Unit 5

Introduction to Laser

LASER stands for Light Amplification by Stimulated Emission of Radiation.

Q1. What is a Laser?

A laser is an optical device that produces a highly **intense, coherent and monochromatic beam** of light through the process of stimulated emission. The term LASER is an acronym **for Light Amplification by Stimulated Emission of Radiation**.

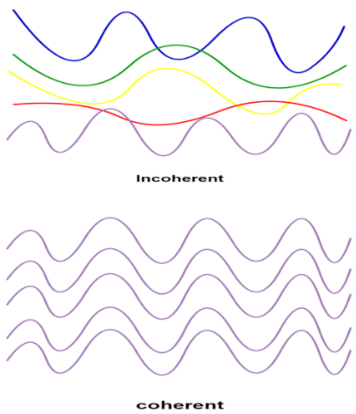
The working principle of a laser originates from three fundamental atomic processes: **absorption, spontaneous emission and stimulated emission**. When an atom in the ground state absorbs a photon of suitable energy, it jumps to a higher energy level, a process known as **absorption**. An excited atom may return to a lower state by emitting radiation in a random direction; this is **spontaneous emission**. However, if an incoming photon of energy equal to the difference between the energy levels interacts with an excited atom, it forces the atom to release another photon that is identical in phase, direction and energy to the incoming one. This phenomenon is called stimulated emission, and it is the key to laser action. When more atoms are maintained in the excited state than in the ground state, a condition known as population inversion is achieved. Under this condition, stimulated emission dominates, resulting in the amplification of light and formation of a laser beam.

Q2. What are the Characteristics of Laser Light?

Laser light has five major characteristics:

Monochromaticity:
Laser light contains a single wavelength or a very narrow range of wavelengths.
This occurs because stimulated emission produces photons of one fixed energy difference.

Coherence:
Laser light waves maintain a constant phase relationship. This includes both temporal coherence (phase stability over time) and spatial coherence (phase stability across the beam).



Directionality:
Laser beams have extremely low divergence. They travel long distances without spreading significantly.

High Intensity:
A large number of photons travel together in a small region, making the laser beam very intense.

Polarization:
Most lasers produce photons whose electric field vibrates in the same plane, giving the beam a fixed polarization.

Q3. What are Einstein coefficients? Explain the three quantum processes.

Einstein introduced three coefficients to describe the interaction between radiation and matter in terms of transitions between two energy levels E_1 and E_2 of an atom, where $E_2 > E_1$. The atom in the lower level E_1 has population N_1 and in the upper level E_2 has population N_2. The three basic processes are absorption, spontaneous emission and stimulated emission.

In absorption, an atom in the lower energy level E_1 absorbs a photon of energy $h\nu = E_2 - E_1$ and jumps to the upper level E_2. The probability per unit time that one atom will absorb a photon is proportional to the radiation energy density $\rho(\nu)$. Einstein wrote this probability as $B_{12}\rho(\nu)$, where B_{12} is called the Einstein coefficient of absorption. The total number of upward transitions per unit time is then

$$R_{\text{abs}} = B_{12}\rho(\nu)N_1.$$

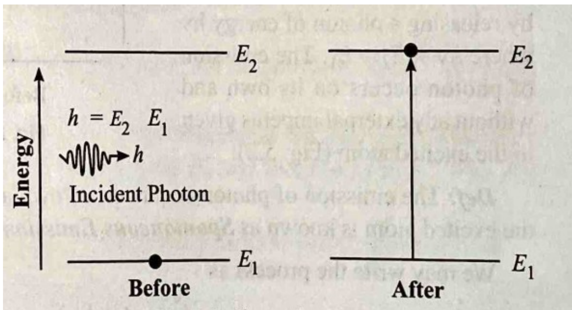


Fig. 5.1: Absorption Process

In spontaneous emission, an atom in the excited state E_2 can drop to the lower state E_1 without any external influence. The emitted photon has energy $h\nu = E_2 - E_1$, but its direction and phase are random. Einstein assumed that the probability per unit time for one excited atom to decay spontaneously is a constant A_{21}, called the Einstein coefficient of spontaneous emission. The total number of spontaneous downward transitions per unit time is

$$R_{\text{sp}} = A_{21}N_2.$$

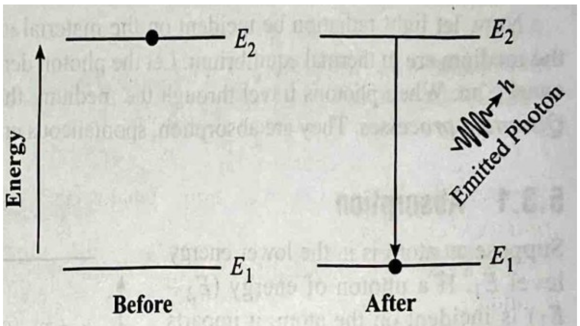


Fig. 5.2: Spontaneous emission process

In stimulated emission, an incident photon of energy $h\nu$ interacts with an excited atom in level E_2 and forces it to drop to level E_1, emitting a second photon identical to the first in energy, direction, phase and polarization. The probability per unit time for this process is proportional to $\rho(\nu)$ and is written as $B_{21}\rho(\nu)$, where B_{21} is the Einstein coefficient of stimulated emission. The total number of stimulated transitions per unit time is

$$R_{\text{st}} = B_{21}\rho(\nu)N_2.$$

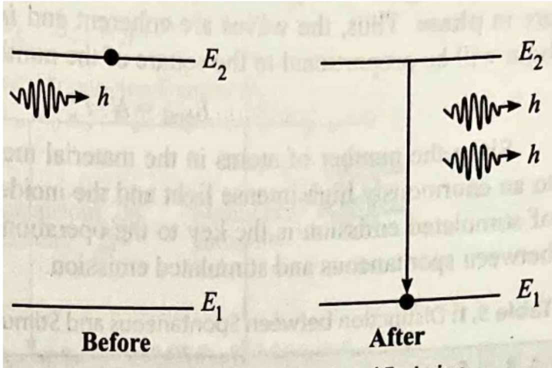


Fig. 5.3: *Process of Stimulated Emission*

Thus the three coefficients A_{21}, B_{12} and B_{21} fully describe the radiative transitions between two energy levels and are fundamental in the theory of lasers.

Q4. Derive the relations between Einstein coefficients.

Einstein considered a collection of atoms in thermal equilibrium with black body radiation at temperature T. Under equilibrium, the rate of upward transitions from E_1 to E_2 must be equal to the total rate of downward transitions from E_2 to E_1. The upward rate is due only to absorption and is

$$R_{\text{up}} = B_{12}\rho(\nu)N_1.$$

The downward rate has two contributions, spontaneous and stimulated emission, hence

$$R_{\text{down}} = A_{21}N_2 + B_{21}\rho(\nu)N_2.$$

At equilibrium $R_{\text{up}} = R_{\text{down}}$, therefore

$$B_{12}\rho(\nu)N_1 = A_{21}N_2 + B_{21}\rho(\nu)N_2.$$

The ratio of populations N_2/N_1 in thermal equilibrium is given by the Boltzmann distribution

$$\frac{N_2}{N_1} = \exp\left[-\frac{E_2 - E_1}{kT}\right] = \exp\left[-\frac{h\nu}{kT}\right].$$

Substituting N_2 in the equilibrium condition and solving for $\rho(\nu)$ gives

$$\rho(\nu) = \frac{A_{21}}{B_{12}\exp\left[\frac{h\nu}{kT}\right] - B_{21}}.$$

But the energy density of black body radiation is known from Planck's law as

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3}\frac{1}{\exp\left[\frac{h\nu}{kT}\right] - 1}.$$

By comparing the two expressions for $\rho(\nu)$, Einstein obtained two important relations. First, the coefficients for absorption and stimulated emission must be equal,

$$B_{12} = B_{21}.$$

Second, the ratio between spontaneous and stimulated emission coefficients is

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

These are called Einstein relations. They show that stimulated emission is unavoidable whenever spontaneous emission exists and that spontaneous emission is dominant at low radiation densities, whereas stimulated emission becomes significant when the radiation energy density $\rho(\nu)$is high.

Q5. What is a metastable state and why is it important for lasers?

A metastable state is an excited energy level of an atom or ion in which the lifetime of particles is unusually long compared to ordinary excited states. For normal excited states, the lifetime is of the order of 10^{-8}seconds because atoms quickly return to lower levels by spontaneous emission. In a metastable state, the probability of spontaneous emission is very small, so the lifetime can be as long as 10^{-3}seconds or more.

Because of this long lifetime, atoms pumped into a metastable level do not decay immediately. They accumulate and form a large population in that level. At the same time, the lower laser level either has a much shorter lifetime or quickly empties by non-radiative processes. As a result, the number of atoms in the upper laser level (metastable state) can become greater than the number in the lower level. This condition is called population inversion and is essential for laser operation. Without a metastable state, it is very difficult to achieve population inversion because atoms would decay back too quickly.

Q6. What is population inversion? Derive the thermal population ratio.

Population inversion is the condition in which the population of atoms in a higher energy level exceeds the population in a lower energy level, that is

$$N_2 > N_1.$$

This is opposite to the normal thermal equilibrium situation, where the lower level always has more atoms than the higher level.

Under thermal equilibrium, the number of atoms N_i in an energy level E_i at temperature T is governed by the Boltzmann distribution

$$N_i \propto \exp\left[-\frac{E_i}{kT}\right].$$

For two levels E_1 and E_2, the population ratio is

$$\frac{N_2}{N_1} = \exp\left[-\frac{E_2 - E_1}{kT}\right] = \exp\left[-\frac{h\nu}{kT}\right].$$

Since $(E_2 - E_1)$ and $h\nu$ are positive, the exponential factor is always less than one, so $N_2 < N_1$. This means population inversion can never occur in thermal equilibrium; an external energy supply called pumping is required to push atoms into higher levels and create $N_2 > N_1$.

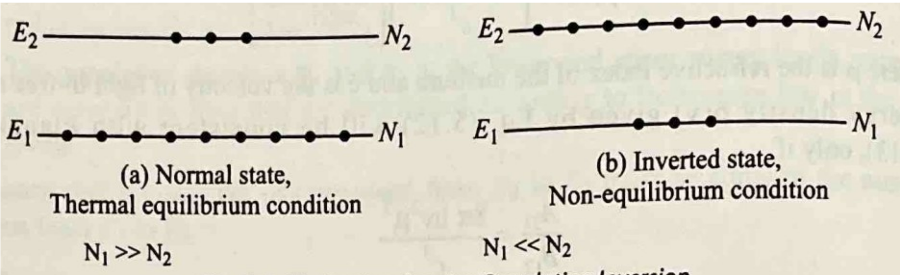


Fig. 5.6: *Illustration showing Population Inversion*

Q7. What is pumping in a laser?

Pumping is the process of supplying external energy to the active medium of a laser in order to transfer atoms from a lower energy level to a higher energy level, preferably a metastable state, and thereby achieve population inversion. The external energy may be in the form of optical radiation, electric discharge or chemical reaction.

In optical pumping, an intense light source such as a xenon flash lamp is used to excite the atoms of the active medium. In electrical pumping, an electric discharge through a gas transfers energy to the gas atoms or ions. In semiconductor lasers, forward bias across a p–n junction injects electrons and holes, and their recombination provides the required pumping. The effectiveness of pumping determines how quickly population inversion is built up and how much laser output power can be obtained.

Q8. What is lasing action? Describe the sequence of events in laser operation.

Lasing action is the complete process by which a laser generates a coherent, intense and directional beam of light. It involves four essential steps: pumping, population inversion, stimulated emission and optical feedback.

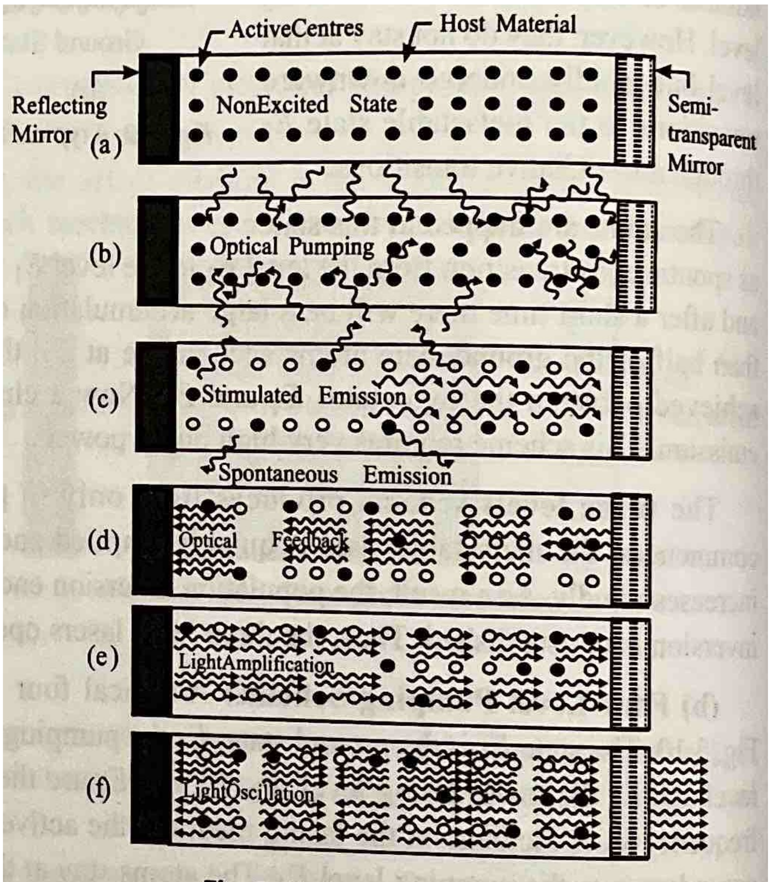


Fig. 5.11: Steps in LASER action

Initially, pumping raises a large number of atoms from the ground state to higher energy levels. Many of these atoms eventually reach a metastable state, and due to its long lifetime they accumulate there. When the number of atoms in the metastable state exceeds the number in the lower laser level, population inversion is achieved.

If a photon of suitable energy $h\nu$passes through the inverted medium, it can stimulate excited atoms to emit more photons of the same energy, phase and direction. These newly created photons in turn stimulate further emissions, resulting in a chain reaction of stimulated emission and rapid amplification of light intensity.

The active medium is placed between two mirrors forming an optical resonator. One mirror is fully reflecting and the other is partially transmitting. Photons traveling along the axis of the resonator are repeatedly reflected back and forth, stimulating more emissions and building up a powerful, coherent standing wave inside the cavity. A small fraction of this amplified light escapes through the partially transmitting mirror as the output laser beam. The combination of gain from stimulated emission and feedback from the resonator sustains continuous lasing action as long as pumping maintains the population inversion.

Problem 1. For a two-level system, the spontaneous emission coefficient is $A_{21} = 8.0 \times 10^7$ s^{-1}. The transition frequency is $\nu = 5.0 \times 10^{14}$ Hz. Using the Einstein relation, calculate B_{21}.

Solution.
The relation between A_{21} and B_{21} is

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

Thus

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

Substitute $A_{21} = 8.0 \times 10^7 \text{ s}^{-1}$, $h = 6.626 \times 10^{-34}$ J s, $c = 3 \times 10^8 \text{ m s}^{-1}$, $\nu = 5 \times 10^{14}$ Hz.

Computing gives

$$B_{21} \approx 7.0 \times 10^{19} \text{ m}^3\text{J}^{-1}\text{s}^{-2}$$

Problem 2.
A laser transition occurs at wavelength $\lambda = 600$ nm. Calculate the ratio N_2/N_1at temperature $T = 300$ Kunder thermal equilibrium and comment on the possibility of inversion.

Solution.
First find the photon energy

$$E_2 - E_1 = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3 \times 10^8)}{600 \times 10^{-9}} = 3.31 \times 10^{-19} \text{ J}.$$

The Boltzmann ratio is

$$\frac{N_2}{N_1} = \exp\left[-\frac{E_2 - E_1}{kT}\right] = \exp\left[-\frac{3.31 \times 10^{-19}}{(1.38 \times 10^{-23})(300)}\right].$$

The denominator $kT = 4.14 \times 10^{-21}$ J, so the exponent is approximately -80. Thus

$$\frac{N_2}{N_1} \approx e^{-80} \approx 1.8 \times 10^{-35},$$

which is extremely small. Hence almost no atoms occupy the upper level in thermal equilibrium, and population inversion is impossible without pumping.

Problem 3.
In a certain laser medium, the upper laser level has a lifetime of $\tau_2 = 1$ msand the lower laser level has a lifetime of $\tau_1 = 10^{-8}$ s. Explain, using these lifetimes, why this system is suitable for achieving population inversion.

Solution.
The average number of atoms in each level depends on how long they remain in that level. A lifetime of 1 msmeans atoms in the upper level stay there a long time, so atoms pumped into this level accumulate and create a large population. A lifetime of 10^{-8} sfor the lower level means atoms quickly leave this level through non-radiative transitions, so its population remains small. Therefore, even moderate pumping can lead to $N_2 > N_1$, i.e., population inversion. This analysis shows why a long-lived metastable upper level and a short-lived lower level are desirable for laser action.

Q9. Explain the construction, working, energy-level diagram and characteristics of a Ruby Laser.

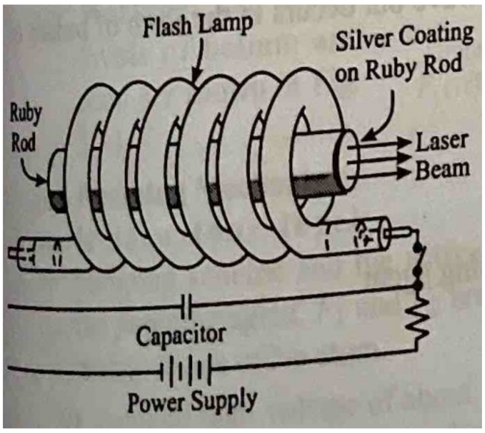
A Ruby Laser is the **first laser ever invented** by Theodore Maiman in 1960. It is a **solid-state, pulsed laser** that uses **synthetic ruby** as its active medium. Ruby is a crystal of **Al_2O_3 (aluminium oxide) doped with Cr^{3+} (chromium ions)**.

The ruby laser mainly consists of:

(a) Active Medium: The active medium is a cylindrical rod of synthetic ruby, typically **4–10 cm long** and **0.5–1 cm in diameter**. Chromium ions (Cr^{3+}) replace some Al^{3+} ions inside the crystal and are responsible for absorption and emission of light.

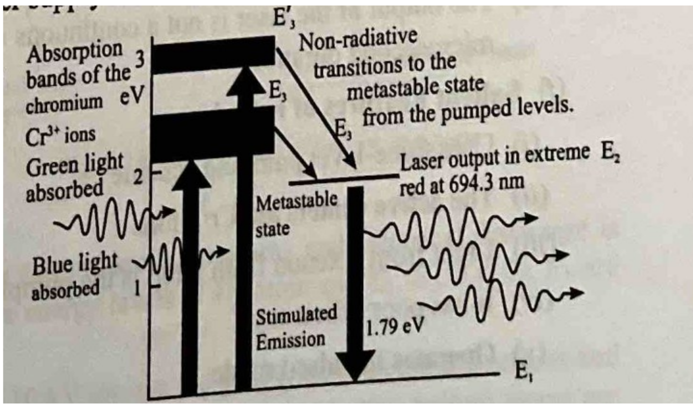
(b) Optical Pumping Source: A **helical xenon flash lamp** is wound around the ruby rod. When the lamp is flashed, it produces intense light that excites Cr^{3+} ions.

(c) Optical Resonator: Both ends of the ruby rod are optically polished.
One end is **fully reflecting**, and the other is **partially reflecting**, forming a Fabry–Perot resonator. This cavity provides feedback required for amplification.



Energy-Level Diagram: Ruby laser works on a **three-level scheme**

- **Ground state (E_1):** Most ions remain here initially.
- **Pumping band (E_3):** Cr^{3+} ions absorb pump light and move to this high-energy level.
- **Metastable state (E_2):** After non-radiative relaxation, ions reach this level. This level has a **long lifetime (~10^{-3} s)**, allowing population inversion.



Laser Transition: The stimulated transition occurs between

$$E_2 \longrightarrow E_1$$

emitting red light of wavelength **694.3 nm**.

Working of Ruby Laser

Step 1: Optical Pumping - When the xenon flash lamp emits intense light, Cr^{3+} ions absorb photons and move from the ground state E_1 to the pumping band E_3.

Step 2: Non-Radiative Transition - Ions in E_3 lose some energy (as heat) and fall to the metastable state E_2. Because E_2 has a long lifetime, ions accumulate here, forming **population inversion**.

Step 3: Stimulated Emission - When a photon of wavelength 694.3 nm passes through the rod, it stimulates ions in E_2 to drop to E_1, producing identical photons (same wavelength, direction and phase).

Step 4: Amplification and Output - Photons bounce inside the resonator between the mirrors. Each reflection causes more stimulated emissions, amplifying the photon count. Finally, part of the light escapes through the partially reflecting mirror as the **laser pulse**.

Mode of Output

Ruby laser always operates in **pulsed mode**, not continuous, because:

1. A three-level system requires more input energy.
2. Flash lamps deliver energy in pulses.

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5. Wavelength of Ruby Laser

The emitted wavelength is given by:

$$\lambda = \frac{hc}{E_2 - E_1}$$

For ruby: $\lambda = 694.3$ nm

Characteristics of Ruby Laser

- Produces **red light** at 694.3 nm.
- Works in **pulsed mode** due to flash lamp pumping.
- Has **high peak power**, low average power.
- Beam is **highly monochromatic and coherent**.
- Output is **narrow and directional**.
- Suitable for **holography, medical surgery and material processing**.

Q10. Explain the construction, working, energy-level diagram and characteristics of a He–Ne Laser.

The He–Ne (Helium–Neon) laser is a **gas laser** that produces a stable, continuous, and highly coherent beam of light. Its most common output wavelength is **632.8 nm** (red light). It operates on a **four-level laser scheme**, which makes it easier to achieve population inversion compared to ruby lasers. He–Ne lasers are widely used in laboratories, supermarkets (barcode scanning), interferometry and holography.

Construction of He–Ne Laser

A He–Ne laser mainly consists of:

(a) Discharge Tube: A long glass tube (30–80 cm) filled with a gas mixture of **Helium and Neon** in the ratio 10:1. Pressure inside the tube is around **1 torr for He** and **0.1 torr for Ne**.

(b) Electrodes: High-voltage DC supply (2–3 kV) is connected across the tube to create an electrical discharge. This discharge excites helium atoms.

(c) Optical Resonator: The ends of the tube are fitted with two mirrors:

1. **Fully reflecting mirror**
2. **Partially transmitting mirror** (allows output beam)

These mirrors form a Fabry–Perot resonator, providing optical feedback.

(d) Gas Mixture Function: Helium is used for efficient **energy transfer**. **Neon** provides the **actual laser transition**.

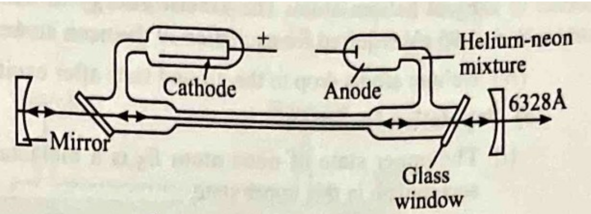


Fig. 5.13: Schematic of a He-Ne laser

Energy-Level Diagram Explanation

He–Ne laser uses a four-level scheme:

1. **Helium excitation:**
   The electric discharge excites He atoms to higher metastable states.
2. **Resonant Energy Transfer:**
   Excited He atoms collide with Ne atoms.
   Since the energy levels of He* and Ne* are very close, He transfers its energy to Ne:

$$He^{*} + Ne \rightarrow He + Ne^{*}$$

3. **Population Inversion:**
   Neon atoms accumulate in the upper laser level because it is metastable.
4. **Laser Transition:**
   The main laser emission occurs when Ne atoms drop from the excited level to a lower energy level, producing **632.8 nm red light**.

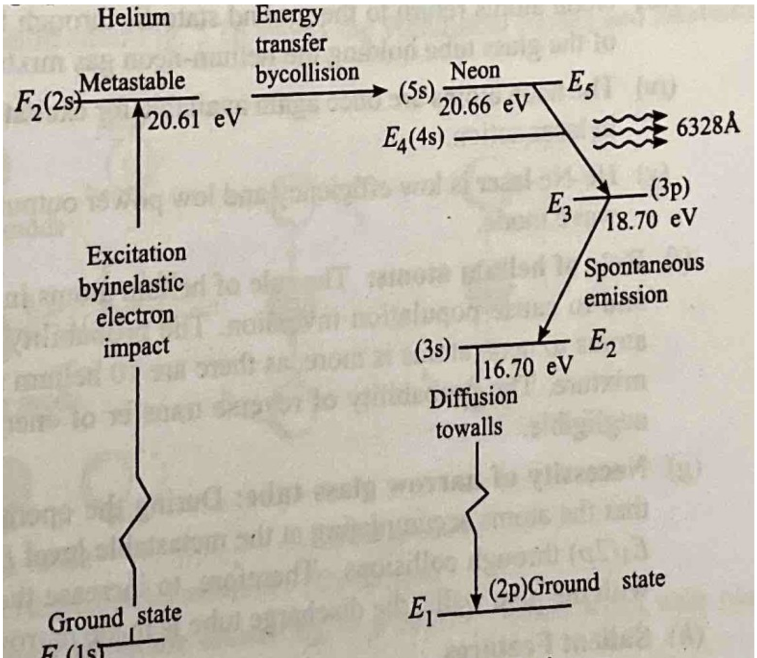


Fig. 5.14: Energy levels of helium and neon

Working of He–Ne Laser

Step 1: Electrical Pumping - High voltage ionizes the He–Ne gas mixture. Fast electrons excite helium atoms from the ground state to higher states.

Step 2: Energy Transfer to Neon - Excited helium atoms collide with neon atoms. Because their excitation energies are nearly equal, energy is transferred efficiently. Neon atoms reach the upper laser state, creating **population inversion**.

Step 3: Stimulated Emission - A Ne atom in the upper laser level emits a photon of wavelength **632.8 nm** when stimulated by an incoming photon. This photon has identical properties: direction, energy, phase and polarization.

Step 4: Resonator Amplification - The emitted photons bounce between the two mirrors inside the resonator. Each reflection produces more stimulated emissions, increasing intensity.

Step 5: Output Beam - A narrow, intense, coherent beam emerges through the partially reflecting mirror.

Wavelength of He–Ne Laser

$$\lambda = 632.8 \text{ nm}$$

Corresponding frequency:

$$\nu = \frac{c}{\lambda}$$

This wavelength lies in the **visible red region**.

Characteristics of He–Ne Laser

- Produces **continuous-wave (CW)** output.
- Output beam is **highly coherent and stable**.
- Has **very low divergence**, making the beam extremely directional.
- Emits red light of **632.8 nm** (other wavelengths possible).
- Easy to operate and relatively low-cost.
- Lower power (~1–5 mW), suitable for educational and alignment applications.

Problem 1:

Calculate the frequency of the He–Ne laser that emits at 632.8 nm.

Solution:

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{632.8 \times 10^{-9}}$$
$$\nu = 4.74 \times 10^{14} \text{ Hz}$$

Problem 2:

Find the photon energy for the 632.8 nm He–Ne laser.

Solution:

$$E = \frac{hc}{\lambda}$$
$$E = \frac{(6.626 \times 10^{-34})(3 \times 10^{8})}{632.8 \times 10^{-9}}$$
$$E = 3.14 \times 10^{-19} \text{ J}$$

Convert to eV:

$$E = \frac{3.14 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.96 \text{ eV}$$

Problem 3:

If a He–Ne laser outputs 2 mW of power and each photon has energy 3.14×10^{-19}J, calculate the number of photons emitted per second.

Solution:

$$N = \frac{P}{E}$$
$$N = \frac{2 \times 10^{-3}}{3.14 \times 10^{-19}}$$
$$N \approx 6.37 \times 10^{15} \text{ photons/sec}$$

Q. Explain the construction, working, energy-level diagram and characteristics of a CO_2 Laser.

The CO_2 laser is one of the most powerful and efficient gas lasers. It emits radiation mainly at **10.6 µm** and **9.6 µm** in the infrared region. It operates as a **molecular gas laser** and uses a **four-level energy scheme**. The CO_2 laser is widely used in industries for **cutting, welding, drilling and medical surgery** because of its high continuous-wave output power.

Construction of CO_2 Laser - A CO_2 laser consists of the following major components:

(a) Discharge Tube - A long glass or quartz tube filled with a gas mixture of **CO_2, N_2 (Nitrogen) and He (Helium)**.

Typical proportions:

- $CO_2 \approx 20\%$
- $N_2 \approx 40\%$
- He $\approx 40\%$

The gas pressure is usually between 2 to 5 torr.

(b) Electrodes - High voltage electrodes are placed at both ends of the tube. A strong electric discharge excites the gas molecules.

(c) Optical Resonator - Two mirrors are fixed at the ends:

- One mirror is **fully reflecting**
- The other is **partially transmitting** for output laser beam

(d) Cooling System - CO_2 lasers generate large amounts of heat. A water cooling or air cooling system is used to maintain temperature stability.

(e) Gas Circulation - Helium helps remove excess heat from the CO_2 molecules, increasing efficiency.

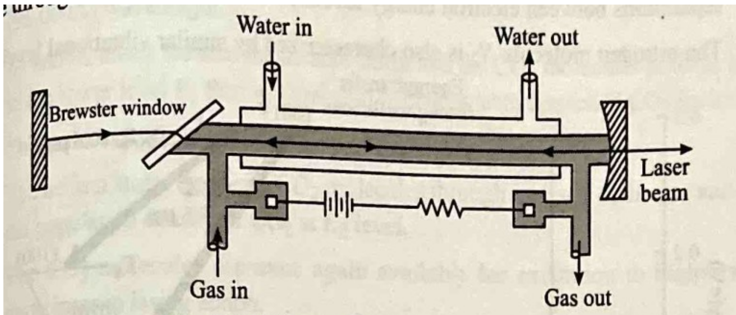


Fig. 5.15: Schematic of a carbon dioxide laser

Energy-Level Diagram Explanation - CO_2 molecules have **vibrational energy levels**. The important vibrational modes are:

- Symmetric stretching
- Bending

- Asymmetric stretching

The laser transitions occur between vibrational levels of these modes.

Role of Nitrogen (N_2):

- N_2 molecules get excited easily by electrical discharge.
- They have a metastable vibrational energy level.
- This energy level matches the vibrational energy of CO_2 upper laser level.

Thus, energy is transferred from N_2 to CO_2 efficiently:

$$N_2^* + CO_2 \rightarrow N_2 + CO_2^*$$

This process creates **population inversion** in CO_2.

Laser Transitions:

The main laser emissions are:

- **10.6 µm**
- **9.6 µm**

These transitions occur between vibrational levels of CO_2.

Working of CO_2 Laser

Step 1: Electrical Pumping - High voltage energizes electrons in the discharge tube. These electrons collide with N_2 molecules and excite them to higher vibrational states.

Step 2: Resonant Energy Transfer - Excited N_2 molecules collide with CO_2 molecules. Because their vibrational energies are nearly equal, N_2 efficiently transfers its energy to CO_2. Thus, CO_2 reaches the **asymmetric stretching vibrational level**, which acts as the upper laser level.

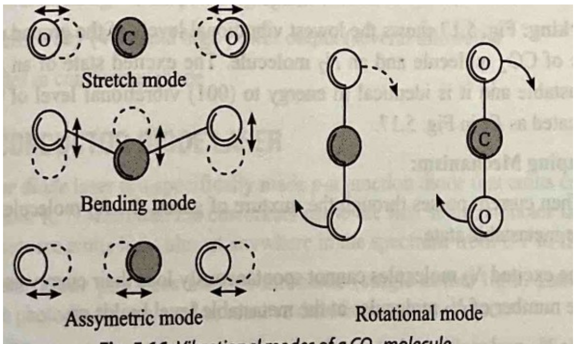


Fig. 5.16: Vibrational modes of a CO_2 molecule

Step 3: Population Inversion - CO_2 molecules accumulate in the upper vibrational level, while the lower levels empty quickly. This creates strong population inversion.

Step 4: Stimulated Emission - When CO_2 molecules drop from the upper level to the lower vibrational level, they emit infrared photons at **10.6 µm**.

Step 5: Optical Feedback and Output - The mirrors reflect photons back and forth, stimulating more emissions and increasing power. Part of the amplified infrared beam exits through the partially transmitting mirror as the laser output.

Step 6: Cooling by Helium - Helium atoms help remove excess heat and bring molecules down to the lower levels quickly. This increases the efficiency of the laser.

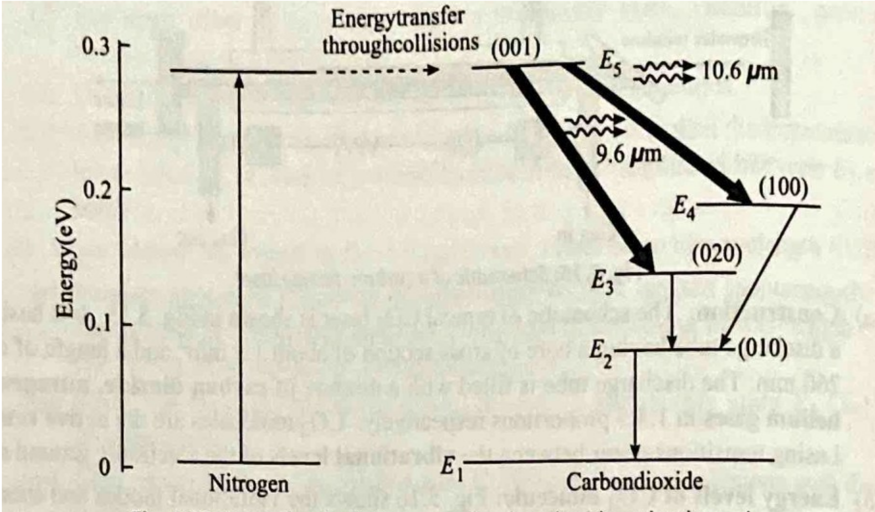


Fig. 5.17: Energy levels of nitrogen and carbon dioxide molecules and transitions between the levels

5. Wavelength of CO_2 Laser

Primary emission:

$$\lambda = 10.6\ \mu m$$

Secondary emission:

$$\lambda = 9.6\ \mu m$$

Characteristics of CO_2 Laser

- Highest efficiency among all gas lasers (≈ 20–30%).
- Provides **high continuous-wave power** (several kW).
- Emits in the **infrared region**.
- Beam is highly coherent and directional.
- Needs cooling due to high thermal load.
- Used for cutting, welding, engraving and medical surgery.

Q. Explain the construction, working, energy-level diagram and characteristics of a Semiconductor Diode Laser.

A semiconductor diode laser is a **solid-state laser** that uses a **forward-biased p–n junction** as its active medium. It is compact, efficient, low-cost and capable of high-speed modulation.

Because of these advantages, diode lasers are widely used in **CD/DVD drives, optical fiber communication, barcode scanners and laser pointers**. The most common semiconductor used is **Gallium Arsenide (GaAs)**, which emits in the near-infrared region.

Construction of Semiconductor Diode Laser

A diode laser is similar in appearance to a Light Emitting Diode (LED), but it has additional features to enable stimulated emission:

(a) p–n Junction

The active region is formed at the interface of p-type and n-type semiconductor materials. Forward bias causes carrier injection into this junction.

(b) Active Region

Just around the junction, electrons from the n-side and holes from the p-side recombine. This narrow region is responsible for light generation.

(c) Optical Cavity

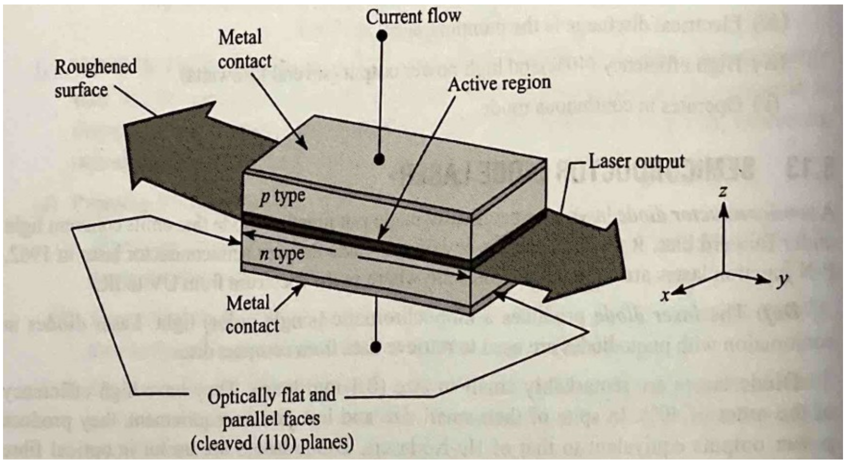
The two opposite faces of the semiconductor crystal are **cleaved** to form natural mirrors. These parallel faces act as a **Fabry–Perot resonator**.

(d) Electrical Contacts

Metallic contacts supply forward bias to the diode.

(e) Heat Sink

A small heat sink is attached because semiconductor lasers generate heat during operation.



Energy-Level Diagram Explanation

Semiconductor lasers operate based on **band theory**, not discrete atomic levels.

- Electrons occupy the **conduction band**.
- Holes occupy the **valence band**.
- The energy gap between these two bands is called the **band gap energy (E_g)**.

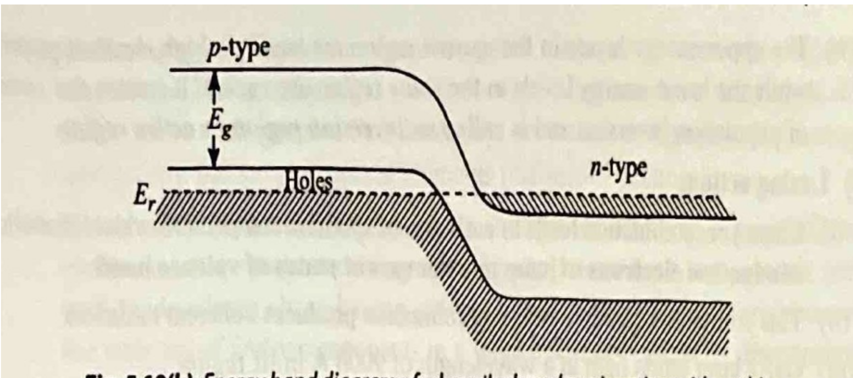


Fig. 5.18(b): Energy band diagram of a heavily doped p-n junction without bias

When electrons fall from the conduction band to the valence band, they recombine with holes and release photons of energy:

$$E = h\nu = E_g$$

The corresponding wavelength is:

$$\lambda = \frac{hc}{E_g}$$

Population inversion is achieved when a large number of electrons are injected into the conduction band through **strong forward bias**.

4. Working of Semiconductor Diode Laser

Step 1: Forward Bias

When the diode is strongly forward biased, electrons and holes are injected into the junction region.
Electron concentration increases in the conduction band, and hole concentration increases in the valence band.

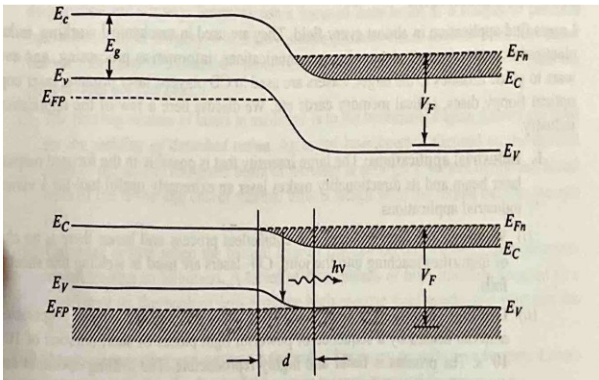


Fig. 5.18(c): Laser diode under forward bias

Step 2: Population Inversion

Because the injection is extremely high, more electrons accumulate in the conduction band than in thermal equilibrium. This results in **population inversion** between the conduction and valence bands.

Step 3: Spontaneous Emission

Some electrons recombine spontaneously with holes, producing incoherent photons. This is similar to LED operation.

Step 4: Stimulated Emission

Some of the spontaneously emitted photons travel along the plane of the junction. These photons stimulate more electrons to recombine, generating a large number of coherent photons.

Step 5: Optical Feedback

The cleaved crystal surfaces reflect photons back and forth, forming an optical resonator. This enhances stimulated emission and amplifies light.

Step 6: Laser Output

A small percentage of photons escape through one cleaved face, producing a **highly directional laser beam**.

5. Wavelength of Semiconductor Laser

For GaAs diode laser:

$$E_g = 1.43 \text{ eV}$$
$$\lambda = \frac{hc}{E_g}$$

This gives:

$$\lambda \approx 850 \text{ nm}$$

which lies in the **near-infrared region**.

6. Characteristics of Semiconductor Diode Laser

- Produces **continuous-wave (CW)** output.
- Very **small in size** (few mm).
- Highly **efficient** and requires little power.
- Output is **monochromatic**, **coherent** and **highly directional**.
- Can be **directly modulated** at very high speeds.
- Operates on **band-to-band transitions**, not atomic levels.
- Common wavelengths: **780 nm, 850 nm, 1300 nm, 1550 nm**.

Q. Explain the working of a Barcode Scanner using Laser.

1. Introduction

A barcode scanner is an optical device that uses a **laser beam** to read information encoded in the form of black and white bars. The laser used is usually a **low-power semiconductor diode laser** because it is safe, coherent and highly directional. The reflected light pattern is converted into electrical signals to decode the stored information.

2. Principle of Operation

A barcode consists of alternating **black bars** and **white spaces**.

- **Black bars absorb** most of the laser light.
- **White spaces reflect** the laser light strongly.

Because of this reflectivity difference, the scanner can distinguish between bars and spaces.

3. Construction of Barcode Scanner

A typical laser barcode scanner contains:

(a) Laser Diode

Produces a narrow red laser beam (usually 650 nm).

(b) Oscillating Mirror

Moves the laser beam across the barcode in a scanning motion.

(c) Photodiode Detector

Collects reflected light and converts it into electrical signals.

(d) Signal Processor

Processes the electrical signals and converts them into digital data.

(e) Output Interface

Sends the decoded data to a computer or display unit.

4. Working of Barcode Scanner

1. **Laser Emission:**
   A red laser beam is projected onto the barcode.
2. **Scanning Action:**
   A rotating or oscillating mirror sweeps the beam across the barcode.
3. **Light Reflection:**
   White areas reflect light strongly, while black bars reflect weakly.
4. **Detection:**
   A photodiode collects the reflected light.
   The intensity variation of the reflected light generates an analog voltage signal.

5. **Signal Processing:**
   The analog signal is converted into digital pulses representing the pattern of bars and spaces.
6. **Decoding:**
   A microprocessor interprets the pattern and converts it into numerical or character data.

5. Advantages of Laser Barcode Scanner

- High accuracy
- Fast scanning
- Works at long distances
- Reliable even under low light
- Safe and low-power laser

Teaching Script for Barcode Scanner

Start by showing a real barcode label. Ask, "Why do black and white bars look different to a laser?"
Explain reflectivity differences.
Draw a barcode and sketch a laser beam scanning across it.
Explain how the photodiode converts reflected light into electrical signals.
Show how the microprocessor decodes the pattern into digits.
Give an example of scanning a product at a supermarket.

Numerical Problem – Barcode Scanner

Problem:

A barcode scanner uses a 650 nm diode laser. Calculate the frequency of the laser light.

Solution:

$$\nu = \frac{c}{\lambda}$$
$$\nu = \frac{3 \times 10^8}{650 \times 10^{-9}}$$
$$\nu = 4.61 \times 10^{14} \text{ Hz}$$

Q. Explain the working of LIDAR in autonomous vehicles.

1. Introduction

LIDAR stands for **Light Detection and Ranging**.
It is a remote sensing technology that uses **laser pulses** to measure distances, map surroundings and detect obstacles. In autonomous (self-driving) vehicles, LIDAR is a crucial sensor that provides a **3D view** of the environment.

2. Principle of Operation

LIDAR works using the **time-of-flight (TOF)** principle.

A short laser pulse is emitted, hits an object and returns to the detector.
The distance is calculated using:

$$d = \frac{ct}{2}$$

where:
d= distance to object
c= speed of light
t= round-trip time taken by the laser pulse

3. Construction of a LIDAR System

A typical LIDAR unit consists of:

(a) Laser Source

Often an IR or visible laser diode producing short pulses.

(b) Rotating Mirror Assembly

Sweeps the laser beam across a 360° field of view.

(c) Photodetector

Receives reflected pulses and converts them into electrical signals.

(d) Processor

Calculates distance, speed and position of obstacles.

(e) 3D Mapping Unit

Generates a point cloud that represents the environment.

4. Working of LIDAR

1. **Pulse Emission:**
   The LIDAR sends out rapid laser pulses (up to millions per second).
2. **Propagation and Reflection:**
   Each pulse travels through the air, strikes an object and reflects back.
3. **Detection:**
   Photodetector records the arrival time of the reflected pulse.
4. **Distance Calculation:**
   The onboard processor calculates distance using the TOF equation.
5. **3D Environment Mapping:**
   By rotating the laser beam and collecting reflected signals, LIDAR creates a **point cloud** — a detailed 3D map of the surroundings.

6. **Obstacle Detection and Tracking:**
LIDAR continuously updates the map to detect moving and stationary objects.

5. Why LIDAR is Important in Autonomous Vehicles

- Produces accurate 3D maps
- Works in low-light and nighttime conditions
- Can measure exact distance, speed and size of obstacles
- Provides 360° awareness
- Has very high spatial resolution

Teaching Script for LIDAR

Start by asking students: “How does a car know what’s around it?” Introduce LIDAR as the “eyes” of an autonomous vehicle.
Draw a simple diagram showing car → laser pulse → object → return pulse.
Write the equation $d = ct/2$and use a quick numerical example.
Explain how rotating mirrors create a 360° scan.
Show how many such pulses create a 3D point cloud.
Conclude by relating LIDAR to braking, steering and collision avoidance.

Numerical Problems – LIDAR

Problem 1:

A LIDAR pulse takes 200 ns to return after hitting an obstacle.
Calculate the distance.

Solution:

$$d = \frac{ct}{2}$$
$$d = \frac{(3 \times 10^8)(200 \times 10^{-9})}{2}$$
$$d = 30 \text{ m}$$

Problem 2:

A LIDAR system emits 100,000 pulses per second. If each pulse returns in 100 ns, what is the maximum measurable distance?

Solution:

$$d = \frac{(3 \times 10^8)(100 \times 10^{-9})}{2}$$
$$d = 15 \text{ m}$$

Problem 3:

The distance to an obstacle is measured as 50 m. Find the round-trip time of the LIDAR pulse.

Solution:

$$t = \frac{2d}{c}$$
$$t = \frac{2(50)}{3 \times 10^8}$$
$$t = 3.33 \times 10^{-7}\ \text{s} = 333\ \text{ns}$$

1. Introduction to Fibre Optics

Optical fibre is a long, thin, transparent strand of glass or plastic designed to transmit light from one point to another with extremely low loss. The basic principle behind fibre optics is that light can be guided inside the fibre through multiple internal reflections. Because optical fibres offer **high bandwidth, low signal loss, immunity to electromagnetic interference, and high security**, they are widely used in modern communication systems, medical endoscopy, sensing technology and structural health monitoring.

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2. Principle of Total Internal Reflection (TIR)

Optical fibres work on the fundamental principle of **total internal reflection**.

Total internal reflection occurs when:

1. Light travels from a **denser medium (higher refractive index n_1)** to a **rarer medium (lower refractive index n_2)**,
2. The angle of incidence is **greater than the critical angle**, where

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

When these conditions are met, **all incident light is reflected back** into the denser medium with no leakage. In optical fibres, the core has refractive index n_1, and the cladding has refractive index $n_2$where $n_1 > n_2$. Thus, light travelling through the core gets trapped by TIR and propagates through the fibre over long distances.

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3. Construction of Optical Fibre

An optical fibre has three main parts:

(a) Core

- Central region where light propagates.
- Made of glass or plastic with refractive index n_1.
- Diameter ranges from **5 µm to 100 µm** depending on fibre type.

(b) Cladding

- Surrounds the core and has slightly lower refractive index n_2.
- Ensures total internal reflection.

(c) Protective Jacket (Buffer Coating)

- A polymer layer covering the cladding.
- Provides mechanical strength and protection from moisture, bending and environmental conditions.

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4. Acceptance Angle and Numerical Aperture (NA)

Acceptance Angle (θ_a):

The maximum angle at which light can enter the fibre and still undergo TIR inside the core.

The acceptance angle is given by:

$$\sin\ \theta_a = \sqrt{n_1^2 - n_2^2} \cdot \frac{1}{n_0}$$

where $n_0$is the refractive index of outside medium (usually air = 1).

Numerical Aperture (NA):

Numerical aperture measures the light-gathering ability of an optical fibre.

$$NA = n_0 \sin\ \theta_a = \sqrt{n_1^2 - n_2^2}$$

Higher NA → more light accepted → better coupling efficiency.

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5. Classification of Optical Fibres

Optical fibres are classified based on:

(A) Based on Material

- **Glass fibre**
  High performance, used for communication.

- **Plastic fibre**
  Flexible, low-cost, short-distance use.

(B) Based on Mode of Propagation

1. **Single-mode fibre (SMF)**
   - Very small core (~8–10 µm)
   - Light travels in a single path
   - High bandwidth, long-distance communication
2. **Multi-mode fibre (MMF)**
   - Larger core (~50–100 µm)
   - Light travels in multiple rays
   - Suitable for short distances

(C) Based on Refractive Index Profile

1. **Step-index fibre**
   - Abrupt change between core index and cladding index.
2. **Graded-index fibre**
   - Refractive index of core gradually decreases from center to edge.
   - Reduces modal dispersion and improves speed.

---

6. Losses in Optical Fibre

Optical fibres experience power loss as light travels through them. Major losses are:

(A) Absorption Loss

Due to impurities (OH^- ions, metal ions) inside the fibre material absorbing light energy.

(B) Scattering Loss

Caused by microscopic variations in material density.
Rayleigh scattering is dominant at low wavelengths.

(C) Bending Loss

Occurs when fibres are bent too sharply.
Two types:

- **Macro-bending loss**: large bends
- **Micro-bending loss**: small, irregular bends

(D) Dispersion Loss

Broadening of light pulses due to different propagation speeds:

1. Modal dispersion
2. Chromatic dispersion
3. Material dispersion

These limit distance and bandwidth.

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7. Applications of Optical Fibre

(A) Optical Fibre for Communication Systems

Optical fibres are the backbone of modern telecommunication networks.

Advantages:

- Extremely high bandwidth
- Very low signal loss over long distances
- Immunity to noise and electromagnetic interference
- Secure transmission
- Lightweight and flexible

Used in:

- Telephone networks
- Internet backbones
- Cable TV
- Undersea communication cables
- Data centers

Signal transmission uses **light pulses** generated by semiconductor lasers or LEDs. At the receiver end, a photodiode converts light back into electrical signals.

(B) Fibre Optic Sensors for Structural Health Monitoring

Optical fibres can also act as **sensors**, not just communication channels.
They are embedded into structures like bridges, dams, tunnels, buildings, aircraft wings, and wind turbine blades.

Working Principle

Changes in strain, pressure, temperature or vibration alter the properties of light in the fibre (intensity / wavelength / phase).
These changes are monitored to assess structural integrity in real time.

Advantages

- Immune to electromagnetic interference
- Can be embedded inside concrete or composite materials
- Extremely sensitive
- Long life and low maintenance
- Suitable for continuous remote monitoring

Applications:

- Bridge crack monitoring
- Earthquake-resistant building assessments
- Pipeline leak detection
- Railway track strain monitoring
- Aircraft structural load monitoring