Parul® University
VADODARA, GUJARAT

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# Engineering Physics II
## (SUBJECT CODE: 303192102)


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# UNIT- 4
# Lasers and Fibre Optics

# What to Study in Laser !!!

1. What is an Ordinary light?
2. What is Laser light?
3. Characteristics of LASERs
4. Difference between Ordinary Light and LASER light
5. Coherence Length
6. Light-Matter Interaction-
   (i) Stimulated Absorption
   (ii) Spontaneous Emission
   (iii) Stimulated Emission

6. Relation between Einstein's co-efficients
7. Population Inversion and Metastable states
8. Components of Laser
9. Working of LASER
10. Schemes of Population Inversion
11. RUBY LASER
12. He-Ne Laser
12. Semiconductor diode laser
13. Applications of LASERs
14. Numericals

# What is Light !!!

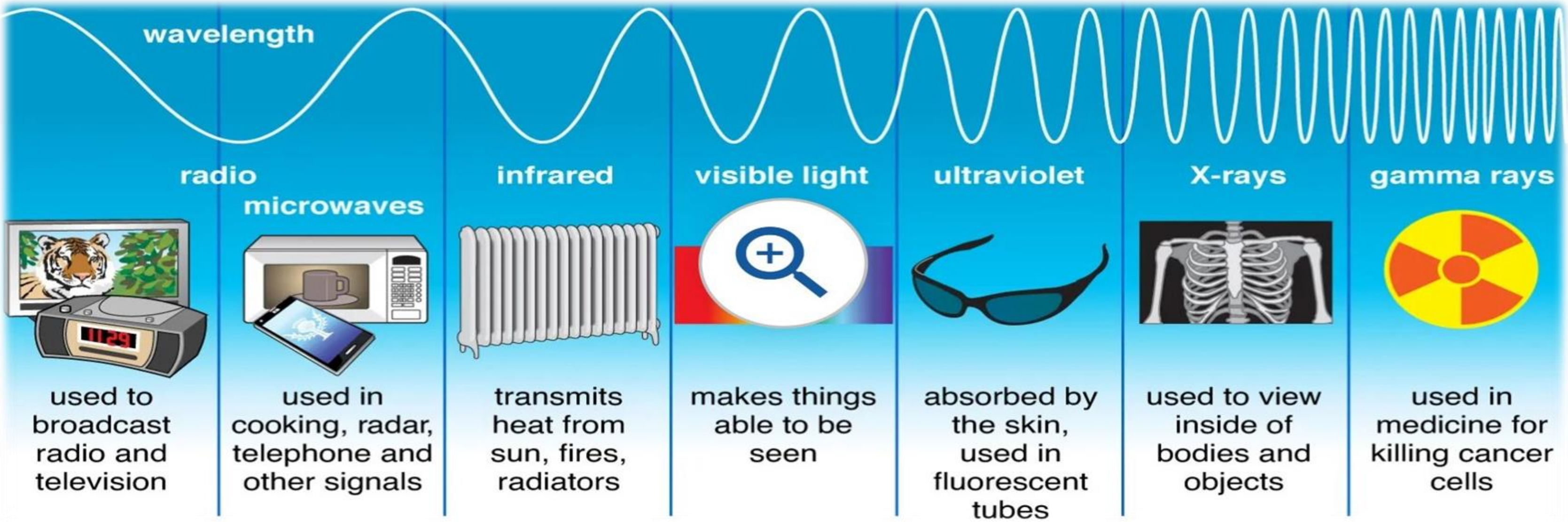
- Light is a form of electromagnetic radiation that is visible to the human eye.
- It is a type of energy that travels in the form of waves, and it is part of a broader spectrum of electromagnetic radiation.
- The electromagnetic spectrum encompasses a wide range of frequencies and wavelengths, with light falling within a specific region of this spectrum.

# Sources of Ordinary Light !!!

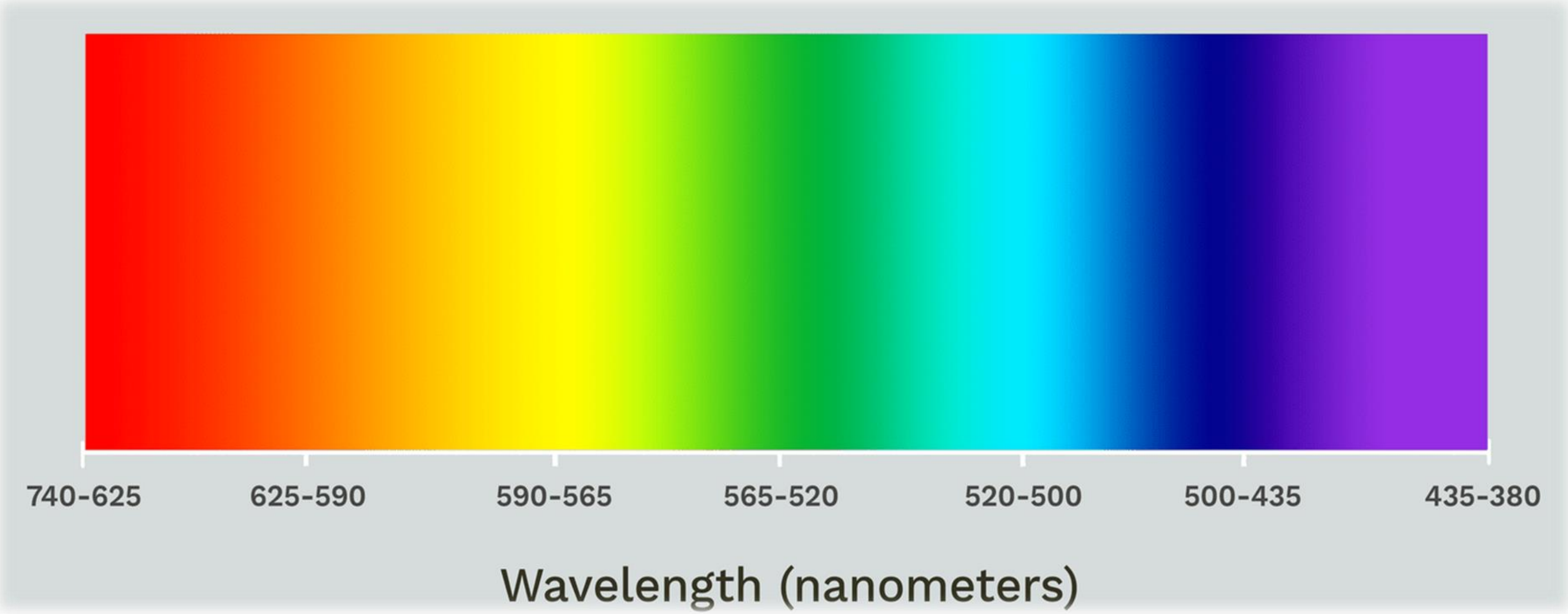
# Electromagnetic Spectrum

**SPEED:** In a vacuum, light travels at a constant speed **($3.00 \times 10^8$ m/s)**, denoted as c. This speed is one of the fundamental constants in physics.

**ELECTROMAGNETIC SPECTRUM:** Light is just one portion of the electromagnetic spectrum, which includes various types of electromagnetic radiation such as **radio waves, microwaves, infrared radiation, visible, ultraviolet radiation, X-rays, and gamma rays.** Each type of electromagnetic radiation has a specific range of wavelengths and frequencies.



# Visible Spectrum




**WAVELENGTH AND COLOR:** The different colours of light are associated with different wavelengths. In the visible spectrum, shorter wavelengths correspond to colours like violet and blue, while longer wavelengths correspond to colours like red and orange.

**ENERGY:** The energy of a light wave is directly proportional to its frequency. This relationship is described by the equation **$E=h\nu$**, where **$E$** is the energy, **$h$** is Planck's constant, and **$\nu$** is the frequency of the light wave.

## LASER –
## Light Amplification by Stimulated Emission of Radiation

A device that stimulates atoms or molecules to emit light at particular wavelength and amplifies that light producing a highly **coherent, monochromatic** and **highly intense narrow beam of radiation**.

# History of LASER

**1916**

- Albert Einstein gave the theoretical prediction of "**Stimulated Emission**" which is fundamental to the operation of all lasers.

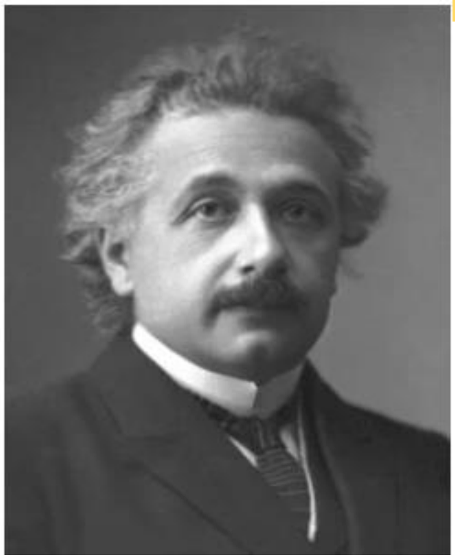
**1958**

- C.H. Townes and his co-workers constructed first MASER (Microwave Amplification By Stimulated Emission Of Radiation) using ammonia based on the prediction of Einstein.
- Townes and Schawlow proposed a method of extending MASER principle to visible light.

**1960**

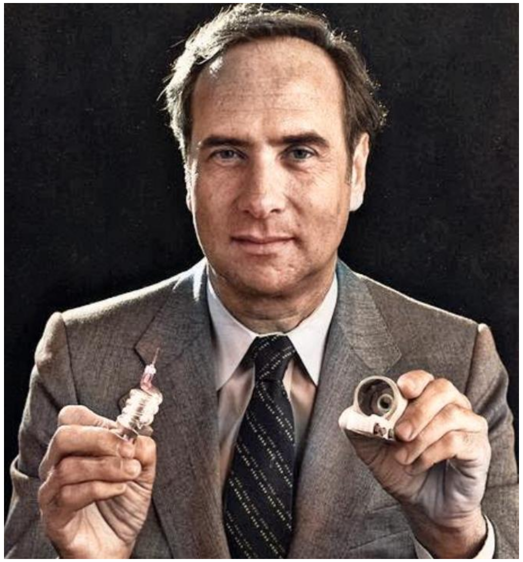
- T. Maiman built the first **LASER (RUBY LASER).**
- Laser is also called **Optical MASER.**

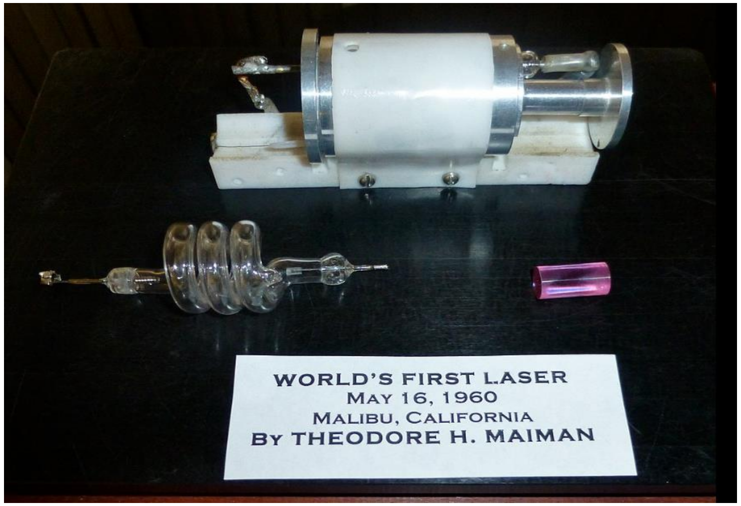
# History of LASER



**Albert Einstein** gave the theoretical prediction of “**Stimulated Emission in 1916**

**T. Maiman with his laser in July 1960**



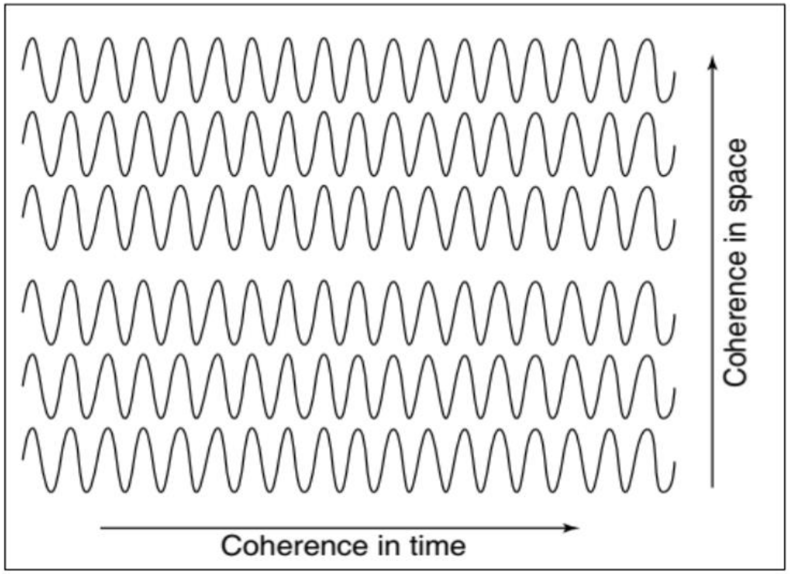


# Characteristics/Properties of LASER light

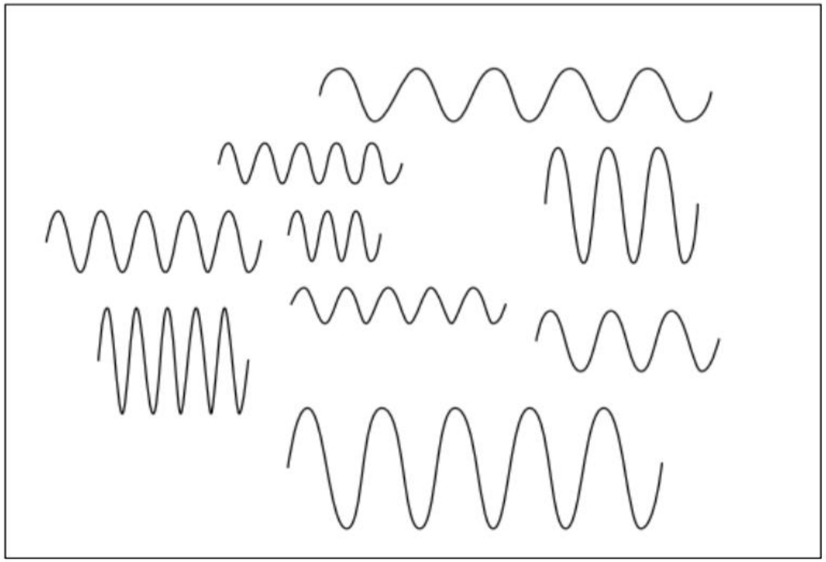
LASER encompasses interaction between atoms and molecules of matter and electromagnetic field.
The beam emitted by laser can have following features:
**(1) High Degree Of Coherency (2) Highly Monochromatic (3) Highly Directional**
**(4) Highly Intense**

1. **Laser is highly coherent.**
2. **Laser is highly monochromatic** unlike ordinary light which means that all laser rays have same wavelength and frequency when they are emitted from same source.
3. **Laser can be directed to a distant object and travel as a parallel beam** with only negligible spreading due to diffraction effect. Hence its highly directional unlike ordinary light which emits light in all directions and is highly divergent. In LASER, divergence is in some mm.
4. **Laser emits light** in the form of narrow beam with energy concentrated in a small region of space. So, the **beam intensity is tremendously large and stays constant with distance** unlike ordinary light.

# COHERENT (LASER) and INCOHERENT (ORDINARY) Light




Group of coherent photons

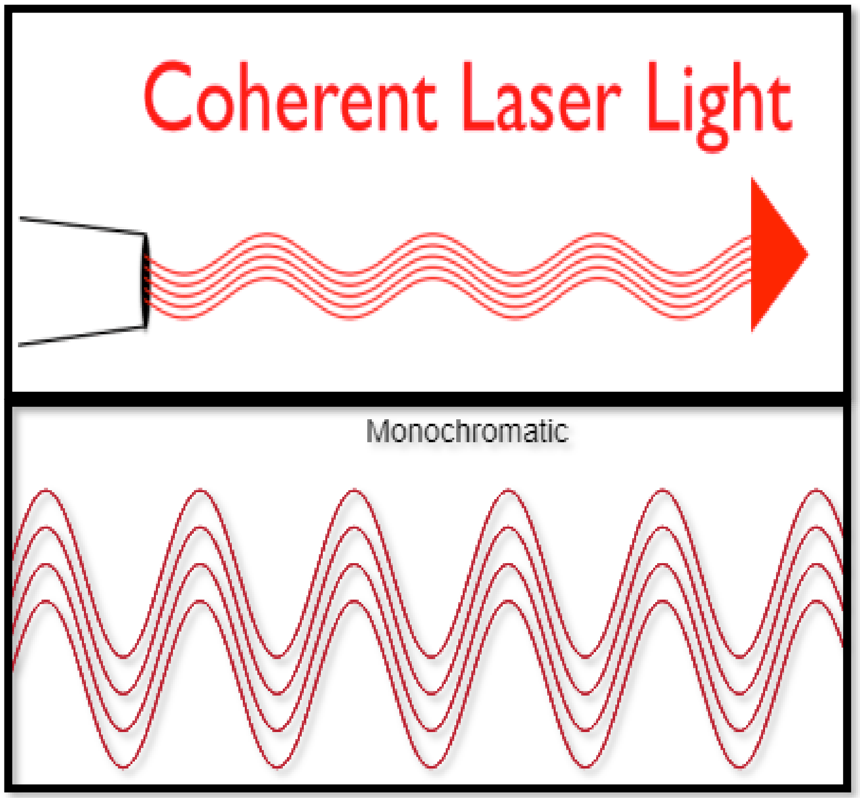


Group of incoherent photons

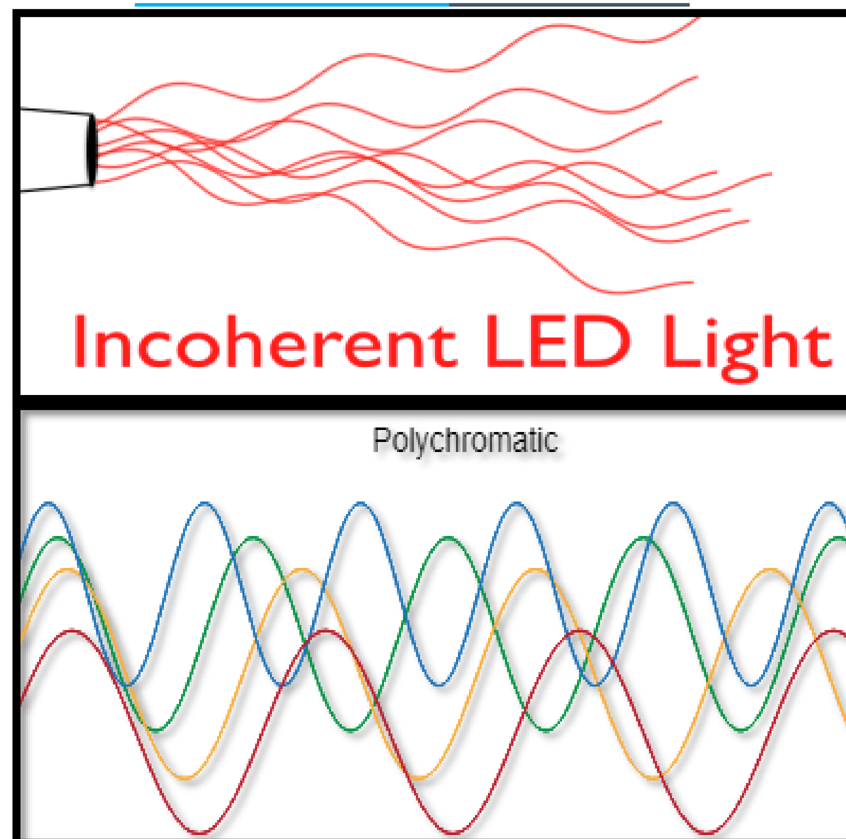
**Coherence** is related to zero or constant/definite phase relationship at different points of time and space. For a source to be coherent, it must emit radiation of single frequency or frequency spread must be small. Laser is highly coherent but ordinary light is incoherent in nature as they emit light waves with no constant phase difference with each other, they comes from independent atoms which emit on time scale of $10^{-8}$ s.

# Characteristics/Properties of LASER light

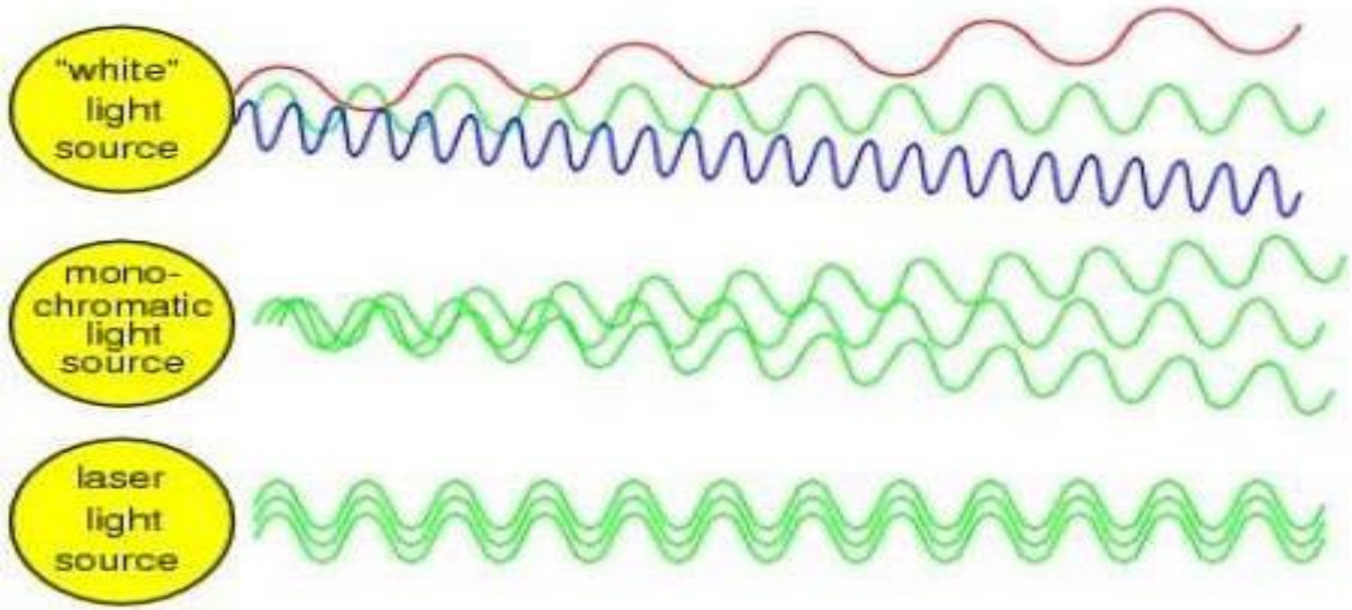
## LASER LIGHT




## ORDINARY LIGHT



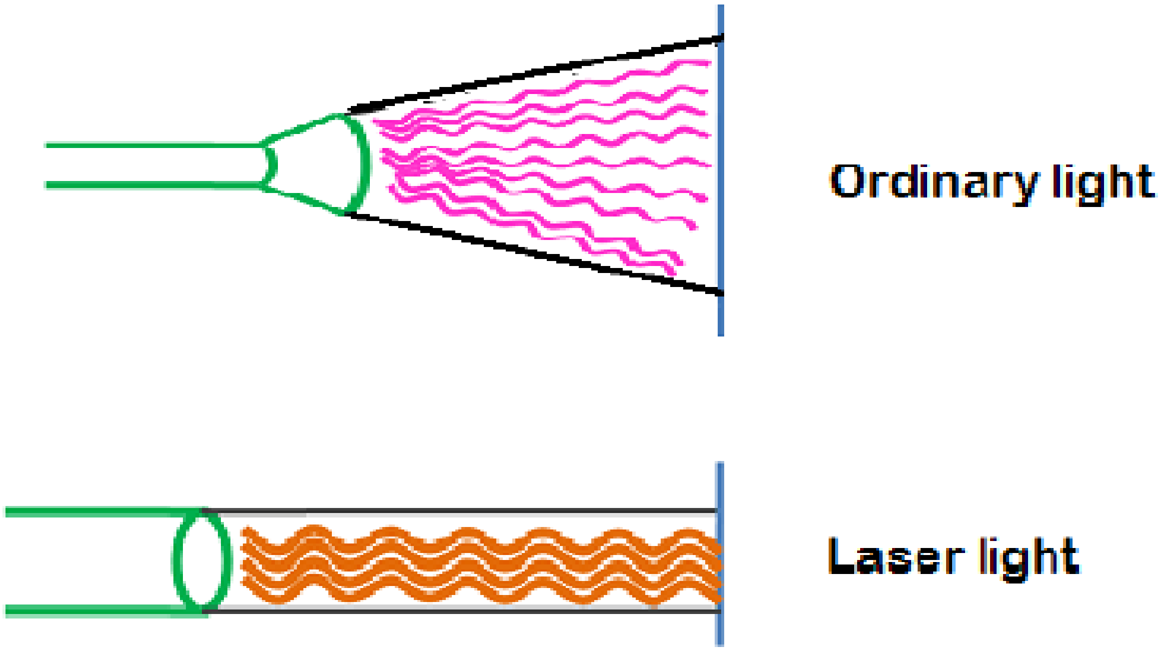
# Properties of Laser Light : Monochromatic




If each light coming from a source has only one frequency (single wavelength) of oscillation, the light is said to be <u>monochromatic</u> and the source is called <u>monochromatic source.</u> Light from traditional monochromatic sources spreads over a wavelength range of (100 Å -1000 Å ).

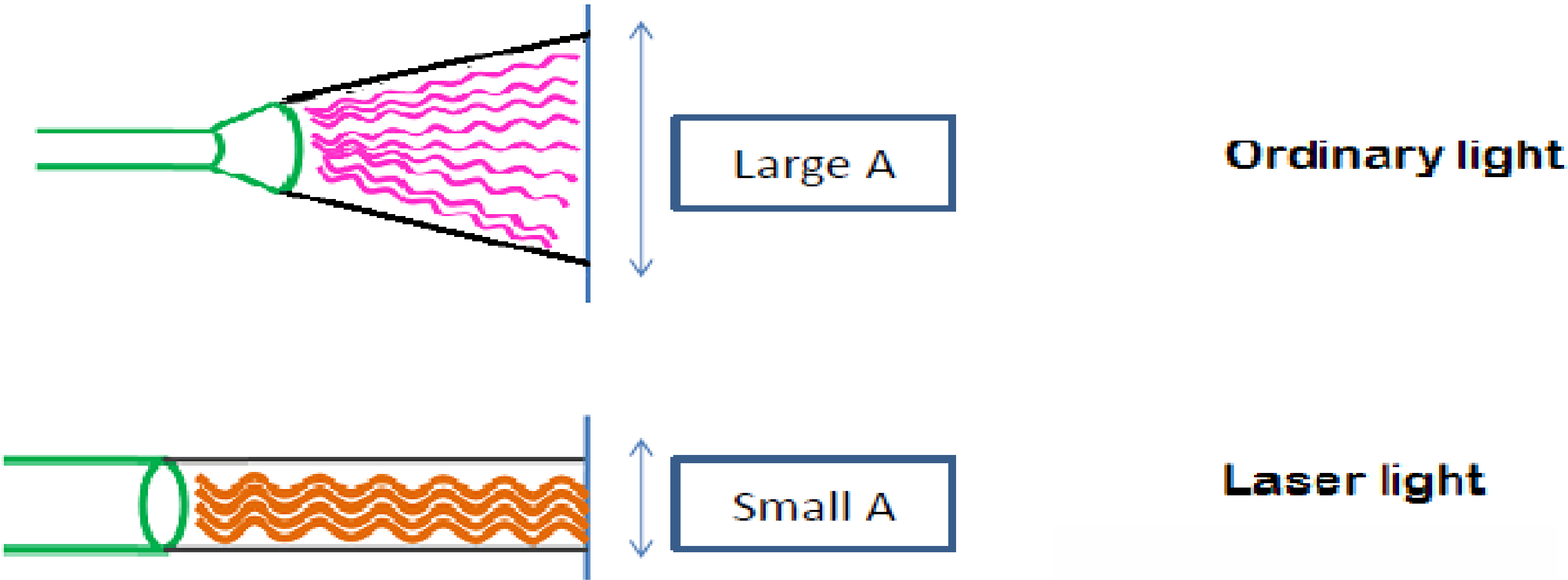
On the other hand, the light from lasers is highly monochromatic and contains a very narrow range of a few angstroms (< 10 Å).

# Properties of Laser Light : Highly Directional (Collimated) Beam




**Laser light can travel very large distance without divergence and without loss of energy. It's angular spreading will be less. Hence it possesses "high degree of directionality".**

# Properties of Laser Light : Highly Intense beam




$$Intensity\ I = \frac{E}{A \times t}$$

**Since ordinary light spreads in all directions, the intensity reaching the target is very less. In laser, due to high directionality, the intensity reaching the target is of high intensity. Example: 1 mW power of He-Ne laser appears to be brighter than the sunlight.**

# Coherence Length

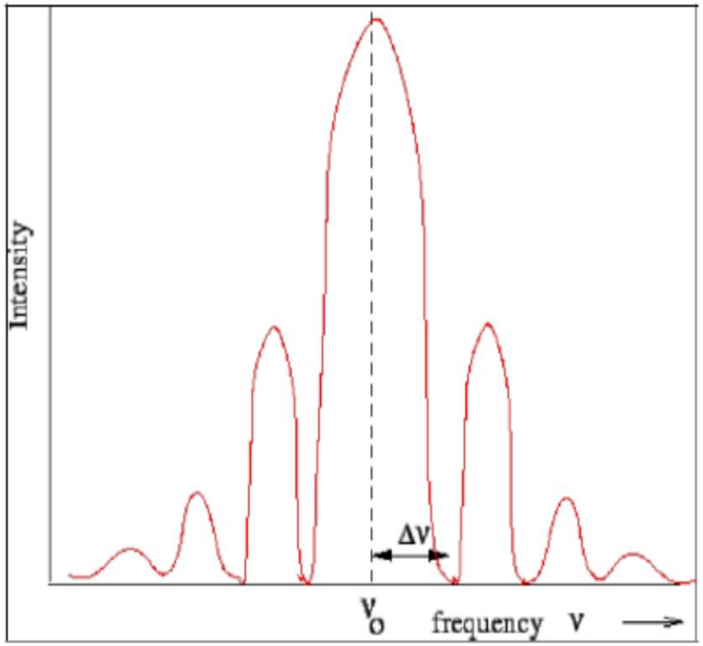
*COHERENCE LENGTH*

$$l = \frac{c}{\Delta\nu}$$

$$Also\ \nu = \frac{c}{\lambda} \therefore \frac{\Delta\nu}{\Delta\lambda} = \frac{c}{\lambda^2}$$

$$\therefore \Delta\nu = \frac{c}{\lambda^2}\Delta\lambda$$

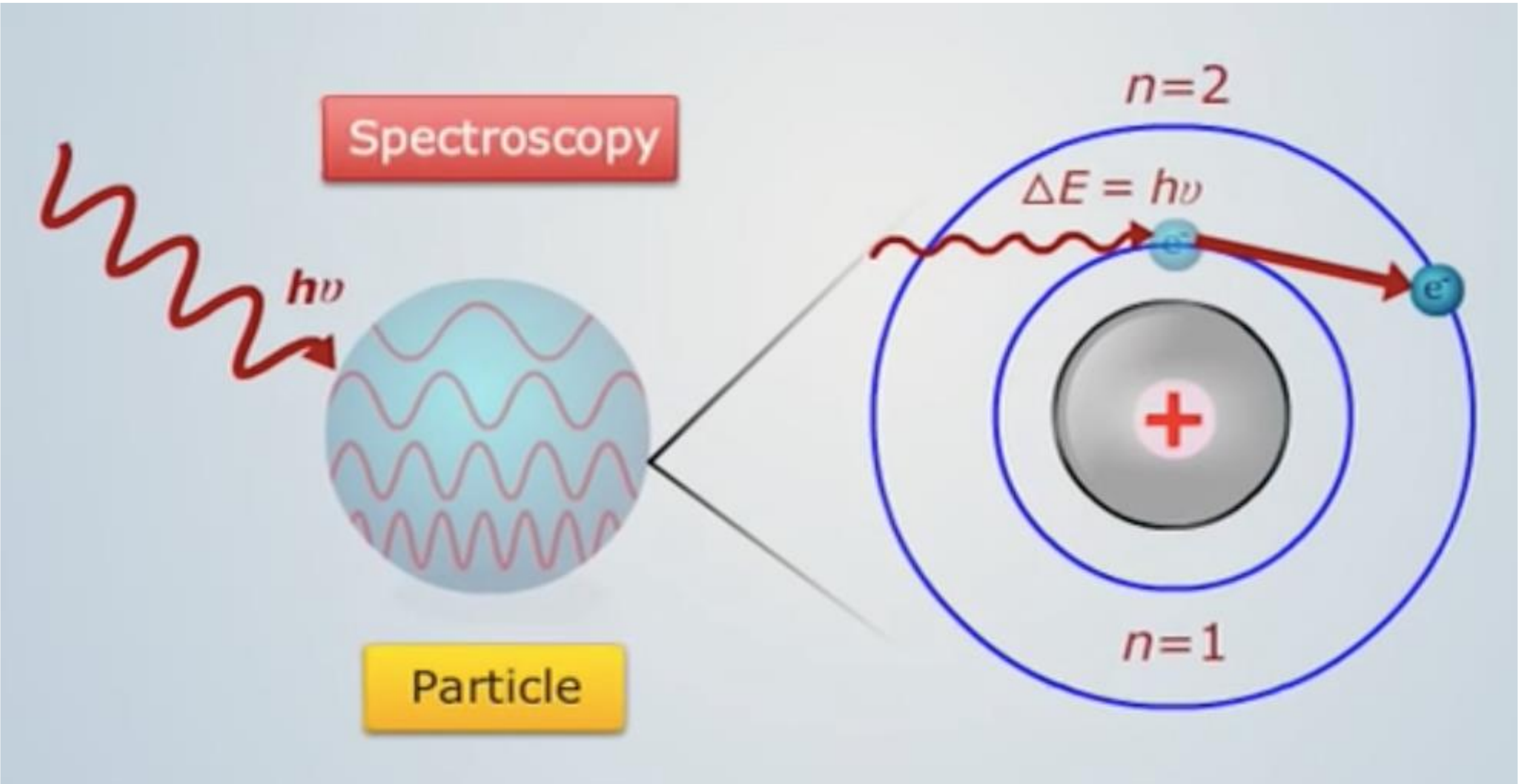
$$l = \frac{c}{\frac{c}{\lambda^2}\Delta\lambda} = \frac{\lambda^2}{\Delta\lambda}$$




Since $\Delta\lambda$ is very small, coherence length is very high. Pulse width is narrow.

**Coherence length is a measure of how far electromagnetic waves, can maintain a consistent phase relationship. In optics, it describes the distance over which the wave front of a light wave remains relatively stable.**

# Interaction of Electromagnetic Radiation with Matter

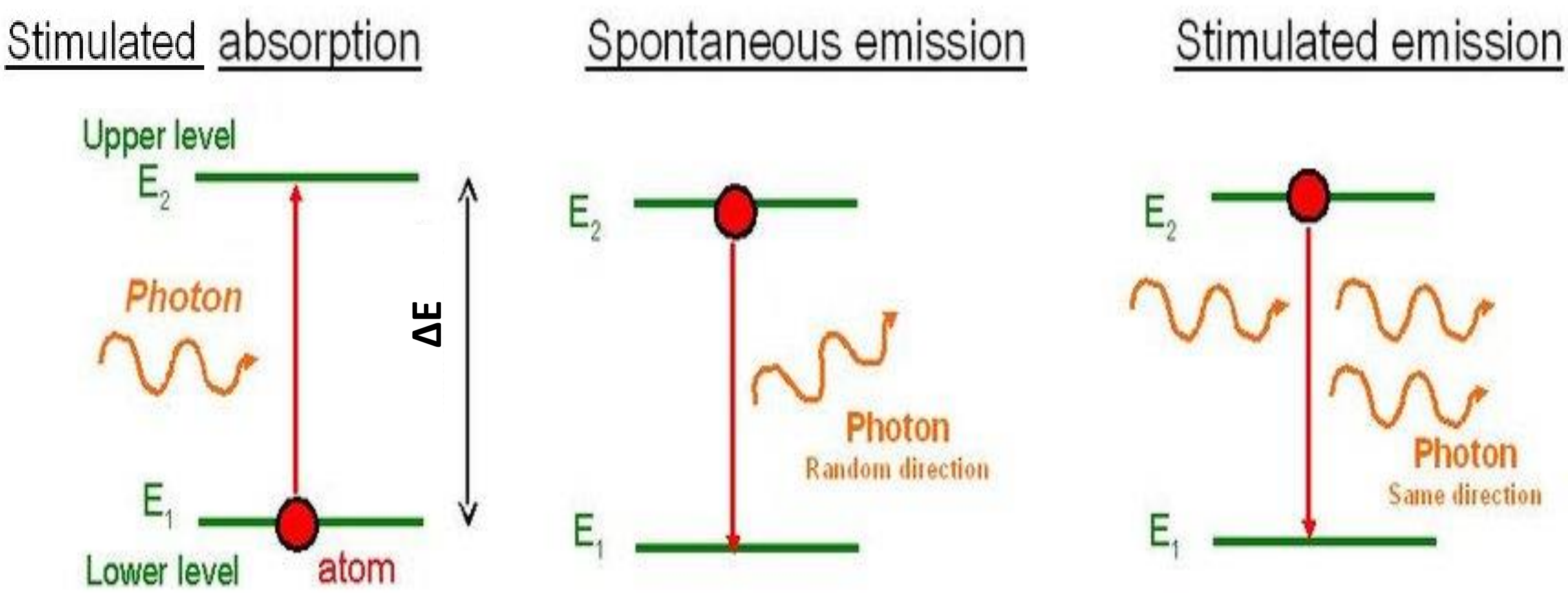


## Interaction of Electromagnetic Radiation with Matter

Einstein explained the interaction of e-m radiation with matter with the help of three processes.

1. **Stimulated Absorption**
2. **Spontaneous Emission**
3. **Stimulated Emission**

# Interaction of e-m Radiation with Matter : Einstein's Theory




Condition — $h\nu = E_2 - E_1 = \Delta E$

# Einstein's theory of matter-radiation interaction

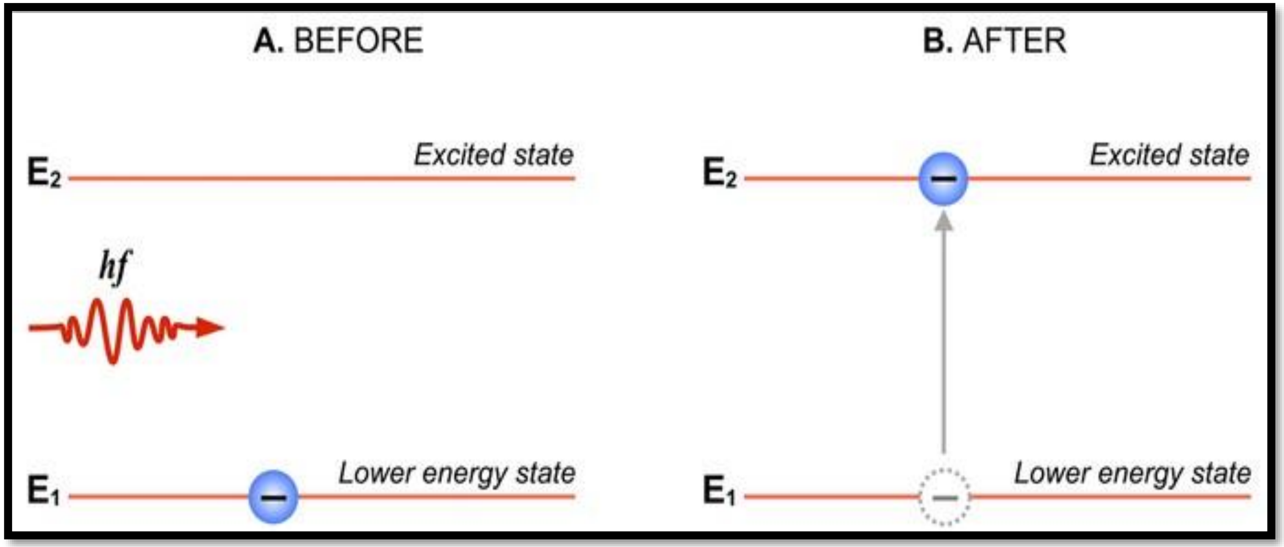
- Bohr's theory of an atom states that an electron revolving in orbits around the nucleus can only have certain (discrete) values of energies. These are referred to as the atom's energy levels.

- Bohr proposed that light emission takes place when the atom makes a transition from an excited state (of energy $E_2$ state to a relaxation (of energy $E_1$ state.

$$h\nu = E_2 - E_1 \qquad \text{..........(i)}$$

# Interaction of matter with radiation: Stimulated Absorption

- Consider an atom is initially in lower energy state ($E_1$).
- A photon of energy **$h\nu$ (= $E_2$ - $E_1$)** when incident on the atom in ($E_1$), it is absorbed by the atom.
- On absorbing the energy, the atom transits to its higher energy state ($E_2$).
- This phenomenon in which the atom transits to the higher energy state with the help of external agent (radiation energy) is called **STIMULATED Absorption.**



# Interaction of matter with radiation: Stimulated Absorption

- An absorption process is represented by
- $E_2 = E_1 + h\nu$

  $\Rightarrow E_2 - E_1 = \Delta E = h\nu$

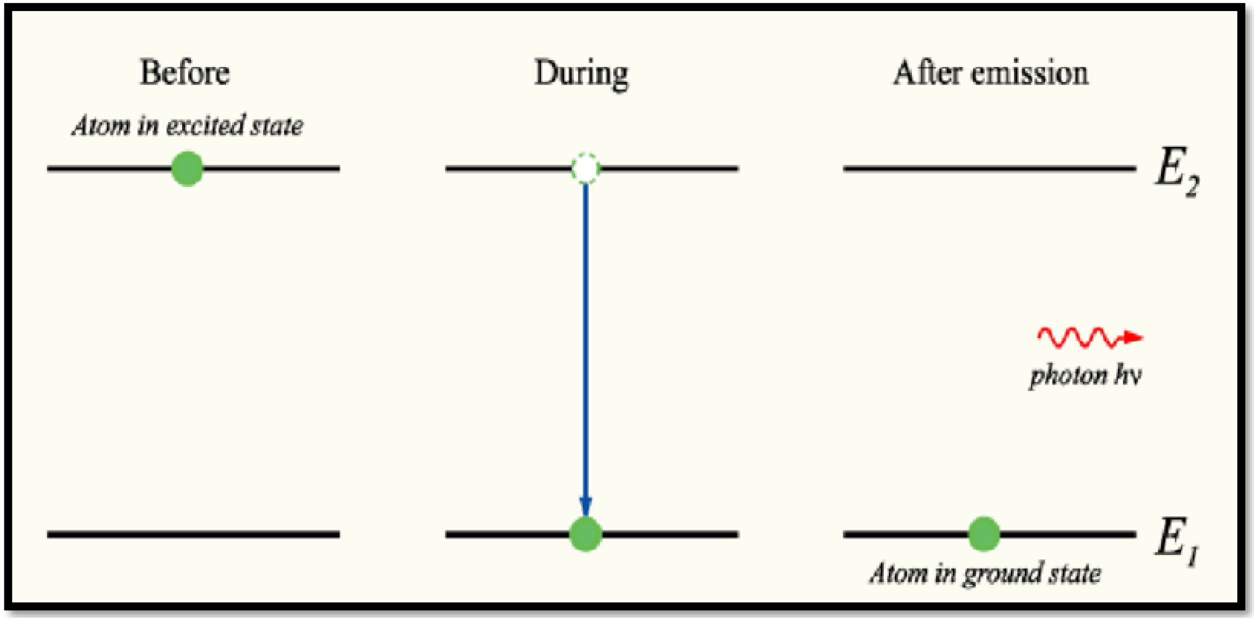
- The probability of occurrence of this absorption from state 1 to state 2 is directly proportional to the energy density of the radiation

$P_{12} = B_{12}\ \rho(\nu)$ ..............(ii)

Where the proportionality constant $B_{12}$ is known as the Einstein's coefficient of absorption of radiation.

# Interaction of matter with radiation: Spontaneous Emission

- Lifetime of upper energy state is very short.
- Consider an atom is initially in excited state ($E_2$).
- It can come down to the ground state $E_1$ by emitting a photon of energy **hν (= $E_2$ - $E_1$)** on its own after $10^{-8}$ s (**without any external agent).**
- This process is called **SPONTANEOUS Emission.**



- The probability of occurrence of this spontaneous emission transition from state 2 to state 1 depends only on the properties of states 2 and 1 and is given by
- $P'_{21} = A_{21}$ ............(iii)

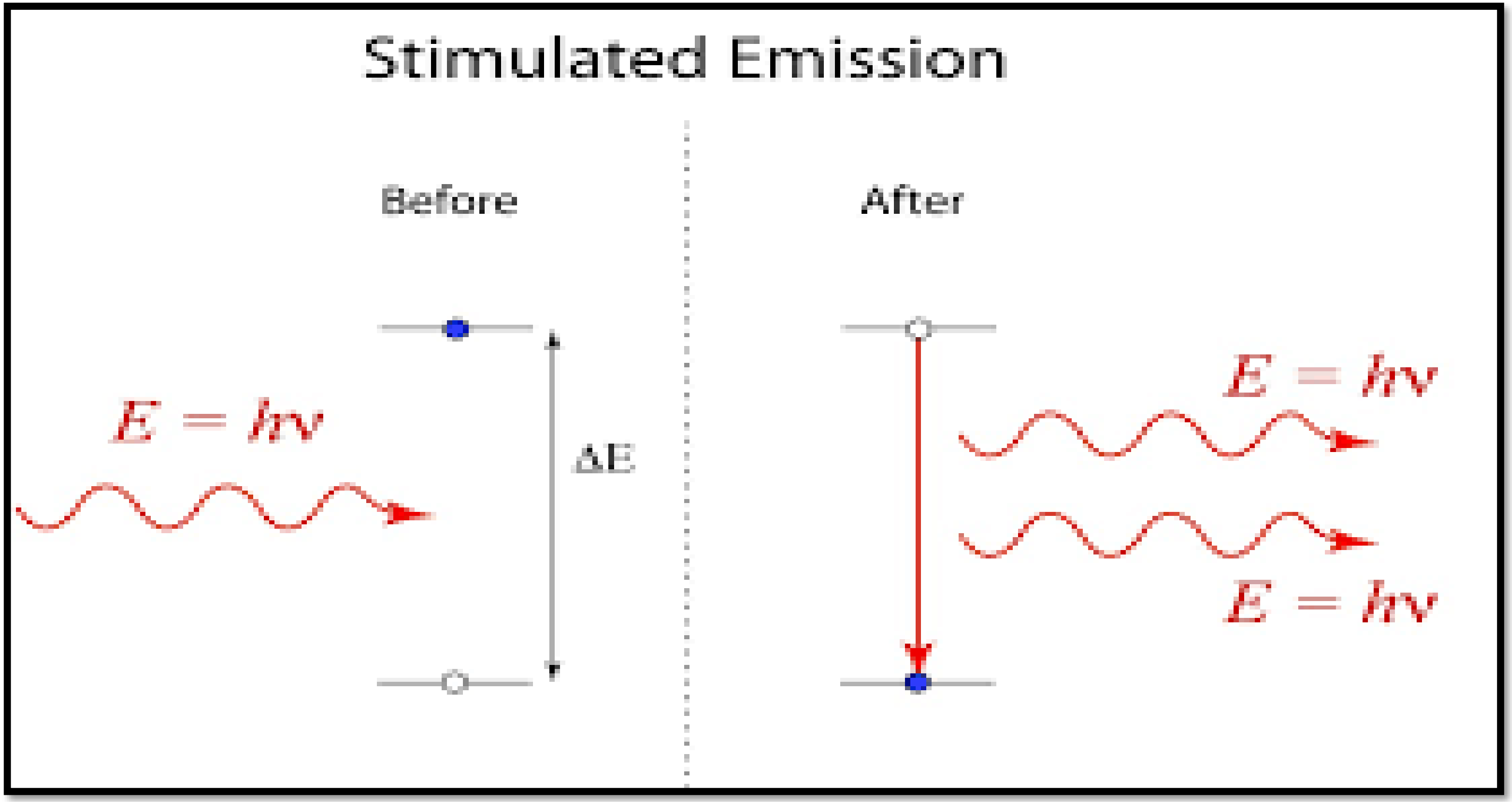
**Where $A_{21}$ is known as the**

**Einstein's coefficient of spontaneous emission of radiation.**

# Interaction of matter with radiation: Stimulated Emission

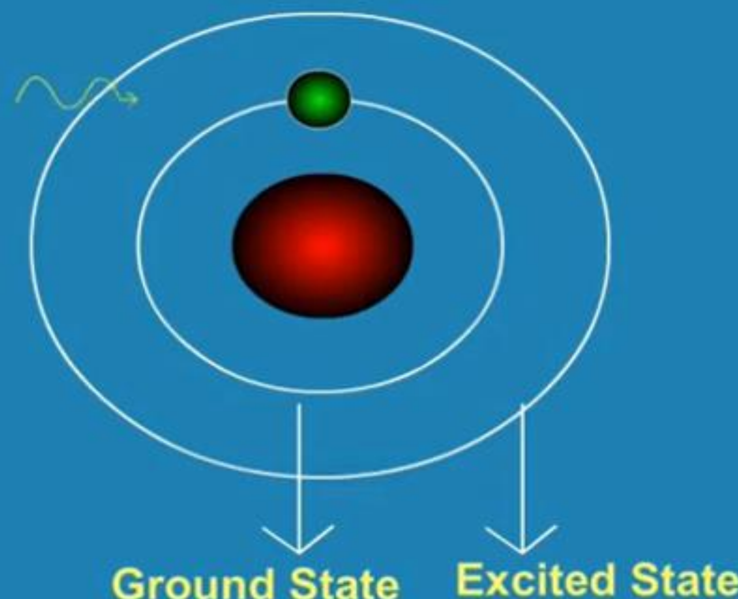
- Stimulated emission is induced emission, in which an incident photon of energy $h\nu$ causes an emission from upper state $E_2$ to the lower state $E_1$, which is represented by
- $h\nu = \Delta E = E2 - E1$
- The probability of occurrence of stimulated emission transition from the upper level 2 to the lower level 1 is proportional to the energy density **ρ** $(\nu)$ of the radiation and is expressed as
- $P''_{21} = B_{21}\, \rho(\nu)$ .......... **(iv)**

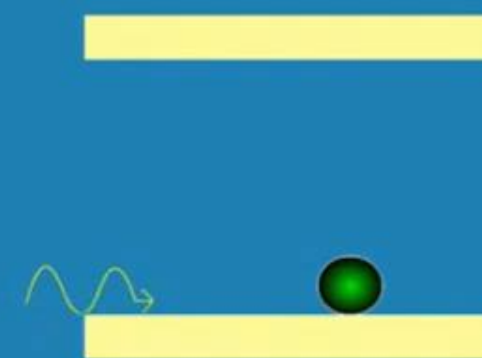
# Interaction of matter with radiation: Stimulated Emission



# Absorption

When a photon of energy h$\nu$ is incident on the atom
state then it excites to higher state .This phenomen
"absorption".



# Relation between Einstein's Coefficients

**Let us consider an assembly of independent atoms which can exists only in 2 levels, 1 and 2 with energies $E_1$ and $E_2$. Let $N_1$ and $N_2$ be the number of atoms per unit volume in the states 1 and 2 respectively. These numbers are called Population of respective levels.**
**At thermal equilibrium, the no of atoms present in a particular energy is determined by Maxwell's-Boltzmann Statistics, i.e.**

$$N_2 = N_1 \exp\{-(E_2 - E_1)/KT\}$$

**Where,**
**K= Boltzmann's constant = 1.38 x $10^{-23}$ J/K**
**T= Absolute Temperature in Kelvin**
**We have these following equations:**

Here,
$B_{12}$= Einstein Coefficient Stimulated Absorption
$B_{21}$=Einstein Coefficient of Stimulated Emission
$A_{21}$=Einstein Coefficient of Spontaneous Emission

The Rate of Stimulated Absorption ($R_1$) transition is given by:

$$R_1(\text{St. Absorption}) = B_{12}\,\rho(\nu)\,N_1 \quad \text{----- (1)}$$

The Rate of Spontaneous Emission **($R_2$)** is given by:

$$R_2\,(\text{Sp. Emission}) = A_{21}\,N_2 \quad \text{-------- (2)}$$

The Rate of Stimulated Emission **($R_3$)** is given by:

$$R_3\,(\text{St. Emission}) = B_{21}\,\rho(\nu)\,N_2 \quad \text{------ (3)}$$

# Relation between Einstein's Co-efficients

**Under thermal equilibrium,**

| |
|---|
| **The number of atoms absorbing photons per second/unit volume** |
| **= The number of atoms emitting photons per second /unit volume** |

Thereby, we can write, $(R_1) = (R_2) + (R_3)$

$$\text{i.e.} \quad B_{12}\,\rho(\nu)\,N_1 = A_{21}\,N_2 + B_{21}\,\rho(\nu)\,N_2$$

Or, $\rho(\nu) = \dfrac{A_{21}N_2}{(B_{12}N_1 - B_{21}N_2)}$

**Dividing the above equation by $B_{21}.N_2$, we get,**

$$\rho(\nu) = (A_{21} / B_{21}) / \left[\frac{B_{12}\,N_1}{B_{21}\,N_2} - \frac{B_{21}\,N_2}{B_{21}\,N_2}\right]$$

**Thereby,** $\rho(\nu) = \dfrac{A_{21}}{B_{21}} \dfrac{1}{\left(\frac{B_{12}\,N_1}{B_{21}\,N_2} - 1\right)}$ ……. **(4)**

**Now, we know that**

$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}} = e^{(E_2-E_1)/kT} = e^{h\nu/kT}$$

**Where (h = Planck's constant: k = Boltzmann's constant)**

Putting the values in equation (4), the values of $N_1/N_2$, we have,

$$\rho(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{B_{12}}{B_{21}} e^{h\nu/kT} - 1\right)} \quad \text{.... (5)}$$

Now, for an ideal 2 level system, as we have considered, must result in a radiation similar to a black body radiation, hence ρ(ν) is given by Planck's Radiation law,

i. e. $$\rho(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{\left(e^{h\nu/kT} - 1\right)} \quad \text{........ (6)}$$

# Relation between Einstein's Co-efficients

Comparing, equations **(5) & (6)**, we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{and} \quad B_{12} = B_{21} \qquad \text{----- (7)}$$

Where c = speed of light

**These relations are known as Einstein's Relations.**

We can observe that :

R = Rate of spontaneous Emission / Rate of Stimulated Emission

Or, $R = A_{21} N_2 / [\, B_{21} N_2\, \rho(\nu)] = \exp(h\nu / KT) - 1$

**If R>>1,** probability of stimulated emission is negligible compared to spontaneous emission.

**If R<<1**, probability of stimulated emission predominates.

So, stimulated emission is negligible compared to spontaneous emission in OPTICAL region.

## Let's discuss the physical significance of these relations:

1. We have $B_{12} = B_{21}$, (from equation 7) which states that the probability of stimulated emission is numerically equal to the probability of stimulated absorption. So stimulated emission is an reverse process of stimulated absorption, but their rates are not same because stimulated emission is proportional to the no of atoms per unit volume in $E_2$ excited state, i.e $N_2$ while stimulated absorption is proportional to the no of atoms per unit volume in $E_1$ ground state, i.e $N_1$.

2. Again, we have from equation (7),

$$A_{21} / B_{21} = 8\pi h\nu^3 / c^3,$$

Therefore, $B_{21} = (A_{21} \,.\, c^3) / 8\pi h\nu^3$

Which implies that the co-efficient of Stimulated Emission $B_{21}$ is inversely proportional to the third power of frequency of radiation.

**3. R' = Rate of Stimulated Emission / Rate of Stimulated Absorption**

$$R' = [B_{21} N_2 \rho(\nu)] / [B_{12} N_1 \rho(\nu)] = N_2 / N_1$$

**This shows, at thermal equilibrium, the number of atoms per unit volume $N_1$ in ground state is very large in comparison to number of atoms in excited state , i.e. $N_1 >> N_2$.**

**But to achieve higher rate of stimulated emission we should have $N_2 >> N_1$.**

# Conditions for achieving Light amplification

**In practice, absorption and spontaneous emission always occurs together with stimulated emission. The laser operation is achieved when simulated emission exceeds in a large way than the other two processes.**
**A light amplification only occurs when these 3 conditions are fulfilled, they are as follows:**

1. **Population at the excited level should be large than that of lower energy level ($N_2 >> N_1$). Artificial situation known as Population Inversion is to be created in the medium.**

2. **The ratio of $B_{21}/A_{21}$ should be very large and this can be achieved by choosing a metastable state at the higher level..**

3. **The energy density of radiation $\rho(\nu)$ should be very large. Large number of photons in the active medium are required. It is made larger by enclosing the emitted radiation in the optical resonant cavity formed by 2 parallel mirrors. The radiation is reflected many times till the photon density reaches to a very high value and stimulated emissions are triggered on a large scale.**

# Multiplication of Photons in LASER

- **When a photon strikes an excited atom, the single photon transforms into two identical photons. Those two photons can then strike other excited atoms, resulting in 4 photons and then 8 and so on. This is how amplification of light happens and we get a coherent monochromatic highly intense laser beam.**

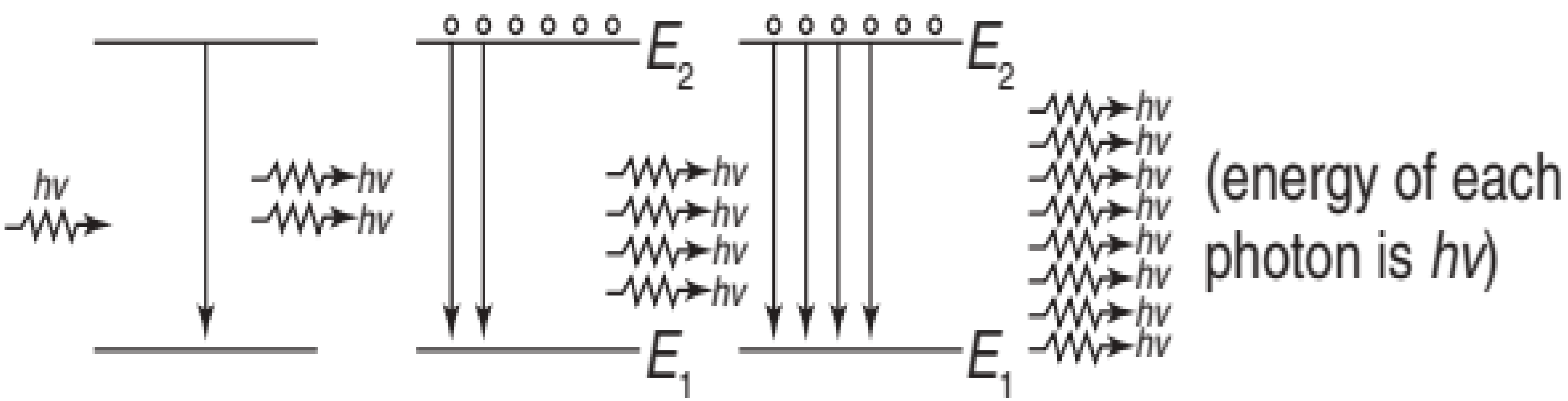
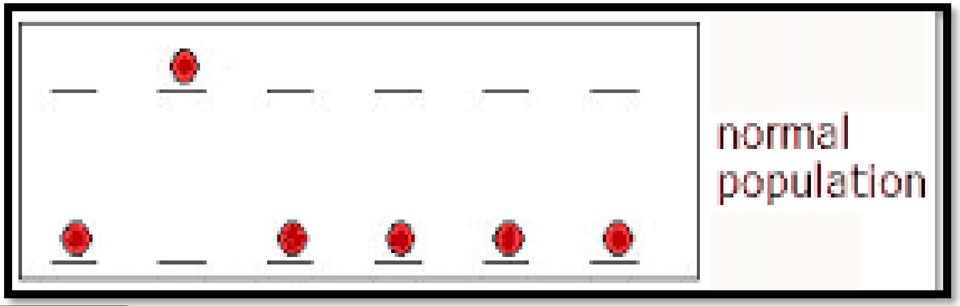
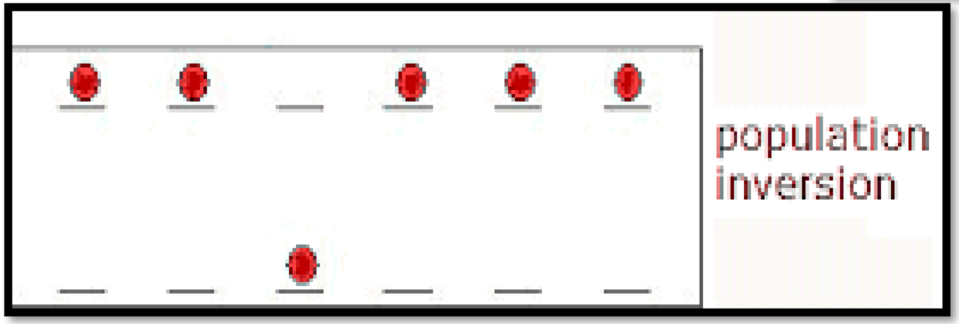



Image Source: Engineering Physics by H K Malik and A K Singh

# Population Inversion

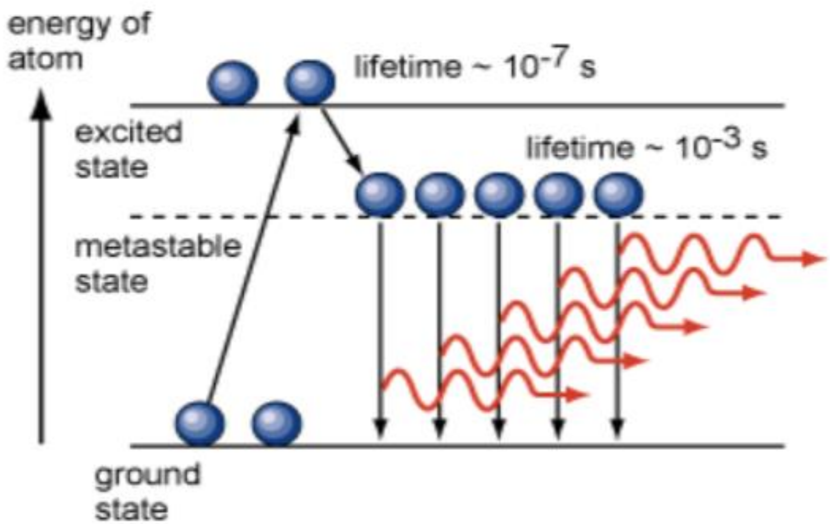



**Definition : Population Inversion is an artificial non-equilibrium process/condition of the material that is established by generation of large numbers of atoms in the higher energy state than ground state (N2>>N1).This is achieved by pumping.**

[At ordinary conditions N1 > N2, i.e., the population in the ground or lower state is always greater than the population in the excited or higher states.]

# Metastable States




**Metastable states** are excited states which have relatively longer lifetime due to slow radiative or non-radiative decay.

Population inversion can be established if the lifetime of the excited states (metastable) is $10^{-6}$ to $10^{-3}$ s which is considerably more than the lifetime of the ordinary excited state levels.

Metastable state can be obtained in a crystal system containing impurities. These levels lie in the forbidden band gap of the host crystal.

# Spontaneous Emission Vs. Stimulated Emission

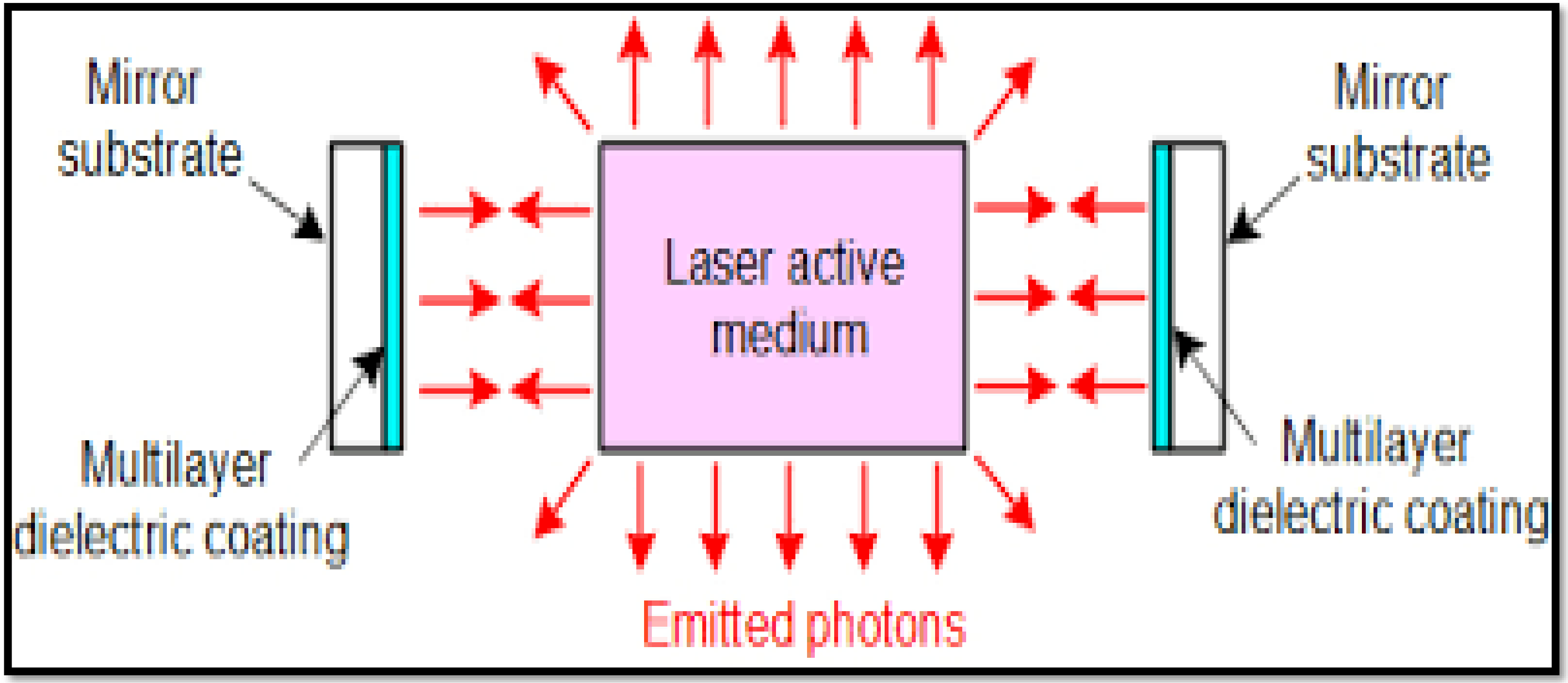
| NO: | Spontaneous emission | Stimulated emission |
|---|---|---|
| 1. | The spontaneous emission was postulated by Bohr | The stimulated emission was postulated by Einstein |
| 2. | Additional photons are not required in spontaneous emission | Additional photons are required in stimulated emission |
| 3. | One photon is emitted in spontaneous emission | Two photons are emitted in stimulated emission |
| 4. | The emitted radiation is polychromatic | The emitted radiation is monochromatic |
| 5. | The emitted radiation is incoherent | The emitted radiation is coherent |
| 6. | The emitted radiation is less intense. | The emitted radiation is highly intense |
| 7. | The emitted radiation have less directionality Example: light from sodium or mercury lamp | The emitted radiation have high directionality Example: light from laser source. |

# Components of Laser

**Laser requires three Components:** **1) Active Medium/Gain Medium**

**2) Pumping scheme**

**3) Optical Cavity/Resonator**



# Components of Laser: Active Medium

## 1) Active Medium:

- The fundamental component of laser is material medium which is known as an Active/Gain Medium.
- This active medium can be solid, liquid or gaseous in nature. After the invention of ruby laser (solid state laser), other active media such as glasses, plastics, liquids, gases and even plasma were used.
- In Active Medium, only a small fraction of the atoms are responsible for the light amplification known as **ACTIVE CENTRES**. The rest part of the medium behaves as a Host and supports the active centres in the bulk.
- An active medium should possess good mechanical, thermal and optical properties as well as transparency to stimulated radiation and laser output.

# Components of Laser : Pumping techniques

**2) Pumping techniques:**

- To produce population inversion, the method of raising the atoms from lower energy state to higher energy state is called **pumping.**

- The most commonly used pumping methods are:

I. Optical pumping

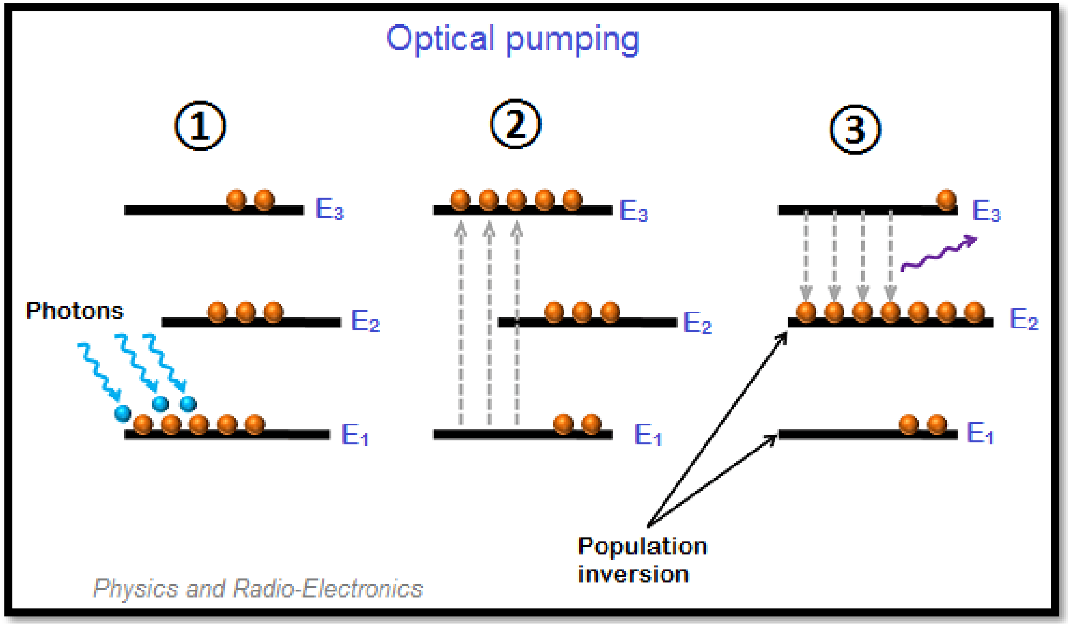
II. Electrical discharge pumping

III. Chemical pumping

# Components of Laser : Pumping techniques

## I. Optical pumping:

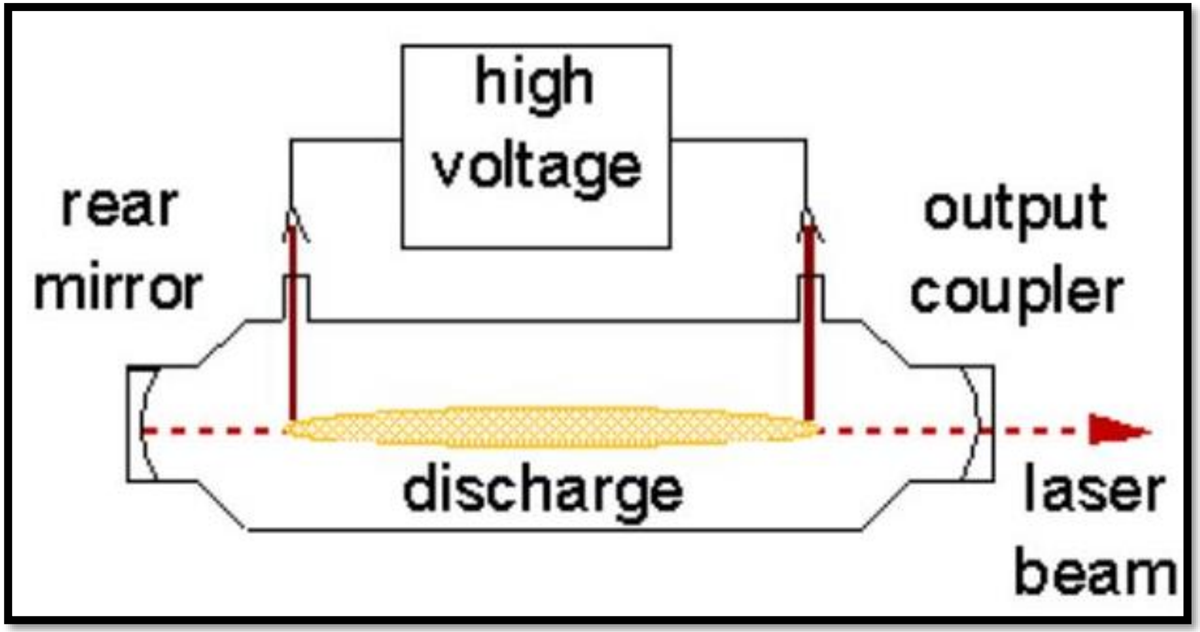
- Majorly used in solid state laser.
- Xenon flash tubes are used for optical pumping.
- Examples of optically pumped lasers are ruby, Nd: YAG Laser



# Components of Laser : Pumping techniques

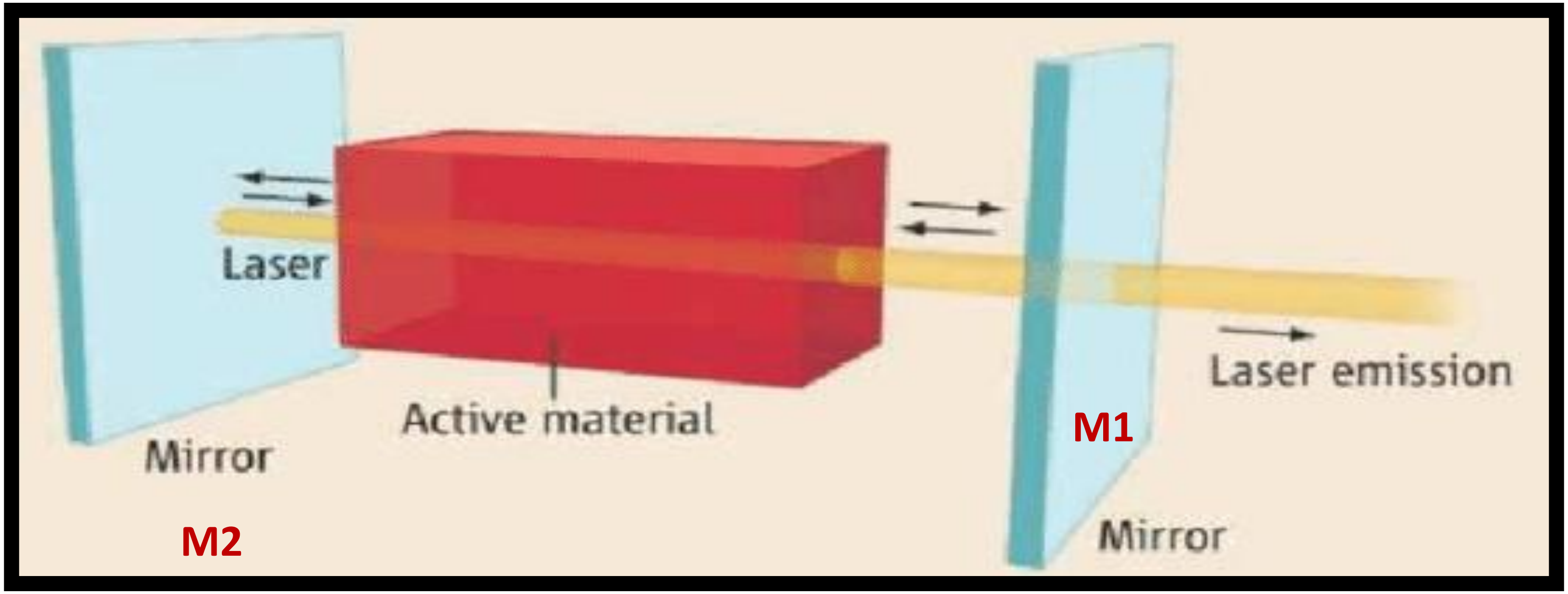
## II. Electrical discharge pumping

- Electrical discharge pumping is used in gas lasers.
- Electrical discharge pumped lasers are He-Ne laser, CO2 laser, argon-ion laser, etc



# Components of Laser: Optical Cavity/Resonator

**Optical resonator** is a pair of plane parallel mirrors set on optic axis which defines the direction of laser output. One is perfectly reflecting mirror and the other surface is partially reflecting mirror. In this resonant cavity, the intensity of photons is raised tremendously through stimulated emission process (amplification of stimulated photons).



# Working of Laser: Lasing Action

- **The atoms excited with the light of suitable wavelength jumps from ground states $E_1$ to excited state $E_2$ by absorbing incident photons. They can't remain in excited state for more than $10^{-8}$ s and drops back by spontaneous emission.**

- **During this, many of the atoms get dropped in the metastable state where the atoms can stay for a longer time than that of its excited state as the lifetime of an atom in metastable state is greater than its excited state. So, due to their longer stay, a large number of atoms exist in the metastable state than that in ground state indicating population inversion ($N_2 >> N_1$).**

- **When population inversion is achieved using pumping, then one or more atoms may be excited spontaneously by emitting a photon hv. This photon acts as a stimulant and is made to strike the atoms present in the metastable state.**

- **The atoms thus gets excited and it is stimulated to emit a photon of same energy as that of the stimulating photon.**

# Working of Laser: Lasing Action

- As the both stimulated and stimulating photons passes through active medium, it initiates the process of stimulated emission in the active medium by repeated stimulated emission with the help of optical resonator.

- Photons travelling parallel to the optic axis of the resonator are partially reflected by M1 and transmitted part of beam gives laser output. The photons emitted in the other direction will traverse a relatively short path length in the material and die out soon.

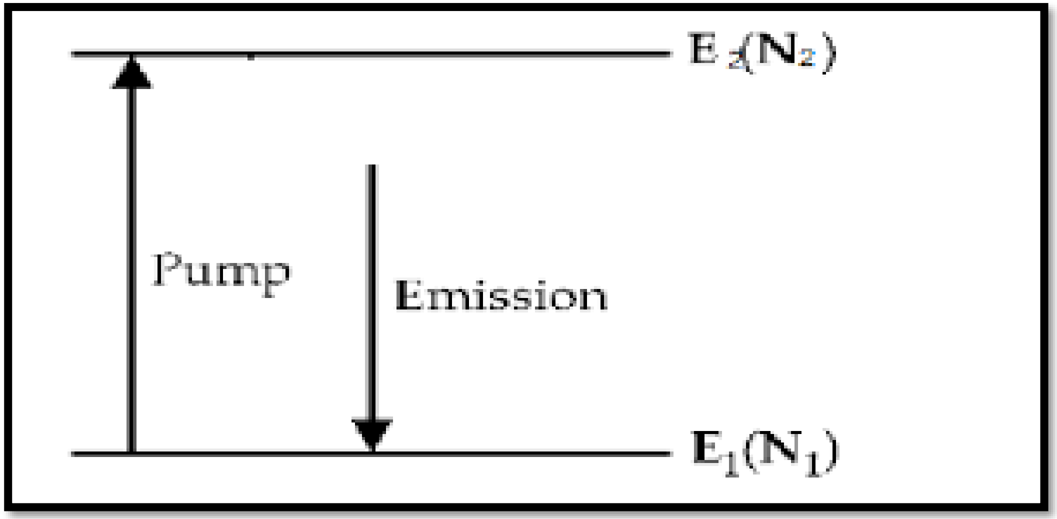
- Reflected photons acts as a positive feedback for active medium as they enter again into the active medium and initiates further stimulated emission. These photons are totally reflected back by the second totally reflecting mirror M2 into active medium and their number increases due to further stimulated emission.

- Multiplication of photons occur and light gets amplified. These photons have same energy, direction and phase as that of incident photons. **Hence, a highly intense , monochromatic and unidirectional LASER light is obtained.**

# Schemes for Population Inversion

## I. Two-level System:

- Two energy level E1 and E2
- Einstein coefficients (or constants) for the upward ($B_{12}$) and downward ($B_{21}$) transitions can be found easily and are equal, i.e.$B_{12} = B_{21}$.
- **Population inversion cannot be achieved in two level system.**
- **Solution: Metastable state**
- Metastable state : an energy state where electrons can stay for a longer time.



# Population Inversion is not possible in Two-level System

- Consider the case of two-level system having energies $E_1$ and $E_2$ such that $E_2 > E_1$. We can easily find that the Einstein coefficients for the upward ($B_{12}$) and downward ($B_{21}$) transitions are equal, i.e., $B_{12} = B_{21}$.
- It means, even with strong pumping, the population distribution in upper and lower levels can only be made equal.
- This is due to the fact that the probability for raising an electron to the upper level (stimulated absorption) and probability of falling back of an electron to the lower level (stimulated emission) are exactly the same.
- In other words, we can say that the numbers of electrons going up and coming down will be the same, and both the levels will be equally populated.
- So, we cannot achieve population inversion in the case of two energy levels system. Therefore, It requires either three or four level systems to attain population inversion.

# Schemes for Population Inversion

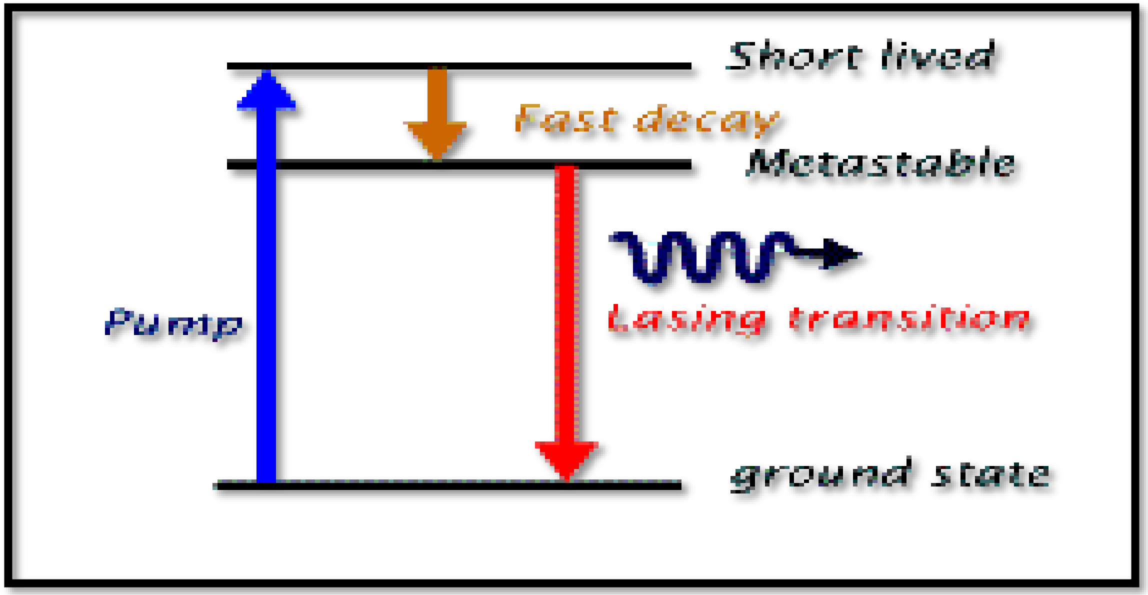
## II. Three-Level System:

- Atoms are pumped to an excited state $E_3$.
- In addition to this excited state (e.g. $E_3$) the system has a metastable state (e.g. $E_2$).
- $E_3$ has short life time and the atoms transits from the upper level $E_3$ i.e. they spontaneously decay into the metastable state $E_2$.
- This transition is usually weakly radiative or non-radiative (energy is released to the lattice which give rise to phonons).

# Schemes for Population Inversion

## II. Three-Level System:

- Atoms decay from the higher level to the metastable level state, which results in a population inversion between the metastable level and ground state.
- Population inversion can only be achieved by pumping to a higher level, followed by rapid radiative or non-radiative transfer to the upper laser level.



# Schemes for Population Inversion

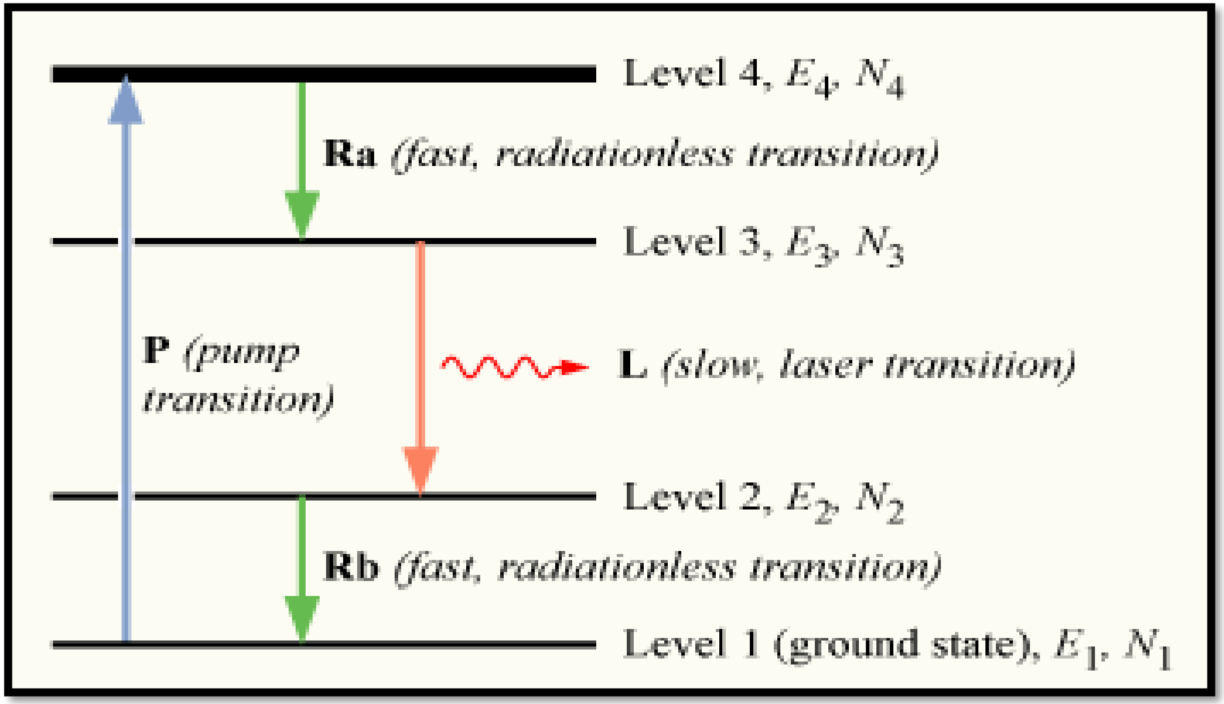
## III. Four-Level System:

- Four energy levels, $E_4 > E_3 > E_2 > E_1$ with corresponding populations of N1, N2, N3 and N4.
- The atoms are excited by optical pumping from the $E_1$ ground state in the $E_4$ level.
- By rapid decay (non-radiative transition) they come to the metastable energy level $E_3$.
- The population inversion takes place between level $E_3$ with level $E_2$
- Lifetime of the transition of $E_3$ to $E_2$ is long compared to $E_4$ to $E_3$.

# Schemes for Population Inversion

## III. Four-Level System:

- Atoms in the metastable state $E_3$ start spontaneous and stimulated emission in the $E_2$ energy level.
- The transition from the $E_2$ energy level $E_1$ is just as fast as the $E_4$ level.
- This rapidly de-energized atom leads to a negligible population in the $E_2$ state and maintains the population inversion..



# Comparison between four level and three level laser

- ✓ **The large pumping power is required to establish population inversion in three level pumping scheme while relatively small pumping power is required in four level scheme.**

In the three-level pumping scheme, the lower level involved in population inversion is ground level. Therefore, more than half of the ground level atoms have to be send up to the upper level. As the number of atoms in the ground level is very large, high pump power is required to establish the required population inversion.

While in the four-level pumping scheme, the lower level involved in population inversion is ideally empty and population inversion condition is readily established even if a smaller number of atoms reach at the upper level.

- ✓ **In case of three level scheme, light output is in pulsed form, while in four level scheme, light output is in *continuous wave* (CW) form.**

In three level pumping scheme, once stimulated emission commences, the population inversion condition changes to normal population condition. Laser output ceases as soon as the excited atoms drop to the ground level. Lasing occurs again only when the population inversion is re-established. The light output therefore is a pulsed output.

In four level scheme, the condition of population inversion can be held without interruption and light output is obtained continuously so in continuous wave (cw) mode.

# RUBY LASER (Solid State Laser)

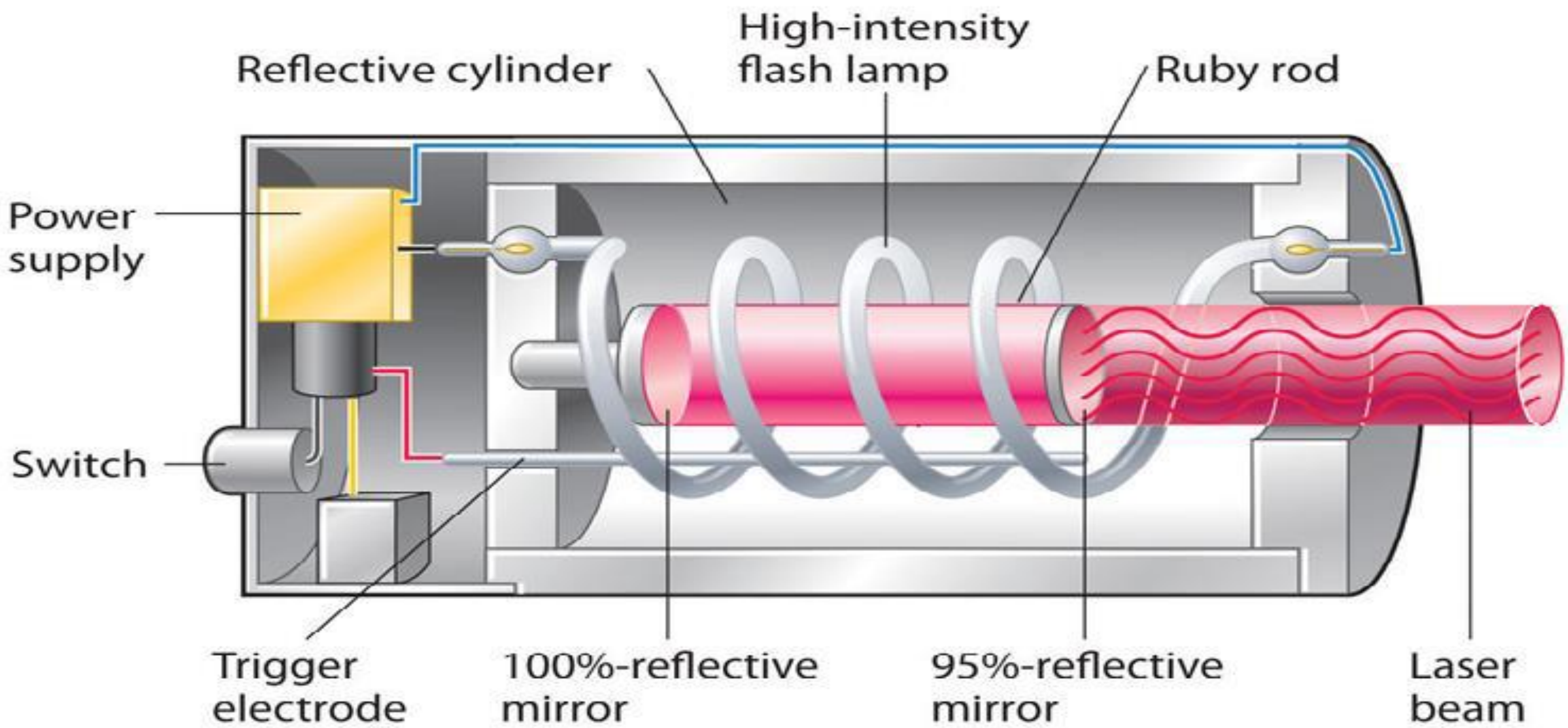



**Figure 1(a)** **Ruby Laser belongs to the class of solid state Lasers**

-

# RUBY LASER – Description

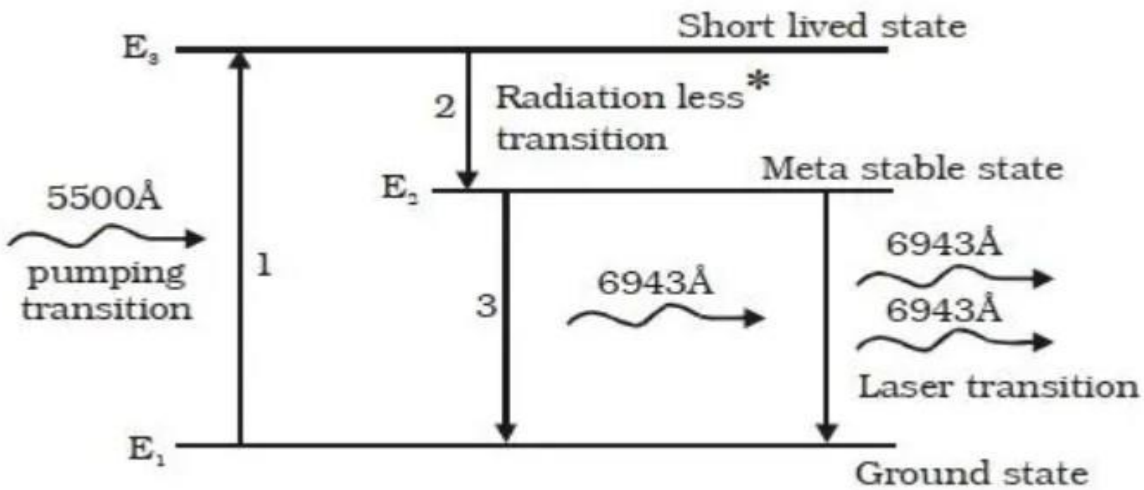
- ✓ **A solid state laser is one in which the active centres are fixed in a crystal or glassy material. Solid state lasers are electrically non-conducting. They are also called Doped insulator lasers. Historically, the ruby laser was the first laser invented in 1960 by T. Maiman, USA.**

- ✓ **Ruby laser rod is a synthetic ruby crystal Al2O3 crystal, doped with chromium ions at a concentration of about 0.05% by weight Cr 3+ ions are the actual active centres and have a set of three energy levels suitable for realizing laser action whereas aluminium and Oxygen atoms are inert.**

- ✓ **Ruby laser is in the form of cylindrical rod having size 2 to 30 cm in length and 0.5 to 2 cm in diameter whose both ends are optically flat. Its ends are grounded and polished such that the end faces are exactly parallel and are also perpendicular the axis of the rod. One face is silvered to achieve 100% reflection while the other is silvered to give 10% transmission & 90%. reflection.**

- ✓ **The Laser rod is surrounded by a helical photographic flash lamp filled with xenon. Whenever activated by the power supply the lamp produces flashes of white light. The space between two faces is known as the resonant cavity in which the light intensity can be built by multiple reflections and through stimulated emission. The ruby rod is wound by a helical flash light tube.**

# RUBY LASER – Working Mechanism




energy level diagram of ruby laser

**Figure 1(b)**

**Ruby laser uses a three-level pumping scheme.**

**In this laser, chromium ions are the active centres which are responsible for the laser transitions.**

**Here some of the $Al^{3+}$ ions in the crystal lattice are replaced by $Cr^{3+}$ ions.**

**The $Al_2O_3$ is the host crystal and Cr atoms are called activator atoms. Chromium ion gives the transparent $Al_2O_3$ crystals a pink or red-colour depending upon their concentration.**

# RUBY LASER – Working Mechanism

**A simplified energy level diagram of chromium ions is shown in figure 1b above.**

1. In the normal state, most the chromium ions in the ground state E1. When light from flash lamp is activated, (~λ = 5500 Å) is made to fall on Ruby Rod, the incident photons are absorbed by Chromium ions and rise to the excited state $E_3$.
2. The energy levels in this bands have a very small lifetime ($\sim 10^{-9}$ s). Hence, the excited $Cr^{3+}$ ions rapidly loose some of the energy to the crystal lattice & undergo non radiative transitions. They quickly drop to the levels $E_2$.
3. Released energy by the excited ions are absorbed by the lattice in which it is embedded and gets dissipated in the from of heat. $E_2$ is the metastable state having a lifetime of approximately 1000 times more than the lifetime of $E_3$. Therefore, $Cr^{3+}$ ions accumulate at $E_2$ level and population inversion is established between $E_2$ and $E_1$ levels.

# RUBY LASER – Working Mechanism

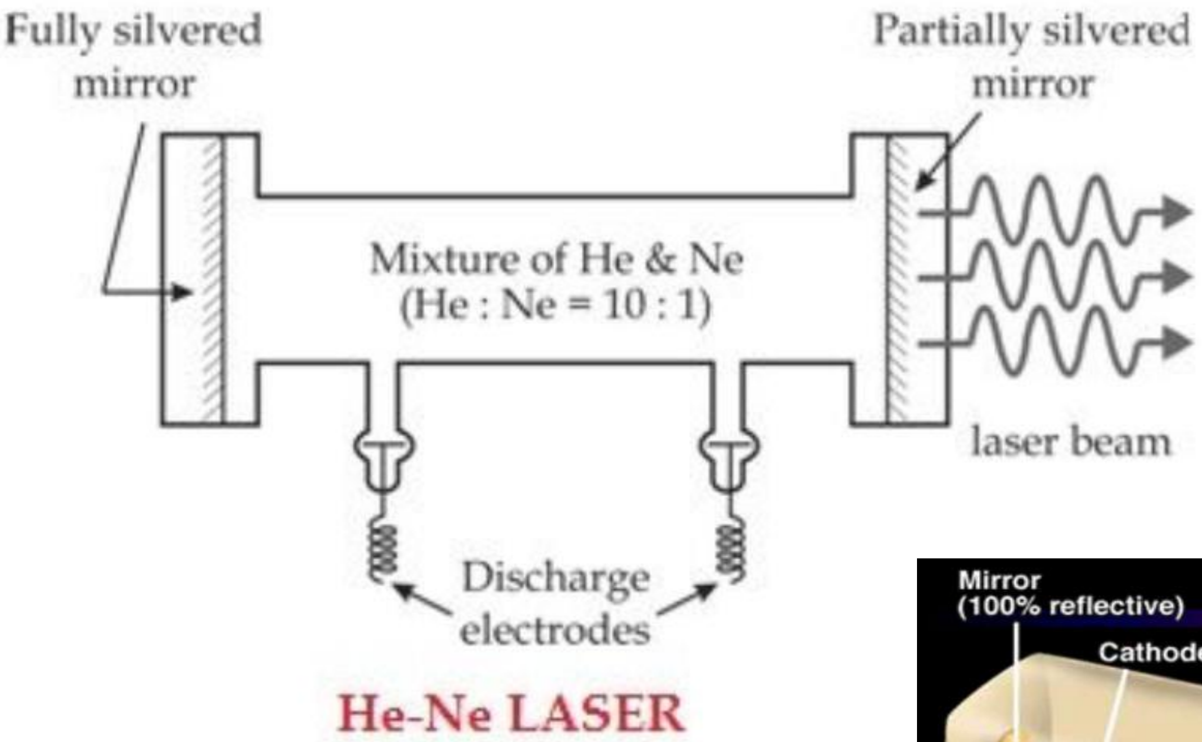
4. When an excited ion passes spontaneously from the metastable to ground state, it emits a photon of wavelength **6943 Å**.
This photon travels parallel to the axis of ruby rod and stimulates the surrounding ions present in the metastable state then by stimulated emission other photons are emitted which are in phase of stimulating atoms photons. These photons (6943 Å) travelling along the axis of Ruby rod are repeatedly reflected by the end mirrors M1 and M2 and light amplification takes place. A strong, coherent and intense beam emerges out of front mirror.

## RUBY LASER IS A PULSED LASER

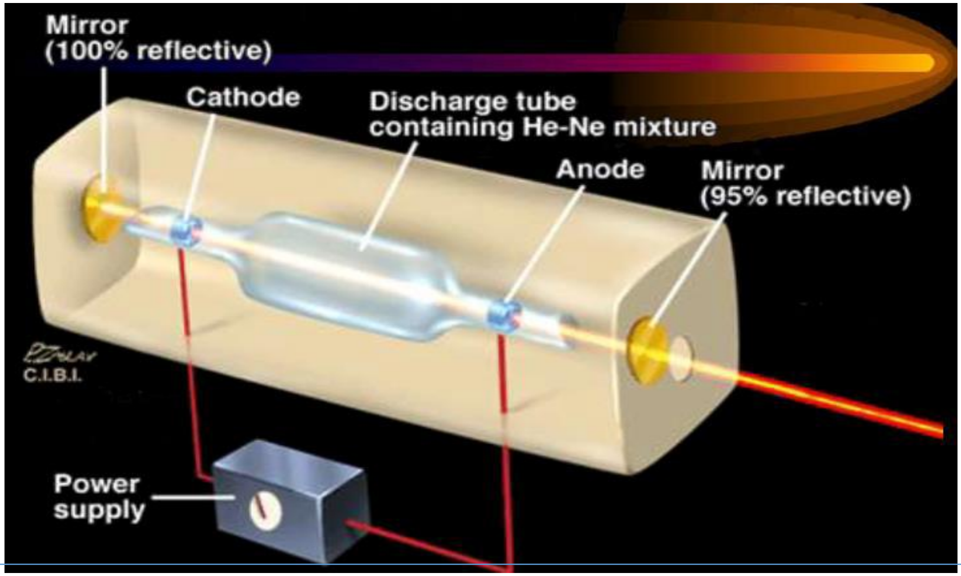
Ruby laser doesn't operate throughout this period. Its output occurs in the form of irregular pulses of microsecond duration. It is because the stimulated transition occur faster than the rate at which population inversion is maintained on the crystal. Once stimulated, transition commence, the metastable state $E_2$ gets depopulated very rapidly and at the end of each small pulse, the population at $E_2$ has fallen below the threshold value required for sustained emission of light.
As a result, lasing ceases & laser becomes inactive. The next pulse appears after the population inversion is once again restored. The process repeats.
The Ruby Laser operates at about 1% efficiency & it may produce a laser beam of 1 mm to 25 mm in diameter in pulses.
**ADVANTAGE**: Very strong beam and its construction is simple & operation is easy.
It is Known as PRACTICAL LASER.

# He-Ne Laser

Figure 2(a)




He-Ne is a Four level LASER System



# He-Ne Laser- Construction

He-Ne Laser is the first Continuous Gas laser and was made by A. JAVAN, Benett & Herriott in 1961, to overcome the drawback of pulsed form of RUBY LASER.

1) It consists of a quartz tube having the size about 1.5 cm in diameter and about 20-40 cm in length.
2) The both ends of the lube are sealed by optical plane and parallel mirrors, one of them being partially silvered (90% reflective) and the other one is fully silvered (100%, reflective).
3) In this laser system, a quartz tube is filled with a mixture of Helium and Neon gas in the ratio 10:1 respectively at a pressure of about 0.1 mm of mercury. This mixture acts as the active medium.
4) On the axis of the tube 2 mirrors are arranged externally which form the Fabry-Perot optical resonator.

# He-Ne Laser: Working Mechanism

**He-Ne Laser employs a four-level pumping scheme. The energy levels of Helium and neon are shown beside [Figure 2(b)].**

- ✓ **When the power is switched on, a high voltage about 10 KV is applied across the gas.**
- ✓ **It is sufficient to ionize the gas. The electrons and the ions produced in the process of discharge are accelerated towards the anode and cathode respectively.**

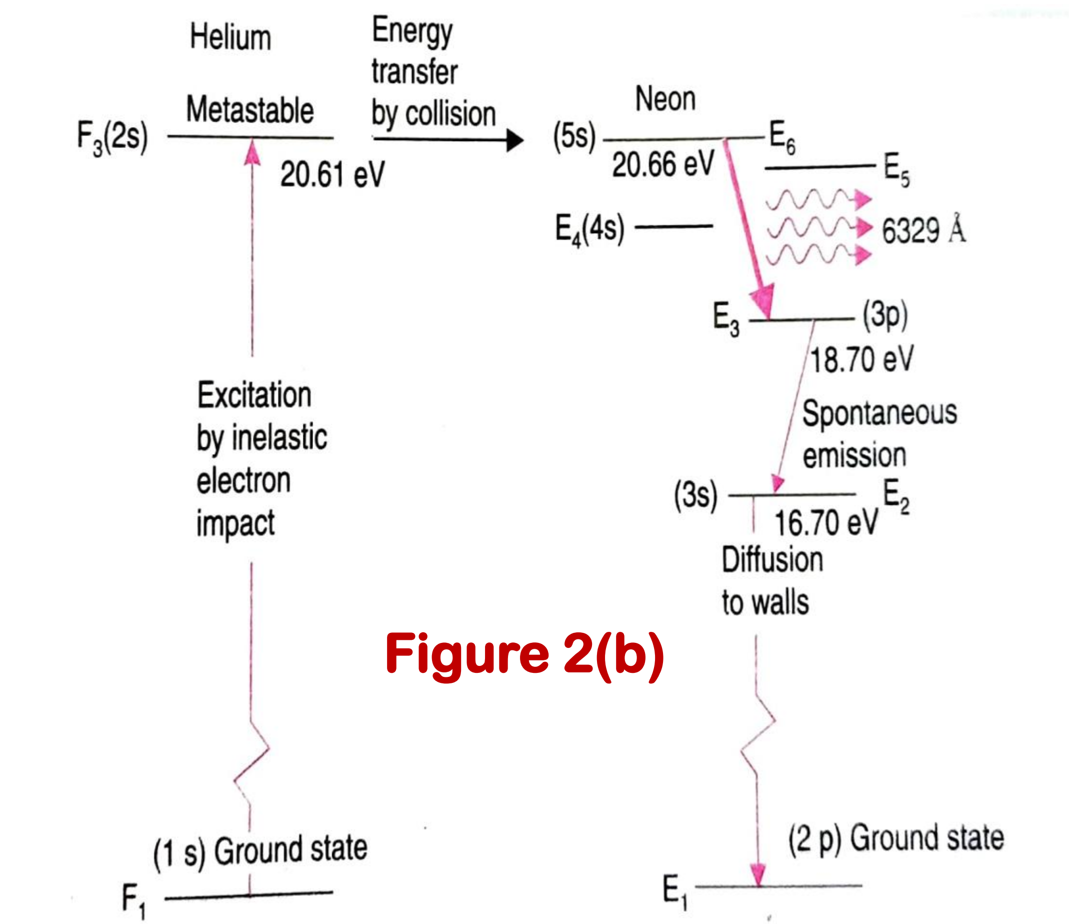



**Figure 2(b)**

Energy level diagram for a helium-neon laser. Only the relevant energy levels are shown.

# He-Ne Laser: Working Mechanism

- ✓ The energetic electrons excite helium atoms through collisions. One of the excited levels of helium F3 ($2'S_0$) is at 20.61 eV above the ground level. It is a metastable level and the excited helium atom cannot return to the ground level through spontaneous emission.

- ✓ However, it can return to the ground level by transferring its excess energy to a neon atom through collision. Such an energy transfer can take place when the two colliding atoms have identical energy levels. Such an energy transfer is known as **resonant energy transfer.**

# He-Ne Laser: Working Mechanism

- ✓ One of the excited levels of neon E6 (5s) is at 20.66 eV, which is nearly at the same level as F3 of helium atom. Therefore, resonant transfer of energy can occur between the excited helium atom and ground level neon atom. The kinetic energy of helium atoms provides the additional 0.05 eV required for excitation of the neon atoms. Helium atoms drop to the ground state after exciting neon atoms. This is the pumping mechanism in He-Ne laser. The role of helium atoms is to excite neon atoms and to cause population inversion.

- ✓ The probability of energy transfer from helium atoms to neon atoms is more, as there are 10 helium atoms per 1 neon atom in the gas mixture. The probability of reverse transfer of energy from neon to helium atom is negligible.

- ✓ The upper state of neon atom $E_6$ is a metastable state. Therefore, neon atoms accumulate in this upper state. The $E_3$ (3p) is sparsely populated at ordinary temperatures, and a state of population inversion is readily established between $E_6$ and $E_3$ levels. Random photons emitted spontaneously prompt stimulated emission and lasing occurs. **The transition $E_6$ to $E_3$ generates a laser beam of red colour of wavelength 6328 Å.**

- ✓ From the level $E_3$ the neon atoms drop to $E_2$ (3s) level spontaneously. $E_2$ level is however a metastable state. Consequently, neon atoms tend to accumulate at $E_2$ level. It is necessary that these atoms are brought to the ground state $E_1$(2p) quickly; otherwise the number of atoms at the ground state will go on diminishing and the laser ceases to function.

# He-Ne Laser: Working Mechanism

- ✓ The only way of bringing the atoms to the ground state is through collisions. If the discharge tube is made narrow, the probability of atomic collisions with the tube walls increases. Because of frequent collisions with the walls, the neon atoms rapidly drop to the ground level and will be available for excitation once again.

He-Ne laser operates in CW mode and is widely used in laboratories as a monochromatic source. It is also widely used in laser printing, bar code reading, etc.

# Semiconductor diode Laser

- ✓ A semiconductor diode laser is a specially fabricated PN junction device, which emits coherent light when it is forward biased. <u>It was demonstrated in 1962 by US groups led by R.Hall.</u>
- ✓ It is made from <u>Gallium arsenide (GaAs) </u>which operated at low temperatures and emitted light in the near IR region.
- ✓ The PN-junction lasers can emit light almost anywhere in the spectrum from UV to IR. Diode lasers are remarkably small in size (0.1 mm long). They have high efficiency of the order of 40%. Modulating the biasing current easily modulates the laser output. They operate at low powers.
- ✓ In spite of their small size and low power requirement, they produce power outputs equivalent to that of He-Ne lasers. The chief advantage of a diode laser is that it is portable.
- ✓ Because of the rapid advances in semiconductor technology, diode lasers are mass produced for use in optical fibre communications, in CD players, CD-ROM drives, optical reading, high speed laser printing etc.

# Semiconductor Laser: Construction

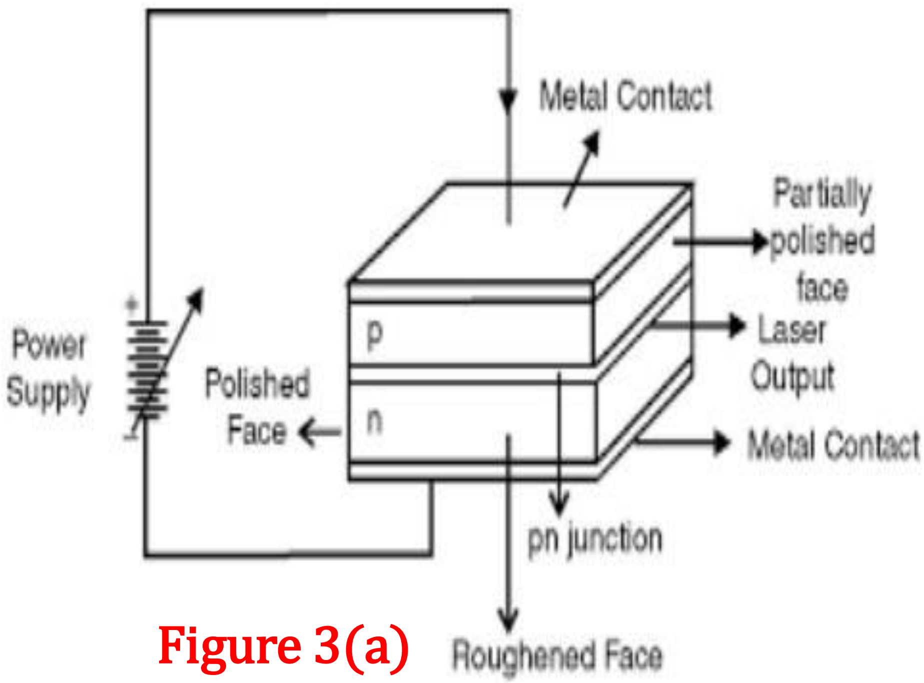



Figure 3(a)

- A simple diode makes use of the same semiconductor material, say, GaAs on both sides of the junction.
- Starting with a heavily doped n-type GaAs material, a p-region is formed on its top.
- The diode is extremely small in size. Typical diode chips are 500 μm long and about 100 μm wide and thick.
- The top and bottom faces are metallized and metal contacts are provided to pass current through the diode.

- The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The polished faces constitute the Fabry Perot resonator.
- The two remaining sides of the diode are roughened to eliminate lasing action in that direction. The entire structure is packaged in small case like the metal case.

# Semiconductor Laser: Working

- Population inversion is required for producing stimulated emission.
- A semiconductor cannot be regarded as two-level atomic system. It consists of electrons and holes distributed in the respective energy bands. Therefore, laser action in semiconductors involves energy bands rather than discrete levels.
- In semiconductors, electrons are not associated with specific atoms but are injected into the conduction band from the external circuit.
- Therefore, the conduction band plays the role of excited level while the valence band plays the role of ground level. Population inversion requires the presence of a large concentration of electrons in the conduction band and a large concentration of holes in the valence band.

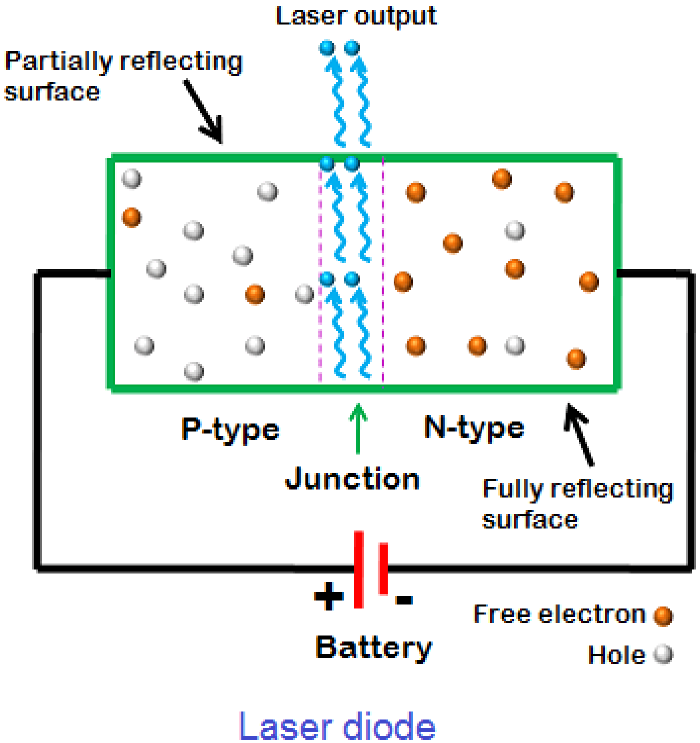


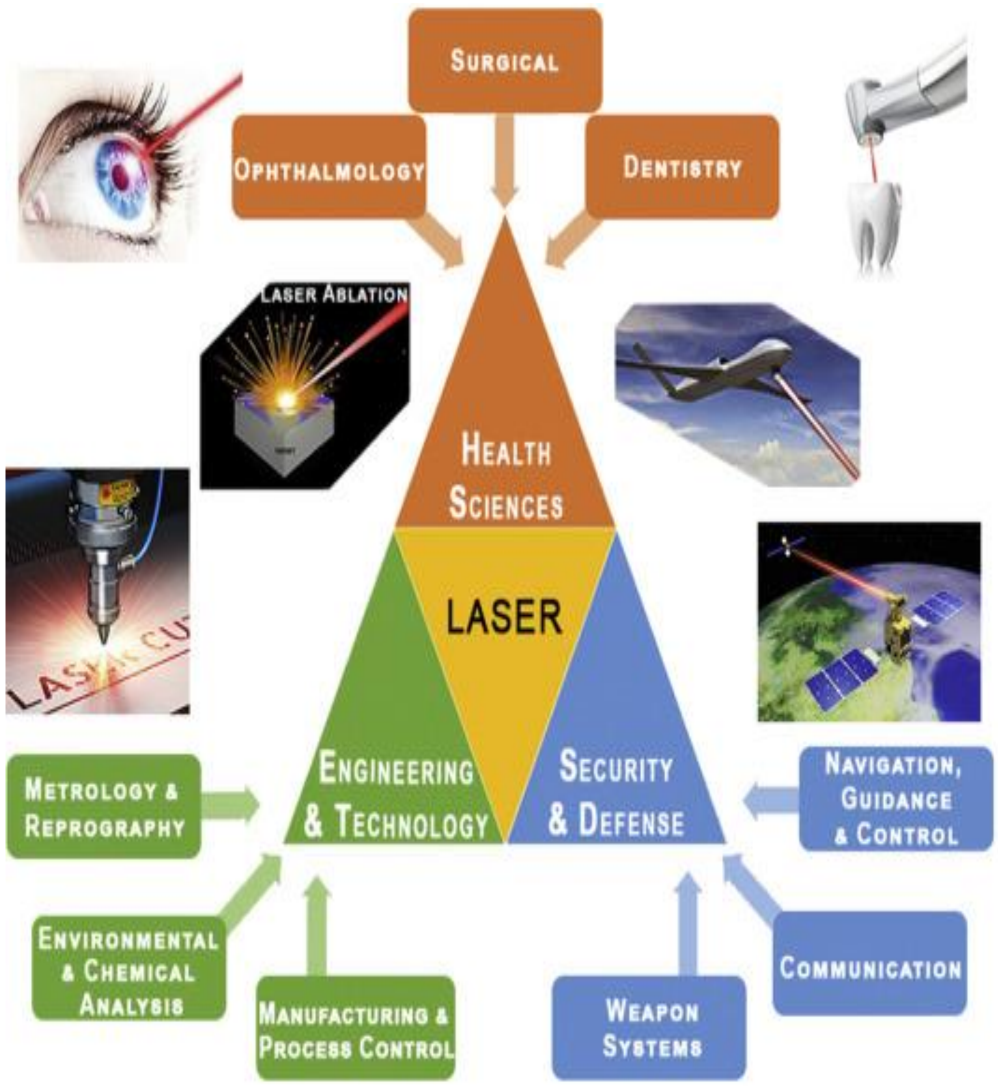

Figure 3(b)

A simple way to achieve population inversion is to use a semiconductor in the form of a PN-junction diode formed from heavily doped p-type and n-type semiconductors.

# Semiconductor Diode Laser: Working Mechanism

- At low forward current level, the electron-hole recombination causes spontaneous emission of photons and the junction acts as an LED.
- As the forward current through the junction is increased the intensity of the light increases linearly.
- However, when the current reaches a threshold value, the carrier concentrations in the junction region will rise to a very high value.
- As a result, the junction region contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band. Holes represent absence of electrons.
- Thus, the upper energy levels in the narrow region are having a high electron population while the lower energy levels in the same region are vacant.
- Therefore, the condition of population inversion is attained in the narrow junction region. This narrow zone in which population inversion occurs is called an **inversion region** or **active region**.
- Chance recombination acts of electron and hole pairs lead to emission of spontaneous photons. The spontaneous photons propagating in the junction plane stimulate the conduction electrons to jump into the vacant states of valence band.
- This stimulated electron-hole recombination produces coherent radiation.
- GaAs laser emits light at a wavelength of 9000 Å in IR region.

# APPLICATIONS of LASERS




✓ **Computers**

_ In LAN (local area network), data can be transferred from memory storage of one computer to other computer using laser for short time.

_ Lasers are used in CD-ROMS during recording and reading the data.

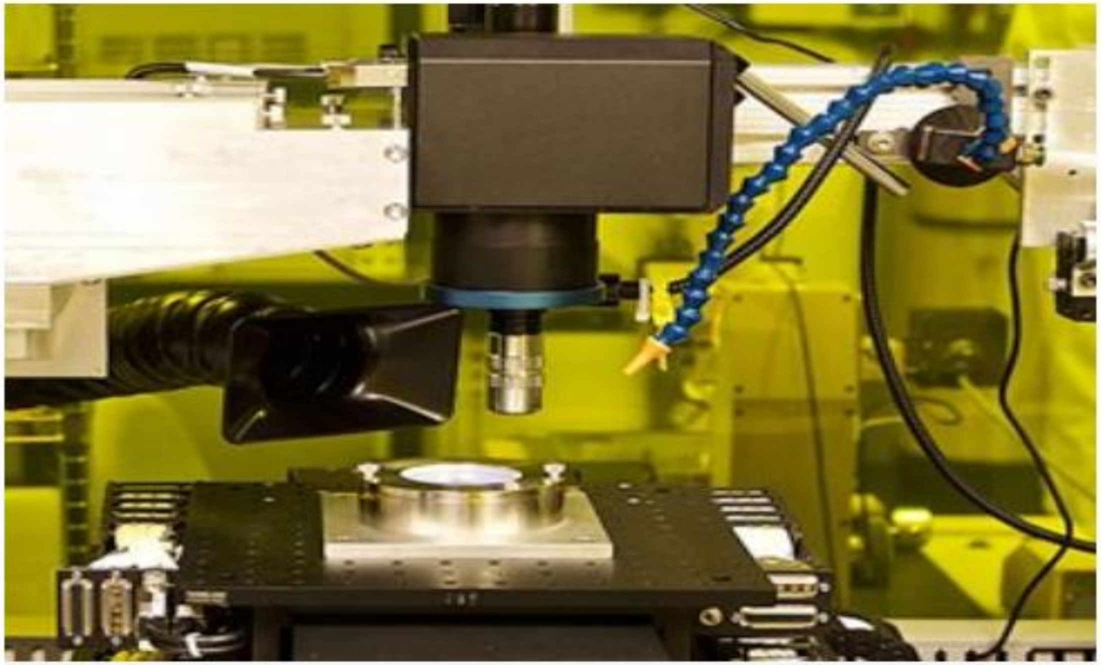
✓ **Communication:**

The light signals can be modulated with the information to be sent by either light emitting diodes or lasers using optical fibers.

## Surface Texturing

**Lasers are one of the most widely used tools in manufacturing and can create fine features that are difficult or impossible to make using traditional machining equipment.**

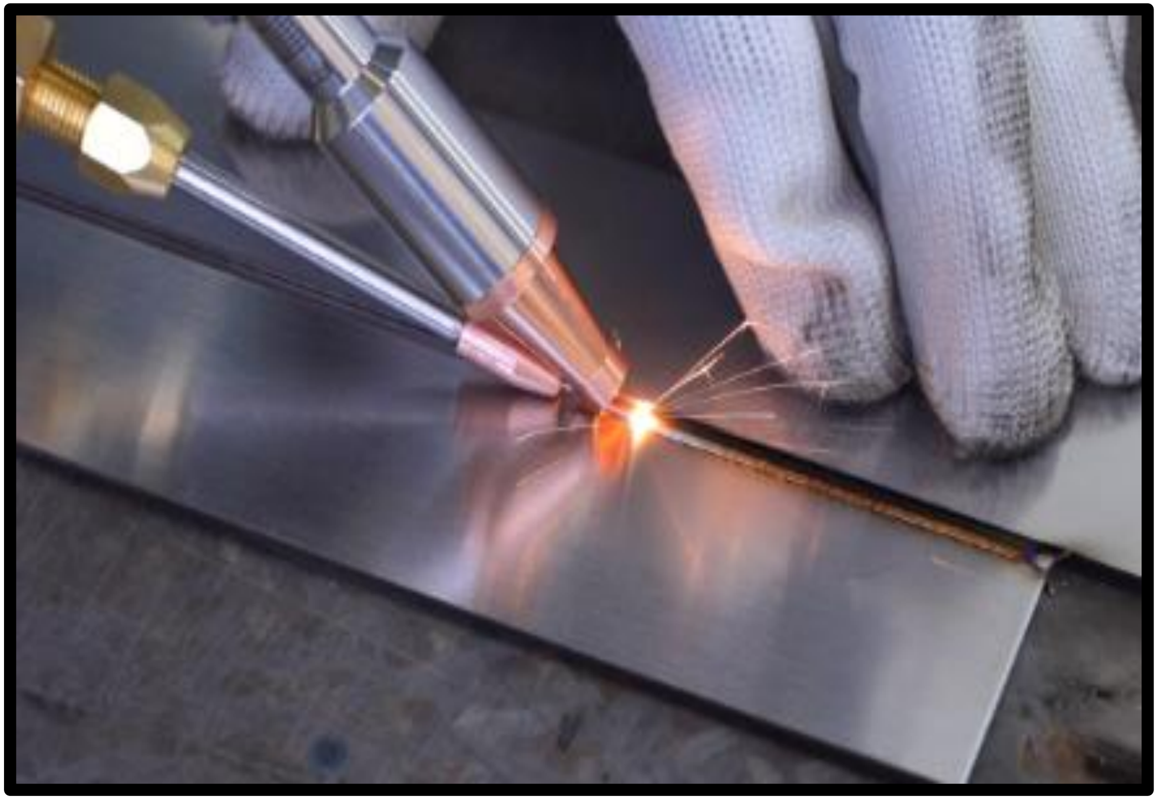
# Laser Drilling



Lasers are incredibly accurate at drilling micron-sized holes in a wide range of materials. Image: Laser Light

**This process focuses the laser beam to create holes in materials involving melting and vaporization of materials to form a hole.**

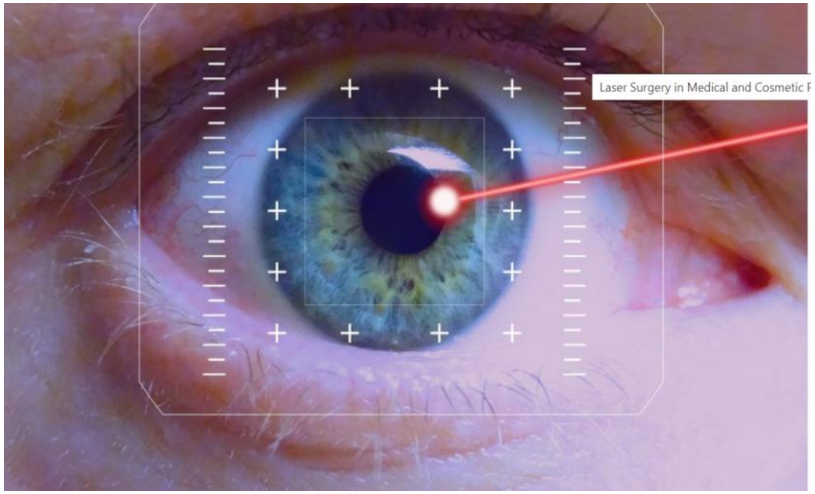
# Laser Welding



This process is especially effective for products with complex geometries or dissimilar materials that are difficult to join together

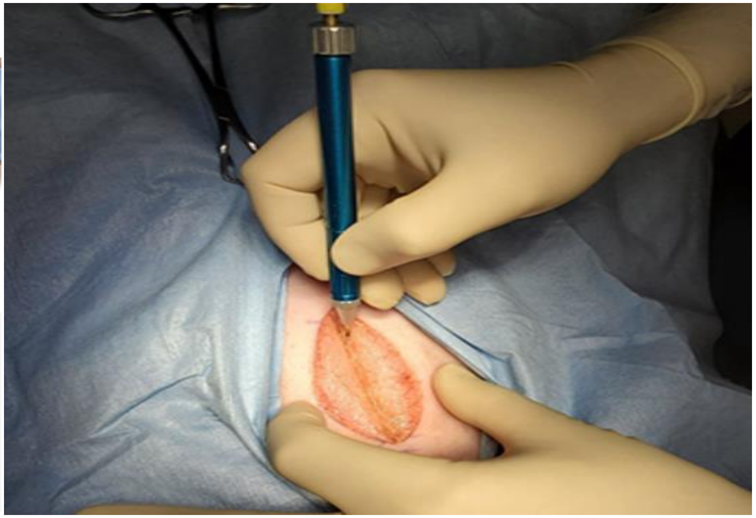
# Laser cutting

# Lasers in Medical sectors




- ✓ **Medical uses**: Lasers are used in retinal treatment, dental procedures, delicate surgeries to cut blood-rich tissue such as the liver etc. Pulsed neodymium laser is employed in the treatment of liver cancer. Argon and carbon dioxide lasers are used in the treatment of liver and lungs.

Laser treatment uses an intense, narrow beam of light to remove or destroy abnormal tissue. It is often used to treat precancers on the surface of the body, such as actinic keratosis, and may be used to treat some types of skin cancer.



**(1) Determine energy and momentum of a photon of a laser beam of wavelength 6328 Å.**

**Given h = 6.63 × $10^{-34}$ J.s , c = 3 × $10^{8}$ m/s**

Hint: $E = h\nu = \frac{hc}{\lambda}$

$$p = \frac{E}{c} = \frac{hc}{\lambda}\frac{1}{c} = \frac{h}{\lambda}$$

Solution: $\boldsymbol{E} = h\nu = \frac{hc}{\lambda} = \frac{(6.63\times10^{-34}\ J.s)\ (3\times10^{8}\ m/s)}{(6328\times10^{-10}\ m)}$

$$= 0.003143 \times 10^{-16} J$$

$$= \frac{0.003143\times10^{-16} J}{1.6\times10^{-19}} = \mathbf{1.96\ eV}$$

$$\boldsymbol{p} = \frac{E}{c} = \frac{hc}{\lambda}\frac{1}{c} = \frac{h}{\lambda} = \frac{6.63\times10^{-34}\ J.s}{6328\times10^{-10}\ m} = \mathbf{1.048 \times 10^{-27}\ \frac{kg.m}{s}}$$

**(2) Find the ratio of population of the two states in a He-Ne laser that produces light of wavelength 6328 Å at 27°C. ($\boldsymbol{k = 1.38 \times 10^{-23} J/K}$)**

Hint: $\dfrac{N_2}{N_1} = e^{-(E_2 - E_1)/kT}$

Solution: $E_2 - E_1 = h\nu = \dfrac{hc}{\lambda} = \dfrac{(6.63\times10^{-34}\ J.s)\,(3\times10^{8}\ m/s)}{(6328\times10^{-10}\ m)}$

$$= 0.003143 \times 10^{-16} J$$

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT} = exp\left[\frac{-(0.003143\times10^{-16} J)}{(1.38\times10^{-23}\ J/K)(300K)}\right]$$

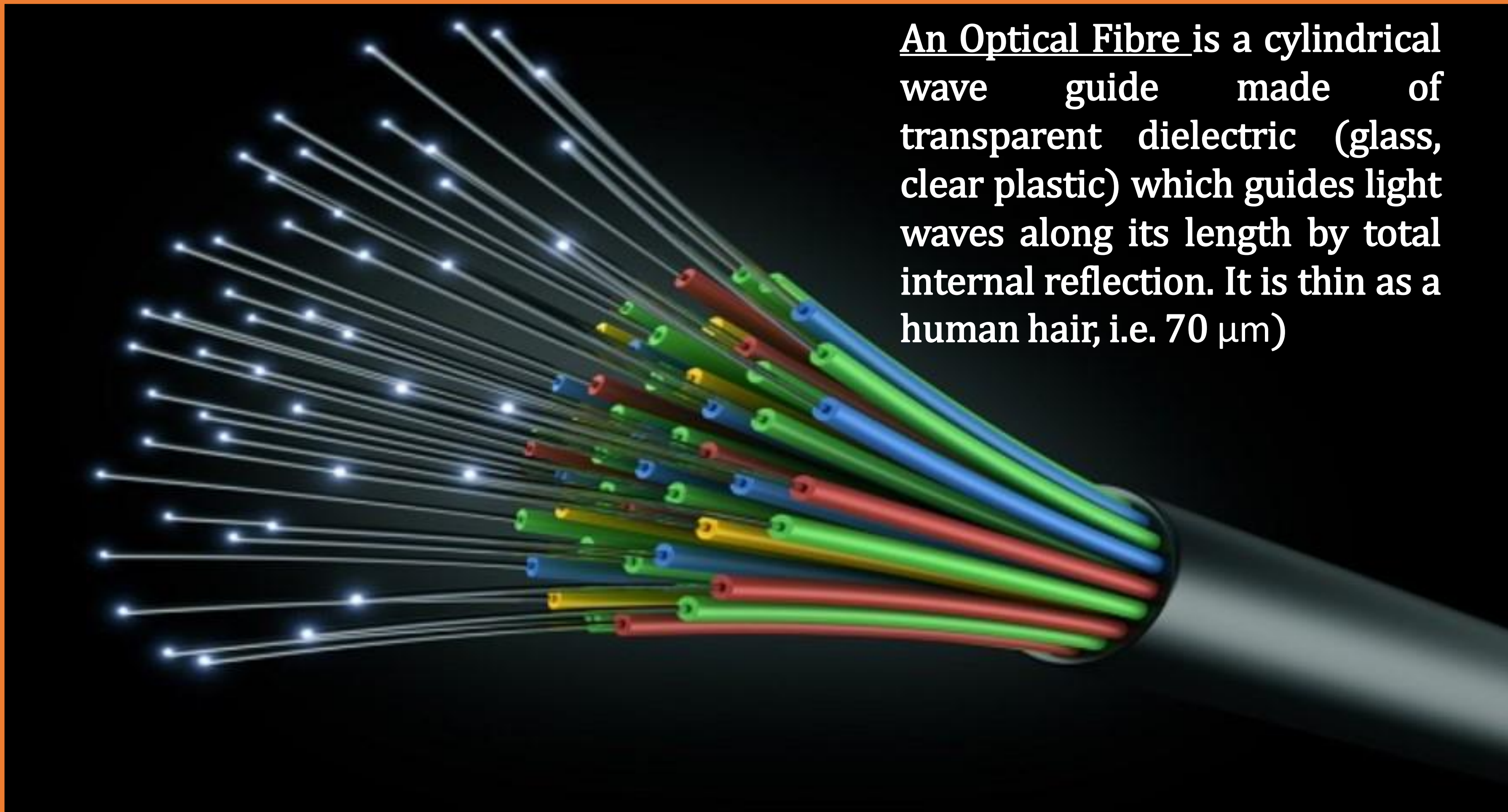
$$= exp[-75.92]$$

$$\boldsymbol{\frac{N_2}{N_1} = 1.07 \times 10^{-33}}$$

# What to Study in Fibre Optics

1. **What is (a) Fibre Optics?**
   **(b) Optical Fibre?**
2. Structure of Optical Fibre
3. Working principle of Optical Fibre
4. Total Internal Reflection
5. Acceptance Angle and Numerical Aperture
6. Fractional difference of R.I.
7. Classification Of Optical Fibre
8. Power Loss in Optical Fibre
9. Advantages of Optical Fibre
10. Applications of Optical Fibre
11. Numericals

# Section II : FIBRE OPTICS



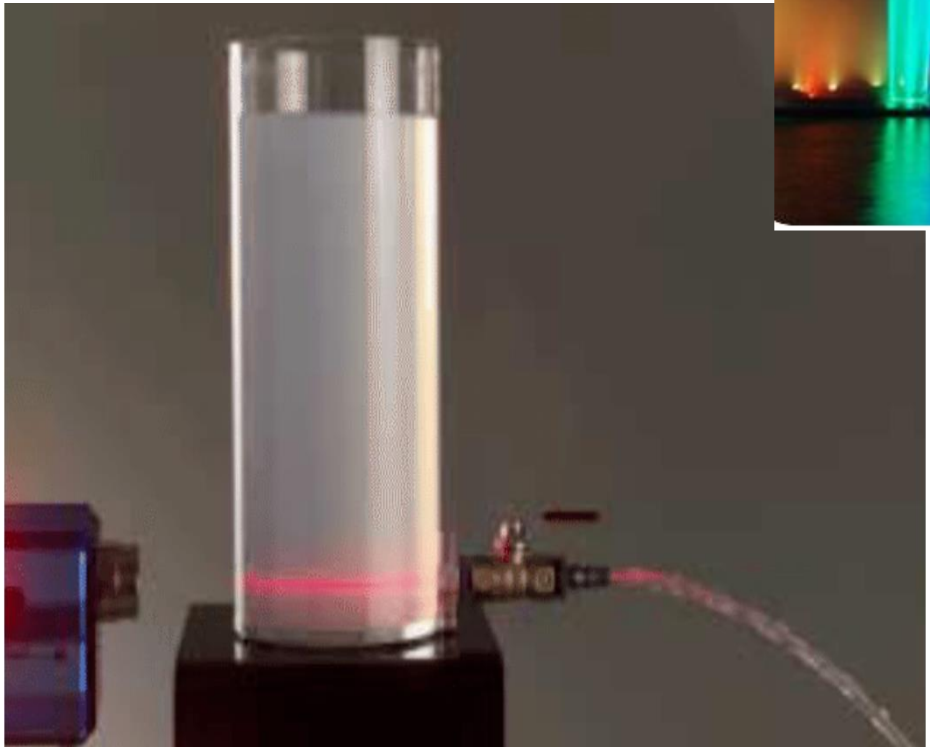
An Optical Fibre is a cylindrical wave guide made of transparent dielectric (glass, clear plastic) which guides light waves along its length by total internal reflection. It is thin as a human hair, i.e. 70 μm)

**Fibre optics is a technology in which electrical signals are converted into optical signals, transmitted through a thin glass fibre and reconverted into electrical signals. In 1950, Kapany coined the term Fibre Optics.**

**Narinder Singh Kapany** (31st October 1926 – 4th December 2020) was an Indian-American physicist, best known for his work on optical fibres. He is the inventor of fibre optics.

Kapany's research and work encompassed fiber-optics communications, lasers, biomedical instrumentation, solar energy and pollution monitoring.

## Tyndall Experiment on TIR



## Water Fountain Showing TIR

# OPTICAL FIBRE : STRUCTURE

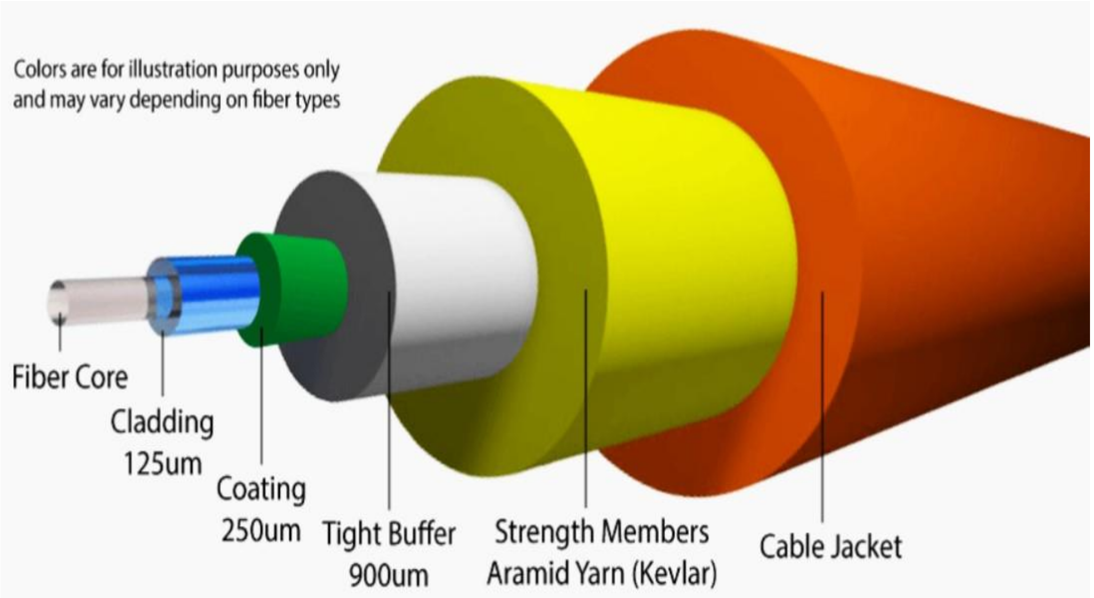
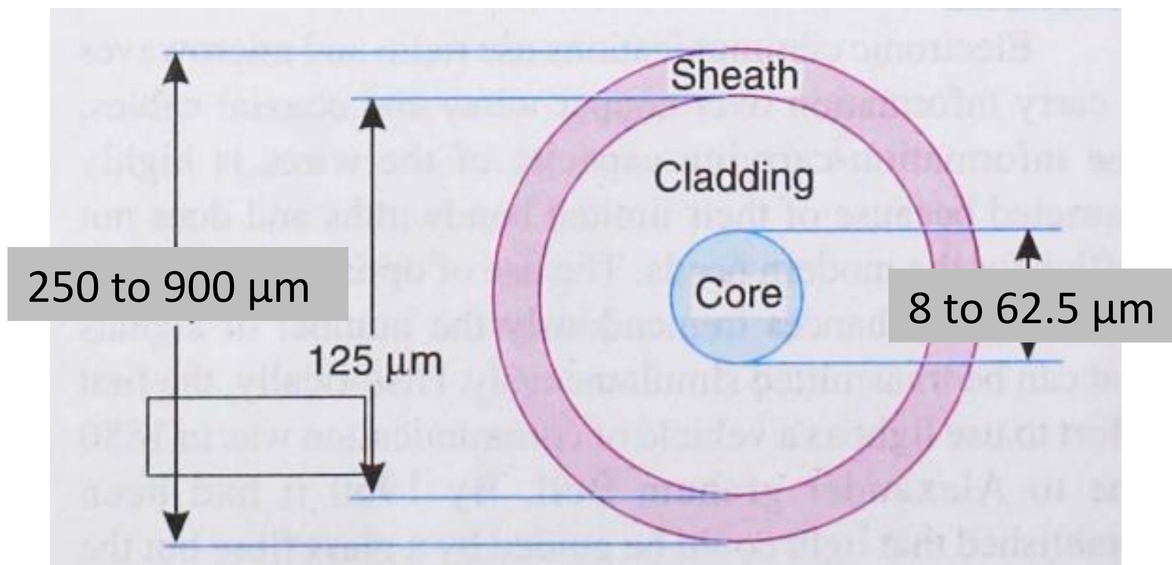



Figure 4(a) - Internal Structure Of Optical Fibre



# OPTICAL FIBRE : STRUCTURE

**A practical optical fibre is cylindrical in shape and has 3 co-axial regions**

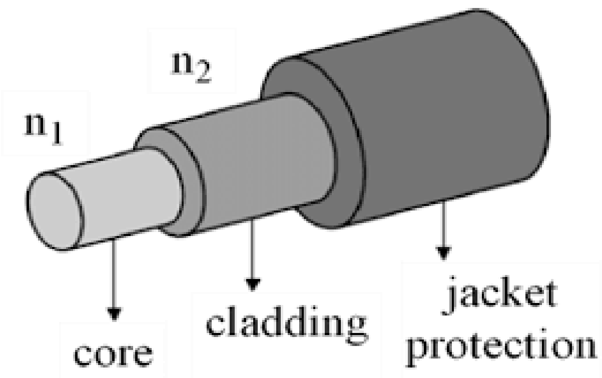
**CORE : (Silica, Germanium)**
The innermost cylindrical region is the light guiding region known as core. Diameter of the core is 8.5-62.5 $\mu$m.

**CLADDING (Pure silica)**
CORE is surrounded by a co-axial middle region having diameter of the order 125 $\mu$m, is known as CLADDING.
The refractive index $n_2$ of "Cladding" is always lower than that of Core whose refractive index is $n_1$.

**OUTER SHEATH:**
The outermost protective layer is called buffer coating or sheath. It is a plastic coating given to the cladding for extra safeguard to provide physical and environmental protection for the fibre. The fibre is elastic in nature and can vary in size from 250-900 $\mu$m.

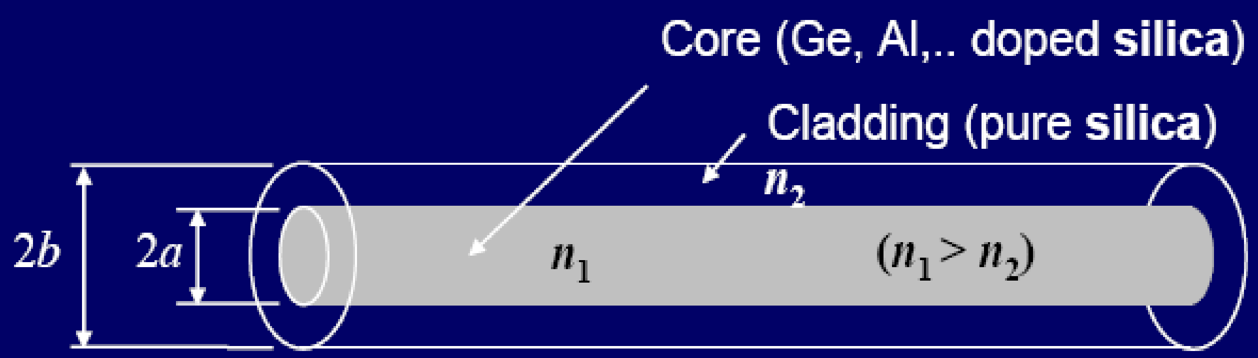
**Necessity of cladding**

- ✓ Keep size of fibre constant
- ✓ Protects fibre from physical damage
- ✓ Prevents leakage of light
- ✓ Increases the rate of transmission of data



# OPTICAL FIBRE : STRUCTURE

**Optical fibers are cylindrical dielectric waveguides**




**Typical dimensions**

| | |
|---|---|
| **Core diameter** | $2a = 9$ to $62.5\ \mu m$ |
| **Cladding diameter** | $2b = 125\ \mu m$ |

**Typical values of refractive indices**

| | |
|---|---|
| **Core:** | $n_1 = 1.461$ |
| **Cladding:** | $n_2 = 1.460$ |

# OPTICAL FIBRE : Principle

- The propagation of light in an optical fibre from one of its end to the other end is based on the principle of **Total Internal Reflection (TIR)**.

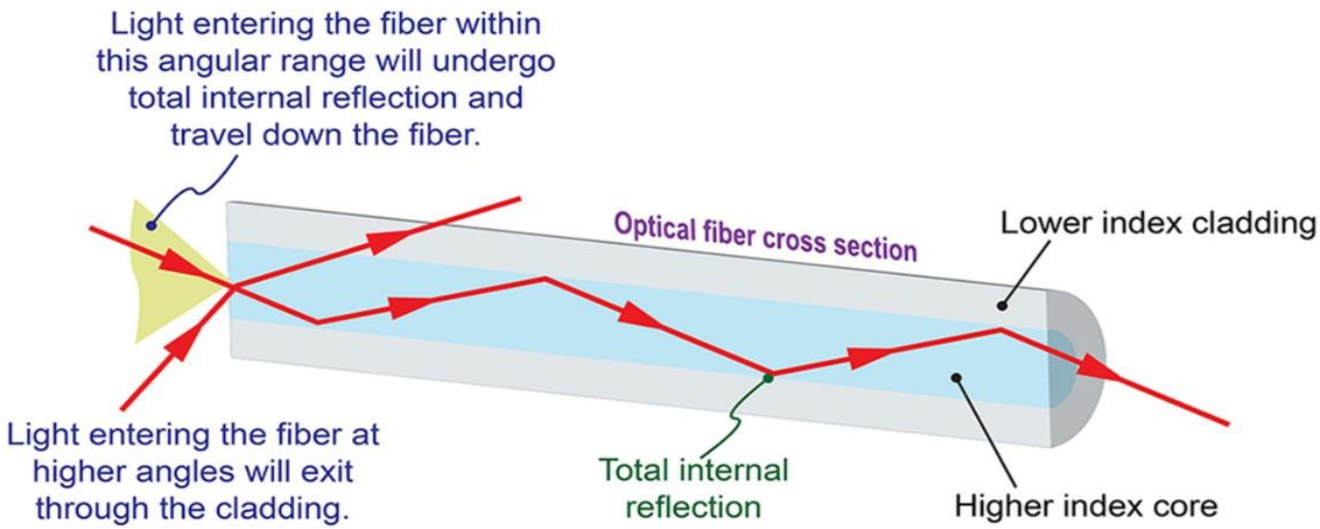
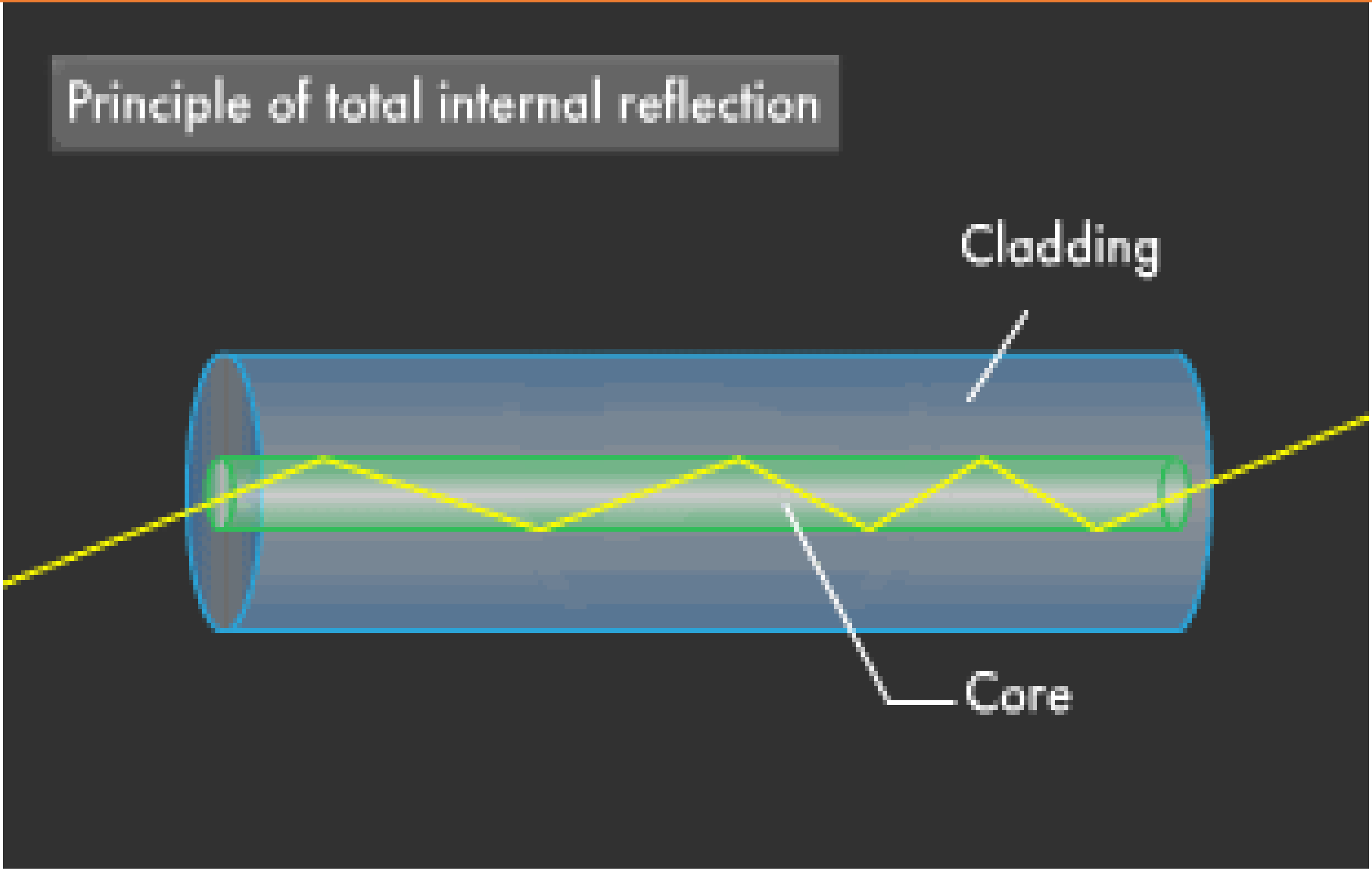



**Figure 4(b)**

## Basic Operation of an OPTICAL FIBRE

**When light enters one end of the fibre, it undergoes successive total internal reflections from sidewalls and travels down the length of the fibre along a zigzag path as shown. A small fraction of light may escape through the sidewalls but a major fraction emerges out from the exit end of the fibre. Light can travel through fibre even if it is bent.**

# OPTICAL FIBRE : Principle



# Total Internal Reflection

- A medium having a lower refractive index is said to be an optically **rarer medium** while a medium having a higher refractive index is known as an optically **denser medium**. When a ray of light passes from a **denser medium to a rarer medium**, it is bent away from the normal in the rarer medium.

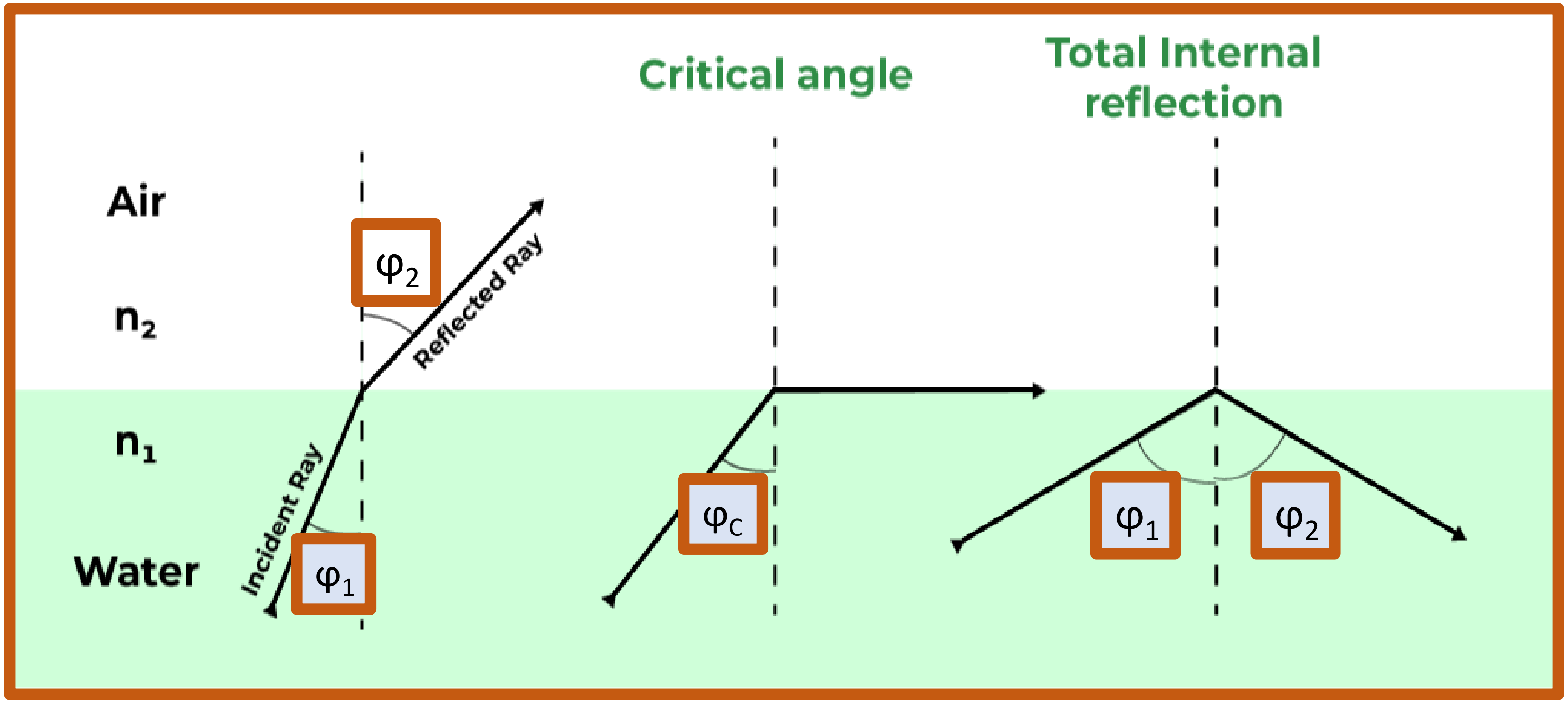



Figure 5 - Total Internal Reflection

# Total Internal Reflection

- Snell's law for this case may be written as
- $\boxed{\sin \phi_2 = \left(\frac{n_1}{n_2}\right) \sin \phi_1}$ .....(1) Where $\phi_1$ is the angle of incidence of light ray in the denser medium and $\phi_2$ is the angle of refraction in the rarer medium. Also $n_1$>$n_2$. When the angle of incidence, $\phi_1$ in the denser medium is increased, the transmission angle, $\phi_2$ increases and the refracted rays bend more and more away from the normal.
- At some particular angle $\phi_C$ the refracted ray glides along the boundary surface so that $\phi_2$=90°.
- At angles greater than $\phi_C$ there are no refracted rays at all. The rays are reflected back into the denser medium as though they encountered a specular reflecting surface.
- If $\boldsymbol{\phi_1 < \phi_C}$, the ray refracts into the rarer medium
- If $\boldsymbol{\phi_1 = \phi_C}$, the ray just grazes the interface of denser-to-rarer media
- If $\boldsymbol{\phi_1 > \phi_C}$, the ray is reflected back into the denser medium
- The phenomena in which light is totally reflected from a denser-to-rarer medium boundary is known as total internal reflection.
- The rays that experience total internal reflection obey the laws of reflection.
- When $\boldsymbol{\phi_1 = \phi_C, \phi_2 = 90°}$
- From eq.(1), $\boldsymbol{n_1 \sin \phi_C = n_2 \sin 90° = n_2}$ [ as, sin $\mathbf{90°}$ = 1]
- $\boldsymbol{Therefore,}$ $\boxed{\boldsymbol{\sin \phi_C = \frac{n_2}{n_1}}}$ .....(2)

# Acceptance Angle

**We consider a step-index optical fibre (figure 6) with its core & cladding having refractive indices $n_1$ and $n_2$ respectively. Let no be the refractive index of the outside medium. Let a ray of light is incident on the entrance aperture of the fibre at an angle $\theta_1$ with the axis. If $\theta_2$ be the angle of refraction we get from Snell's Law, we get,**

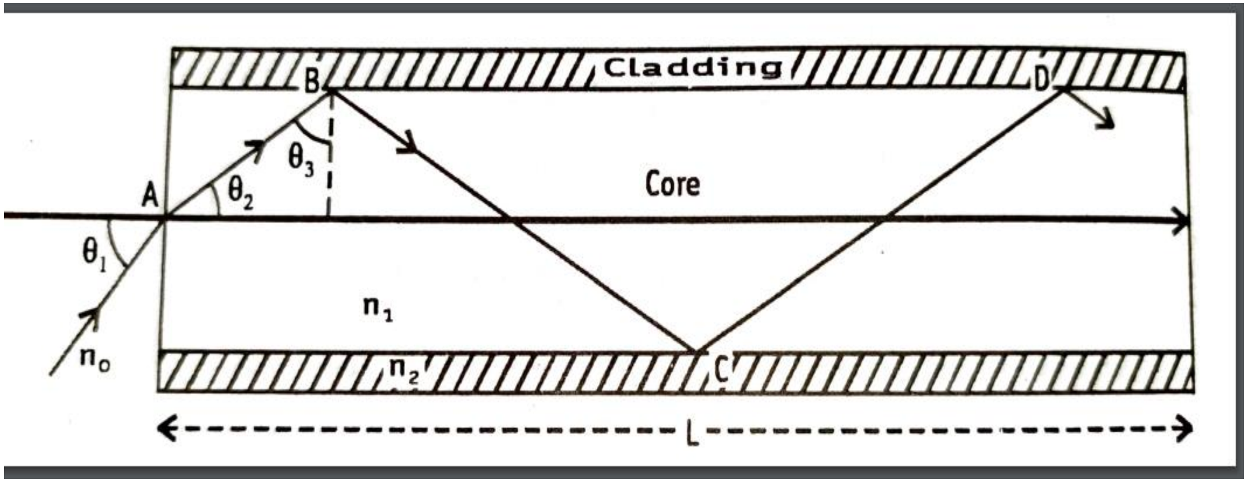



Figure 6

$$n_o \sin\theta_1 = n_1 \sin\theta_2 \text{ ----(1)}$$

In order to keep the light inside the core, the angle of incidence $\theta_3$ of at the core-cladding interface must not be less than the critical angle θc.

Again from fig, we can write $\boldsymbol{\theta_3 = 90° - \theta_2}$

If $\underline{\boldsymbol{\theta_1}}$ is increased, $\underline{\boldsymbol{\theta_2}}$ increases and hence $\underline{\boldsymbol{\theta_3}}$ decreases. So, there is a maximum value of of $\underline{\boldsymbol{\theta_A}}$ **of** $\underline{\boldsymbol{\theta_1}}$, for which $\underline{\boldsymbol{\theta_3}}$ is not less than **θc**. and the ray undergoes Total internal reflection at core-cladding interface. This angle $\theta_A$ is known as ACCEPTANCE angle.

# Acceptance Angle/ Acceptance Cone

Acceptance angle $\theta_A$ : The maximum angle of incidence for which any ray is totally internally reflected at the interface and therefore, transmitted without loss. A cone of light of semi-angle $\theta_A$ is Known as **Acceptance CONE**. *Acceptance angle is the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre*

- Thus only those rays that are incident on the face of the fibre making angles less than acceptance angle $\theta_A$ will undergo repeated TIR and reach other end of the fibre. The larger acceptance angle make it easier to launch light into the fibre.
- In 3D, the light rays, contained within the core having a full angle 2θ are accepted and transmitted along the fibre. This is called **Acceptance Cone (Figure 7).** Light incident at an angle beyond $\theta_A$ refracts through the cladding and the corresponding optical energy is lost

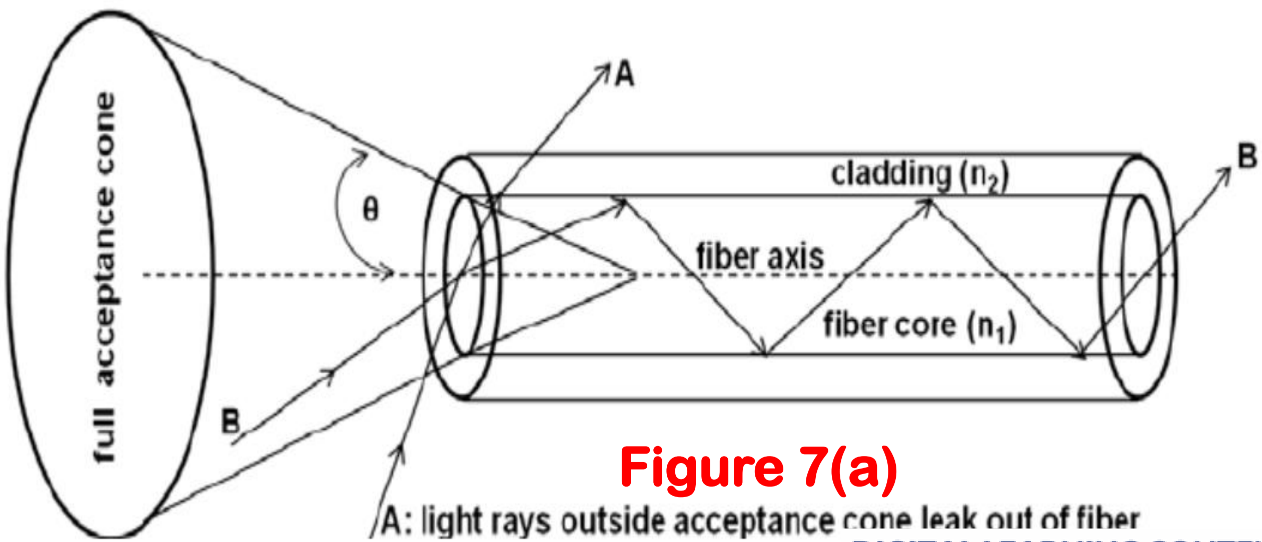
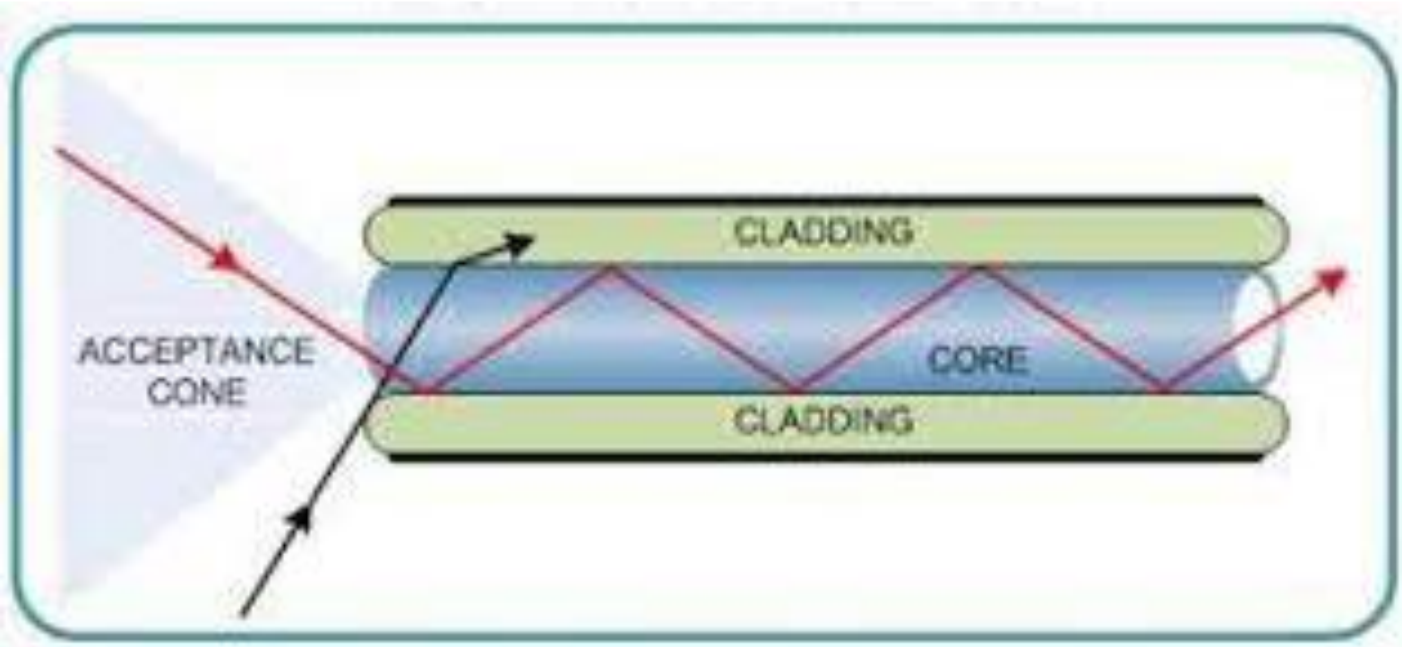



Figure 7(a)

# Acceptance Angle/ Acceptance Cone



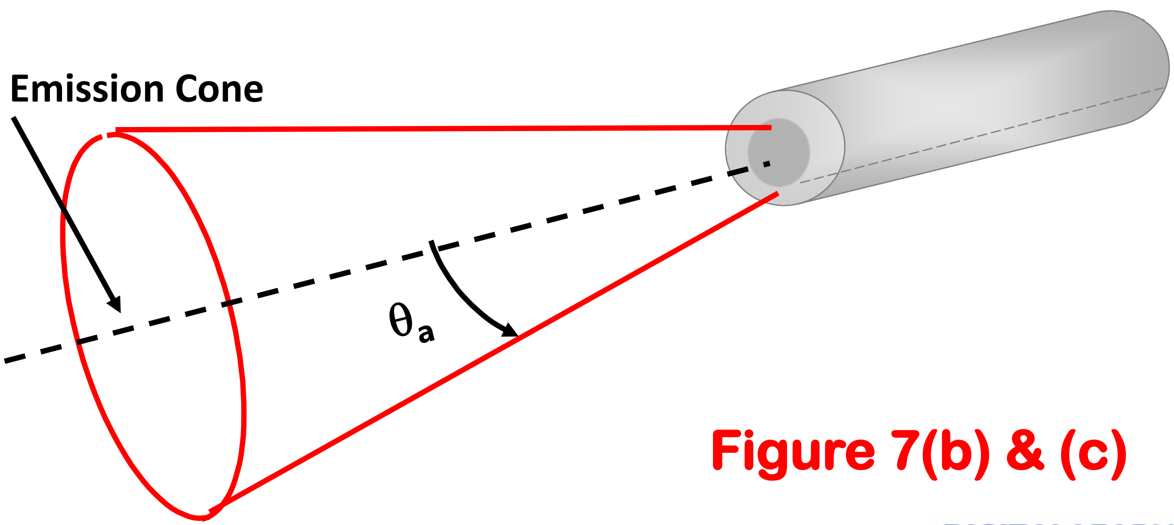




Figure 7(b) & (c)

# Numerical Aperture

✓ To determine $\theta_A$, we have,

$n_o \sin\theta_1 = n_1 \sin\theta_2$ ----(1)

Again, we can write

$n_o \sin\theta_1 = n_1 \sin\theta_2 = n_1 \sin(90°- \theta_3) = n_1 \cos\theta_3$ ------ ( from figure 6)

For conditions, $\theta_1 = \theta_A$, we have $\theta_3 = \theta_c$ (where, $\theta_c$ = critical angle)

Putting these conditions we can write,

$n_o \sin\theta_A = n_1 \cos\theta_c$ ---- (2)

We know that $\sin\theta_c = n_2/n_1$ ----(3). Thereby, we can write,

$$n_0 \sin\theta_A = n_1\sqrt{1-\sin^2\theta_C} = n_1\sqrt{1-\frac{n_2^2}{n_1^2}} = \sqrt{n_1^2 - n_2^2}$$ ----(4)

# Numerical Aperture

**The quantity $n_o \sin \theta_A$ is defined as the NUMERICAL APERTURE (NA) of the fibre**

*It is seen from eq.(4) that NA is dependent only on the refractive indices of the core and cladding materials and does not depend on the physical dimensions of the fibre.*
*The value of **NA ranges from 0.13 to 0.50**. A large NA implies that a fibre will accept large amount of light from the source.*

- Not all rays entering the fiber core will continue to be propagated down its length. Only rays with sufficiently shallow grazing angle (i.e. angle to the normal > $\theta_C$) at the core-cladding interface are transmitted by TIR.
- **Any ray incident into fiber core at angle > $\theta_A$ will be transmitted to core-cladding interface at an angle < $\theta_C$ and will not follow TIR.**
- **Larger the Numerical Aperture, greater is the amount of light accepted by the fibre from the external source.**
- It is obvious that the larger the diameter of the core, the larger the acceptance angle.
- For a lens or a fiber, the NA is commonly defined as the sine of half the maximum angle of acceptance.
- For multimode fibers, the equation shown calculates the NA using the index of refraction (n) of the core and cladding.

# Fractional Difference of Refractive Index

- The fractional difference $\Delta$ between the refractive indices of the core and the cladding is known as fractional refractive index change. It is expressed as ,

$$\boxed{\Delta = (n_1 - n_2)/n_1}$$

- This parameter is always positive because $n_1$ must be larger than $n_2$ for the total internal reflection condition. In order to guide light rays effectively through a fibre, $\Delta \ll 1$.
- Typically, $\Delta$ is of the order of 0.01.

## 1. Based on Refractive Index

(a) Step-index fibres

(b) Graded-index (GRIN) fibres

- Step Index refers to the fact that the refractive index of the core is constant along the radial direction and abruptly falls to a lower value at the cladding and core boundary.
- In the case of GRIN fibres, the refractive index of the core is not constant but varies smoothly over the diameter of the core. It has a maximum value at the centre and decreases gradually towards the edge of the core.

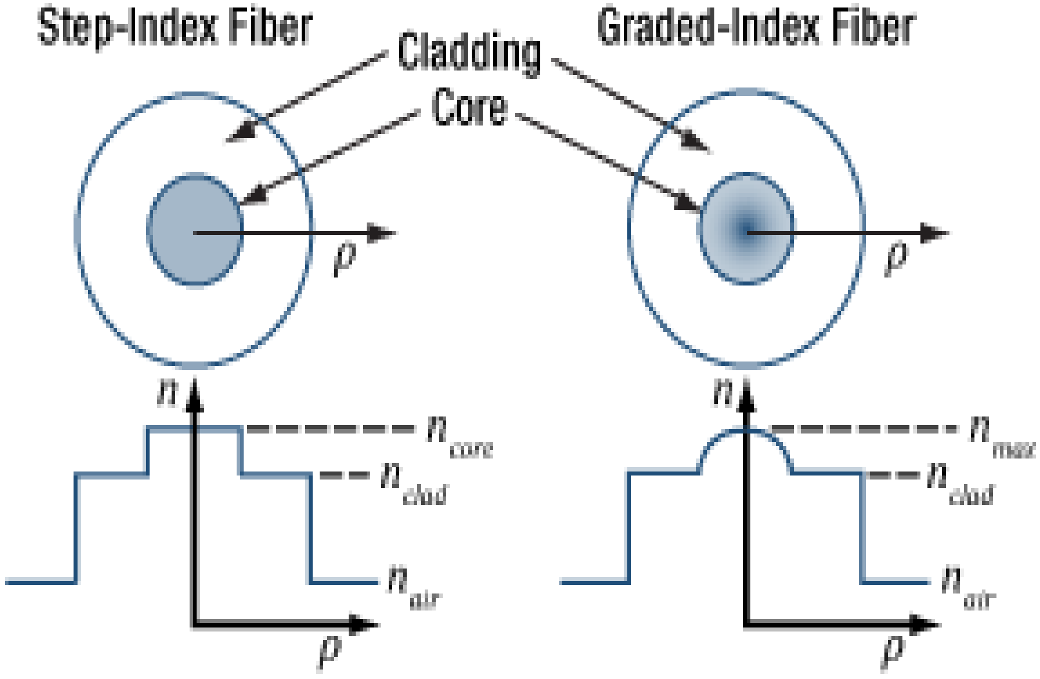



Figure 8 (a) STEP-Index Fibre (b) STEP-Index Fibre

- At the core-cladding interface, the refractive index of the core matches with the refractive index of the cladding. the refractive index of the cladding is constant.

# Classification of Optical Fibre

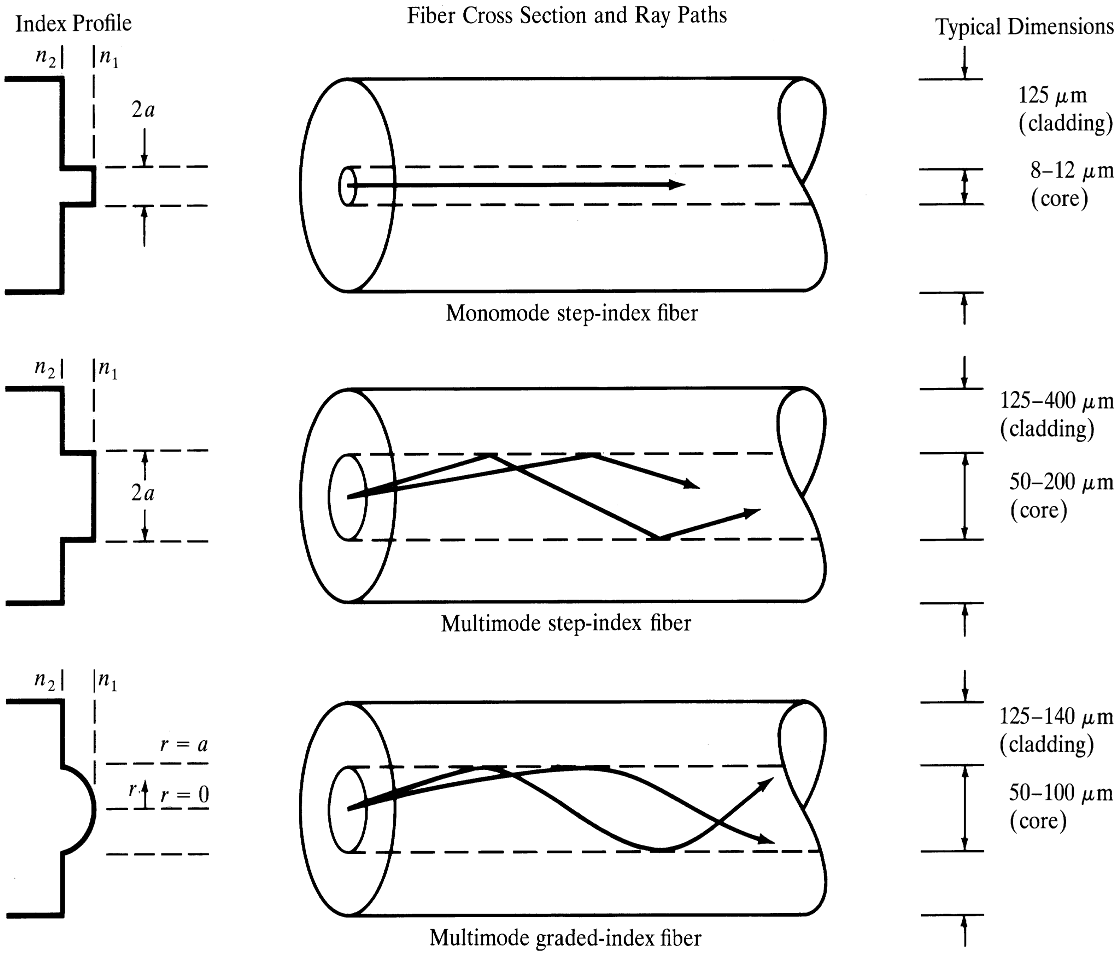
2. Based on Modes: On the basis of light propagation optical fibres are classified into

(a) Single Mode Step-INDEX fibres

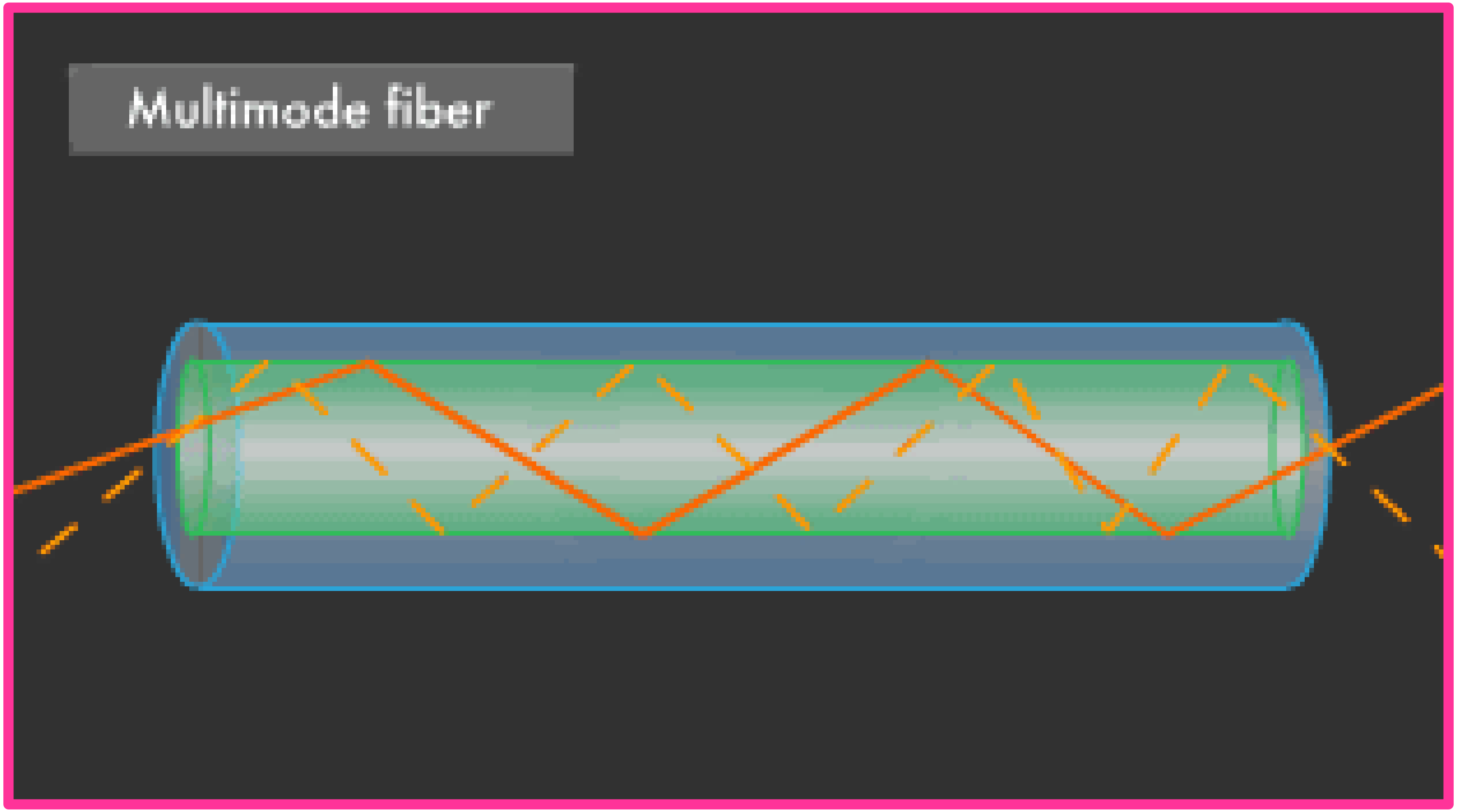
(b) Multimode Step-INDEX fibres

(c) Graded-INDEX (GRIN) fibres

**(a) SMF (single mode step index fibre)** has a very fine thin core of diameter of 8 µm to 12µm at is usually made of germanium doped silica. The core is surrounded by a thick cladding. refractive index. The cladding is composed of silica lightly doped with phosphorous oxide. The external diameter of the cladding is of order of 125 µm. The fibre is surrounded by an opaque protective sheath. The refractive index of the fibre changes abruptly at the core cladding boundary.



# Classification of Optical Fibre



# Classification of Optical Fibre

**(b) A multimode step index fibre (MMF)** is very small much similar to the single mode step index fibre except that it's case is of larger diameter. The core diameter is of the order of 50-100um which is very large compared to the wavelength of light. External diameter of cladding is 150-250 μm.

Multimode step index fibres allow finite number of guided modes. Many zigzag paths of propagation are permitted in a MMF. The path length along the axis of the fibre is shorter while other Zigzag paths are longer. Because of this difference, the lower order modes reach the end of the fibre earlier. while the high order modes reach after some delay causing intermodal dispersion.

**(c) Graded-Index GRIN fibres**

A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive index. Therefore, the refractive index of the core varies with distance from the fibre axis. It has a high value at the centre and falls of with increasing radial distance from axis. Such a profile causes a periodic focussing of light propagating through the fibre. So all rays travelling through the fibre, irrespective of their modes of travel, will have almost the same optical path length and reach the output end of the fibre at the same time.

# Losses in FIBRE OPTICS

As a light signal propagates through a fibre it suffers loss of amplitude and changes in shape. The loss of amplitude is referred to as attenuation and the change in shape as distortion.

**Attenuation**: When an optical signal propagates through a fibre, power of the signal decreases exponentially with distance. The loss of optical power as light travels down a fibre is known as **Attenuation** (Measure of decay of signal strength of Light POWER). The attenuation of optical signal is defined as the ratio of the optical output power from a fibre of length L to the input optical power.

**If Pi** is the optical power launched at the input end of the fibre, then the power **Po** at a distance L down the fibre is given by,

$$\alpha = \frac{10}{L} \log \frac{P_i}{P_o}$$

Where,

$\alpha$= **fibre attenuation coefficient**

In case of an ideal fibre, $P_0 = P_i$ and the attenuation would be zero.

The unit of measurement of attenuation is decibel/kilometre (dB/km).

This is the Logarithmic relationship between the optical output power and the optical input power.

# Advantages of Optical Fibres over metal wires

**Fibre Optics have many advantages compared with traditional metal communications lines, which are listed as follows:**

- ✓ Fibre optics cable can carry more data as their bandwidth is greater than metal cables.
- ✓ Fibre optic cables are less susceptible than metal cables to interference.
- ✓ Fibre optic cables are much thinner and lighter than metal wires.
- ✓ Through fibre optic cables the data can be transmitted digitally rather than analogically.
- ✓ Attenuation through fibre optics cables are very low in transmitting the data Lover long distance so there is no need of repeaters.

# Applications

- **Optical Communications:** Traditionally, electronic communications were carried out by sending electrical signals through copper cables, coaxial cables or waveguides. In recent years optical fibres are being used, where light signals replace electrical signals.

- **Transmission of LIGHT:** Optical Fibres are used for transmission of light to illuminate hard to reach places or to conduct light out of such places.

- **Transmission of images:** A flexible bundle of optical fibre is called fibrescope . It is extensively used in carrying images. Light is passed down the outer fibres from the sources and the reflected light is piped alone the inner fibres.
- **Sensors:** Sensing Acoustic fields, magnetic fluids temperature etc.
- **Coupler:** Used to couple two electrical circuits without introducing a direct link.

# Applications

**Medical Applications:**

- The fibre optic endoscope is used to inspect internal organs for diagnostic purposes.
- A laser beam guided by optical fibre is used to reattach detached retina and to correct defective vision.
- The optical energy transmitted through a optical fibre is used to evaporate built-up plaque that is blocking an artery.
- In cancer treatment, special chemicals are injected that penetrates only the cancerous cells. Infra red energy transmitted via the fibre illuminates the affected area and is absorbed by the special chemical in the cancerous cells. The heat generated destroys the cancerous cells.

**Military Applications:**

- An aircraft, a ship or a tank needs tons of copper wire for wiring of the communication requirement, control mechanism etc. Use of optical fibre in place of copper reduces weight.
- Fibre guided missiles are used in recent wars. Sensors mounted on the missile transmit video information through the optical fibre to a ground control van and receive commands from the van again. The control van continuously monitors the missiles position to ensure that the missile precisely hits the target.

# Numericals

**(1) Calculate the numerical aperture and acceptance angle of an optical fiber from the following data**

**$n_1$(core) = 1.55, $n_2$(cladding) = 1.50**

Hint:
$$\mathrm{NA} = \sqrt{(n_1^2 - n_2^2)}$$
$$\theta_0 = \sin^{-1}\left[\sqrt{(n_1^2 - n_2^2)}\right]$$

Solution:
$$\mathbf{NA} = \sqrt{(n_1^2 - n_2^2)} = \sqrt{(1.55^2 - 1.50^2)} = \sqrt{0.1525} = \mathbf{0.3905}$$
$$\boldsymbol{\theta_0} = \sin^{-1}\left[\sqrt{(n_1^2 - n_2^2)}\right] = \sin^{-1}[0.3905] = \mathbf{22.98^0}$$

**(2) Optical Power of 1 mW is launched into an optical fiber of length 100 m. If the power emerging from the other end is 0.3 mW. Calculate the fiber attenuation.**

Hint: $$\alpha = \frac{10}{L}\log\left[\frac{P_i}{P_O}\right]$$

Solution: $$\boldsymbol{\alpha} = \frac{10}{L}\log\left[\frac{P_i}{P_O}\right] = \frac{10}{0.1\ km}\log\left[\frac{1\ mW}{0.3\ mW}\right] = \mathbf{52.28\ dB/km}$$

# Numericals on UNIT 4

1. A step index fibre has a core of refractive index 1.55 and a cladding of refractive index 1.53. Find the numerical aperture and the acceptance angle of the fibre.

2. A step index fibre has a core of refractive index 1.50 and a cladding of refractive index 1.40. If the fibre is used in a water environment, finds its numerical aperture and acceptance angle. The r. i. of water is 1.33.

3. Optical power of 1 mW is launched into an optical fibre of length 100 m. If the power emerging from the other end is 0.3 mW, calculate the fibre attenuation.

4. What is the attenuation in dB/km, if 15 % of the power fed at the launching end of a $\frac{1}{2}$ km fibre lost during propagation.

5. An optical fibre has clad of RI 1.50 and NA of 0.39. Find the RI of the core and the acceptance angle.

6. The power of a signal after propagating through an optical fibre of 1.5 km length is reduced to 25% of its original value. Compute the fibre loss in dB/km.

7. Find the attenuation in an optical fibre of length 500m, when a light signal of power 100 mW emerges out of the fibre with a power 90 mW.

8. The attenuation of light in an optical fibre is estimated at 2.2 dB/km. What fractional initial intensity remains after 2 km & 6 km.

9. Calculate:
(a) The cladding Index
(b) The critical internal reflection angle
(c) The external critical acceptance angle
(d) The numerical aperture
of a glass clad fibre made with core glass of RI 1.5 and cladding is doped to give a fractional index difference of 0.0005.

# BOOKS FOR REFERENCE

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- ✓ A Textbook of Engineering Physics by
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