UNIT-II

LASERS & OPTICAL FIBERS

Overview

Unit II consists of 5 lessons in LASERS. In lesson 1 you will be introduced to properties, principle of Laser & important requisites for Laser action. The lesson 2 will give you the idea of conditions of a laser system. The lesson 3, gives the idea of thermal equilibrium, Einstein's constants and based on these knowledge there is a derivation of energy density equation. In lesson 4, you will be introduced to principle, construction and working of semiconductor laser and Co_2 laser system. In lesson 5, you will learn important applications of lasers.

Objectives:

At the end of this unit-II, you should be able to know:

- What is laser?
- Understand the properties of laser.
- Explain the requisites of laser emission
- Conditions for laser actions
- Principle of laser action
- Understand the dependency of energy density for laser system
- Production of laser beam by different methods
- Important applications of laser

Introduction

The term LASER is the acronym for Light **A**mplification by **S**timulated **E**mission of **R**adiation. It is basically opto-electronic device. In the year 1916, the theory behind laser was established by Albert Einstein and he got the Nobel Prize in the year 1921.

Albert Einstein framed a theory that if an electron in an exited state is collided by a photon of the light energy, then the exited electron would drop down to a lower energy state and emit a photon of the same energy and wavelength that would move in phase and direction as that of the colliding photon. Such coherent sources are known as lasers. The light beam from laser source with coherence lengths up to 10^{14} Hz will make many applications and experiments possible. Prior to Einstein's theory, the light sources of coherence length available was up to 10^7 only, which would not possible to discover the new era applications.

Lesson-1 Properties & Principle of Laser

Objectives:

At the end of this lesson you will be able to:

- Understand what is laser
- Know how laser beam is different from other light sources
- Understand the concept of absorption & emission of energy
- Understand atomic excitation

3.1 Introduction:

Interaction of radiation with matter requires certain conditions. When radiation interacts with matter, the energy state or atomic state of the matter gets disturbed. It leads to the change in its energy state. If the transition is from lower state to higher state, it absorbs the incident energy of the transition. In reverse direction, such as higher state to lower state, it emits its energy by the way of photon.

3.1.1Properties of Laser

Laser is a light beam which is

- Monochromatic
- Coherent in nature
- Highly directional
- Low convergence
- Travel as a narrow beam
- Spreads very little
- Does not fade even after long distance

3.1.2 Requisites of a laser system

There are three requisites for a laser system:

- A source of pumping energy in order to establish a population inversion.

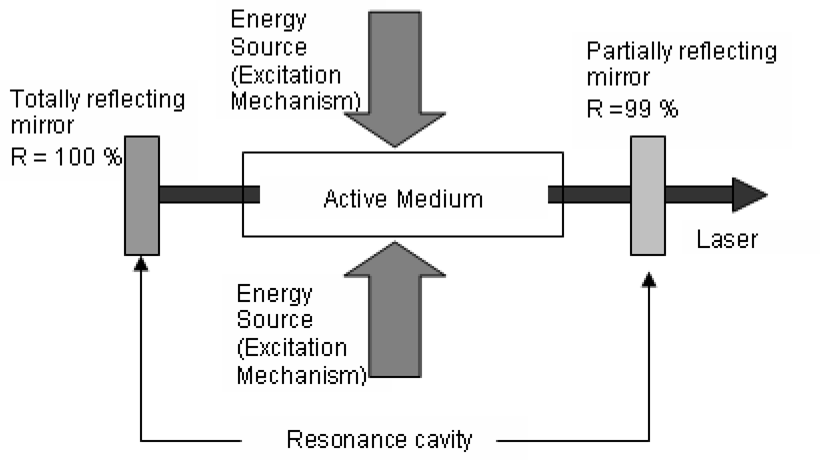
- An active medium with a suitable set of energy levels to support laser action. A medium in which light gets amplified is called an active medium. The medium may be solid liquid or gas. Out of the different atoms in the medium only small fraction of the atoms are responsible for stimulated emission and consequent light amplification.
- An optical cavity or resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses.

That means: an excitation source for pumping action, an active medium which supports population inversion, a laser cavity.

The process of achieving a large number of atoms in excited state than ground state is called “Population Inversion”.

The number of atoms in the higher (excited) energy state must be greater than in lower (ground) state (i.e., $N_2 > N_1$) and the process by which population inversion is achieved is called “Pumping”. Excitation of atoms from lower energy state to a higher energy state by supplying energy from an external source is called pumping. There are various types of excitation or pumping mechanisms available, the most commonly used ones are optical, electrical, thermal or chemical techniques. For example, Solid state lasers usually employ optical pumping from high energy xenon flash lamps (e.g.Ruby, Nd:YAG). Gas lasers use an AC or DC electrical discharge through the gas medium, electron beam bombardment or a chemical reaction. The DC electrical discharge is most common for 'small' gas lasers (e.g., Helium-neon, Argon ion).

The process which leads to emission of stimulated photons after establishing the population inversion is referred to as lasing. The transition from the metastable state back to the ground state is the ‘lasing’ transition, induced by a passing photon. In order to sustain laser action, one has to confine the laser medium and the pumping mechanism in a special way that should promote stimulated emission rather than spontaneous emission. This is achieved by bounding the laser medium between two mirrors as shown in figure below. On one end of the active medium is the high reflectance mirror (100% reflecting) or the rear mirror and on the other end is the partially reflecting or transmissive mirror or the output coupler. The laser emanates from the output coupler, as it is partially transmissive. Stimulated photons can bounce back and forward along the cavity, creating more stimulated emission as they go. In the process, any photons which are either not of the correct frequency or do not travel along the optical axis are lost.

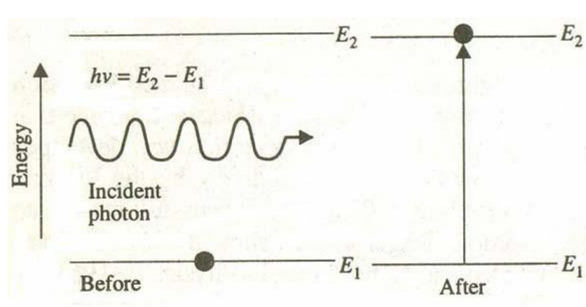


3.1.3 Basic principles

The interaction of radiation with atoms leads to the following three distinct processes in the medium.

1. Absorption 2. Spontaneous Emission 3. Stimulated Emission

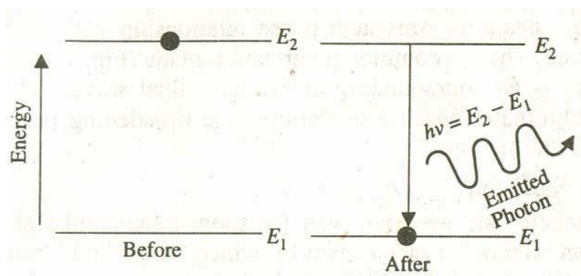
Absorption: When an atom in the state E_1 absorbs an incident photon of energy hν (= E_2- E_1) and makes a transition to higher energy state E_2, the process is known as induced absorption or simply absorption.



$$\mathbf{A + h\nu = A^*}$$

Where A is an atom in the lower state and A^* is the excited state of the atom.

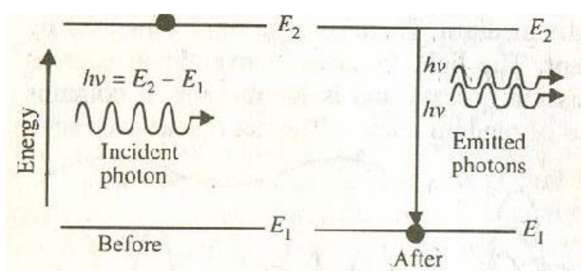
Spontaneous Emission: The excited state is highly unstable and atoms always seek out the least available energy state. When atom in the excited state E_2 comes down to a lower energy state E_1 by emitting a photon of energy hν (= E_2-E_1) without the aid of any external agency, the process is termed as spontaneous emission.



$$\mathbf{A^* \longrightarrow A + h\nu}$$

The direction of the emitted photons is random and radiation is incoherent.

Stimulated Emission: When a photon of right energy is incident on an atom in the excited state, the incident photon stimulates the atom to make downward transition. The photon thus emitted will have same phase and energy as that of the incident photon. This process is known as stimulated emission.



$$\mathbf{A^* + h\nu \longrightarrow A + 2h\nu}$$

The importance of this interaction is that the two photons emerging out will travel in the same direction, with exactly same energy and perfectly in phase. This is the interaction responsible for the generation of laser beam. This is the basic principle of laser system.

Self test questions

1. Explain the properties of laser.
2. Explain the principle of laser system.
3. Define the term induced absorption.
4. Define the term spontaneous emission.
5. Define the term stimulated emission.

Lesson 2
Objectives:

At the end of this lesson, you will be able to:

- Understand two important conditions for laser
- Understand the term population and population inversion
- Familiar the term metastable state
- Understand the term 3 level & 4 level atom interaction

3.2 Introduction

In this lesson, first we will go through conditions for laser emission. That is population inversion and metastable state. These two conditions are unusual for a atom in the thermal equilibrium conditions.

3.2.1 Conditions for laser action

The lasing action does not work easily for two reasons.

1. It is difficult to maintain the atoms in their excited states until they are stimulated to emit the photon. The excited atoms have a natural tendency to drop back to their ground state due to the spontaneous emission.
2. Atoms in their ground state undergo absorption by using photons from the beam that is being built, there by hindering the process of continuous stimulation and emission.

For continuous laser beam emission these two problems are to be solved. The conditions for continuous laser action are the population inversion and metastable state.

3.2.2 Population inversion

The term population means the number of atoms available at a given energy state. For good lasing action to take place, the population of atoms must be more in an excited state than in the ground state. Under normal thermal equilibrium conditions, the population is more in the lower energy state than in the excited state. This condition is to be reversed and it is known as population inversion. Population inversion is an unusual situation but very much essential for lasing action. This can be achieved by some artificial means known as pumping [the process of raising the energy level using an external source of energy] energy in to the active medium.

3.2.3 Metastable state

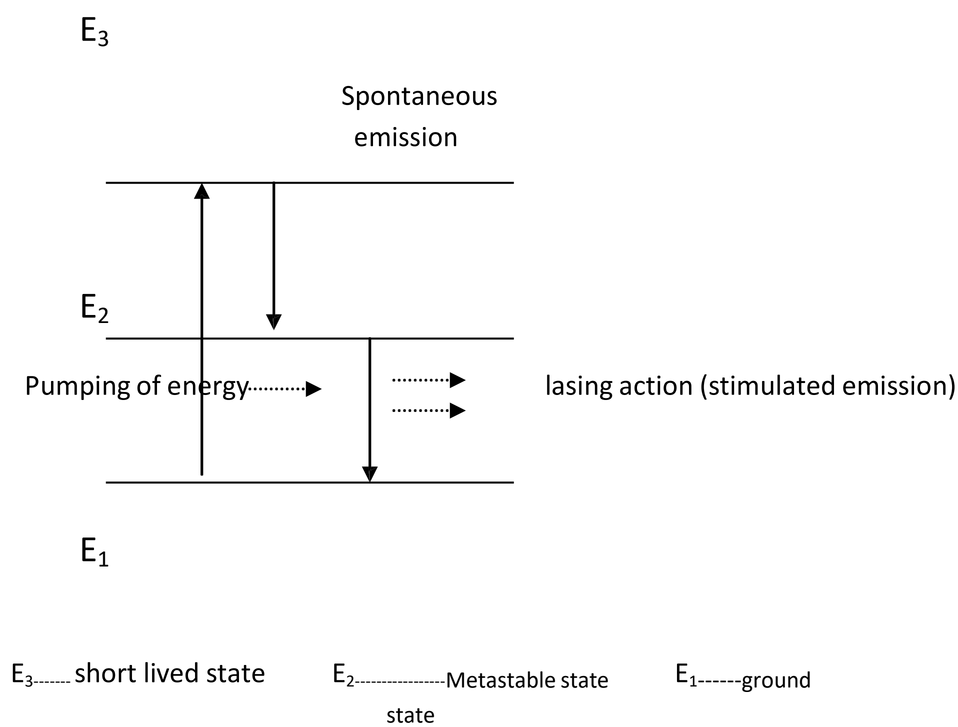
There are two types of metastable state. They are

1. Three energy level atom

2. Four energy level atom

3.2.3.1 Three energy level atom transition

The second important condition for lasing action is to retain the excited atom in a metastable state. Metastable state is a lower excited energy state in which atom stays more time than the excited state.



In a lasing material, the atoms originally in the ground state are pumped in to the excited state using an external source of energy. However, this is a short lived state [about10^{-8} sec] and due to spontaneous emission, the excited state decays rapidly to the lower excited state. This lower excited state is referred as metastable state. In metastable state, the atom stays longer time [about 10^{-3} sec] than the excited state. Stimulated emission can occur by passing a photon of right energy during the transition of atoms from metastable state to the ground state. This is basically a three-level atom lasing action and used in a ruby laser system. The laser produced from this lasing action is a pulsed laser.

Self test questions

1. What are two conditions for laser action?
2. What is meant by population?
3. What do understand from the term population inversion?
4. Explain metastable state of energy.
5. What is active medium?
6. What is meant by pumping?

Lesson 3 Energy Density

Objective:

At the end of this lesson you will be familiar with what is energy density, thermal equilibrium, Einstein's coefficients for energy absorption, emission. There is an energy density derivation based on Einstein's coefficients at thermal equilibrium. Based on the final equation you can solve few problems.

3.3 Introduction

Consider two energy levels E_1 and E_2 of a system having population densities N_1 and N_2 respectively. A radiation of energy density E_ν is incident on the system.

Rate of absorption $R_{12} \propto E\nu N_1$

$$R_{12} = B_{12}E\nu N_1 \text{ ---------------------- } (1)$$

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

Rate of spontaneous emission $R_{21} \propto N_2$

$R_{21} = A_{21}N_2$ ---------------------- (2)

Where A_{21} is called Einstein coefficient of spontaneous emission radiation.

Rate of stimulated emission $R^*_{21} = B_{21}E\nu N_2$ ------------------- (3)

where B_{21} is called Einstein's coefficient of stimulated emission of radiation.

In thermal equilibrium state, the populations of different energy states E_1, E_2 etc. are fixed by the Boltzman factor.

The population ratio is given by the equation

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

where k is the Boltzmann constant. The negative exponent in the above equation indicates $N_2 << N_1$ at equilibrium. This means more number of atoms is in the lower energy level than excited energy level. This state is known as normal state of energy. Atoms in the lower energy level E_1 occasionally absorb radiation and make a transition to upper energy level E_2. Similarly atoms in the upper energy level will occasionally emit radiation and make a transition to the lower level. In order to maintain N_1 & N_2 constant, the number of upward transition must be equal to the number of downward transitions. Thus total absorption is equal to total emission.

3.3.1 Expression for energy density at thermal equilibrium using Einstein's coefficients

Let us consider an assembly of atoms at temperature T in thermal equilibrium with radiation frequency ν and energy density E (ν). Let N_1 and N_2 be the number of atoms in lower energy state E_1 and higher energy state E_2 respectively at any given instant.

In thermal equilibrium,

Rate of upward transition = rate of downward transition.

$$R_{12} = R_{21} + R^{*}_{21}$$

Ie $$B_{12} N_1 E(\nu) = A_{21} N_2 + B_{21} N_2 E(\nu) \text{ ---------------- } (4)$$

where E(ν) is the energy density.

This relation was predicted by Einstein and the coefficients B_{12}, B_{21}, and A_{21} are known as Einstein's coefficients of induced absorption, spontaneous emission and stimulated emission respectively.

$$N_1 B_{12} E(\nu) = N_2 [A_{21} + B_{21} E(\nu)] \text{ ------------- } (5)$$

$$E(\nu) [N_1 B_{12} - N_2 B_{21}] = N_2 A_{21} \text{ ------------ } (6)$$

$$E(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} \text{ -------------------- } (7)$$

Multiplying equation (6) by $1/N_2 B_{21}$ we get,

$$E(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{N_1}{N_2}\left[\frac{B_{12}}{B_{21}}\right] - 1\right)} \text{ ---------------------- } (8)$$

Thermodynamically it was proved by Einstein that the probability of stimulated absorption must be equal to the probability of stimulated emission. Thus,

$$B_{12} = B_{21} \text{ ------------------------- } (9)$$

$$E(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{N_1}{N_2} - 1\right)} \text{ ------------------- } (10)$$

Boltzmann has shown that the atomic population at different energy levels at a given temperature T is given by the equation,

$$N_2 = N_1 e^{-(E_2 - E_1)/kT} \text{-------------------- (11)}$$

The negative sign in the exponent indicates that $N_1 << N_2$ under equilibrium condition.

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/kT} \text{-------------------- (12)}$$

$$\frac{N_1}{N_2} = e^{h\upsilon/\mathrm{kT}} \text{-------------------- (13)}$$

where $h\upsilon = (E_2 - E_1)$ and 'k' is Boltzmann constant, h is the Planck's constant and 'υ' is the frequency.

Therefore equation (10) becomes,

$$E(\upsilon) = \left(\frac{A_{21}/B_{21}}{e^{\left(\frac{h\upsilon}{kT}\right)} - 1} \right) \quad \text{-------------------- (14)}$$

This is the formula for energy density of photons in equilibrium with atoms in energy states E_1 and E_2 at temperature T and frequency υ.

We know from Planck's radiation formula,

$$E(\upsilon) = \frac{8\pi h v^3}{c^3} \left(\frac{1}{e^{\left(\frac{h\upsilon}{kT}\right)} - 1} \right) \text{---------------------(15)}$$

While comparing equation 14 & 15 we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3} \quad \text{-------------------------------- (16)}$$

The equation (16) is the ratio between spontaneous emission & stimulated emission coefficients. The ratio is proportional to υ^3. This shows that the probability of spontaneous emission increases rapidly with the energy difference between the two states.

Solved Examples

1. For the given laser system, calculate the difference in energy between metastable state and ground state electron. The wavelength of the ruby laser beam is 6493 Å.
   Given data λ = 6493 Å
   Constant h = 6.63×10^{-34} Js
   Constant c = 3 x 108 m/s

Solution:

The difference in energy between any two states is given by the relation

$$\Delta E = hc$$

$$\Delta E = \frac{6.63 x 10^{-34}\ x\ \ 3\ x 10^{8}}{6493\ x 10^{10}}$$

$\Delta E = 3.06 \times 10^{-19}$ J

To convert into electron volt divide the value by charge of the electron,

$\Delta E = 3.06 \times 10^{-19} / 1.6 \times 10^{-19}$

ΔE = 1.91 eV

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2. A He – Ne laser is emitting a laser beam with an average of 4.5mW. Find the number of photons emitted per sec by the laser. The wavelength of emitted radiation is 6328 A˚.

Wavelength of the emitted light, λ = 6328 A˚ = 6328×10^{-10} m

Power output = 4.5mW

No of photons emitted/sec = ?

We know that the energy difference,

$\Delta E = h\nu = hc/\lambda$ Joule

$$= 6.63 \times 10^{-34} \times 3 \times 10^{8} / 6328 \times 10^{-10}$$

This energy difference becomes the energy of each of the emitted photon. If N is the number of photons emitted per sec to give a power of 4.5mW, then

$N \times \Delta E$ = 4.5mW = 4.5×10^{-3} J/s

Hence N = $4.5 \times 10^{-3}/3.143 \times 10^{-19}$

$= 1.43 \times 10^{16}$.

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Self test question

2. What are Einstein's coefficients?
3. Derive an expression for energy density at thermal equilibrium using Einstein's coefficient.
4. Write plank's radiation formula.
5. Which type of emission is independent of energy radiation?

Lesson 4

Objectives

After end of this lesson you will able to:

- Know the working of semiconductor laser with energy level diagram.
- Know the working of Co_2 laser with energy level diagram.

3.4 Introduction

Lasers are classified into 4 types. They are 1.Solid state lasers, 2. Gas lasers 3.

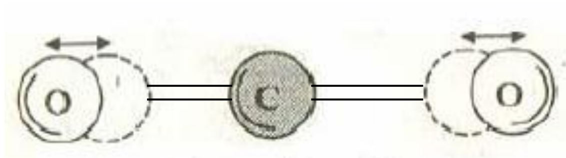
Liquid dye lasers and 4. Solid state diode laser (semiconductor laser). In this lesson you will understand the construction and working of two types of laser system, namely Co_2 laser and semiconductor laser. First one is based on gas and second one is based on solid state diode laser.

3.4.1 CO_2 Laser:

Introduction: It is a molecular gas laser which operates in the middle IR region involving a set of rotational and vibrational transitions. It is a four level laser producing continuous wave (cw) or pulsated output. It was discovered by CKN Patel in 1964.

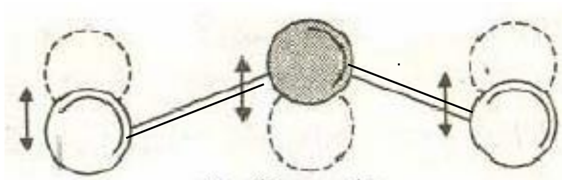
Modes of vibration of a CO_2 molecule:

1. In the symmetric stretching modes, both the oxygen atoms oscillate along the axis of the molecule simultaneously approaching and departing the carbon atom which is stationary. Fundamental frequency ν_1= 1337 cm^{-1}.



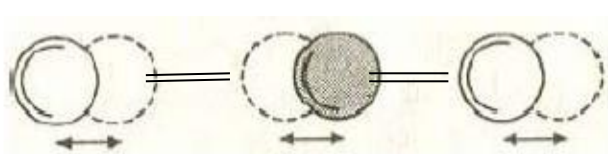
Symmetric stretching mode

2. In the bending mode, atoms move perpendicular to the molecular axis. The bending vibration is doubly degenerate; it can occur in the plane of the figure and the plane perpendicular to it.


Bending mode

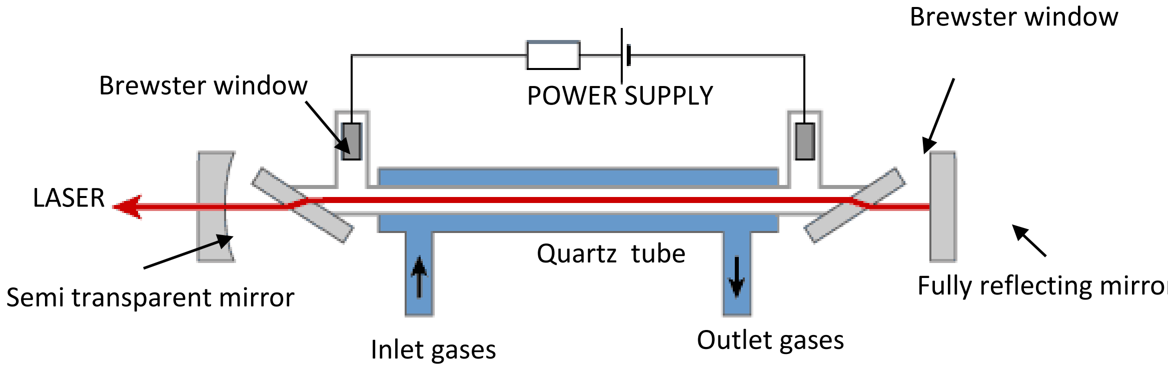
Fundamental frequency ν_2= 667 cm^{-1}

3. In the asymmetric stretching mode, all the three atoms oscillate along the molecular axis; but while both oxygen atoms move in one direction, carbon atom moves in the opposite direction.


asymmetric stretching mode

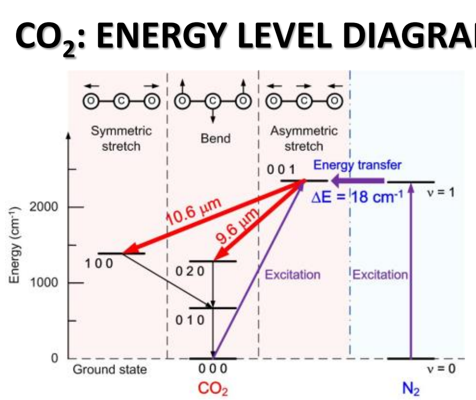
Fundamental frequency ν_3= 2349 cm^{-1}

Construction of CO_2 Laser:



It consists of a long tube of length 5 cm and diameter 2.5 cm. The ends of the tube are closed with alkali halide (NaCl) Brewster windows (for plane polarized waves). Outside the ends of the tube, silicon mirrors coated with aluminum are arranged. This forms the resonant cavity. Active medium consists of a mixture of CO_2, N_2 and He gases. The pressure of gases in the mixture is P_{He} = 7 Torr, P_{N2} = 1.2 Torr and P_{CO2} = 0.33 Torr (1m bar = 0.76 Torr). When a high DC voltage is applied to the mixture, pumping mechanism based on electric discharge is used to create population inversion. The electric discharge breaks down CO_2 into O_2 and CO. If water vapor is present in the mixture, then CO_2 is regenerated from CO. The rear mirrors act as optical feedback resonators providing the necessary feedback for the emitted photons. The Brewster angle windows are provided to give polarized output.

Working:



When electric discharge takes place in the gas mixture both N_2 and CO_2 atoms absorb energy and are excited to higher energy level. This energy level matches with one of the vibrational-rotational level of CO_2, shown by C_5 (001) in the figure. More CO_2 atoms are raised to level C_5 by colliding with N_2 molecules. There is an efficient transfer of energy between a N_2 excited level and CO_2 excited level. This is called resonant energy transfer creating a population inversion between the levels C_5 and C_4 and also between C_5 and C_3. The transition from C_5 to C_4 (100) produces 10.6 μm and C_5 (001) to C_3 (020) produces 9.6 μm both lying in the IR region. Other transitions from C_3 and C_2 (010) to C_1 (000) are accomplished through inelastic collision with Helium atoms. Helium atoms are used to deplete the lower energy levels. Also due to high thermal conductivity of He, the heat is conducted away from the laser cavity.

Transitions:

$N_1 - N_2$ excitation; and $C_1 - C_5$ excitation

$C_5 - C_4$ laser 10.6 μm and $C_5 - C_3$ laser 9.6 μm

$C_3 - C_2$ and $C_2 - C_1$ inelastic collision.

The laser output is 100 kW in CW (continuous wave) mode.

CO_2 lasers are more efficient compared to other lasers, efficiency is also high.

3.4.1 Semiconductor laser

Introduction:

The first semiconductor laser was designed by U.S scientists in the year 1962. Semiconductor lasers are very popular because of their compactness, size and very high efficiency. The very first p-n junction laser was built using GaAs gallium- arsenide (infrared type) and GaAsP gallium- arsenide-phosphide (visible) semi conducting materials. Semiconductor laser are again continuous wave laser and are widely used in CD players, optical communication etc.

A semiconductor is a material whose conductivity lies between those of conductor and insulator. Semiconductors are of two types:

a) Intrinsic semiconductors or pure semiconductors

b) Extrinsic semiconductors or doped semiconductors

Extrinsic semiconductors are further classified into two types depending upon the type of majority carriers:

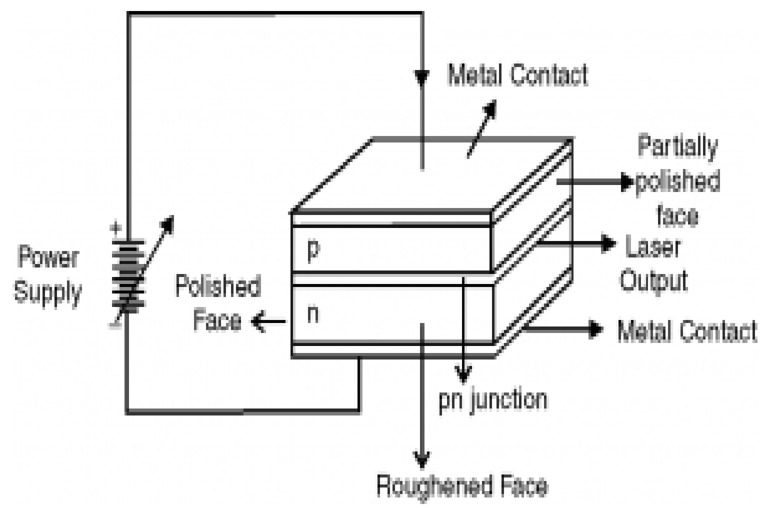
i) n-type semiconductors where electrons are majority carriers.

ii) p- type semiconductors where holes are majority carriers.

When a p-type semiconductor and a n- type semiconductor is joined by special techniques, there will be flow of electrons from n side to p side and flow of holes from p side to n side. After some time, an electric field will be created which will oppose this flow and flow stops. Thus, there will be formation of depletion region. This region is called so because it is depleted from charge carriers.

Construction

One of the example of semiconductor lasers is with the semiconductor Gallium arsenide (GaAs). It is used as a heavily doped semiconductor. Its n-region is formed by heavily doping with tellurium in a concentration of 3 x 10^{18} to 5 x 10^{18} atoms/cm^3 while its p-region is formed by doping with zinc in a concentration of around 10^{19}atoms/cm^3.



Active medium: Active medium is GaAs. But it is also commonly said that depletion region is the active medium in semiconductor lasers. The thickness of the depletion layer is usually very small (0.1 µm).

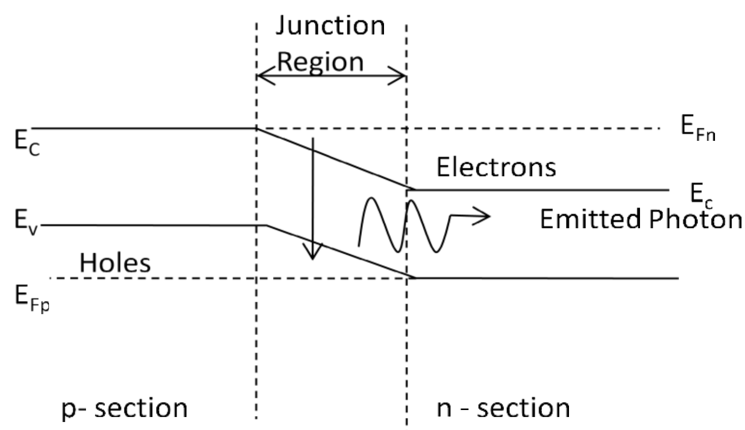
Pumping Source: Forward biasing is used as the pumping source. The p-n junction is made forward biased that is p side is connected to positive terminal of the battery and n side to negative. Under the influence of forward biased electric field, conduction electrons will be injected from n side into junction area, while holes will enter the junction from the p side. Thus, there will again be recombination of holes and electrons in depletion region and thus depletion region becomes thinner.

Optical resonator system: The two faces of semiconductor which are perpendicular to junction plane make a resonant cavity. The top and bottom faces of diode, which are parallel to junction plane, are metalized so as to make external connections. The front and back faces are roughened to suppress the oscillations in unwanted direction.

Working of semiconductor laser

Achievement of population inversion:

When p-n junction diode is forward biased, then there will be injection of electrons into the conduction band along n-side and production of more holes in the valence band along p-side of the junction. Thus, there will be more number of electrons in conduction band comparable to valence band, so population inversion is achieved. When the electrons and holes are injected into the junction region from opposite sides with forward biasing, then population inversion is achieved between levels near the bottom of the conduction band and empty levels near the top of the valence band.



Energy band diagram for semiconductor laser

Achievement of laser

When electrons recombine with the holes in junction region, then there will be release of energy in the form of photons. This release of energy in the form of photons happens only in special types of semiconductors like Galium Arsenide (GaAs with a band gap Eg = 1.4 eV). Otherwise in semiconductors like silicon and germanium, whenever holes and electrons recombine, energy is released in the form of heat, thus Si and Ge cannot be used for the production of laser.

The spontaneously emitted photon during recombination in the junction region of GaAs will trigger laser action near the junction diode. The photons emitted have a wavelength from 8200 Å to 9000 Å in the infrared region.

Since Eg = 1.4eV, the wavelength of emitted light is

$$\lambda = hc/Eg = 8400\ \text{Å}$$

Laser ablation process

Laser ablation is the process of removing material from a solid (or occasionally liquid) surface by irradiating it with a laser beam. At low laser flux, the material is heated by the absorbed laser energy and evaporates or sublimates. At high laser flux, the material is typically converted to a plasma. Usually, laser ablation refers to removing material with a pulsed laser, but it is possible to ablate material with a continuous wave laser beam if the laser intensity is high enough.

The depth over which the laser energy is absorbed and thus the amount of material removed by a single laser pulse depends on the material's optical properties and the laser wavelength and pulse length. The simplest application of laser ablation is to remove material from a solid surface in a controlled fashion. Laser machining and particularly laser drilling are examples; pulsed lasers can drill extremely small, deep holes through very hard materials. Very short laser pulses remove material so quickly that the surrounding material absorbs very little heat, so laser drilling can be done on delicate or heat-sensitive materials, including tooth enamel (laser dentistry). Several workers have employed laser ablation and gas condensation to produce nano particles of metal, metal oxides and metal carbides.

Also, laser energy can be selectively absorbed by coatings, particularly on metal, so CO_2 or Nd:YAG pulsed lasers can be used to clean surfaces, remove paint or coating, or prepare surfaces for painting without damaging the underlying surface. High power lasers clean a large spot with a single pulse. Lower power lasers use many small pulses which may be scanned across an area.

Self test questions

1. Explain the construction and working of Co_2 laser with energy level diagram.
2. Explain construction and working of Semiconductor laser with energy level diagram.

3. Explain the term recombination.
4. What is the function of Brewster window in Co_2 gas laser?
5. Why one end of semi-conductor is partially polished?

Lesson 5 Applications of Laser

Objective

At the end of this lesson we will be able to know about the important applications of laser in general.

3.5 Introduction

Laser finds applications in almost all fields of life like engineering, entertainment, defense, medical, communication etc. The other important applications are laser welding, laser drilling, laser cutting of metals and alloys, fiber optic communication, creation of holography, laser scanning, laser printing, read & write on CD, DVD etc., accurate measurement of distances, laser shows, navigation of aircrafts, eye-retina surgery etc. Out of these applications we will see some of these in detail.

Applications:

In industry: Cutting

Welding

Drilling

3.4.1 Laser welding

Lasers are widely used in metal welding operations. Carbon dioxide (CO_2) and YAG lasers are used for laser welding. CO_2 lasers generate 10.6 μm wavelength laser beams with continuous wave with high power densities. The intense beam from the source melts the metal at the surface and enters deep into the metal which causes welding action. Laser welding can be used to weld dissimilar metals with widely varying physical properties. Metals with different sizes and masses at high electrical resistance can be successfully welded. Temperatures as high as 10,000 ˚C can be attained easily with laser welding.

Advantages:

1. Very small parts say few micron thicknesses can be welded.
2. No contamination on base metal.
3. Welding can be done in side glass chamber
4. Localized heating which will not spread the heat.

3.5.2 Laser drilling

The principle of laser drilling is to heat the metal to its boiling point and vaporize it or remove it by high pressure vapor. Drilling is done by high power pulsed laser of the order of 10^{-4} s to 10^{-3} s duration. The spot to be drilled is focused by a laser beam. The metal vapor interacts with laser beam and electrons get accelerated by electromagnetic radiation. The molten metal get ejected from the hole there by forming drilling operation. Nd-YAG laser is used for metals while CO_2 laser is used for both metallic and non-metallic materials.

Advantages:

1. Holes can be drilled in close vicinity.
2. Drills with high precision.
3. Drill in any direction.
4. No wear of laser tool.
5. Ceramic materials can also be drilled without breaking.

3.5.3Laser cutting

Laser cutting can be done by melting and blowing out molten metal. For blowing out of metal a high velocity gas jet of inert gas is used. Such a process of cutting is termed as gas assisted laser beam machining.

Advantages

1. No need of coolant for cutting.
2. Cutting operation is clean and fast.
3. No mechanical stresses are induced.
4. No problem of wear and tear tools.

5. The heat affected zone is limited.

Self test questions

1. What are the industrial applications of Laser?
2. Give few advantages of laser being used for welding, cutting and drilling?
3. Write a note on Laser ablation?

Optical Fiber

Objective

- Know total internal reflection.
- Know principle of Optical Fiber.
- Know construction of optical fiber.
- Understand acceptance angle.
- Understand numerical aperture.
- Know fractional refractive index change.
- Describe types of optical fibers and its mode of propagation.
- Know what attenuation is.
- Describe point-to-point communication.

Lesson 5 Optical fibre-Principle and Mechanism
Objective

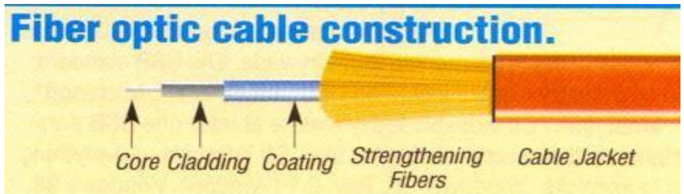
At the end of this lesson we will be able to:

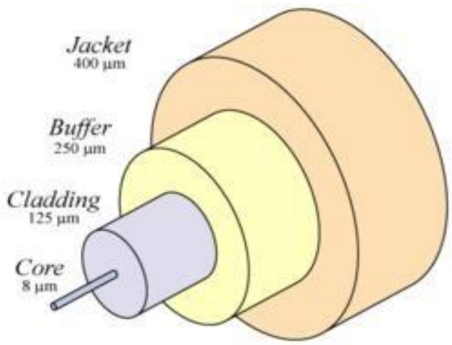
- Understand how total internal reflection takes place in optical fibre.
- Know the parts of optical fibre and its functions.
- Know acceptance angle and numerical aperture.

6.5 Introduction

Optical fibers are very thin about 5-50 μm thickness, flexible and are made up of pure silicon glass. They act as light guide or optical wave guide in the medium of communication using light rays. Optical fibers are dominating the communication world with their capacity to carry a large volume of data, with negligible loss, over the long distances. Optical communication makes use of visible and infrared portion of the electromagnetic spectrum to transmit digital data. It operates with high frequency/short wavelength electro-magnetic transmission. Frequency of operation is 10^{12} to 10^{15} Hz; hence a large volume of data/information can be transmitted through a single channel.

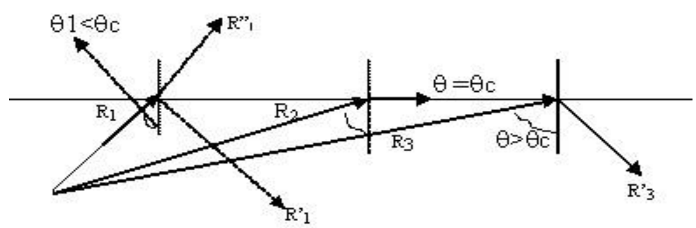
6.5.1 Construction of optical fibre.





Optical fibers are made up of highly pure silica glass thin cylinder called core at the centre, surrounded by a hollow cylinder called cladding, which is also made up of glass but with a lower refractive index than the core material. The cladding is protected by a poly urethane jacket. The core is the transfer medium, while the cladding reflects the light medium inward, while the jacket protects the fiber from the environment.

6.5.2. Total internal reflection



The basic principle of optical fibre communication is based on total internal reflection. The core has a slightly higher refractive index (n_1) than the cladding (n_2). Consider a set of two mediums, having refractive indices n_1 and n_2 whose interface is a plane surface. Let $n_1 > n_2$. When a ray of light R_1 is incident on the interface through the first medium at an angle θ_1, a part of the beam R'_1 gets reflected at the same angle θ_1, while the other part of the beam is transmitted through the second medium at an angle θ_2. Now by snell's law,

$$n_1 \, Sin \, \theta_1 = n_2 \, Sin \, \theta_2 \quad \text{----------------} \ (1)$$

According to snell's law, θ_2 is greater than θ_1, when n_1 is greater than n_2. The values of θ_2 will reach its physical limit of 90˚ for some incident angle $\theta_1 < 90˚$. This value of incident angle at which $\theta_2 = 90˚$ is called critical angle θ_c. For this condition, equation 1 becomes,

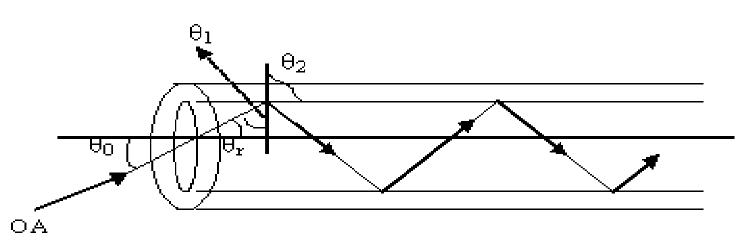
$$n_1 \, Sin \, \theta_c = n_2 \, Sin 90˚$$

$$Sin \, \theta_c = n_2 / n_1$$

$$\theta_c = Sin^{-1}(n_2 / n_1)$$

For incidence angles greater than the critical angle ($\theta_1 \geq \theta_c$), there is no transmitted beam, and the energy of the beam or rays R_3 is completely reflected back into the first medium at an angle θ_1. This is termed as total internal reflection. For absorption losses to be zero, the purity of the medium has to be very high. Hence the core used in optical fibers is of the highest purity.

6.5.3 Acceptance angle



Let n_0 be the refractive index of the medium (air) from where light is launched into the fiber. The light ray refracts at an angle θ_r and strikes the core-cladding interface at an angle θ_1. If the angle θ_1 is greater than critical angle θ_c, the light ray undergoes total internal reflection at the interface since $n_1 > n_2$. According to snell's law, we have

$$n_0 Sin\theta_0 = n_1 Sin\ \theta_r$$

$$Sin\ \theta_0 = (n_1/n_0)\ Sin\ \theta_r \text{ -------------- } (1)$$

For the reflected ray at the core/cladding interface, we know that from Snell's law,

$$n_1\ Sin\theta_1 = n_2\ Sin\theta_2$$

$$n_0 Sin(90 - \theta_r) = n_2\ Sin\ 90\ [\theta_2 = 90 \text{ for total internal reflection}]$$

$$n_1 cos\theta_r = n_2$$

$$cos\theta_r = n_2/n_1 \text{ -------------------- } (2)$$

By rewriting equation (1) we get

$$Sin\theta_0 = \frac{n_1}{n_0}\sqrt{1 - cos^2}\theta_r$$

Substituting the value of $cos\theta_r$, we get

$$Sin\theta_0 = \frac{n_1}{n_0}\sqrt{1 - \frac{n_2{}^2}{n_1{}^2}}$$

$$Sin\theta_0 = \frac{n_1}{n_0}\sqrt{\frac{n_1{}^2 - n_2{}^2}{n_1{}^2}}$$

$$Sin\theta_0 = \frac{n_1}{n_0} x \frac{1}{n_1}\sqrt{n_1{}^2 - n_2{}^2}$$

$$Sin\theta_0 = \frac{\sqrt{n_1{}^2 - n_2{}^2}}{n_0} \quad \text{----------------(3)}$$

Assuming the surrounding medium is air then, n_0 = 1

Hence equation (3) becomes,

$$Sin\theta_0 = \sqrt{n_1{}^2 - n_2{}^2}$$

$$\theta_0 = Sin^{-1}\sqrt{n_1{}^2 - n_2{}^2}$$

The maximum angle θ_0 is called the acceptance angle or acceptance cone half angle of the fiber. Acceptance angle may be defined as the maximum angle that a light ray can have relative to the axis of the fiber and propagate through the fiber. The light rays contained within the cone having a full $2\theta_0$ are accepted and transmitted to the far end. Therefore, the cone is called the acceptance cone. Larger acceptance angles make easier launching.

6.5.4 Fractional refractive index change

It is defined as the ratio of difference between the refractive indices of the core, cladding to the refractive index of the core in an optical fiber. The fractional difference 'Δ' between the refractive index of the core and the cladding is known as fractional refractive index change Δ.

It is given by Δ = (n_1 – n_2)/ n_1

Δ is always positive since n_1 is always greater than n_2 for total internal reflection. In order to guide light rays effectively through a fiber, Δ <<1. Typical value of Δ is 0.01. Larger value of Δ will not be useful for optical communication since multi-path dispersion will take place.

6.5.5 Numerical Aperture

Numerical Aperture is defined as the sine of the maximum acceptance angle. It is a measure of its light gathering power.

Numerical Aperture (NA) = $Sin\theta_0$

Therefore,

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

NA = $\sqrt{(n_1 - n_2)(n_1 + n_2)}$

NA = $\sqrt{(n_1 - n_2)\frac{n_1}{n_1}(n_1 + n_2)}$

NA = $\sqrt{(n_1 + n_2)n_1\Delta}$

Since $n_1 \sim n_2$, $(n_1 + n_2) = 2n_1$

NA = $\sqrt{2n_1^2 n_1\Delta}$

NA = $n_1\sqrt{\Delta}$

Numerical aperture is a measure of the amount of light that can be accepted by a fibre. Numerical aperture is dependent only on n_1 and n_2. Its value ranges from 0.13 to 0.50 for good optical communication.

Self test questions

1. What is total internal reflection?
2. What is Snell's law equation for different medium?
3. Describe the principle of optical fibre.
4. Explain the construction optical fibre.
5. What is acceptance angle?
6. Explain fractional refractive index change and its typical value for good propagation?
7. Explain numerical aperture and its typical value for good communication?
8. Derive an expression for acceptance angle for the optical fibre.
9. Derive an expression for numerical aperture in terms of fractional index change.

Lesson 6 Types of Optical Fibers and modes of propagation

Objective

At the end of this lesson we will able to:

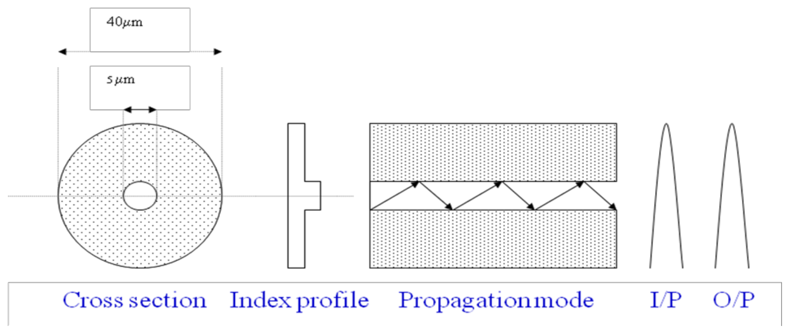
- Know different types of optical fibres.
- Know different types of propagation modes.
- Important application of optical fibre.

6.6 Introduction

All the types of optical fibres and the modes of propagations depend upon the refractive indices of the core and the cladding materials. The refractive index of the cladding is generally kept constant, while that of core may be fixed or varied radically to achieve a suitable propagation mode. Based on the above factors, they are classified into three categories.

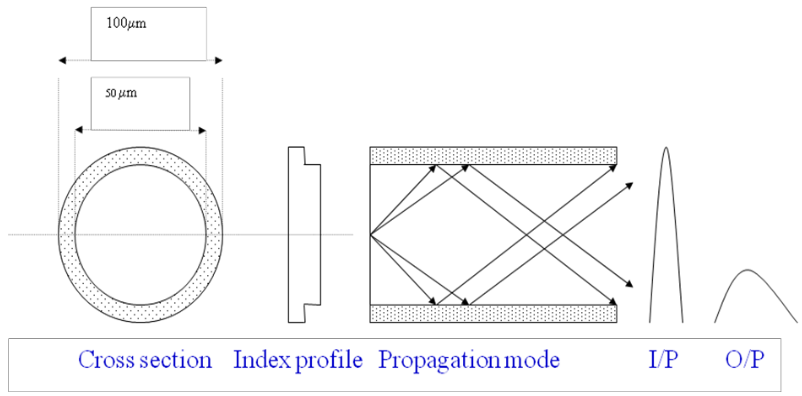
1. Single Mode Step-Index fibre.
2. Multi Mode Step-Index fibre.
3. Multi Mode Graded-Index fibre.

6.6.1 Single Mode Step-Index Fiber



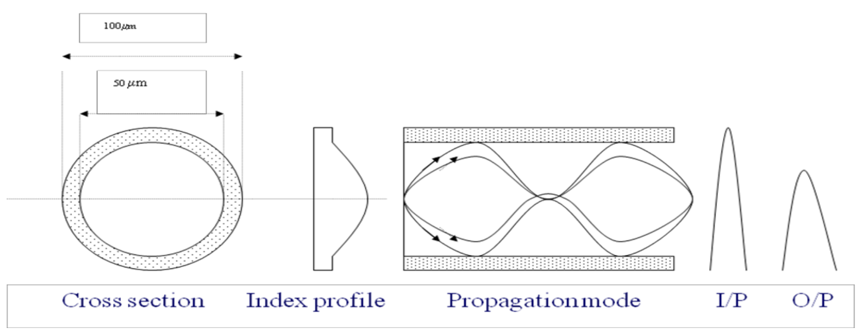
The construction geometry, the refractive index profile, the propagation mode and the waveform for a step-index single mode fiber are illustrated in the above diagram. This fiber is made up of a small core say about 5-10 µm diameter with a thick cladding say about 40-100 µm and a suitable protective sheathing. Both the core and the cladding have uniform, but different refractive indices. Since the profile forms a step due to sharp change in the refractive index between the core and the cladding, it is termed as step-index fiber. This design can transmit only one mode of wave propagation. Most single mode telecommunication fibers are manufactured with a diameter ~4 µm. Since there is only one mode of wave propagation, it eliminates the effect of intermodal dispersion and hence there is no pulse broadening effect. Hence the output pulse closely resembles the input pulse without any change in its shape or intensity (no distortion). Such a fiber with large and fully definable bandwidth is most suitable for long distance, high data rate communication. Also due to small core diameter, only lasers are suitable to effectively couple the light signals into the core of such fibers.

6.6.2 Multi-mode Step-index Fiber



This type of fiber is made up of a thick core about 50-100 μm with a thin cladding about 20-40 μm and a suitable protective plastic sheathing. Here both core and cladding have uniform but different refractive indices. Since it has a large core size, it can transmit a number of modes of wave propagation. The rays travel in a zigzag manner, in which the high angle modes travel a longer distance as compared to the low angle modes, causing intermodal dispersion. Due to this reason a sharp input pulse broadens as it travels long distances in the fiber and the output pulse will be widened pulse resulting with a waveform of distortion. In such fiber, the scattering and absorption losses are more; it is suitable for low bandwidth, short distance communications only. Both Lasers and LEDs can be used as source to input the optical signals into such fibers.

6.6.3 Multi-mode graded-index fiber



The construction of this fibre is similar to that of the multimode step-index fibre, except the refractive index of the core. The refractive index of the core varies across the core diameter (radially graded), while the refractive index of the cladding is fixed. In this type, a number of modes can be transmitted. The rays move in a sinusoidal path through the core. Light travels at a lower velocity in the high index region of the core than that of lower index region. Since the fastest components of the rays take the longer path, and the slower components take the shorter path in the core, the travel time of the different modes will be almost same. This reduces the effect of inter-mode dispersion. Due to this, the losses are minimum, with little pulse broadening. These fibres are most suitable for medium distance communication with large bandwidth. Either Laser or LED's can be used as the source.

Self test questions

1. What is a step-index profile?

2. What is a graded –index profile?
3. What is single mode propagation?
4. What is multi mode propagation?
5. Explain different types of optical fibres and its mode of propagation with neat diagrams.

Lesson 7 Attenuation and point-to-point communication

Objective

At the end of this lesson we will be able to:

- Explain what attenuation is.
- Know how effectively the light rays are propagated in point to point communication

6.7.1 Introduction to attenuation

Attenuation is also known as fiber loss is an important parameter in the design of optical fibers for communication systems. Attenuation is the loss of intensity as it travels in the fiber due to the increasing distances, which reduce the average power reaching at the receiving end. A minimum amount of light intensity is required at the receiving end to recover the signal accurately. In fact the transmission distance is desired by the attenuation property of the fiber. The fiber losses are measured in unit of dB/Km which will vary with the wavelength of the optical signal transmitted. The typical losses in the 0.8 to 1.8µm wavelength range, is of the order of 0.2 to 5 dB/Km. The fiber loss is more for shorter wavelengths which is about 5 dB/Km in the visible region of the light spectrum. The fiber losses may be due to various reasons like scattering, absorption, dispersion and extensive fiber bends. The net attenuation is calculated by the equation,

$$\alpha = -\frac{10}{L} log_{10}\left(\frac{Pout}{Pin}\right) dB/Km$$

Where ‘α’ is the attenuation coefficient,

‘L’ is the length of the fiber,

‘P_{in}’ is the power input of signal sent into the fiber,

And ‘P_{out}’ is the power output at the receiving end.

Solved Examples

1. An optical fiber has a clad of R.I 1.498 and numerical aperture is 0.446. Find its R.I of the core and the acceptance angle.

Solution:

Given n_2= 1.498, N.A = 0.446

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

$$n_1{}^2 = (NA) + (n_2{}^2)$$

$$n_1{}^2 = (0.446)^2 + (1.498)^2 = 2.442$$

$$n_1 = 1.562$$

The R.I of the core is 1.562.

The angle of acceptance $\theta = sin^{-1}\ (NA)$

$$\theta = sin^{-1}\ (0.446)$$

$$\theta = 26.48^o$$

2. Calculate the numerical aperture of an optical fiber. Given the R.I of the core is 1.623 and cladding is 1.522 and also find out the angle of acceptance.

Solution:

$$n_1 = 1.623, \ n_2 = 1.522$$

The numerical Aperture

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

$$\sqrt{(1.623)^2 - (1.522)^2}$$

= 0.0563

The angle of acceptance, $\theta = sin^{-1}\ (NA)$

$$\theta = sin^{-1}\ (0.0563)$$

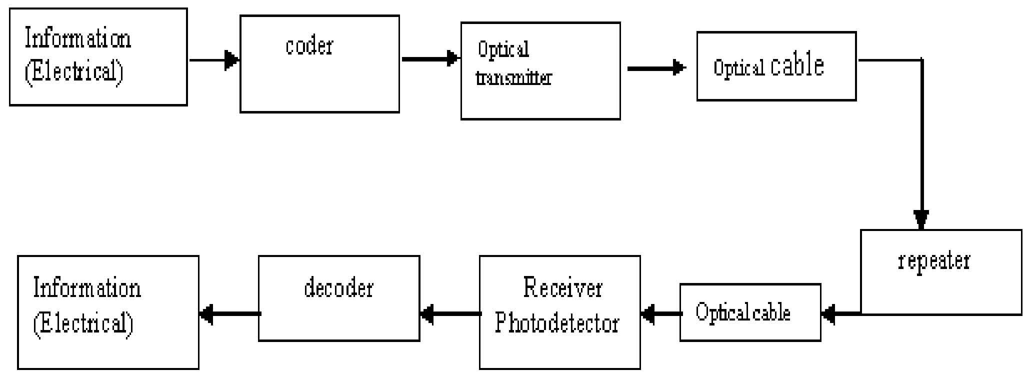
$$\theta = 34.30^{o}$$

6.7.2 Applications of optical Fibers

Optical fibers have many applications in the field of data transfer, medical,

engineering, entertainment, audio-video transfer, communications etc. One of the most important applications is point to point communication which will be discussed below.

Point-to-point communication



An optical fiber acts as the channel of communication and transmits the information/data in the form of optical waves. A simple point to point communication system has few components like an input information coder, laser transmitter, fiber cable, repeater, receiver and decoder. The information/data will be in the form of electrical signal which will be converted into optical signal by the coder. This optical signal (pulses) will be sent into the fiber cable with required incident angle (within the limit of acceptance cone angle) by modulating the light source (laser/LED/diode). After certain distances, depending upon the type of fiber, repeaters will be kept to boost the signal. Finally, the optical signal arrives at the receiver's end. There, first it will be converted into the electrical signal by the decoder and then it will be amplified up to the requirement. This is how information is transmitted from one point to the other point by the optical fiber.

Advantages

1. The materials used for making optical fibers are dielectric in nature. So it does not produce or receive any electromagnetic and RF interferences.
2. Not affected by corrosion and moisture.
3. It does not get affected by nuclear radiation.
4. It is easily compatible with electronic devices.
5. No sparks are generated because the signal is optical.
6. It carries very large amounts of information in either digital or analog form due to its large band width.

Self test questions

1. What is attenuation?
2. Explain the point-to-point communication using optical fibers.