losses are of the order 10 dB/km.
5. Meridional rays propagation takes place.	5. Skew rays propagation takes place.
6. Easy to manufacture.	6. Difficult to manufacture.

Material of Fiber

- Material of fiber: Plastic or glass fiber.
- Plastic fiber: Plastic fibers are made either entirely from plastic(core and cladding) or with silica core and plastic cladding.
- Full plastic fiber suffer from high attenuation.
- Plastic fibers are used for short distance(about 100 m), low bandwidth systems in the wavelength range 600 – 700 mm.
- Eg. Polystyrene, it can withstand temperature of about 70^0 C

Material of Fiber

- Glass fibers are made of silica.
- They are used for long distance communication and can withstand temperature of about 400^0 C
- Chemical resistance is high in glass fibers
- Attenuation is less.

Losses in optical fibers

- When light signal propagates through a fiber, it suffers loss of amplitude and change in shape. The loss of amplitude is called as attenuation and the change in shape as distortion.
- Attenuation: The loss of optical power as light travels down a fiber is known as attenuation.
- **Attenuation:** It is the ratio of input optical power (P_i) in to the fiber to the power of light coming out at the output end (P_o).
- Attenuation coefficient is given as, $\alpha = 10/L \log_{10} P_i / P_o$ dB/km.
- Attenuation is mainly due to

1. Absorption 2. Scattering 3. Bending

Losses in optical fibers

1. Absorption Losses:

In glass fibers, three different absorptions take place.

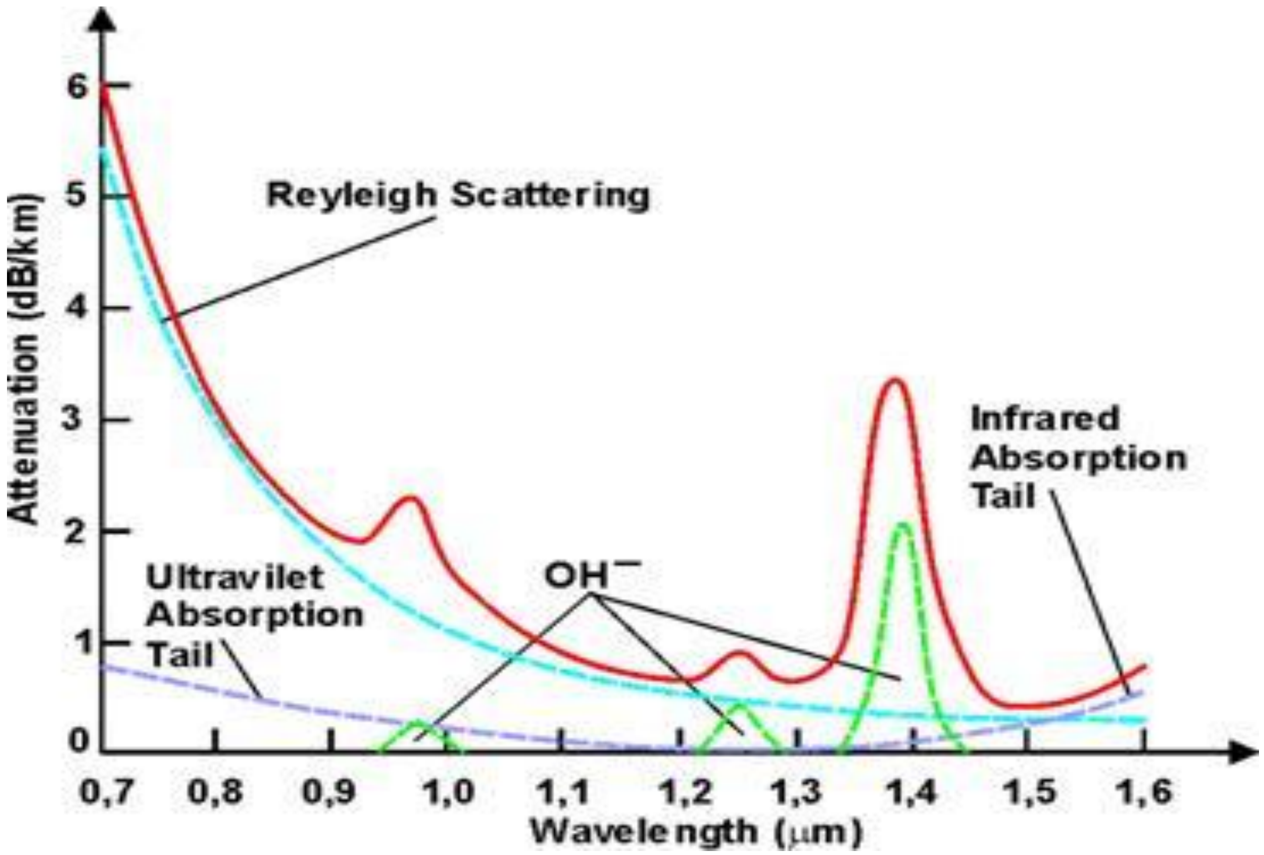
- **Ultra violet absorption**: Absorption of UV radiation around 0.14μm results in the ionization of valence electrons.
- **Infrared absorption:** Absorption of IR photons by atoms within the glass molecules causes heating. This produces absorption peak at 8 μm, also minor peaks at 3.2, 3.8 and 4.4 μm.
- **Ion resonance/OH^- absorption:** The OH^- ions of water, trapped during manufacturing causes absorption at 0.95, 1.25 and 1.39 μm.

Losses in optical fibers

2. Scattering Losses:

- The molten glass, when it is converted in to thin fiber under proper tension creates sub microscopic variations in the density of glass. Dopents(used to change the R.I.) cause inhomogeneity to be present and act as scattering centers in the fiber. This leads to losses.
- This is also known as Rayleigh scattering and depends on the wavelength of light. Scattering losses are inversely proportional to fourth power of λ.(λ^4)
- Wavelength below 800 nm have high Rayleigh scattering losses and wavelength above 1700 nm have high losses due to IR absorption.

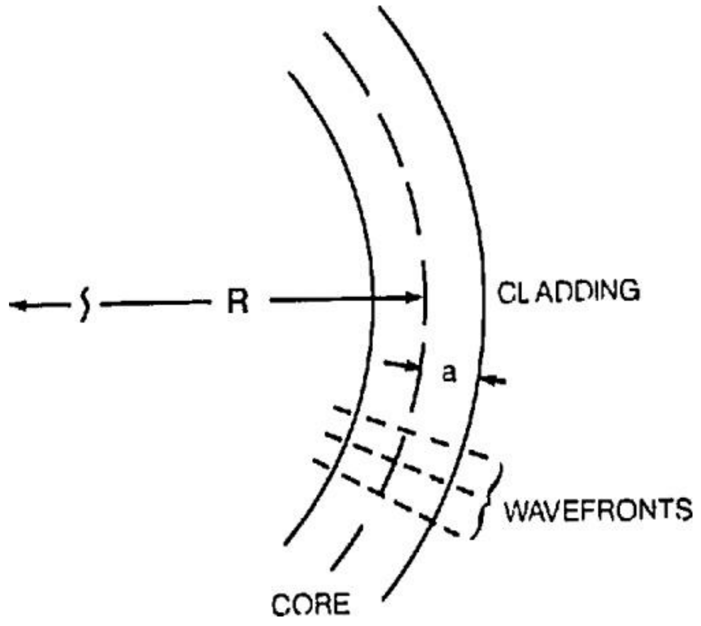
Losses in optical fibers



Losses in optical fibers

3. Bending Losses:

- Wavefront travels perpendicular to the direction of propagation. For this the part of the mode outside the bend has to travel faster than that on the inside.
- But according to Einstein's theory of relativity, in a single wave front one part should not travel with higher velocity than the other part.
- So the part of wave front travelling in cladding medium lost in the form of radiation leads to bending losses.



Losses in optical fibers

- Micro bend is a small scale distortion. It indicates pressure on the fiber.
- Macro bending is a large scale bend. When a fiber is bent through a large angle it undergoes a strain. The bending strain will affect the R.I. and critical angle of the fiber in that area and leads to losses.

Distortion

- The light pulse transmitted through a fiber are of a given width, amplitude and interval. These light pulses broaden and spread into a wider time interval because of the different times taken by different rays propagating through the fiber. This phenomenon is known as distortion or pulse dispersion. It is expressed in units of ns/Km.

Numerical

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