

# Module - 1

## Lasers & Fibre optics

### Laser

LASER stands for Light Amplification by Stimulated Emission of Radiation. Differing from conventional sources, lasers produce highly directional, monochromatic, coherent and stimulated radiation. Lasing has been extended from microwave(Maser) to  $\gamma$ -rays (Graser)

### Characteristics

1. **Monochromaticity:** The line width of laser beams are extremely narrow. (1 in  $10^{15}$ , in conventional light source, it is 1 in  $10^6$ ). Degree of non-monochromaticity:  $\xi = \Delta\lambda/\lambda = \Delta\nu/\nu$  ( $\Delta\lambda$  or  $\Delta\nu$  is variation in wavelength or frequency of light)
2. **Directionality:** Laser can travel very long distances without divergence.

$$\text{Divergence: } \Delta\theta = \frac{r_2 - r_1}{D_2 - D_1} \text{ or } \frac{D^2}{\lambda} \text{ (Reliegh's range)}$$

For laser: 0.01 milliradian

for search light 0.5 radian  $\Rightarrow$  divergence

#### 3. Coherence

**Spatial coherence:** If a wave maintains a constant phase difference or in phase at two different points on the wave over a time  $t$ , then the wave is said to have spatial coherence.

**Temporal coherence:** If there is no change in phase over a time  $t$  at a point on the wave, then it is said to be coherent temporally during that time. (these reference points are taken on electric field)

#### 4. Brightness/intensity

Laser produce highly intense beams, because more light energy is concentrated in a small region. Also laser light is coherent, so at a time many photons are in phase. They superimpose to produce a wave of larger amplitude. Hence resultant intensity ( $\propto \text{amplitude}^2$ ) is very high.

## Some terms

### Coherence length ( $L_c$ )

Propagation distance over which a coherent wave maintains a specified degree of coherence or phase difference. For He-Ne  $L_c = 600\text{km}$

$$\text{Non-chromaticity} \propto \frac{1}{L_c}$$

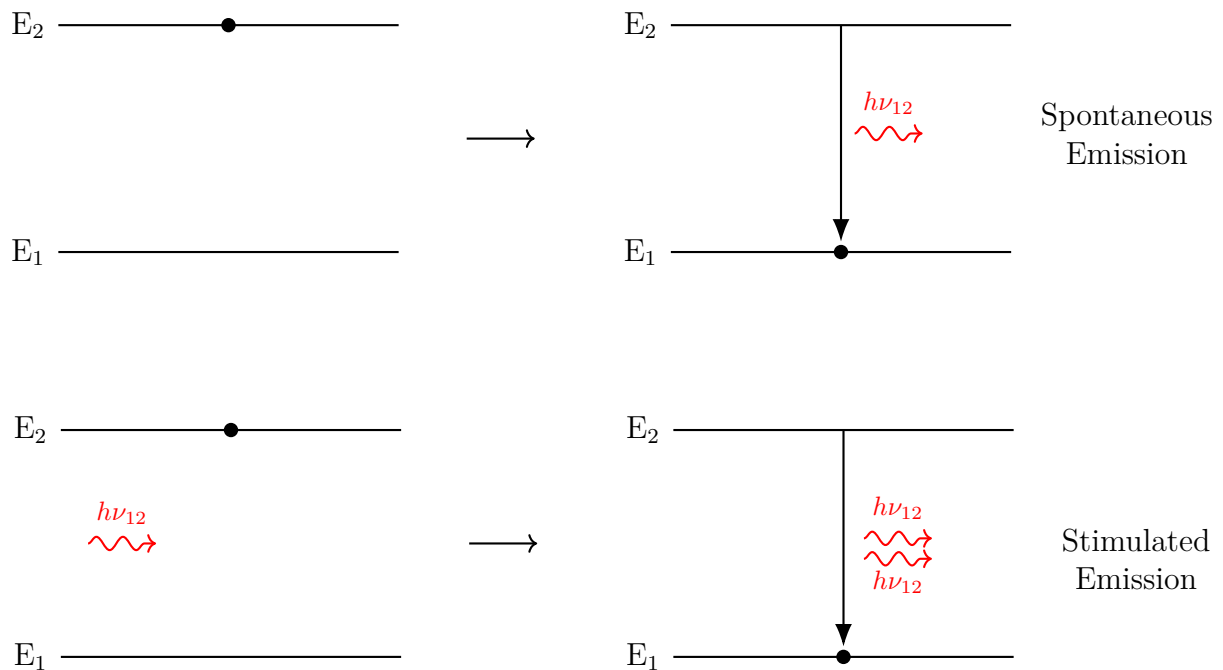
### Coherence time( $\tau_c$ )

Time over which a propagating wave remains coherent or the maximum time interval for which the wave have definite phase relation.

For He-Ne:  $\tau_c = 2 \times 10^{-3} \text{ s}$

Sodium lamp:  $10^{-10} \text{ s}$

## Spontaneous & stimulated emission



## Spontaneous emission

Atom initially at excited state makes transition voluntarily on its own, without aid of any external agency, to ground state, and emits photon of energy

$$h\nu_{12} = E_2 - E_1$$

Different atoms of medium emits light at different times and different directions. Hence emitted photons are incoherent. The rate of emission is independent of incident energy (as no energy is supplied to the system.)

## Stimulated emission

Here photon having energy  $h\nu_{12}(= E_2 - E_1)$  impinges on (or passes in the vicinity of) an atom present in its excited state and atom is stimulated to make transition to ground state and gives off a photon of energy  $h\nu_{12}$ . Emitted photon is in phase with the incident photon. These two travel in same direction and possess same frequency. They're coherent.

### Note

At thermal equilibrium, all energy transitions are equally probable

Spontaneous emission	Stimulated emission
Polychromatic radiation	Monochromatic radiation
Low intensity	High intensity
Low Directionality (so more angular spread during Propagation)	High Directionality (so less angular spread during Propagation)
Spacially and Temporally incoherent radiation	Spacially and Temporally coherent radiation
Takes place when atom transition from higher to lower energy level	Takes place when photon of suitable frequency Stimulates an excited atom to make transition to lower energy level

## Einstein's coefficients

For a system in steady state containing atoms and radiation, ratio of atoms in ground state( $E_1$ ) to atoms in excited state( $E_2$ ) is:

$$\frac{n_2}{n_1} = \exp\left(-\frac{E_2 - E_1}{k_B T}\right) = \exp\left(-\frac{h\nu}{k_B T}\right)$$

- When atom in ground state gets excited to higher state, rate of absorption of radiation is :  $B_{12}n_1\rho_\nu$  ( $\rho_\nu$  = energy density of radiation incident on ground state)
- Rate of spontaneous emission:  $R_{21} = n_2A_{21}$
- Rate of absorption :  $R_{ab} = n_1\rho_\nu B_{12}$
- Rate of stimulated emission:  $R_{12} = n_2\rho_\nu B_{21}$

Where

- $n_1$  = number of available atoms per unit volume
- $n_2$  = number of atoms per unit volume

- $\nu$  = frequency of radiation
- $T$  = absolute temperature of the atoms
- $k_B$  = Boltzmann constant
- $A_{21}$  = probability that atom will spontaneously jump to  $E_1$  (ground state) per unit time (spontaneous emission proportionality constant)
- $B_{12}$  = probability of absorption per unit time (absorption proportionality constant)
- $B_{21}$  = probability that atom will transition from  $E_2$  to  $E_1$  via stimulated emission per unit time (stimulated emission proportionality constant)

### Finding $\rho_v$

Inside the container, radiation is present so, the number of photons per unit volume having frequencies around  $\nu$  in unit range (i.e., radiation density), represented as  $\rho_v$  is given by Planck's black body radiation law as:

$$\rho_v = \frac{8\pi h\nu^3}{c^3 \left[ \exp\left(\frac{h\nu}{k_B T}\right) - 1 \right]}$$

In steady state:

$$R_{ab} = R_{12} + R_{21}$$

$$B_{12}n_1\rho_v = A_{21}n_2 + B_{21}n_2\rho_v$$

(or)

$$\rho_v [B_{12}n_1 - B_{21}n_2] = A_{21}n_2$$

$$\begin{aligned} \rho_v &= \frac{A_{21}n_2}{B_{12}n_1 - B_{21}n_2} = \frac{A_{21}n_2}{n_2 B_{21} \left[ \frac{B_{12}n_1}{B_{21}n_2} - 1 \right]} \\ &= \frac{A_{21}/B_{21}}{\frac{B_{12}n_1}{B_{21}n_2} - 1} \end{aligned}$$

Substituting Equation (6.1) in (6.8) for  $n_1/n_2$ , we have:

$$\rho_v = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}} \exp\left(\frac{h\nu}{K_B T}\right) - 1}$$

In thermal equilibrium state, Equations (6.2) and (6.9) are equal. so,

$$\frac{8\pi h\nu^3}{c^3 \left[ \exp\left(\frac{h\nu}{K_B T}\right) - 1 \right]} = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}} \exp\left(\frac{h\nu}{K_B T}\right) - 1}$$

Under stimulated emission, the probability of upward transitions and probability of downward transitions are equal, so:

$$B_{12} = B_{21} = B \text{ and } A_{21} = A \text{ (say).}$$

Then, Equation (6.10) becomes:

$$\frac{A_{21}}{B_{21}} = \frac{A}{B} = \frac{8\pi h\nu^3}{c^3}$$

The proportionality constants  $A_{21}$ ,  $B_{12}$  and  $B_{21}$  are called Einstein's  $A$  and  $B$  coefficients. From Equations (6.5) and (6.6), the ratio of spontaneous emission rate to stimulated emission rate is:

$$\frac{A_{21}n_2}{B_{21}n_2\rho_v} = \frac{A_{21}}{B_{21}\rho_v}$$

Substituting Equations (6.2) and (6.11) in (6.12) gives:

$$= \frac{8\pi h\nu^3}{c^3} \bigg/ \frac{8\pi h\nu^3}{c^3 \left[ \exp\left(\frac{h\nu}{K_B T}\right) - 1 \right]} = \exp\left(\frac{h\nu}{K_B T}\right) - 1$$

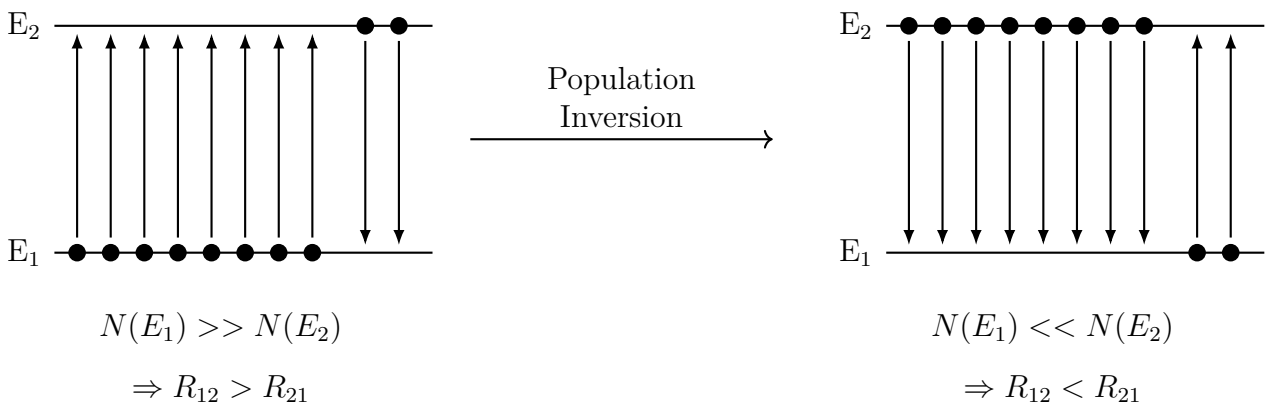
### Note

- Spontaneous emission produce incoherent light
- Stimulated emission produce coherent light

## Population Inversion

**Population inversion:** a state of system in which more members of system are in high energy level than in lower level.

- When photon of Energy  $\Delta E$  (equal to difference in energy level) enters atom probability of absorption = probability of spontaneous emission
- At Room temperature:  $\Delta E = E_2 - E_1 \cong 0.025 \text{ eV}$  (Corresponding to IR radiation of  $6 \times 10^{12} \text{ Hz}$ )



At thermal equilibrium:  $N(E_2)/N(E_1) = e^{-(E_2-E_1)/(kT)}$

**pumping:** Supplying energy to excite atoms to upper levels.

## Metastable state

The atoms excited will undergo spontaneous emission and attain population inversion. These atoms reach an intermediate state between the transitioning states which has more life time than higher energy state. This state is known as **metastable state**. From here, atoms undergo stimulated emission and lasing action takes place. (In two level systems, lasing action doesn't take place because of lack of metastable state)

## Representing transitions

- Absorption:  $A + h\nu \rightarrow A^*$
- Spontaneous Emission:  $A^* \rightarrow A + h\nu$
- Stimulated Emission :  $A^* + h\nu \rightarrow A + 2h\nu$

★ Emitted photon is identical to incident one. (have same frequency, phase, polarisation)

★ Since excited states are highly unstable (atom will return to ground state in less than 1ns) an intermediate energy level (which has life time of  $10^{-3}$  to  $10^{-4}$ s) is required to create stimulated emission. This is achieved by using certain dopants.

## Purity of spectral line

$$\text{Finite purity or sharpness} = \frac{\lambda}{\Delta\lambda}$$

$$\text{Spread of frequency} = \frac{\Delta\nu}{\Delta\lambda}$$

Fading of amplitude is explained by setting  $\Delta\nu$  in time  $\tau_c$  by unity:

$$\tau_c \Delta\nu = 1 \Rightarrow \Delta\lambda = \frac{\lambda^2}{\tau_c c}$$

$$L = c\tau_c = \frac{\lambda^2}{\Delta\lambda} = \lambda Q$$

For Sodium line:  $\Delta\lambda = 0.12\text{\AA}$  For He-Ne laser  $\Delta\lambda = 0.00050.12\text{\AA}$

**1 For a source of monochromatic radiation with wavelength  $5000\text{\AA}$ , and frequency  $6 \times 10^{14}$  Hz, what will be the sharpness for conventional light with  $\Delta\nu = 10^{10}$  Hz and less with  $\Delta\nu = 500$  Hz ?**

### Answer

$$\text{For conventional radiation: } \frac{\Delta\nu}{\nu} = \frac{10^{10}}{6 \times 10^{14}} = 1.67 \times 10^{-5}$$

$$\text{For laser: } \frac{\Delta\nu}{\nu} = \frac{500}{6 \times 10^{14}} = 8.33 \times 10^{-12}$$

**2 For a He-Ne laser, Output diameters are 4 nm and 5 nm at distances 1m and 2m. Calculate beam divergence**

**Answer**

$$\text{Beam divergence} = \frac{R_2 - R_1}{D_2 - D_1} = \frac{.5 \text{ mm}}{1 \text{ m}} = \frac{1}{2} 10^{-3} \text{ rad}$$

**3 For ordinary source of light,  $\tau_c = 10^{-10}$  s. Obtain its sharpness if wavelength is 5400Å**

**Answer**

$$Q = \frac{\Delta\nu}{\nu}$$

$$\nu = \frac{c}{\lambda} = 5.56 \times 10^{14} \text{ Hz}$$

$$\tau_c = \frac{1}{\Delta\nu} \Rightarrow \Delta\nu = 1/\tau_c = 10^{10} \text{ Hz}$$

$$\therefore \text{Sharpness} = \frac{10^{10}}{5.56 \times 10^{14}} = 1.8 \times 10^{-5}$$

**4 A monochromatic source emits light of wavelength 5461Å. Its bandwidth  $\Delta\nu = 10^9$ Hz. Find  $\tau_c$ ,  $L_c$  and frequency stability (sharpness)**

**Answer**

$$\tau_c = \frac{1}{\Delta\nu} = 10^{-9} \text{ s}$$

$$L_c = \tau_c c = 30 \text{ cm}$$

$$\nu = \frac{c}{\lambda} = 5.49 \times 10^{14} \text{ Hz}$$

$$\text{Sharpness} = \frac{\Delta\nu}{\nu} = \frac{10^9}{5.49 \times 10^{14}} = 1.82 \times 10^{-6}$$

**5 At what temperature is the ratio of spontaneous emission to stimulated emission equal to 1 for a source emitting light of wavelength 5000 Å ?**

**Answer**

$$\frac{\text{Spontaneous emission}}{\text{Stimulated emission}} = e^{h\nu/(kT)} - 1 = 1$$

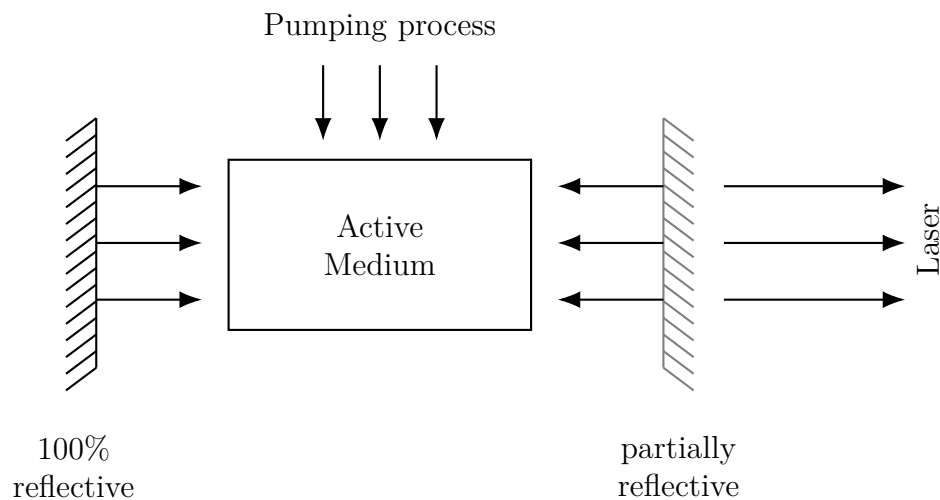
$$\Rightarrow T = \frac{h\nu}{\ln(2)k} = 41543 \text{ K}$$

**6 Find relative population of 2 states in a ruby laser that produces a light beam of wave 6943 Å at 3000 K**

### Answer

$$\begin{aligned}\text{relative population} &= \frac{N_2}{N_1} e^{\frac{E_1 - E_2}{kT}} \\ &= e^{\wedge \left( \frac{-2.86 \times 10^{-19}}{1.83 \times 10^{-25} \times 3000} \right)} \\ &= 1.0002 \times 10^{-3}\end{aligned}$$

## Fabrication of laser



### Some terms

**Active medium:** material in which population inversion takes place. (eg. ruby, Ga-In, He-Ne)

**Active center:** Atoms which can produce more stimulated emission than spontaneous emission: (e.g: Cr in ruby, Ne in He-Ne medium).

**Pumping mechanism:** Adding energy to system. This can be done by:

- Optical pumping (used in ruby laser, xe-flash lamp)
- Direct electron excitation.
- Inelastic atom-atom collisions: electric discharge is employed to cause collision and excitation of atoms. (used in He-Ne)
- Chemical reactions.

## Optical resonance & Resonance cavity

Two mirrors are used to reflect light back into active medium one will be 100 % reflective.(Usually made of dielectric material) and other one is partially reflective.



Two arrangements of mirrors are used to reflect light:

- **plane-parallel:** needs to be strictly parallel (with deviation less than  $1''$  ( $1/3600^{\text{deg}}$ )) and must have smooth surface (irregularities  $< 1/100\lambda$ ).
- **confocal:** need to be parallel (with deviation less than  $0.025^{\text{deg}}$ )

## Types of Laser

- **Pulsed mode:** Train of pulses are produced. It can have produce power in the order of 1MW. (e.g: Ruby laser)
- **Continuous mode:** Light is produced continuously. It has less powerful output (less than 1W) (eg: He-Ne laser)

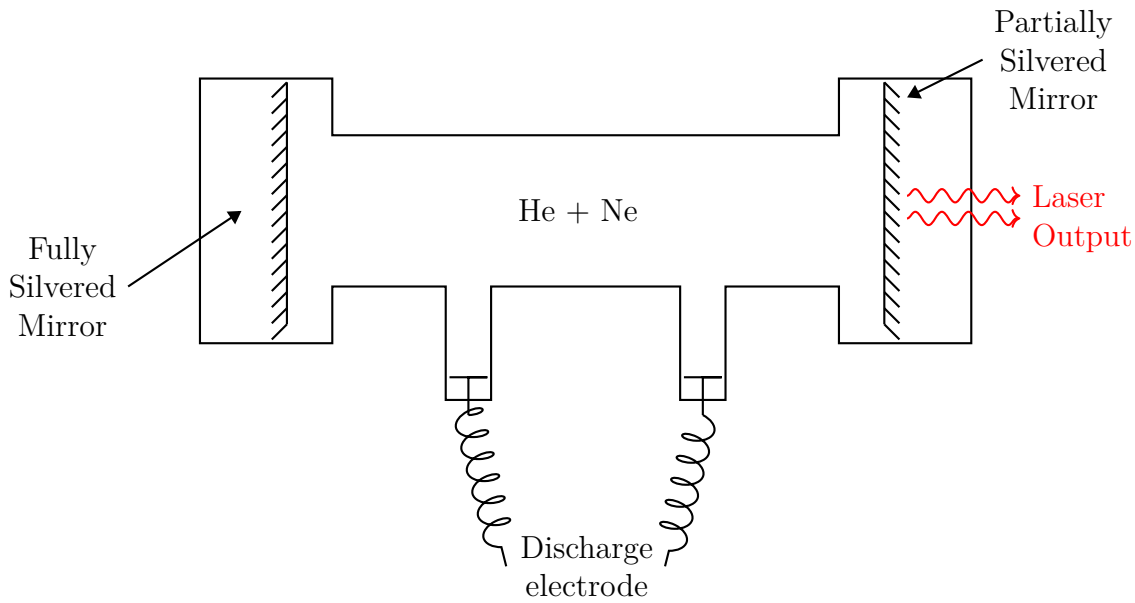
## Uses of Laser

- Used in holograms
- To study the internal structure of molecules.
- To detect earthquakes
- For cutting gilling and welding
- Used to perform surgery
- Used to treat cancer, kidney stone, tumors etc.
- Used to detect and destroy enemy missiles and also to control rockets and satellites.

## Different Lasers

### Helium - Neon Laser

- It is a 4 level Gaseous system.
- Created by Ali Jawan, W. Bennet, D. Harrul in 1962
- It produces continuous output.
- Pumping mechanism: 10kV electron discharge
- Active medium: mixture of He and Ne in 10:1 ratio. (Active center is Ne)
- wavelength of light emitted: 632.8 nm (red color)



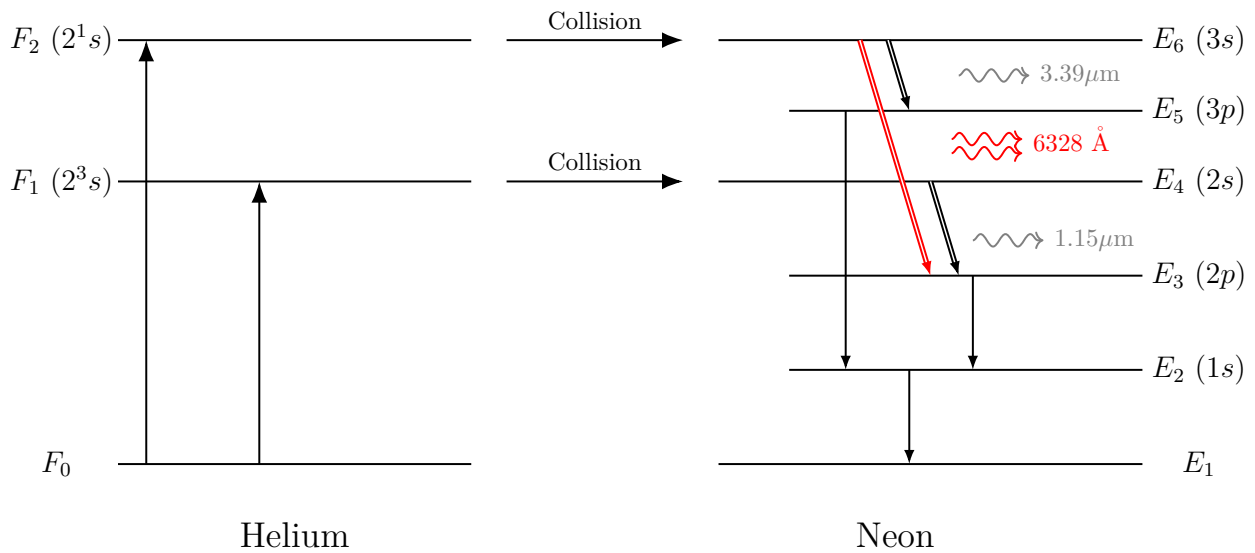
## Working

Due to electric discharge in gas, energetic electron interacts with ground state helium atoms. The impact of  $e^-$  results in exchange of some of its energy to the atom. As a result. Helium atoms gets excited to higher energy levels:  $F_1$  &  $F_2$ . These two energy levels are close to  $E_4$  &  $E_6$  levels of Neon atoms and collision of second kind takes place between them, hence we goes to excited state.  $E_5$  of  $E_3$ .  $E_2$  level of we forms metastable state.

3 types of transition are possible :

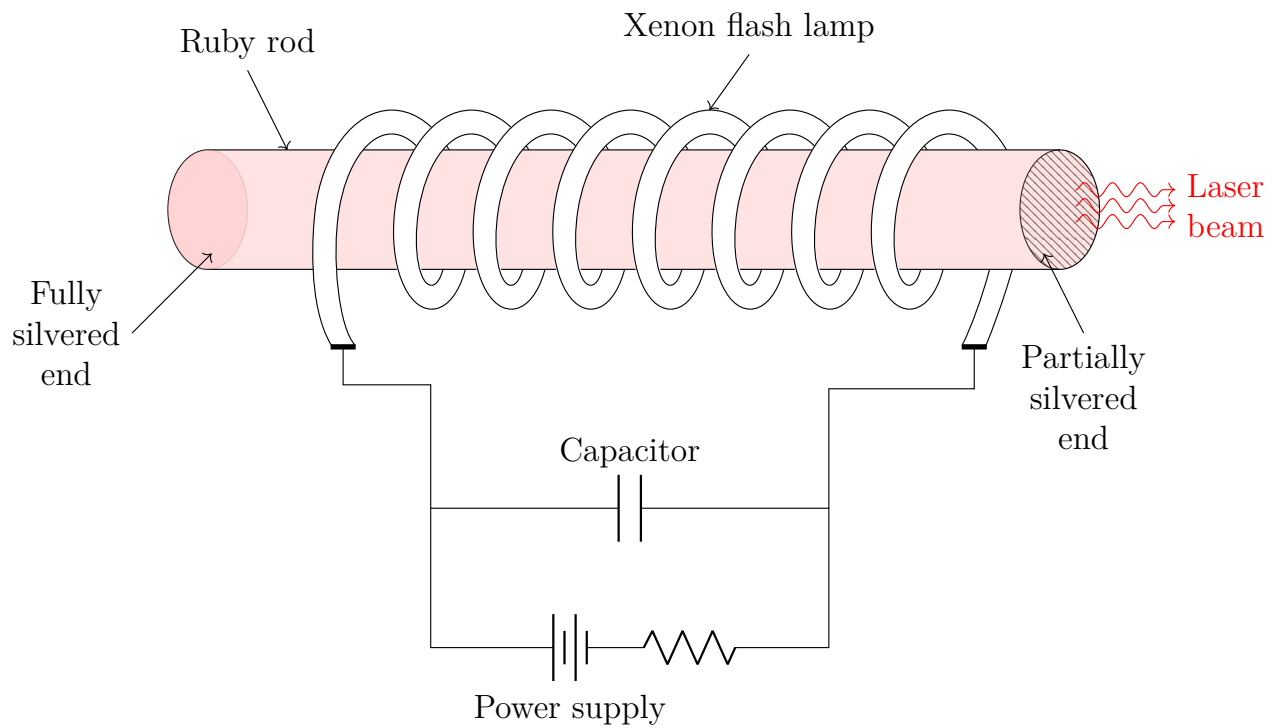
- $E_4 \rightarrow E_3$ , emitting infrared light of  $\lambda = 1.15\mu\text{m}$
- $E_6 \rightarrow E_5$ , emitting  $FR$  of  $\lambda = 3.39\mu\text{m}$
- $E_6 \rightarrow E_3$ , emitting red light of  $\lambda = 632.8 \text{ nm}$

IR light emitted is absorbed by the mirrors. Neon atoms in terminal level  $E_3$  decay very rapially to  $E_2$  metastable state, much faster than spontaneously decaying from  $E_6 \rightarrow E_3$  level. Thus lower level  $E_3$  is kept empty and population inversion is achieved between  $E_6$  &  $E_3$ . Intensity of light produced is inversely proportional to diameter of quartz tube.

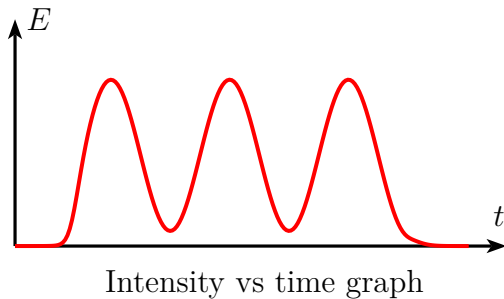


## Ruby Laser

- first laser fabricated
- Created in 1960 by Maiman
- It is a 3 level system
- Produced light in pulsating maner (continuous mode not possible due to heating of active medium)
- Active medium:  $\text{Al}_2\text{O}_3 \cdot \text{Cr}^{3+}$  (0.05-0.5 % of Al atoms are replaced with Cr atoms)
- Pumping source: Xenon lamp. (the lamp has a helical structure that wounds the ruby rod).
- Eavelength of light emitted: 6943  $\text{\AA}$



★ Population inversion is achieved between  $E_m$  &  $E_1$ ,



## Working

$\text{Cr}^{3+}$  ions absorb pumping light and go to excited states  $E_2$  &  $E_3$ . From these a rapid non-radiation transition to the metastable level  $E_m$  takes place. Decay from  $E_m$  is very slow that with sufficient excitation, populations inversion between  $E_m$  &  $E_1$  can occur. Those photons are allowed to pass many times in the active medium with the help of mirrors. When threshold conditions are satisfied, an intense pulse of light of wavelength  $6934\text{\AA}$  is emitted. Continuous operation is not possible due to excessive heating of active medium.

**1 For semiconductor, band gap is  $0.9\text{eV}$ , what is wavelength of light emitted from it?**

**Answer**

$$h\nu = 0.9 \text{ eV} = 1.442 \times 10^{-19} \text{ J}$$

$$\begin{aligned}\therefore \nu &= \frac{1.442 \times 10^{-19}}{h} \\ &= \frac{1.442 \times 10^{-19}}{6.626 \times 10^{-34}} = 2.176 \times 10^{14} \text{ Hz} \\ \therefore \lambda &= c/\nu = 1.38 \text{ } \mu\text{m}\end{aligned}$$

**2 For a He-Ne laser with wavelength 632.8 nm and output power 3.14 mW how many photons are emitted in each minute in operation?**

**Answer**

$$\begin{aligned}\text{Energy of each photon} = h\nu &= \frac{hc}{\lambda} \\ &= \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{632.8 \times 10^{-9}} \\ &= 3.14 \times 10^{-19} \text{ J}\end{aligned}$$

$$\therefore \text{Energy emitted in 1 minute} = 3.14 \text{ mW} \times 60 = 0.1884 \text{ J}$$

$$\therefore \text{Number of photons emitted} = \frac{0.1884}{3.14 \times 10^{-19}} = 6 \times 10^{17}$$

**3 Calculate ratio of population of two states of ruby laser in which transition from one state to another is responsible for emission of photon of wavelength 6928 Å (Assuming that the transition temperature is 18°C)**

**Answer**

$$\text{Transition temperature (T)} = 18^\circ\text{C} = 291\text{K}$$

$$\text{frequency of light emitted } \nu = c/\lambda = \frac{3 \times 10^8}{6928 \times 10^{-10}} = 4.3302 \times 10^{14} \text{ Hz}$$

$$\begin{aligned}\frac{N_2}{N_1} &= e^{\wedge} (-h\nu/(kT)) \\ &= e^{\wedge} (-6.626 \times 10^{-34} \times 4.3302 \times 10^{14} / (1.38 \times 10^{-23} \times 291)) \\ &= e^{-71.45} = 9.32 \times 10^{-32}\end{aligned}$$

# Fibre Optics

Fibre optics deals with transmission of information using light (which has minimal energy loss). Total internal reflection is the principle behind it.

## Total internal reflection

**Total internal reflection:** It is a phenomenon which happens when light traveling from denser to lighter medium will reflect back to the same media if the incident angle is greater than a particular angle (known as critical angle of the media interface).

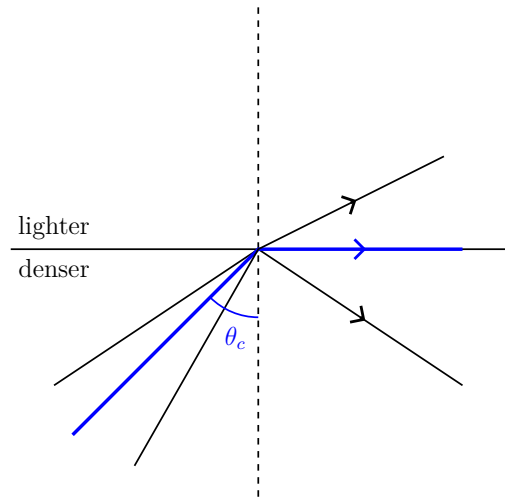
By snell's law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

At critical angle ( $\theta_1 = \theta_c$ ),  $\theta_2 = 90^\circ$

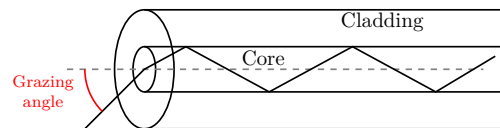
$$\therefore n_1 \sin(\theta_c) = n_2$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

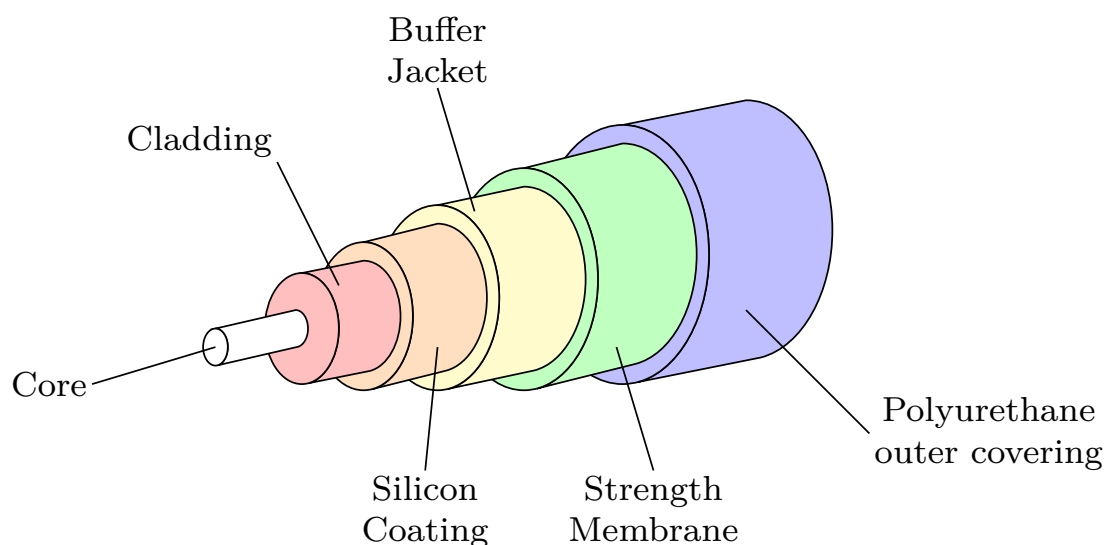


$\theta_c$  for various material interfaces:

- Water - air  $= 49^\circ$
- Diamond - air  $24^\circ$
- Glass - air  $42^\circ$



## Structure of Fiber Optic Cable

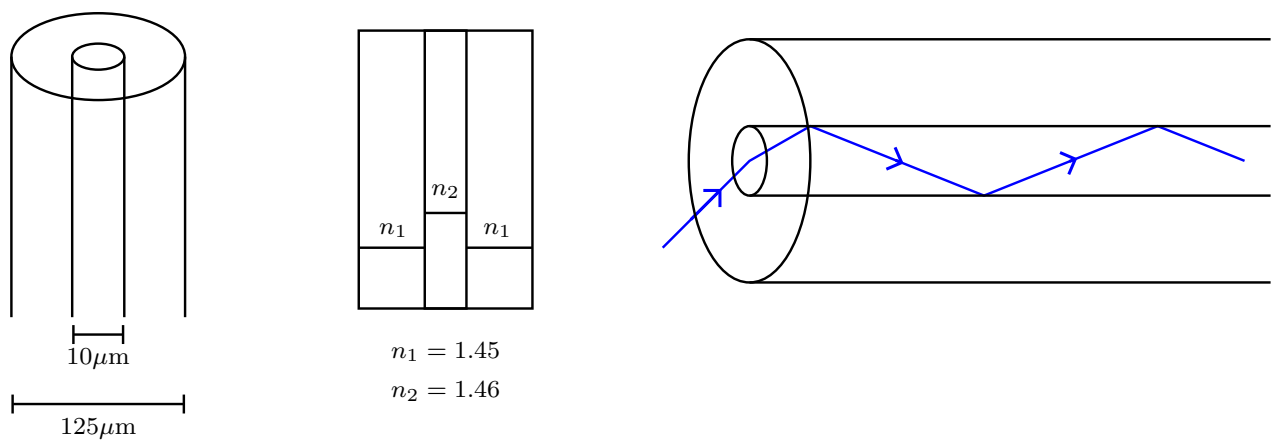


- Polyurethane: for mechanical crushing
- Butfor jacket : to prevent moistume
- Si-coarting : protect from dust & soratches

## Classification of Fibre Optic Cables & Propagation of light in them

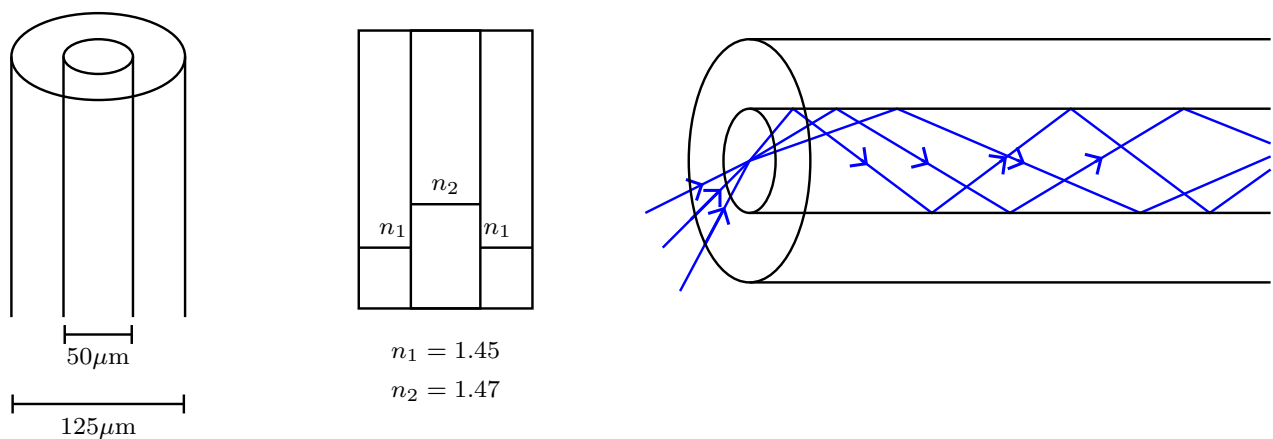
- Based on Index profile: step-index, graded index
- Based on made : single mode, multi mode.

### Step Index Single Mode



- Allows only one path for light
- Bandwidth distance product:  $> 3 \text{ GHzkm}$
- Splicing is difficult.

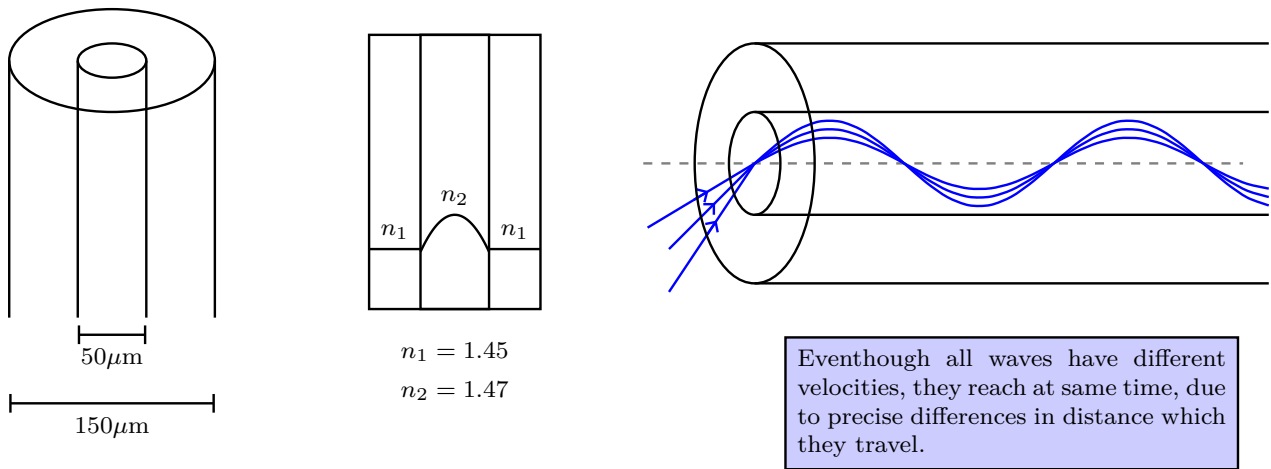
### Step Index Multi Mode



- Allows multiple path for light

- Easier to splice
- Bandwidth distance product (BwDP)  $\sim 300$  MHzkm

## Graded Index Multi Mode



- Gradual decrease in refractive index.
- BWDP  $\approx 3$  GHzkm

## Comparison between different Cables

Step Index	Graded Index
Refractive index changes sharply from core-cladding interface	Refractive index changes gradually from core-cladding interface
Refractive index profile looks like steps	Refractive index profile looks like parabola
Attenuation is more for multimode and less for single mode	Attenuation is usually less
Numerical Aperture is more for multimode and less for single mode	Numerical Aperture is usually less

Single Mode	Multi Mode
Only one mode can propagate through fibre	Allows a large number of modes
Smaller core diameter	Larger core diameter



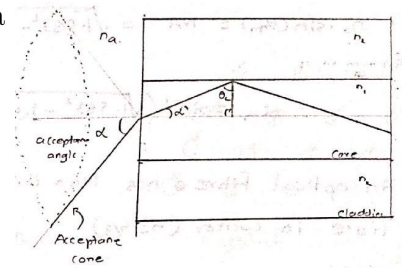
Difference in refractive indices is very less	Difference in refractive indices is more compared to single mode
No multimodal dispersion	There is multimodal dispersion

## Numerical Aperture (NA)

Numerical Aperture is defined as sine of largest angle that an incident ray should have for it to undergo TIR in core

By Snell's law:  $n_a \sin(\alpha) = n_1 \sin(\alpha)$

For TIR, angle of incidence in the medium must be  $> \theta_c$ .  
 $\alpha$  at  $\theta_c$  is called acceptance angle. ( $\alpha_m$ )



$$\begin{aligned}
 n_a \sin(\alpha_m) &= n_1 \sin(90 - \theta_c) \\
 &= n_1 \cos(\theta_c) \\
 &\equiv n_1 \sqrt{1 - \sin^2(\theta_c)} \\
 &= n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \\
 &= \sqrt{n_1^2 - n_2^2}
 \end{aligned}$$

$$\therefore NA = n_a \cdot \sin(\alpha_m) = \sqrt{n_1^2 - n_2^2}$$

**1 An optical fibre has core refractive index of 1.55 & cladding refractive index of 1.50. Calculate Numerical Aperture**

**Answer**

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2 - 1.5^2} = 0.391$$

**2 Calculate acceptance angle of given fibre, if core refractive index = 1.563 cladding refractive index = 1.498**

**Answer**

Assuming refractive index of air ( $n_a$ ) = 1.

$$n_a \cdot \sin(\alpha_m) = \sqrt{1.563^2 - 1.498^2}$$

$$\therefore \text{acceptance angle } (\alpha_m) = \sin^{-1} \left( \sqrt{1.563^2 - 1.498^2} \right) = 26.49^\circ$$

**3 An optical fibre Numerical Aperture = 0.20, refractive index of cladding = 1.59. Find acceptance angle for fibre in water (n=4/3)**

**Answer** Here  $n_a = 4/3$

$$n_a \sin(\alpha_m) = 0.20$$

$$\therefore \alpha_m = \sin^{-1} \left( \frac{3}{4} \times 0.20 \right) = 8.63^\circ$$

**4 For a cable, Numerical Aperture = 0.39, and difference between refractive indices of core and cladding is 0.05. Find refractive index of core**

**Answer**

$$NA = \sqrt{n_1^2 - n_2^2} = 0.39$$

$$n_1^2 - n_2^2 \equiv (n_1 + n_2)(n_1 - n_2) = 0.1521$$

$$\Rightarrow n_1 + n_2 = \frac{0.1521}{n_1 - n_2} = 3.042$$

$$\therefore n_1 = n_{\text{core}} = \frac{(n_1 + n_2) + (n_1 - n_2)}{2}$$

$$= \frac{3.042 + 0.05}{2} = 1.546$$

**5 For step index fibre,  $n_{\text{core}} = 1.52$ ,  $n_{\text{cladding}} = 1.41$ . Find  $\theta_c$**

**Answer**

$$\theta_c = \sin^{-1} \left( \frac{1.41}{1.52} \right) = 68.1^\circ$$