MODULE 3

LASERS AND OPTICAL FIBERS

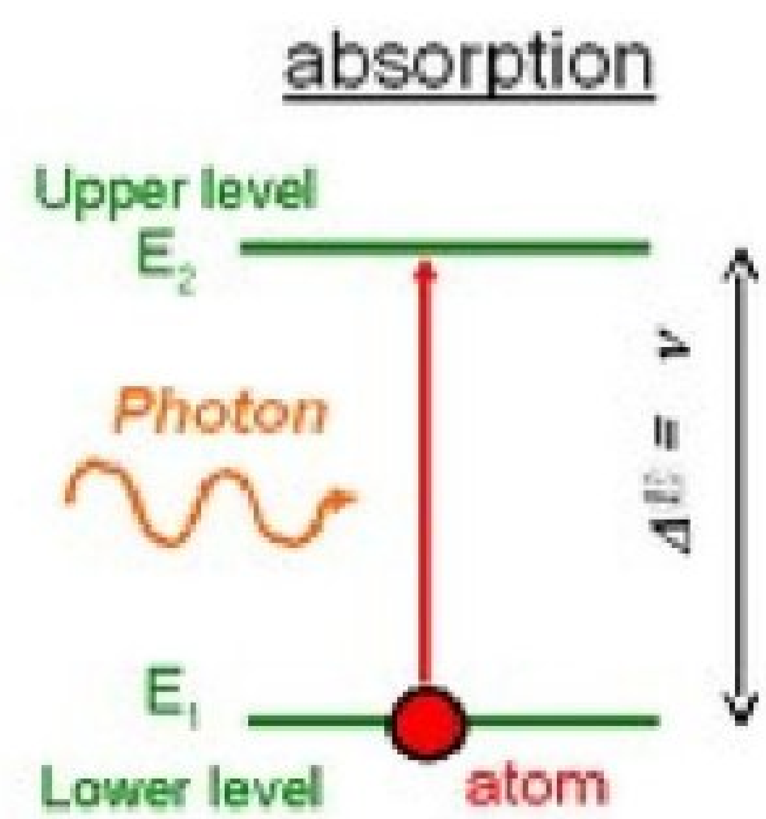
Introduction

Laser is the acronym of light amplification by the stimulated emission of radiation. The characteristics of laser beam are directionality, monochramaticicity, high degree of coherence, highly intensified radiation and focussability. It finds important applications in many areas like holography, spatial frequency filtering and communication.The basic principle involved in lasing action is the phenomenon of stimulated emission which was predicted by Albert Einstein in the year 1917.

Interaction of Radiation and Matter

1. Induced Absorption

. An atom in a lower level absorbs a photon of frequency hν and moves to an upper level. This kind of absorption is called as induced absorption.



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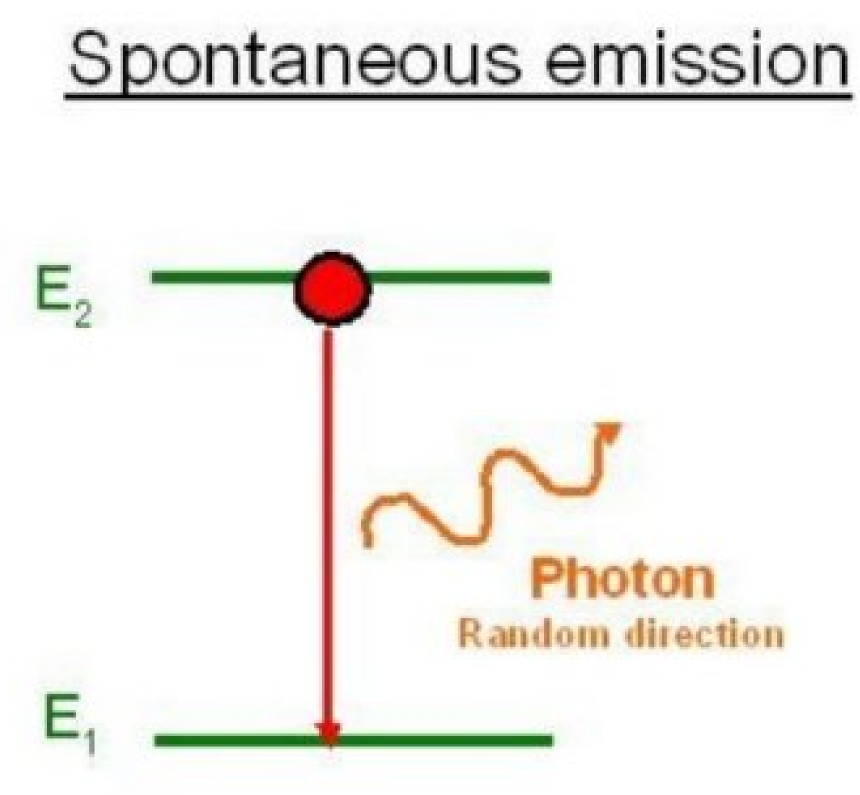
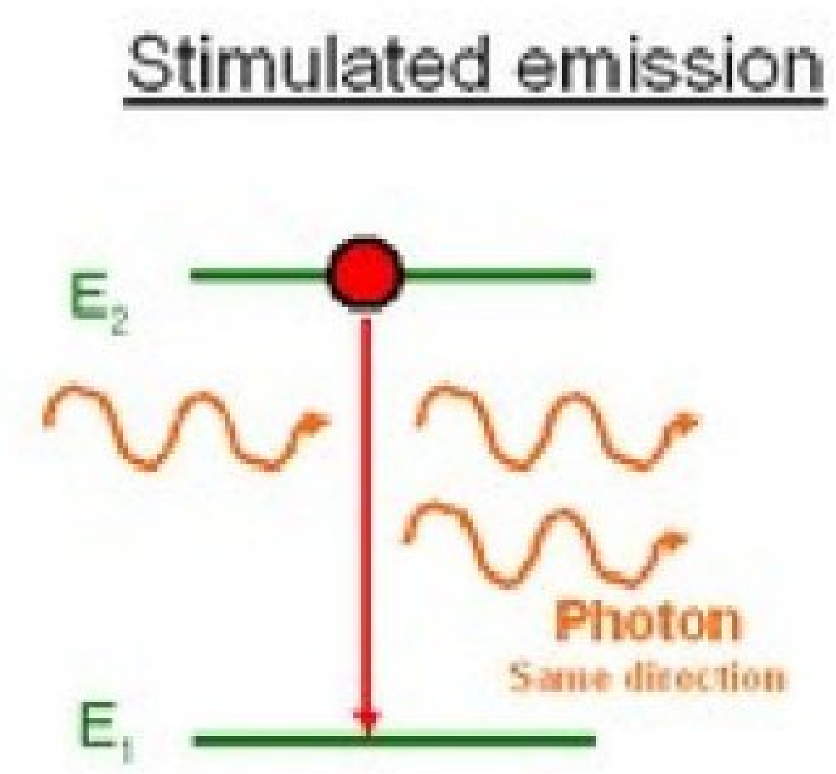
2. Spontaneous Emission

An atom in an upper level can decay spontaneously to the lower level and emit a photon of frequency hν, if the transition between E_2 and E_1 is radiative. This type of emission is called as spontaneous emission.The photon emitted in this phenomenon has a random direction and phase.

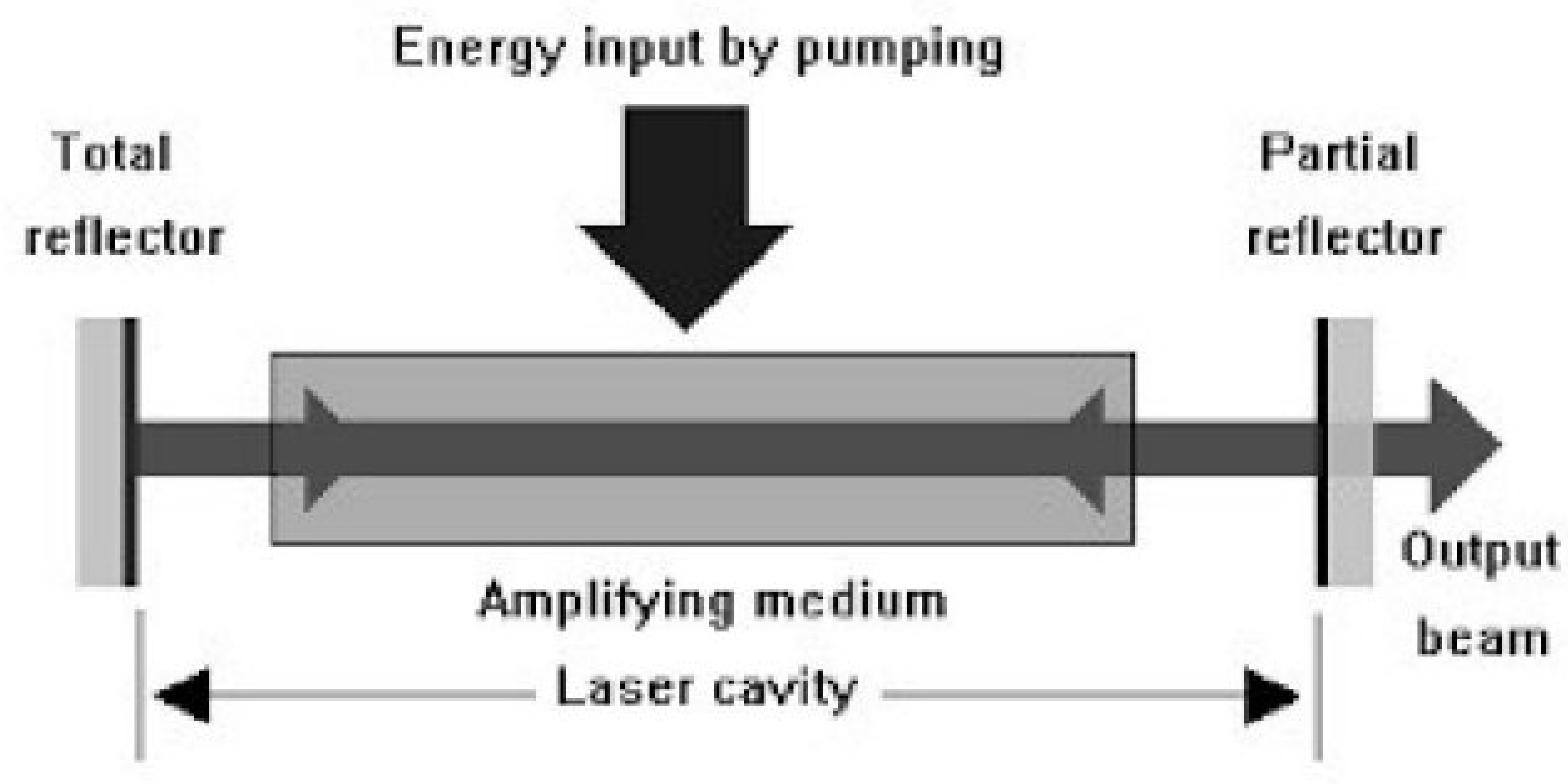


3. Stimulated Emission

An incident photon causes an upper level atom to decay, emitting a stimulated photon whose properties are identical to those of the incident photon. The term "stimulated" underlines the fact that this kind of radiation only occurs if an incident photon is present. The amplification arises due to the similarities between the incident and emitted photons.



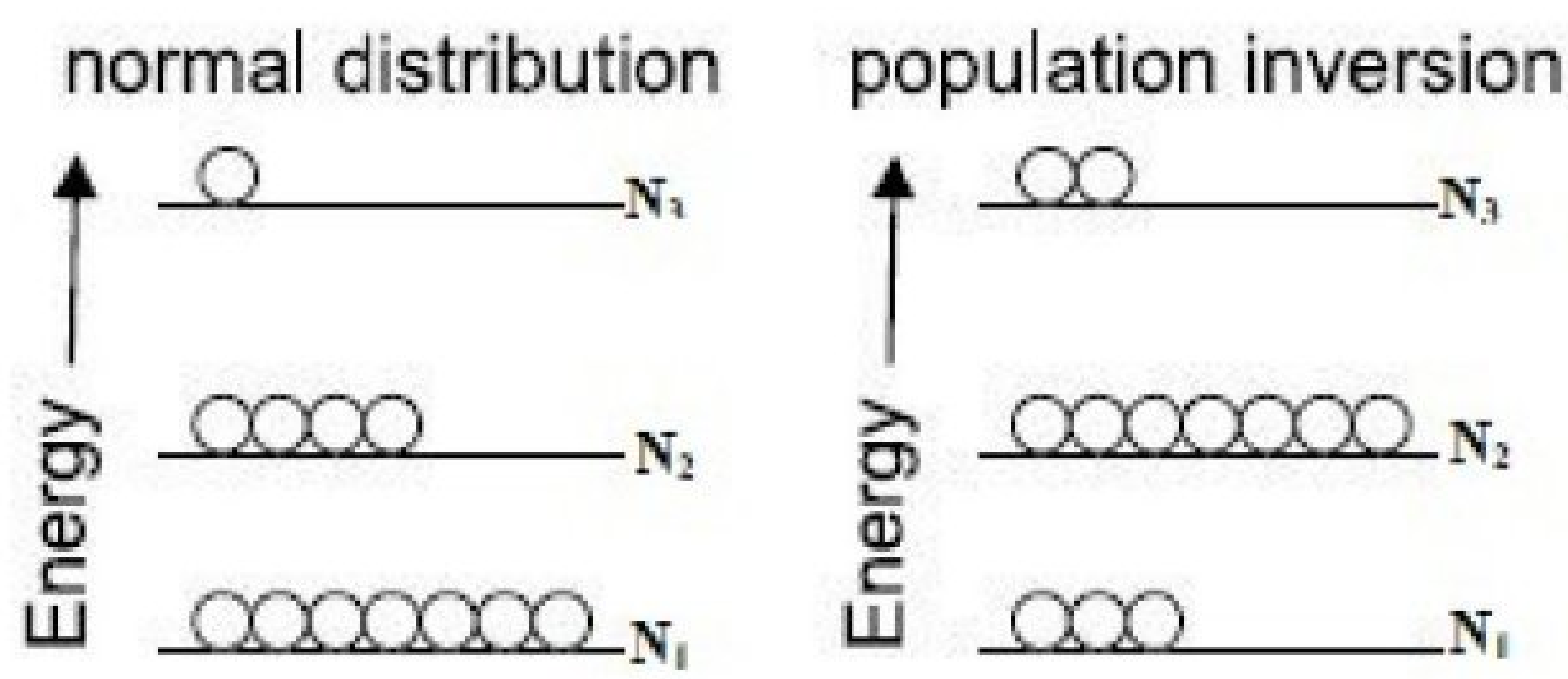
Requisites of a Laser System



Laser requires three components for operation. First an energy source that will raise the system to an excited state. Next there is an active medium which when excited achieves population inversion and subsequently lases. The active medium may be solid, liquid or gas. Third there is a an optical cavity consisting of two mirrors facing each other. The active medium is enclosed by this cavity, one of the mirrors is fully reflecting and the other mirror is partially transparent to let some of the radiation to pass through. The optical cavity is made use of, to make stimulated emission possible in more number of atoms in the active medium. This naturally increases the intensity of the laser beam.

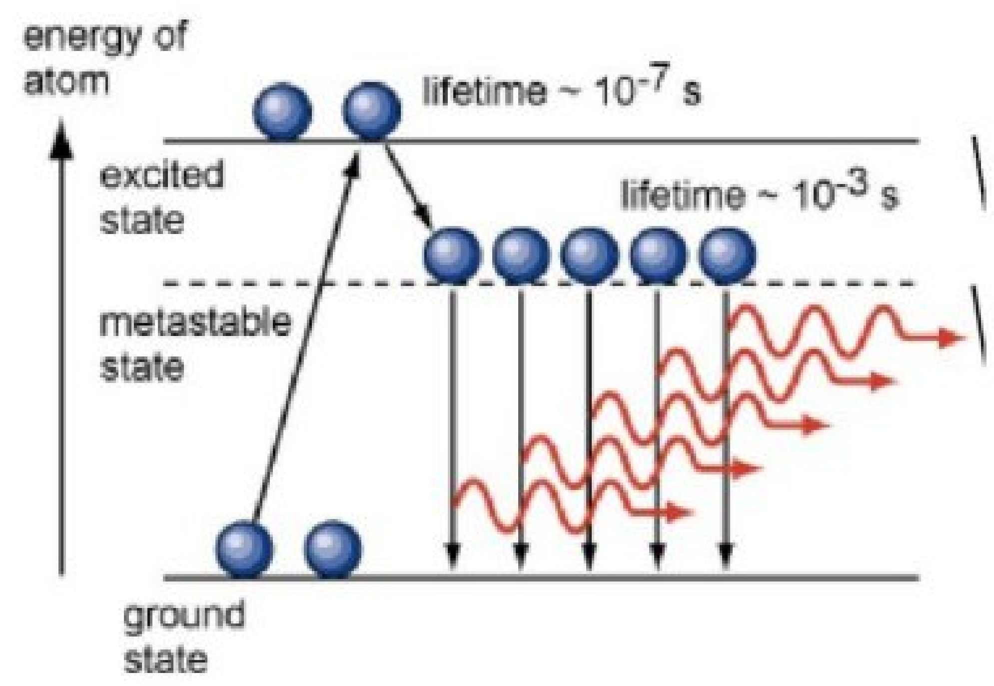
Condition for Laser Action

1. Population Inversion



Whenever an electromagnetic radiation is incident to th system, there will be net absorption for normal distribution, then the system is said to be absorptive rather than emissive since $N_1 > N_2 > N_3$. For the laser action to occur it is neccessary that total emission should lead over absorption, this is possible only if the population of lower energy state is less than the population of higher energy state *i.e,* $N_2 > N_1 > N_3$. This condition is called as population inversion .

2. Metastable State



The energy state whose lifetime is greater than the excited state that is of the order of $10^{-3}s$ is called as meta stable state.

Expression for Einstein's co-efficient and the Energy Density of Incident Radiation

Let the system be at thermal equillibrium which means that the total energy of the system remains unchanged inspite of the interaction that takes place inside the system. Under such condition, the number of photons absorbed by the system per second is equal to the number of photons it emits per second by both stimulated and spontaneous emission processes,

$\therefore$ At thermal equillibrium,

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Rate of Ind. absorption= Rate of spont. emission + Rate of stim. emission

$$\frac{dN_{12}}{dt}/ind.Abs = \frac{dN_{21}}{dt}/spon.emis + \frac{dN_{21}}{dt}/stim.emis$$

$$B_{12}N_1E_\nu = A_{21}N_2 + B_{21}N_2E_\nu \tag{1}$$

$$B_{12}N_1E_\nu - B_{21}N_2E_\nu = A_{21}N_2$$

$$E_\nu(B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$E_\nu = \frac{A_{21}N_2}{(B_{12}N_1 - B_{21}N_2)}$$

$$E_\nu = \frac{A_{21}}{B_{21}}\frac{N_2}{\left[\frac{B_{12}}{B_{21}}.N_1 - N_2\right]}$$

$$E_\nu = \frac{A_{21}}{B_{21}}.\frac{1}{\left[\frac{B_{12}}{B_{21}}.\frac{N_1}{N_2} - 1\right]} \tag{2}$$

$$From\ Boltzmann's\ law,\ we\ have$$

$$N_1 = e^{-E_1/kT}\ , N_2 = e^{-E_2/kT}$$

$$\implies \frac{N_1}{N_2} = e^{\frac{(E_2-E_1)}{kT}}, \frac{N_1}{N_2} = e^{\frac{\triangle E}{kT}}$$

$$\frac{N_1}{N_2} = e^{\frac{h\nu}{kT}} \tag{3}$$

substituting equation (3) in equation(2), we get

$$E_\nu = \frac{A_{21}}{B_{21}}.\frac{1}{\left[\frac{B_{12}}{B_{21}}.e^{\frac{h\nu}{kt}} - 1\right]} \tag{4}$$

From Planck's law of radiation, we have

$$E_\nu = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{e^{h\nu/kt} - 1}\right] \tag{5}$$

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comparing equation(5) and equation (4)

$$\implies \frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \tag{6}$$

$$B_{21} = B_{12} = 1 \tag{7}$$

Equation (6) and (7) represents the Einsteins co-efficients.

For a system to be at thermal equillibrium

$$B_{21} = B_{12} = B \ and \ A_{21} = A$$

Substituting for B_{21}, B_{12}, A_{21} in equation (4), we get

$$\boxed{E_\nu = \frac{A}{B}\left[\frac{1}{e^{h\nu/kT} - 1}\right]} \tag{8}$$

Equation (8) represents the expression for energy density of incident radiation for a system to be at thermal equillibrium.

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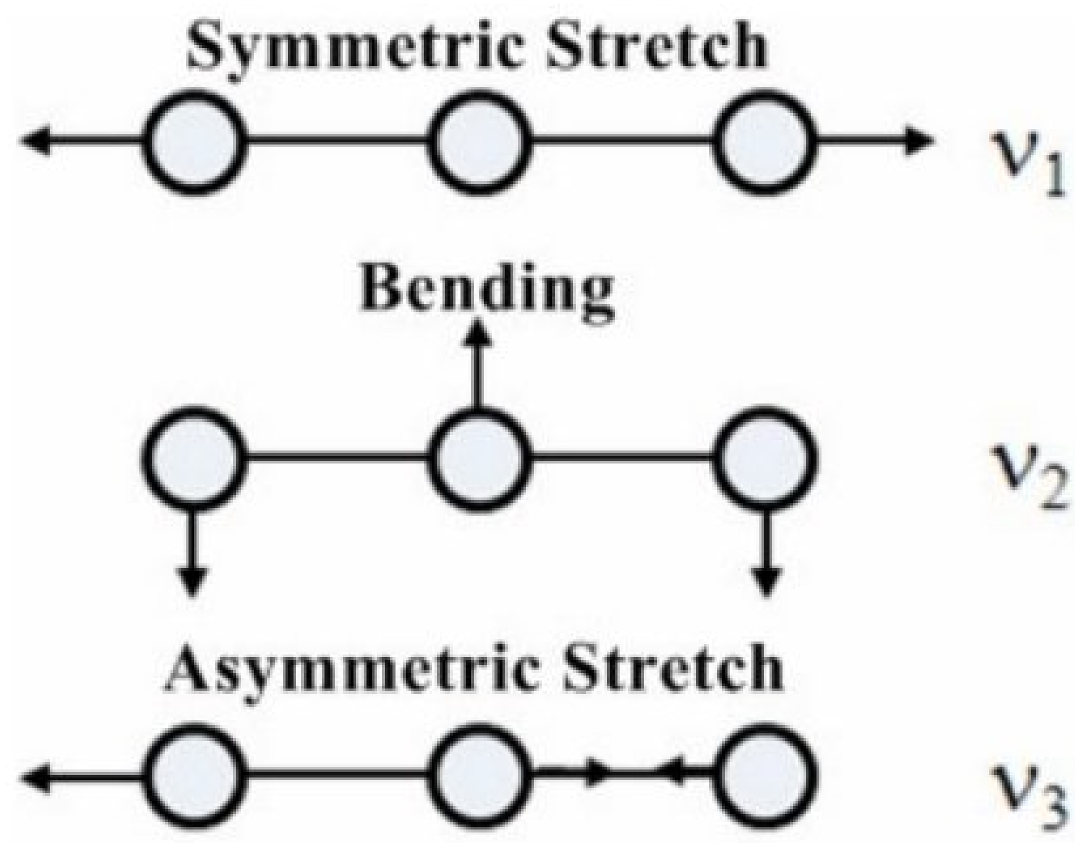
Carbon-dioxide Laser

Vibrational Modes of Carbon-dioxide Laser.



1. Symmetric Stretching Mode

The oxygen atoms in this mode oscillate along the molecular axis either approaching towards or departing away from each other whereas the carbon atom remains stationary.The molecule posses intermediate energy in this state.

2. Bending Mode

In this mode all the three atoms oscillate normal to the molecular axis. During vibration the two oxygen atom pull together in one direction whereas the carbon atom is displaced in another direction.The energy of the molecule in this state will be least.

3. Asymmetric Stretching Mode

In this mode all the three atoms oscillate along the molecular axis where the oxygen atoms move in one direction, while the carbon atom moves in opposite direction and vice versa. The molecule posses highest energy in this state.

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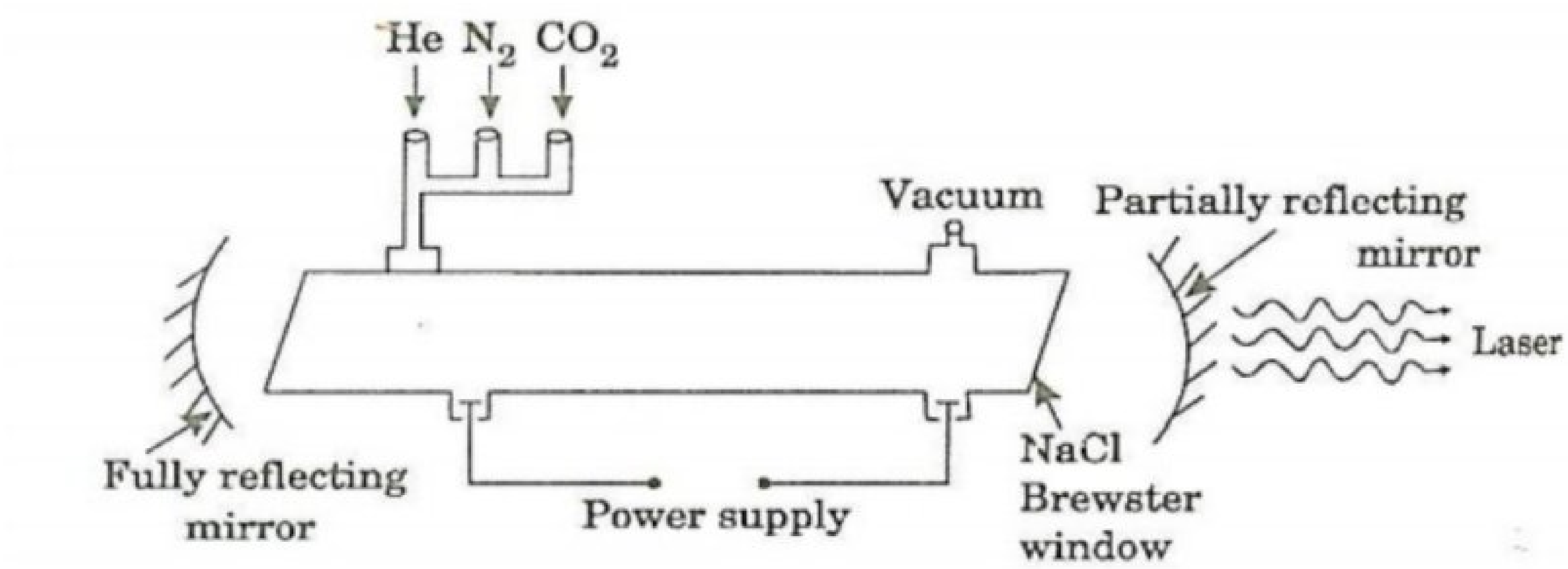
Construction:



- The active or gain medium consists of a mixture of CO_2, N_2 and He gases in the ratio of 1:2:3.
- The ratio of pressures of CO_2, N_2 and He is 1:4:5 and the optimum value of pressure-tube diameter product is around 33 torr mm.
- The tube is provided with two Brewster angle windows which gives the polarized output.
- The rear mirrors acts as optical feedback resonators providing the necessary feedback for emitted photons.
- The nitrogen molecules are used for excitation of CO_2 molecules and addition of He gas mixture enhances the efficiency.

Working:

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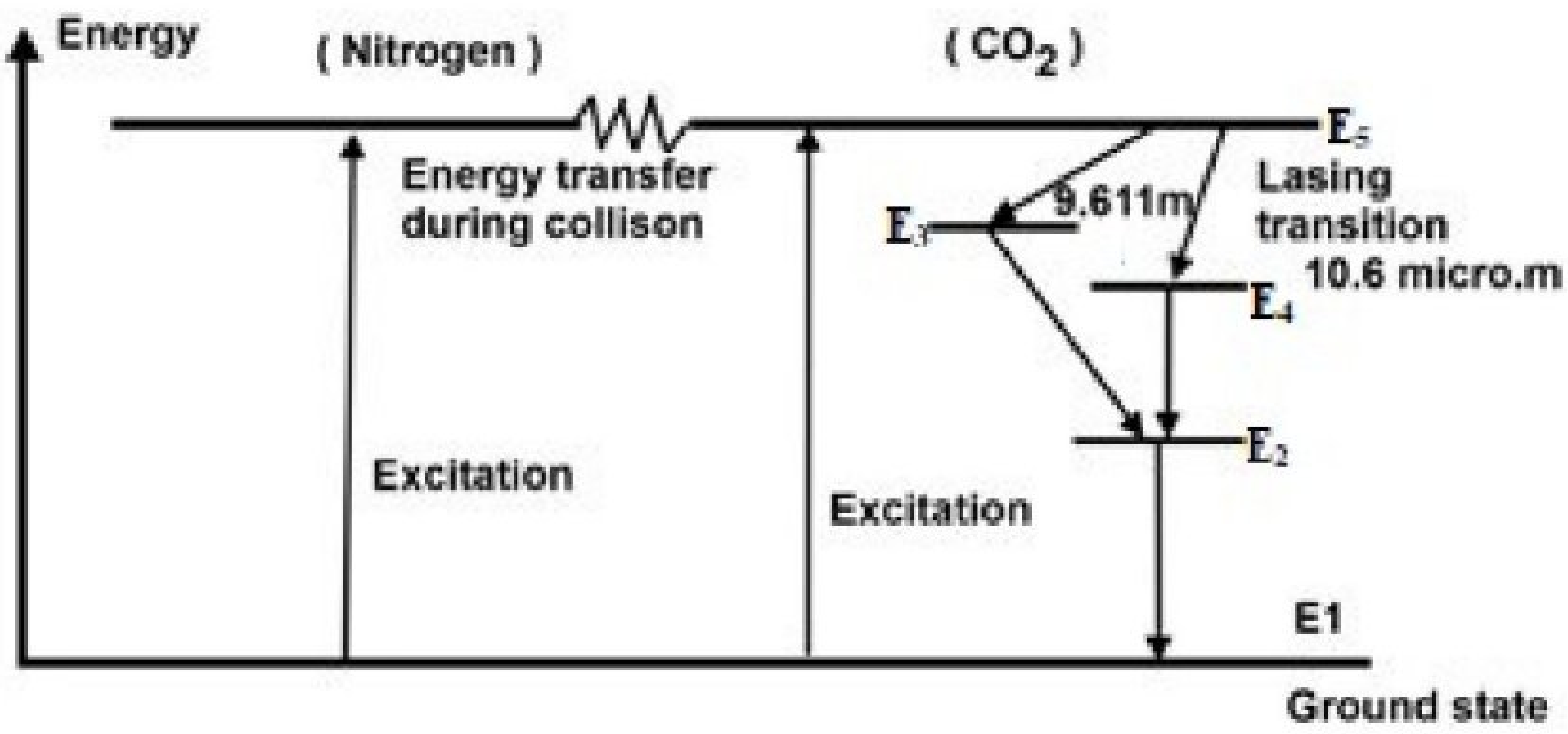

- The vibrational energy levels for N_2 molecule are metastable, this helps in creating population inversion of CO_2 gas laser by means of resonant transfer of energy.
- When a high DC voltage is applied the N_2 *and* CO_2 molecules absorb energy due to electric discharge.
- Due to absorption of energy N_2 *and* CO_2 molecules are excited to higher energy states which are metastable levels with relatively longer lifetime.
- CO_2 molecules are raised to C_5 level by colliding with nitrogen molecules where the resonant transfer of energy takes place.With sufficient pumping the population inversion occurs between C_5 *and* C_4 levels.
- The transition occurs from C_5 *to* C_4 *and* C_5 *to* C_3 producing laser radiation of wavelength $10.6\mu m$ and $9.6\mu m$ respectively. Both emissions lying in the infrared region.
- Carbon-dioxide lasers are capable of producing very high output powers because of the high efficiency upto about 30 percent.
- CO_2 laser finds its applications in welding, drilling and cutting. Medical applications includes bloodless surgery and they are used to monitor pollution in the

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environment, they are used in remote sensing(LIDAR) systems and also in the field of communication due to their low attenuation.

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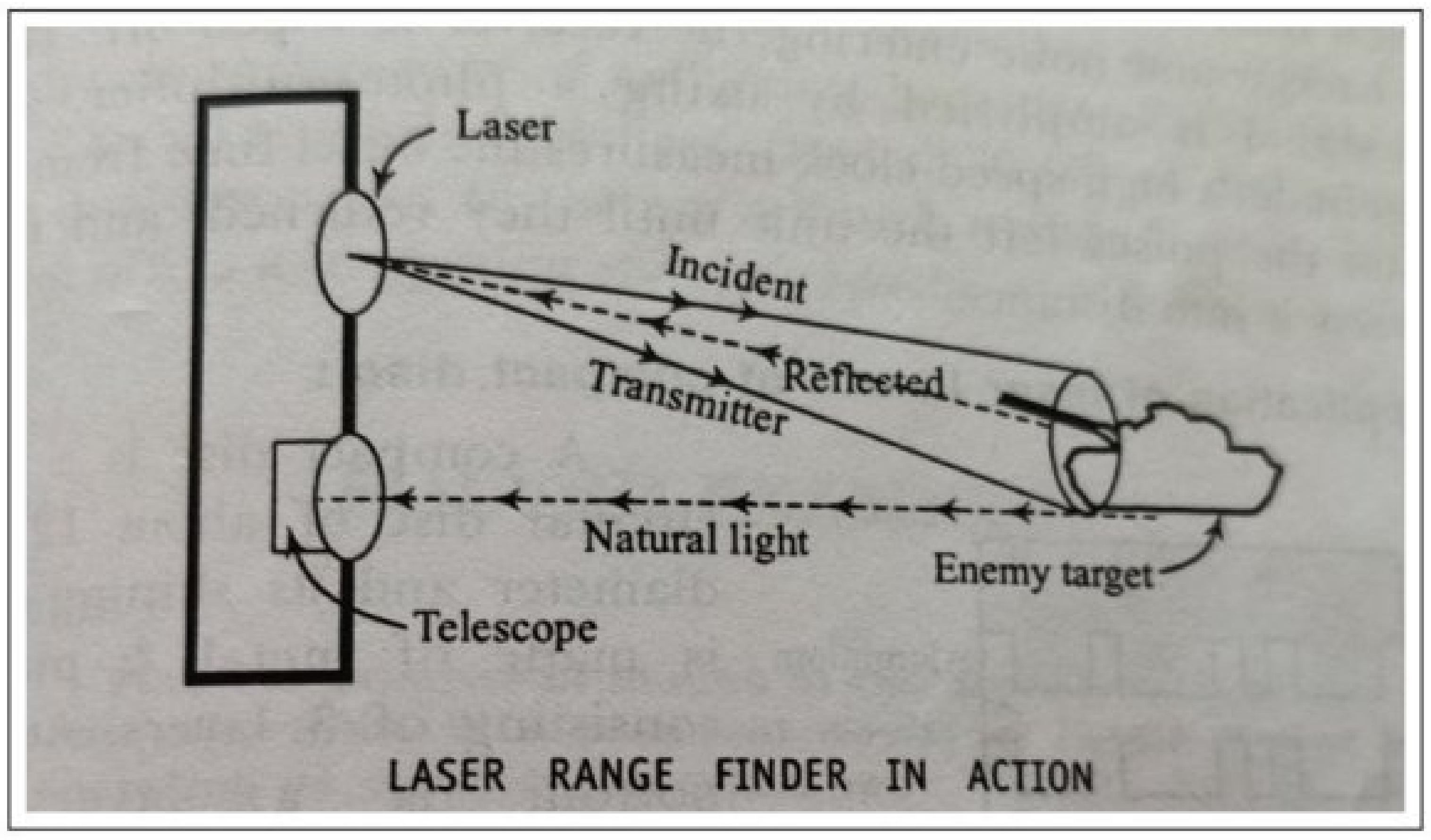
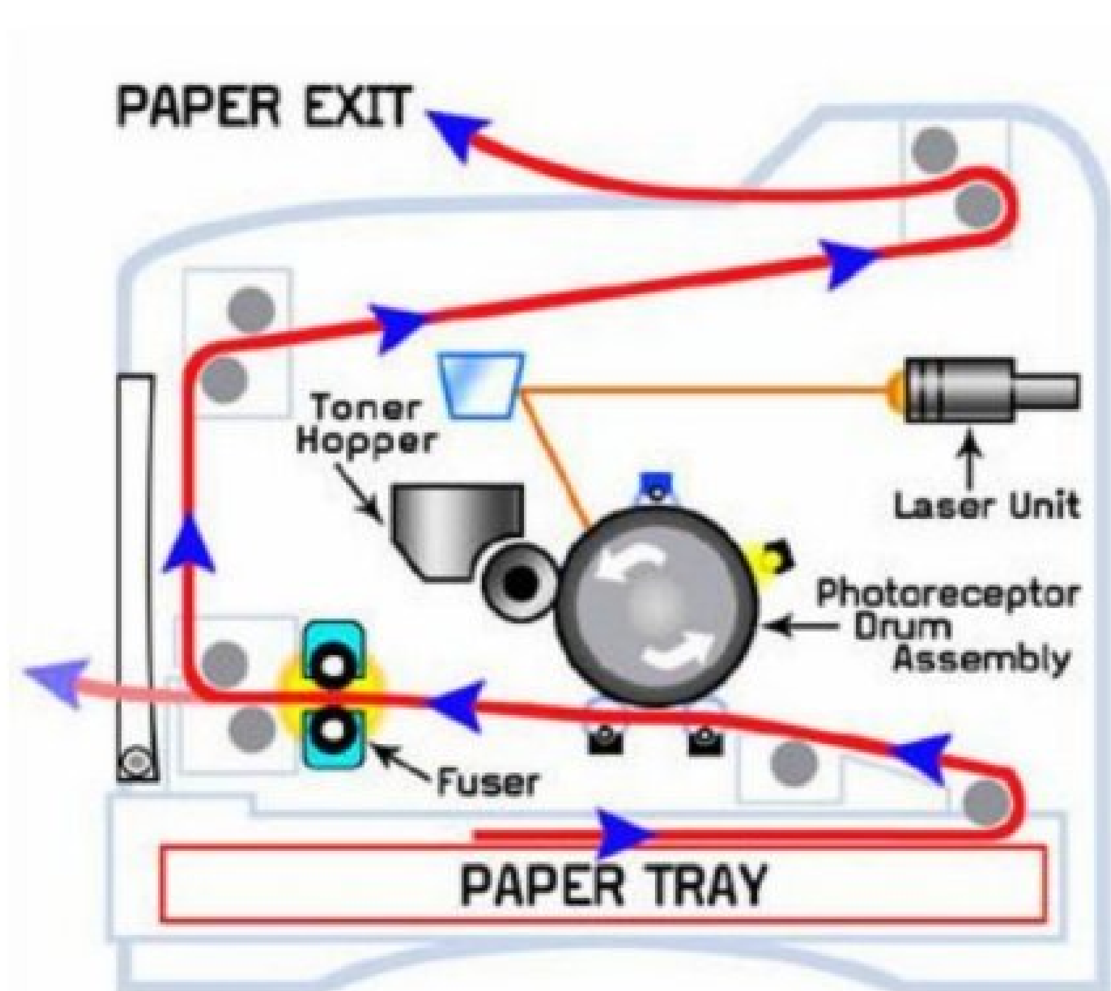
Applications of Laser

1. Laser as Range Finder



The principle behind the working of laser range finder is same as radar. During operation a high powered pulsed laser beam such as Nd-YAG laser is directed towards the enemy target from a transmitter, upon incidence the beam of narrow high peak pulses bounces from the surface of the target as a reflection. A part of reflected beam called echo is received as a signal by the receiver and the background noise entering the receiver is wiped off by the narrow band optical filter which is tuned to the frequency of laser light.Then the signal is amplified by using a photomultiplier. The exact time from the instant the pulses left the unit until they returned is measured by the rangefinders high speed clock and further the data obtained is converted into distance.

2. Laser printing



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1. A laser beam projects an image of the page to be on printed onto an electrically charged rotating photosensitive drum coated with selenium.

2. Photoconductivity allows charge to leak away from the areas which are exposed to light and the area gets positively charged.

3. Toner particles are then electrostatically picked up by the drum's charged areas which have been exposed to light.

4. The drum then prints the image onto paper by direct contact and heat, which fuses the ink to the paper.

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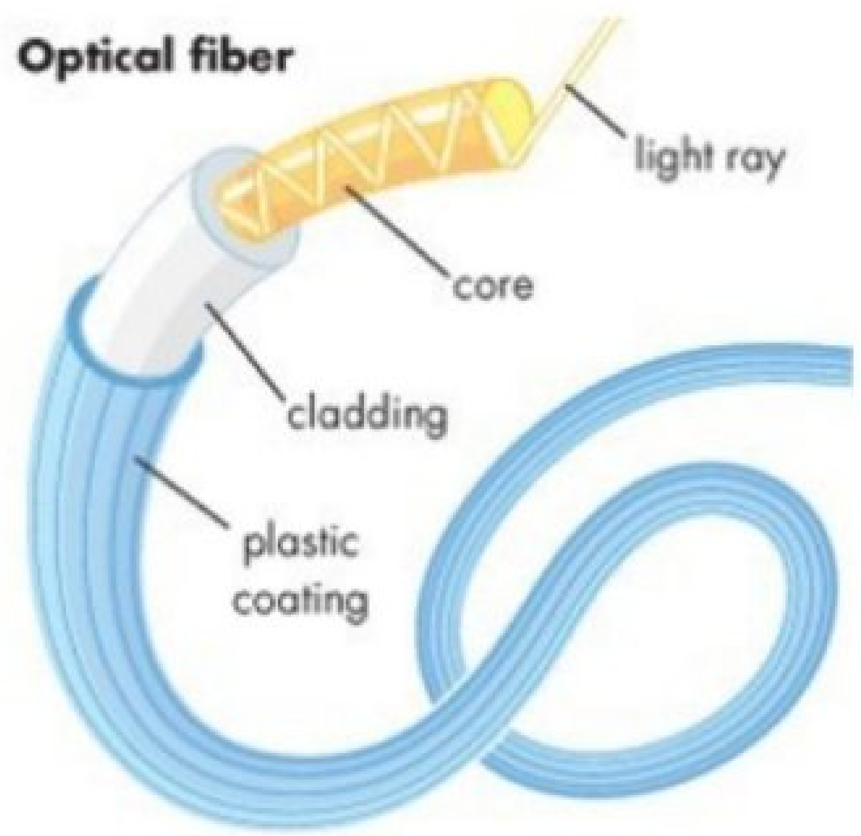
OPTICAL FIBERS

Structure of optical Fiber

Optical fiber consists of inner core and outer cladding where core is held with high refractive index in comparision with cladding and an outer polyurethane jacket to protect fiber from external damages.



Propagation Mechanism of Optical Fiber-Principle of Optical Fiber

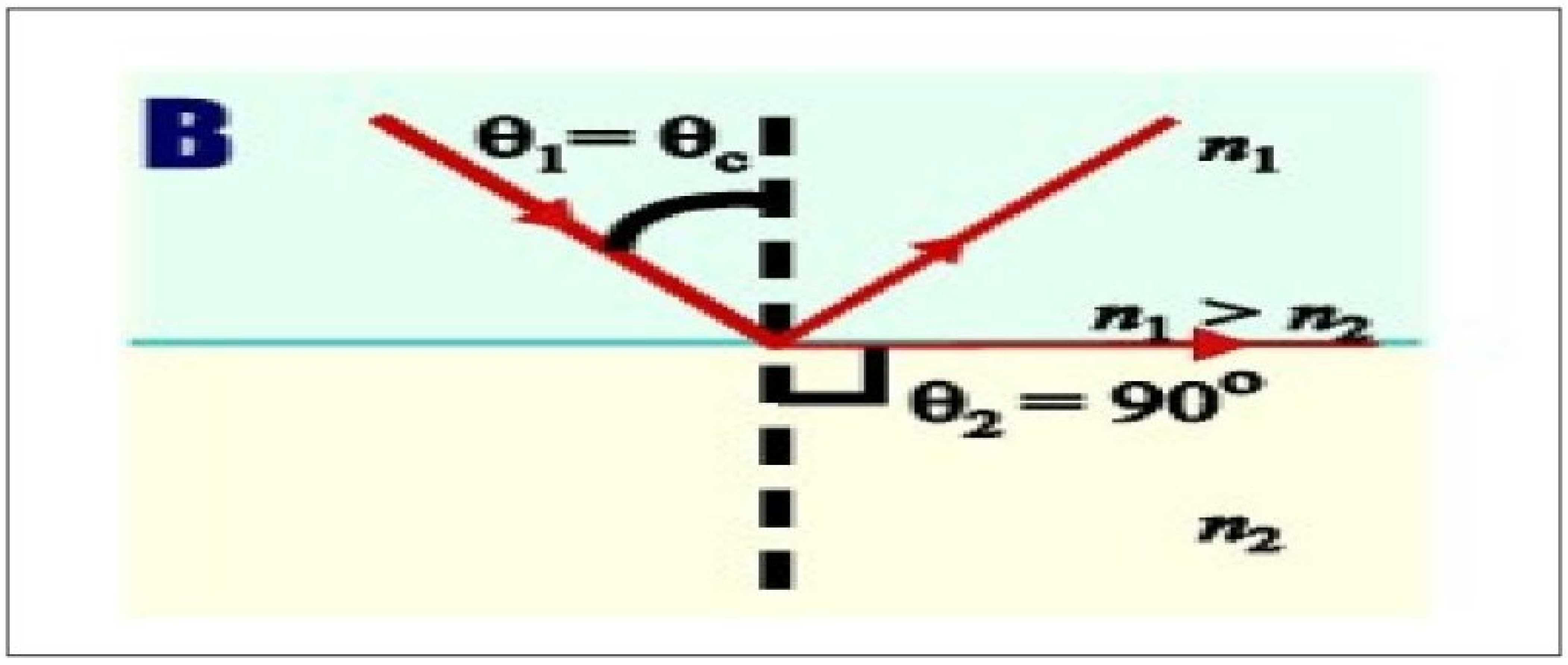


Figure 1: Total Internal Reflection

When a light ray propagates from denser medium to rarer medium it moves away from

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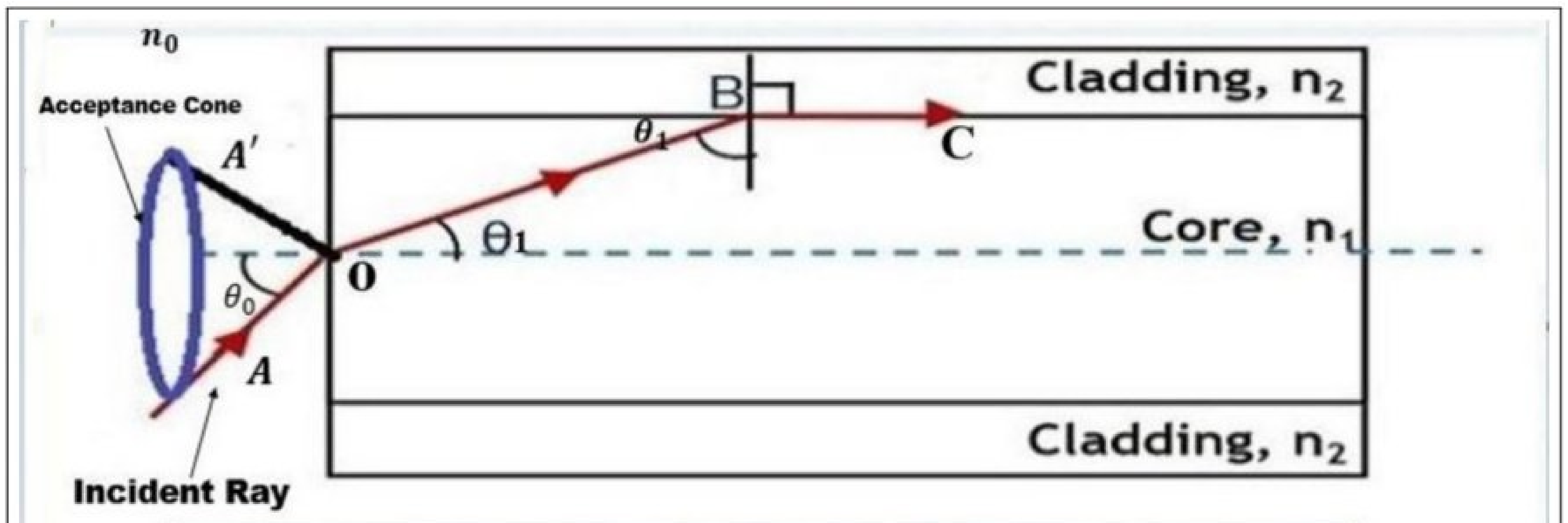
the normal. When the angle of incidence is equal to the critical angle the refracted ray grazes the line which separates denser and rarer medium and when the angle of incidence is greater than the critical angle the light reflects back to its own medium. This phenomenon is called as total internal reflection.

Expression for the Numerical Aperture and Acceptance angle



Ray propagation through Optical Fiber

Let n_0, n_1, n_2 be the refractive indices of surrounding medium, core of the fiber, and cladding respectively. Let AA' represent the acceptance cone at the entry point O. Then all the ray entering the core incident at an angle less than θ_o undergoes total internal reflection.

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By applying Snell's Law at the at the point of entry of the ray AO into the core,

$$n_0 sin\theta_0 = n_1 sin\theta_1 \tag{9}$$

$$At\ the\ point\ `B'\ on\ the\ interface,$$

$$the\ angle\ of\ incidence = (90 - \theta_1)$$

$$Again\ applying\ Snell's\ law\ to\ core\ and\ cladding\ medium$$

$$n_1 sin(90 - \theta_1) = n_2 sin90$$

$$n_1 cos\theta_1 = n_2$$

$$[since\ sin(90 - \theta_1) = cos\theta_1\ and\ sin90 = 1]$$

$$\implies cos\theta_1 = \frac{n_2}{n_1} \tag{10}$$

$$From\ equation\ (1)\ we\ have,$$

$$sin\theta_0 = \frac{n_1}{n_0} sin\theta_1$$

$$sin\theta_0 = \frac{n_1}{n_0}\sqrt{1 - cos^2\theta_1}$$

$$Substituting\ for\ cos\theta_1\ from\ eqn.(2),\ we\ have,$$

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

$$if\ the\ surrounding\ medium\ of\ the\ fiber\ is\ air\ , then\ n_0 = 1$$

$$\implies sin\theta_0 = \sqrt{(n_1^2 - n_2^2)}$$

$$sin\theta_0 = N.A = \sqrt{(n_1^2 - n_2^2)}$$

$$This\ equation\ represents\ the\ expression\ for\ numerical\ aperture.$$

Condition for Propagation of light in the optical fiber

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The light ray will be able to propagate in the optical fiber if the angle of incidence is less than the acceptance angle.

$$\theta_i < \theta_0$$

$$sin\theta_i < sin\theta_0$$

$$sin\theta_i < \sqrt{(n_1^2 - n_2^2)}$$

$$sin\theta_i < N.A$$

The above equation represents the condition for propagation.

Fractional Index Change (△)

It is defined as the ratio of the refractive index difference between the core and cladding to the refractive index of core of an optical fiber.

$$\implies \triangle = \frac{(n_1 - n_2)}{n_1}$$

Relation Between N.A and △

$$N.A = n_1\sqrt{2\triangle}$$

V-number

The parameter which determines the number of modes supported by an optical fiber

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during the propagation of light is called as V-number and is expressed by an equation.

$$V = \frac{\pi d}{\lambda}.\frac{\sqrt{(n_1^2 - n_2^2)}}{n_0}$$

Where, d is the core diameter

n_0 is the refractive index of the surrounding medium

n_1 is the refractive index of the core

n_2 is the refractive index of the cladding

λ is the wavelength of light propagating in the fiber.

If the surrounding medium is air then the same equation can be written as,

$$V = \frac{\pi d}{\lambda}.\sqrt{(n_1^2 - n_2^2)}$$

Then, The Number of Modes $\cong \frac{V^2}{2}$

Types of Optical Fibers

1. Single Mode Optical Fibers

Features of Single Mode Optical fiber:

- It is designed to carry only a single mode of light.
- A typical single-mode optical fiber has a core diameter between 8 and 10 μm and a cladding diameter of 60-70 μm.
- In this type of optical fiber the core material has uniform refractive index.
- The cladding also has uniform refractive index throughout but of slight lesser value

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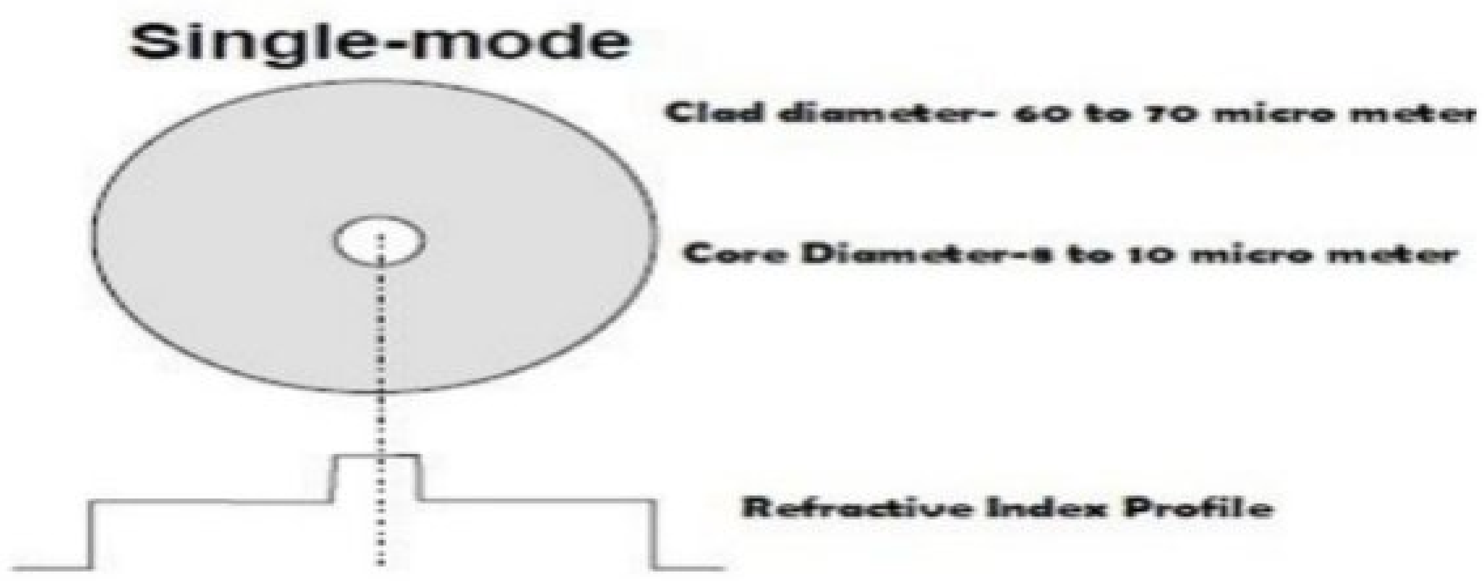
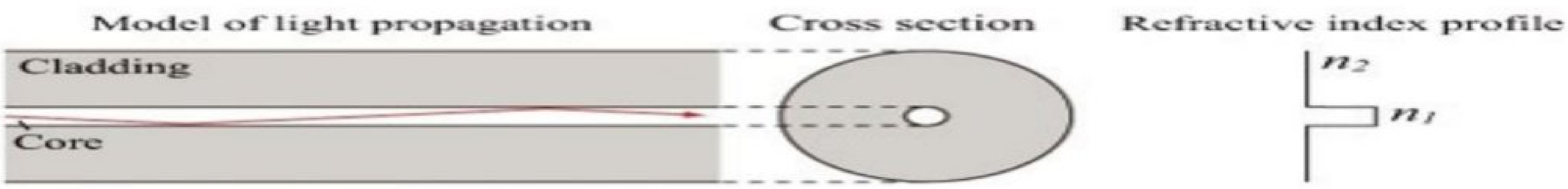


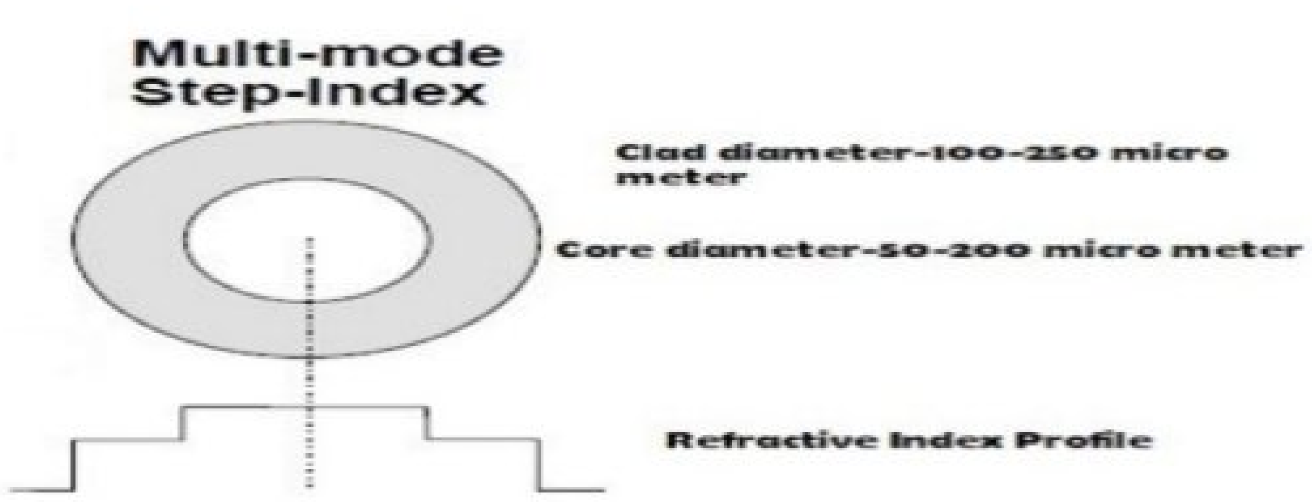


(a)

with respect to core.

- The refractive index profile takes a step function due to uniform refractive index.
- Due to the narrow core the fiber can guide just a single mode.
- Single mode fibers are the most extensively used optical fiber world wide.
- The source of light used in the propagation here is Laser.

2. Step Index Multi-Mode Optical Fibers




(b)

Features of Step Index Multi-Mode Optical fiber:

- The core diameter of the step-index multimode optical fiber ranges from 50 to 200μm.
- The cladding diameter of the step-index multimode optical fiber ranges from 100 to 250μm.

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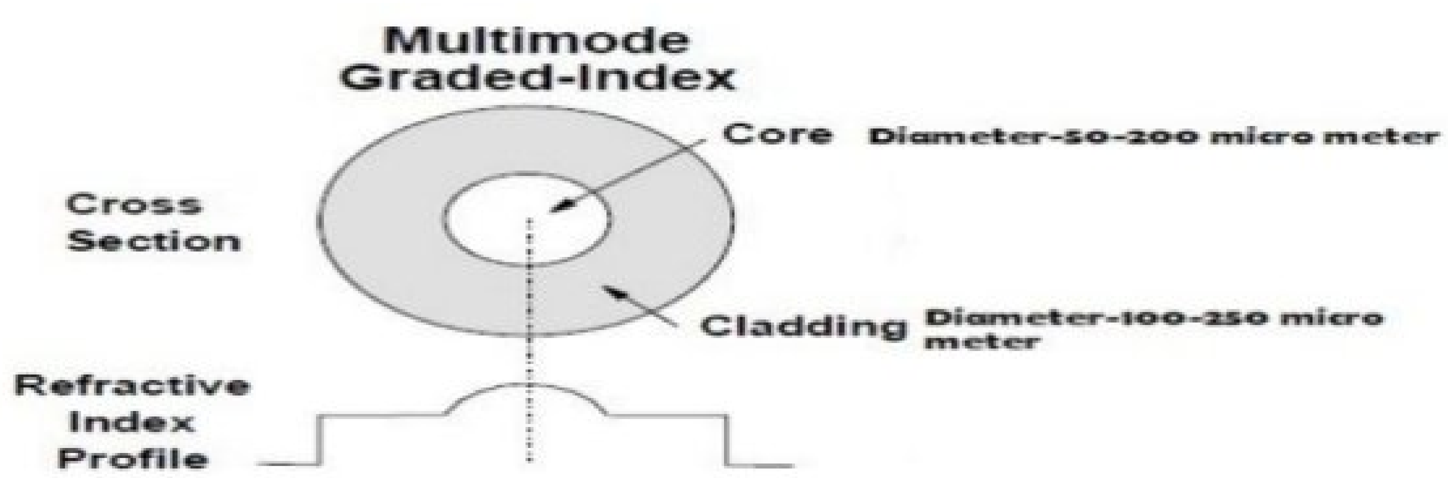
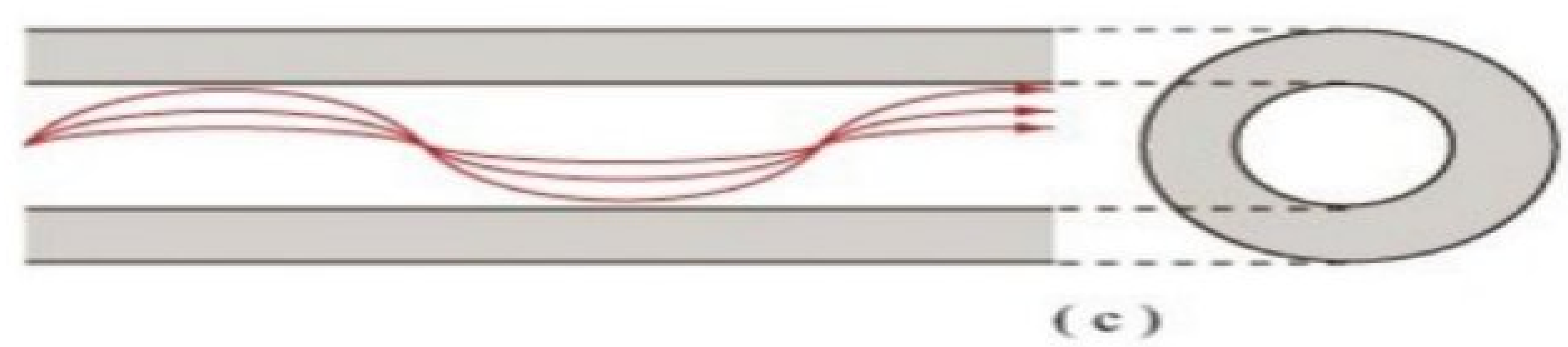
- Since the core has larger diameter by the virtue of which it supports multiple modes of propagation of light.
- The refractive index profile is same as in case of the single mode optical fiber.
- The Laser and LED is used as a source for step-index multimode optical fiber.
- The typical application of this type of optical fiber is in data links which requires lower bandwidth for operation.

3. Graded Index Multi-Mode Optical Fibers(GRIN)





Features of Graded Index Multi-Mode Optical fiber:

- The geometry of the graded index multimode optical fiber is same as the step-index fiber.
- The refractive index of the core decreases radially outward direction from the axis of the fiber and becomes equal to the refractive index of the cladding at the interface.
- The refractive index of the cladding remains uniform throughout.
- This type of optical fiber uses Laser or LED as a source.
- This is the most expensive of all optical fibers which finds its application in the telephone trunk between central offices.

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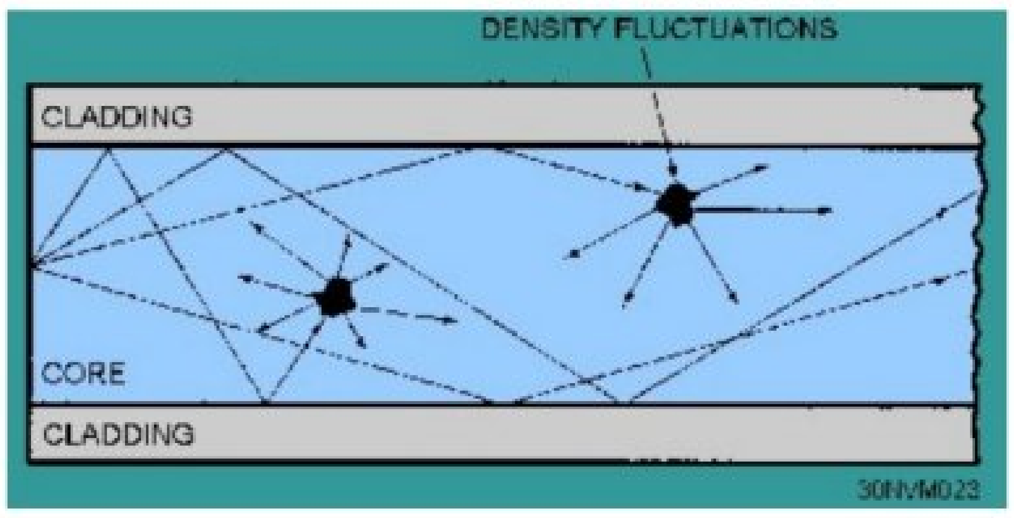
Attenuation In Optical Fibers

1. Absorption Loss:

   - Absorption loss is caused due to the absorption of light energy by molecules in the glass fiber later the light energy gets converted to heat.
   - Absorption is due to extrinsic and intrinsic absorption: Extrinsic absorption is due to absorption of light during propagation by impurities which are trapped within the core of the fiber. Intrinsic absorption is caused by basic fiber material properties due to atomic or molecular imperfections and dislocations, this sets the minimum absorption limit for any optical fiber.

2. Scattering Loss:



   - Scattering losses are caused by interaction of propagating light with density fluctuations within a fiber which are produced during manufacturing stages of optical fibers.
   - During propagation the light propagating interacts with the density areas due to which the energy of the propagating light reduces and scattered light is thrown in different directions.

3. Radiation Loss: Macrobending and Microbending.

   - Macrobend is a situation in which the fiber is physically bent into a large radius of

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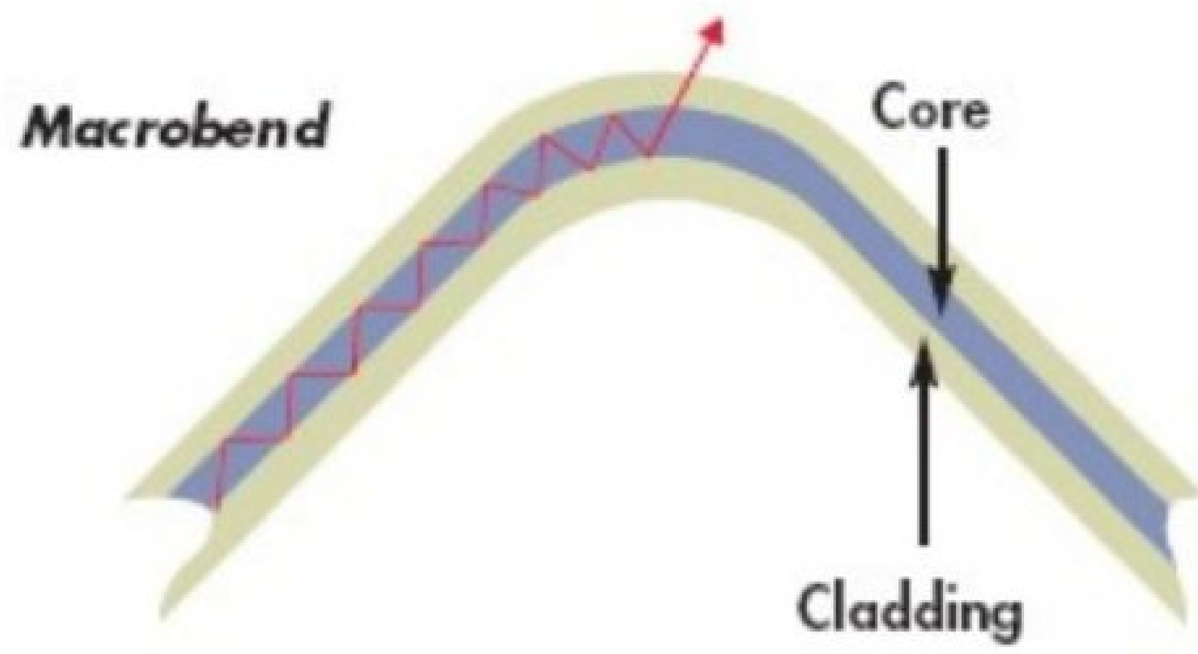

Figure 2: Macrobending

curvature relative to the fiber diameter, because of which the light escapes through the bent portion of an optical fiber.

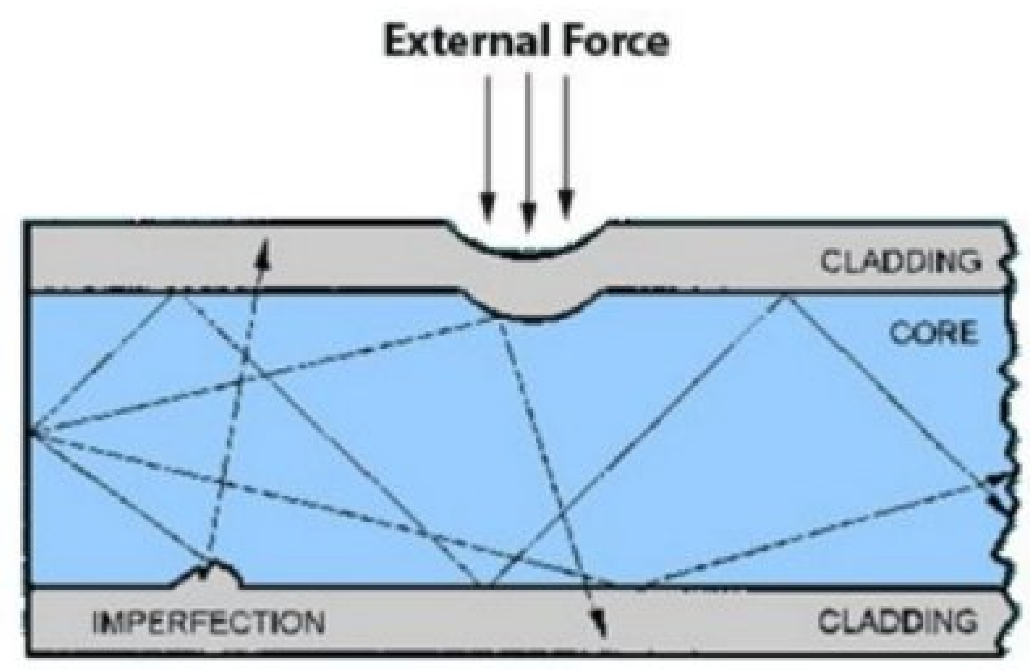

Figure 3: Microbending

- Microbending is caused by a small bend due to the non-uniformity inside the fiber, which occurs due to the non-uniform pressures created during cabling of the fiber or during manufacturing of fiber, thus not satisfying the condition of total internal reflection and light escapes from the fiber.

Attenuation Spectrum of an optical fiber with Communication Windows:

The 1310 nm window had lower dispersion but higher attenuation than the 1550 nm window. Modern single-mode fiber has optimized the 1550 nm window so this is no longer true. But the available multi-mode fiber still has lower dispersion in the 1310 nm window, and this may be preferred for short-distance links.

A 1310 nm laser will have a lower divergence angle at its output than a 1550 nm laser

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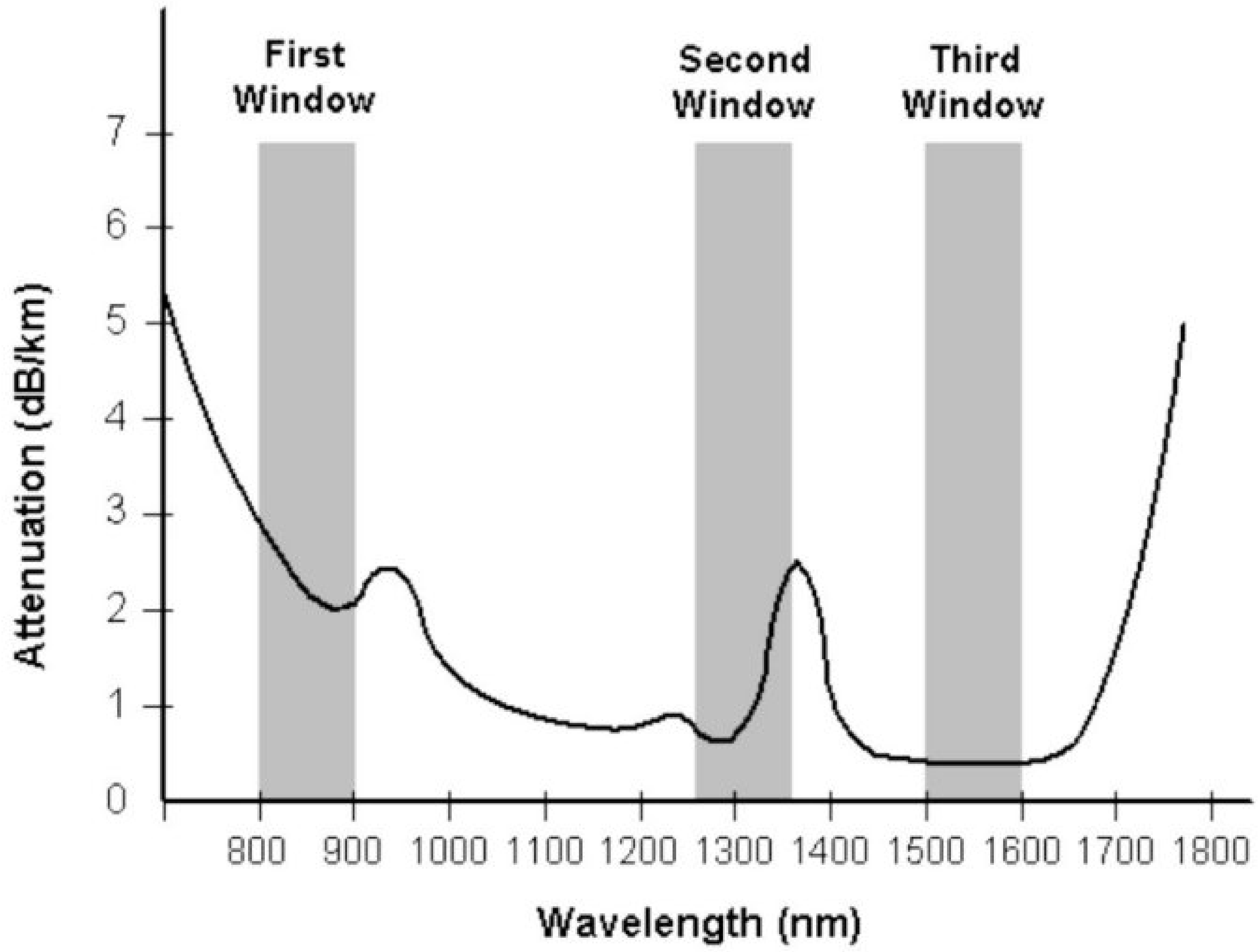

Figure 4: Attenuation Spectrum

with the same aperture size. This may make the optics for coupling the 1310-nm laser into the fiber lower cost than the optics for a 1550-nm laser.

Expression for the attenuation co-efficient.

$$\alpha = -\frac{10}{L} log_{10}\left[\frac{P_{out}}{P_{in}}\right] dB/km$$

where, α - Attenuation co-efficient

L - Length of the fiber through which the light propagates.

P_{in}- power input or intensity of light with which it is launched into the fiber.

P_{out}- power output or intensity of light received as output at the fiber end.

Application of Optical Fiber

Point to point communication using optical fiber

Explanation: It is a technology for transmitting information through optical fibers

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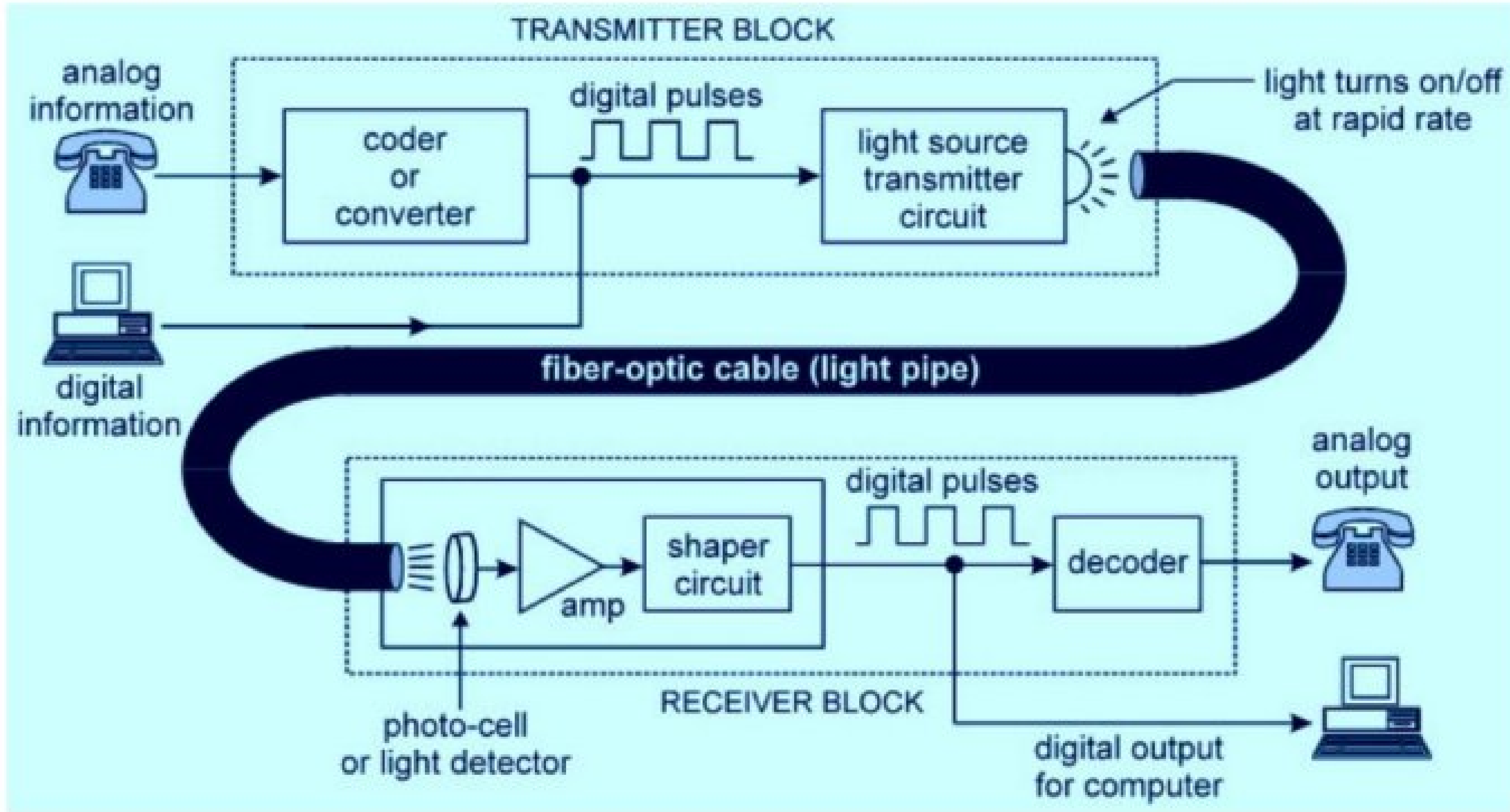

with a single transmitter and single receiver.The digital signal in the form of a stream of electrical pulses are converted into light signals by an optical transmitter that makes use of an optical source such as LED or laser. The transmitter then injects the information carrying light signal into the optical fiber, where the signal undergoes the total internal reflection and reaches another end of the fiber which is connected to the receiver.The receiver consists photo-detector which converts the signal into electrical pulses. The pulses are in turn fed to decoder that converts the sequence of digital data stream into an analog signal, which processes the same information such as data or a voice which was at the transmitted end.

Optical fiber Sensors:

Intensity Based Displacement Sensors:

A displacement sensor is a device that measures the distance between the sensor and an object by detecting the amount of displacement through a variety of elements and converting it into a distance.

Working: Light from the transmitting fibre element is incident on the object under study. The light receiver fibre element is positioned adjacent to the transmitting fibre.

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If the gap between the object and the fibre elements is zero, the light from the transmit fibre would be directly reflected back into itself and a small amount or no light would enter into the receiver fibre. When the object moves away, the gap increases and some of the reflected light is captured by the receive fibre which inturn is carried to the photodetector.

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