MODULE 4 - Photonics

Interaction of radiation with matter – Einstein's A and B coefficients, Prerequisites for lasing actions, Types of LASER – Semiconductor diode LASER, Use of attenuators for single photon sources, Optical modulators – Pockel's effect, Kerr effect, Photodetectors – Photomultiplier tube, Single Photon Avalanche Diode, Optical fiber, Derivation of Numerical aperture, V-number, Number of modes, losses in optical fiber, Mach-Zehnder interferometer, Numerical problems.

Module - 4 Blow-up

Subtopics	Topics to be covered	Duration
Radiation-Matter Interaction	Basic principles (spontaneous & stimulated emission, absorption processes), Einstein A and B coefficients and derivation of expression for energy density.	1 Hour
Lasing Prerequisites	Population inversion, pumping mechanisms, and gain medium requirements (Laser cavity)	½ Hour
Types of laser, Semiconductor Diode Lasers	Types of laser (Solid, Liquid, Gas Lasers) , semiconductor diode laser- Principle, construction and working	1 Hour
Use of attenuators for single photon sources	Single photon Attenuators - Role in quantum communication, intensity control	½ Hour
Optical Modulators-Pockel's effect, Kerr effect	Electro-optic modulators, Pockel's effect, Kerr effect, phase modulation	1 Hour
Photodetectors-single photon avalanche diodes	single-photon avalanche diodes (SPAD) Construction and working, Superconducting Nano-wire Single Photon Detector (SNSPD)	1 Hour
Optical Fibers	Basics of Optical Fibers : Construction and principle (Qualitative), Derivation of numerical aperture, V-number, attenuation & losses	1 ½ Hour
Mach-Zehnder Interferometer & Numericals	Mach-Zehnder Interference principle and working, fiber optics applications, Numerical Problems: LASER on N - Rate emission of photons) & Fiber optics (NA, V-Number and Attenuation)	1 ½ Hour

Introduction: The word LASER was coined as an acronym for Light Amplification by Stimulated Emission of Radiation.

Laser is a device, which emits a powerful, monochromatic collimated beam of light. The emitted light waves are coherent in nature. The first laser, ruby laser was invented by Dr.T.H.Maiman in the year 1960. Since then, the development of lasers is extremely rapid. The laser action is being demonstrated in many solids, liquids, gases and semiconductor.

Characteristics of Laser beam:

Laser is a light source. Laser light has the following important characteristics

- ✓ Coherent
- ✓ High Monochromatic
- ✓ High Directionality
- ✓ Highly Intensity
- ✓ Divergence

i) **Coherent:** The Laser light is coherent. A Laser emits the light waves of same wavelength and in same phase.

ii) **Monochromatic:** If the light coming from a source has only one frequency or single wavelength is called monochromatic source and the light is called monochromatic light. In case of Laser beam, it has the wavelength confirmed to very narrow range of a few angstroms.

iii) **Directionality:** An ordinary source of light emits light in all directions. In case of Laser, the photons of a particular direction are only allowed to escape. Thus, the Laser beam is highly directional.

iv) **Intensity:** The intensity of ordinary light decreases as it travels in the space. This is because of its spreading. The Laser does not spread with distance. It propagates in the space in the form of narrow beam and its intensity remains almost constant over long distance.

v) **Divergence:** Divergence is the measure of its spread with distance. The angular spread in ordinary light is very high because of its propagation in the form of a spherical wave front. The divergence in the Laser beam is negligible. A very small divergence is due to the diffraction of Laser light when it emerges out from the partially silvered mirror.

Interaction of Radiation with Matter:

We know that, when light is absorbed by the atoms 0r molecules, then it goes from the lower energy level or ground state (E_1) to the higher energy level or excited state (E_2) and during this transition from E_2 to E_1, the light is emitted from the atoms or molecules.

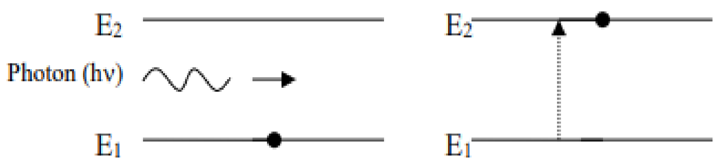
Let us consider an atom exposed to (light) photons of energy $E_2 - E_1 = h\gamma$. Three distinct process takes place,

i. Induced Absorption
ii. Spontaneous Emission
iii. Stimulated Emission

(i) Absorption or Stimulated Absorption:

Consider an atom initially in the ground state of energy E_1. If an electromagnetic radiation of frequency ν is incident on the atom, the atom absorbs energy $h\gamma$ from the radiation and move to the higher energy state E_2, if $h\gamma = E_2 - E_1$. The process by which an atom in a lower energy state can be raised to a higher energy state by absorbing a photon of energy $h\gamma$ is called induced or stimulated absorption.

ATOM + PHOTON → ATOM*



The rate of induced/stimulated absorption of radiation by atoms in the ground state R_{12} *is*, proportional to the following factors,

$$R_{12}\ \alpha \text{ density of radiation energy incident } \rho(\nu)$$

$$R_{12}\ \alpha \text{ the number of atoms per unit volume in the lower level } N_1$$

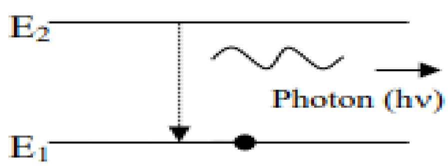
$$R_{12}\boldsymbol{\alpha}\ \rho_{\boldsymbol{\nu}}\ N_1$$

$$\boldsymbol{or}\ R_{12} = \boldsymbol{B_{12}}\ \rho_{\boldsymbol{\nu}}\ N_1 - - - - - (1)$$

Where, B_{12} is the proportionality constant called Einstein coefficient for induced absorption.

<u>(ii) Spontaneous Emission:</u>

Consider the atom in the excited state of energy E_2. The atom will remain in this state for a time of about $10^{-8}\ s$. The atom will fall on its own (without external energy) to the ground state emitting radiation of energy $h\gamma$. The process by which an excited atom jumps from a higher energy state to a lower energy state with emission of a photon is called spontaneous emission.



ATOM* →ATOM + PHOTON

The rate of spontaneous emission of radiation by atoms due to transition from higher to lower level is proportional to the number of atoms per unit volume in the higher-level N_2 only.

$$R_{21}\ \alpha \text{ the number of atoms per unit volume in the higher level } N_2$$

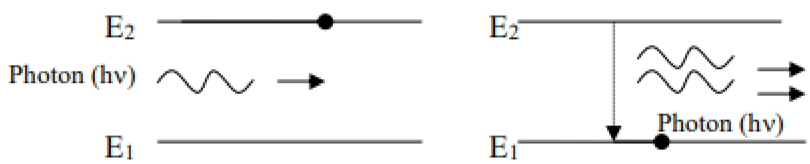
$$R_{21}\boldsymbol{\alpha}\ \ N_2$$

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

Where, A_{21} is the proportionality constant called Einstein coefficient for Spontaneous Emission.

<u>(iii) Stimulated Emission:</u>

Consider an atom in the excited state of energy E_2. If an electromagnetic radiation of frequency γ is incident on the atom, the atom moves to the ground state of energy E_1 by emitting a photon of energy $h\gamma$ along with the incident photon of energy $h\gamma$. This stimulated emission is possible only if the frequency γ of the radiation satisfies the relation, $h\gamma = E_2 - E_1$. The process



in which an atom in a higher energy state jumps to lower energy state with the emission of a photon identical to the incident photon is called as stimulated emission.

$$\text{ATOM}^* + \text{PHOTON} \rightarrow \text{ATOM} + 2\text{ PHOTONS}$$

The rate of stimulated emission of radiation by atoms due to transition from higher to lower level is proportional to, $R_{12}\ \alpha$ density of radiation energy incident $\rho(\nu)$

$R_{21}\ \alpha$ the number of atoms per unit volume in the lower level N_2

$$R_{21}\,\boldsymbol{\alpha}\ \rho_{\boldsymbol{\nu}}\, N_2$$

$$\boldsymbol{or}\ R_{21} = \boldsymbol{B_{21}}\rho_{\boldsymbol{\nu}}\, N_2 - - - - - - (3)$$

Where, B_{21} is the proportionality constant called Einstein coefficient for Stimulated Emission.

Differences between Spontaneous and Stimulated emission: (Not included in syllabus)

S.No	Spontaneous emission	Stimulated emission
1.	Instantaneous emission of light photon due to transition of an atom from higher to lower energy level	Emission of light photon with the help of another photon having energy same as the emitting photon due to transition of atom from higher to lower energy level
2.	The emission has broad spectrum of radiation (many wavelengths)	The emission has monochromatic radiation (single wavelength)
3.	Incoherent radiation (light photons of different phases and different frequencies)	Coherent radiation (light photons of same phase and same frequency)
4.	The light beam has less intensity	The light beam has high intensity
5.	Less directionality and more angular spread. e.g. Light from sodium or mercury	lamp High directionality and less angular spread e.g. Light from a laser source

<u>Einstein's A and B Coefficients:</u>

Consider an atomic system present in a radiation field of Energy density (ν) under equilibrium conditions. Let E_1 and E_2 be the energy levels of the atom with $E_2 > E_1$.

The number of atoms per unit volume in the two levels respectively are N_1 and N_2. The photon emitted due to transition between the levels will have energy$E_2 - E_1 = h\gamma$.

The rate of induced/stimulated absorption of radiation by atoms in the ground state$R_{12}\ is$, proportional to the following factors,

$$R_{12}\ \alpha \text{ density of radiation energy incident } \rho(\nu)$$

$$R_{12}\ \alpha \text{ the number of atoms per unit volume in the lower level } N_1$$

$$R_{12}\boldsymbol{\alpha}\ \rho_{\boldsymbol{v}}\ N_1$$

$$\boldsymbol{or}\ R_{12} = \boldsymbol{B_{12}}\ \rho_{\boldsymbol{v}}\ N_1 - - - - - - (1)$$

Where, B_{12} is the proportionality constant called Einstein coefficient for induced absorption.

The rate of spontaneous emission of radiation by atoms due to transition from higher to lower level is proportional to the number of atoms per unit volume in the higher-level N_2 only. $R_{21}\ \alpha$ the number of atoms per unit volume in the higher level N_2.

$$R_{21}\boldsymbol{\alpha}\ N_2$$

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

Where, A_{21} is the proportionality constant called Einstein coefficient for Spontaneous Emission.

The rate of stimulated emission of radiation by atoms due to transition from higher to lower level is proportional to,

$$R_{12}\ \alpha \text{ density of radiation energy incident } \rho(\nu)$$

$$R_{21}\ \alpha \text{ the number of atoms per unit volume in the lower level } N_2$$

$$R_{21}\boldsymbol{\alpha}\ \rho_{\boldsymbol{v}}\ N_2$$

$$\boldsymbol{or}\ R_{21} = \boldsymbol{B_{21}}\rho_{\boldsymbol{v}}\ N_2 - - - - - - (3)$$

Where, B_{21} is the proportionality constant called Einstein coefficient for Stimulated Emission.

Under Thermal equilibrium:

The absorption rate or the number of photons absorbed per second is equal to the sum of the number of photons emitted per second by spontaneous and stimulated emissions

$$\boldsymbol{rate\ of\ absorption} = \boldsymbol{rate\ of\ emission}\ (\boldsymbol{spontaneous} + \boldsymbol{stimulated})$$

RHS of equation (1) is equal to sum of RHS of equations (2) and (3)

$$B_{12}\ \rho_v\ N_1 = A_{21}\ N_2 + B_{21}\rho_v\ N_2$$

$$B_{12}\ \rho_v\ N_1 - B_{21}\rho_v\ N_2 = A_{21}\ N_2$$

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

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

$$\rho_v = \frac{A_{21}\, N_2}{N_2 \left(B_{12}\ \frac{N_1}{N_2} - B_{21}\right)}$$

$$\rho_v = \frac{A_{21}}{\left(B_{12}\ \frac{N_1}{N_2} - B_{21}\right)} ------ (4)$$

we know that, from maxwell – boltzmann distribution law,

$$N_1 = N_0 e^{\frac{-E_1}{k_B T}} \qquad \text{Similarly, } N_2 = N_0 e^{\frac{-E_2}{k_B T}}$$

Where, $k_B \rightarrow$ Boltzmann constant, T $\rightarrow$ Absolute Temperature

$N_0 \rightarrow$ Number of atoms at absolute zero.

At equilibrium condition we can write the ratio of population levels as follows, i.e.,

$$\frac{N_1}{N_2} = e^{\frac{E_2 - E_1}{k_B T}} \qquad \because\ E_2 - E_1 = h\gamma$$

Then we get, $\frac{N_1}{N_2} = e^{\frac{h\gamma}{k_B T}} ------ (5)$

Substitute eqn (5) in (4), $\rho_v = \frac{A_{21}}{\left(B_{12}\, e^{\frac{h\gamma}{k_B T}} - B_{21}\right)}$

$$\rho_v = \frac{A_{21}}{B_{21}\left(\frac{B_{12}}{B_{21}}\ e^{\frac{h\gamma}{k_B T}} - 1\right)}$$

$$or \quad \rho_v = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{B_{12}}{B_{21}}\ e^{\frac{h\gamma}{k_B T}} - 1\right)} ------ (6)$$

The energy density of radiation at a given temperature as per Planck's radiation formula is

$$\rho_v = \frac{8\pi h\gamma^3}{c^3} \frac{1}{\left(e^{\frac{h\gamma}{k_B T}} - 1\right)} -------- (7)$$

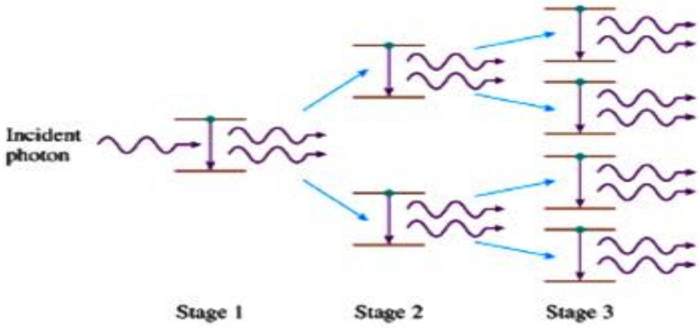
Comparison of equations (6) and (7), we get $\frac{A_{21}}{B_{21}} = \frac{8\pi h\gamma^3}{c^3} ------ (8)$

$$\frac{B_{12}}{B_{21}} = 1, we\ can\ write\ B_{12} = B_{21} = B ------ (9)$$

And taking $A_{21} = A ------ (10)$

The constants A and B in equation (9) and (10) are called as Einstein coefficients

Laser Action:



Consider a LASER system,Let an atom in the excited state is stimulated by a photon of right energy so that atom makes stimulated emission. Two coherent photons are obtained. These two coherent photons if stimulate two atoms in the exited state to make emission then four coherent photons are emitted. These four coherent photons stimulate 4 more atoms in the excited state resulting in 8 coherent photons and so on. As the process continues number of coherent photons increases. These coherent photons constitute an intense beam of LASER. This phenomenon of building up of number of coherent photons so as to get an intense LASER beam is called lasing action. LASER action could be achieved through the conditions population inversion and meta-stable state.

Principle of Laser:

The action of laser is based on stimulated emission and amplification of light. In producing laser, the following conditions must be satisfied.

(1) State of population inversion,

(2) Existence of metastable state and

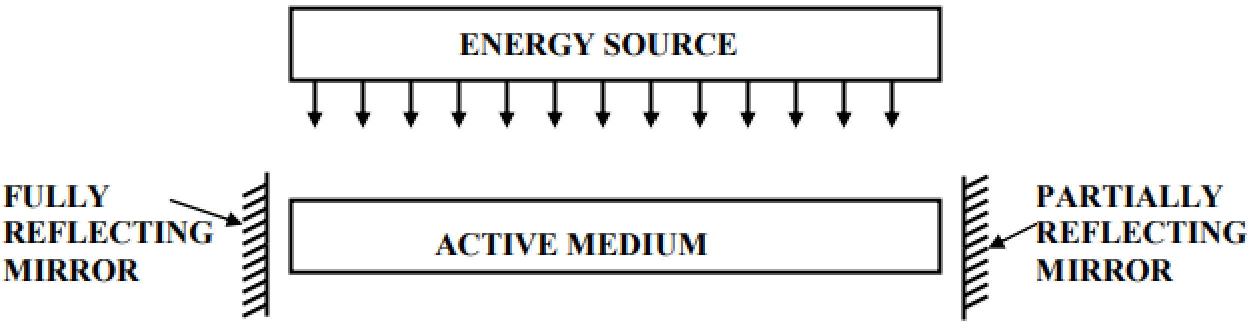
(3) Confinement of emitted photons to achieve population inversion.

Pre-requisites of LASER:

1. Energy Excitation Source: With the help of energy source, the system can be raised to an excited state. With the help of this source, the no. of atoms in higher energy state may be increased and hence the population inversion is achieved. Therefore, energy source may also be called as pumping device.

2. Active Medium or working substance: This working substance must have a metastable state (lifetime ≈10^{-4} sec). Thus when excited by energy source it achieves population inversion. This medium may be solid, liquid or gas.

3. Resonant Cavity: It is a specially designed cylindrical tube the ends of which are silvered, one end being completely silvered while the other is partially silvered. Thus, the light intensity can be increased by multiple reflections. The intense coherent beam can emerge out from partially silvered mirror. The rough structure of resonant cavity is shown below:



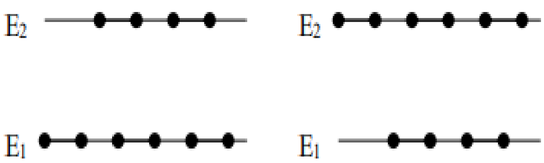
Conditions for Laser Action:

There are two conditions for the laser

- Population inversion
- Metastable state

Population inversion:

Consider a sample having a number of atoms in thermal equilibrium at a certain temperature. If the number N_1 of these atoms are in the ground state of energy E_1 and the number N_2 are in a state of higher energy E_2 then,



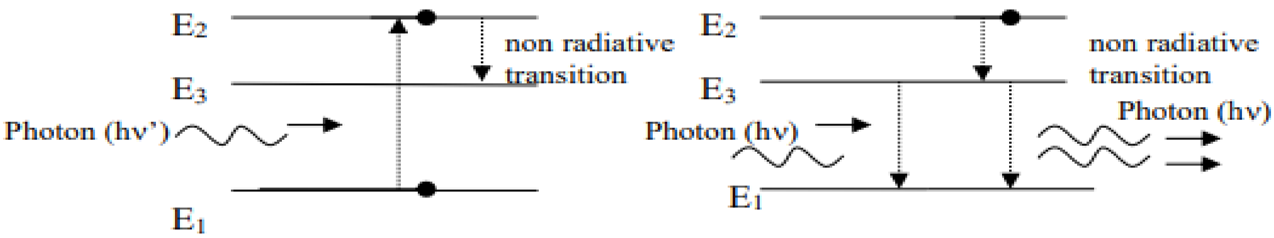
According to Boltzmann's law $\frac{N_2}{N_1} = e^{\frac{E_2 - E_1}{k_B T}}$

Thus $N_2 < N_1$. There will always be less atoms in the excited state than in the ground state. The number of atoms present in a given energy state of a substance at thermal equilibrium is called population of that energy state.

The condition when the number of atoms in an excited state is more than that in the ground state is called population inversion. The process of supplying energy from an external source, to achieve population inversion in a sample, is called pumping.

Metastable State:

Consider a system of atoms that exist in three different energy states namely, ground state (E_1), excited state (E_2) and metastable state (E_3) as shown in the diagram. In the excited state an atom can exist only for a time interval of 10^{-8} s. In the metastable state an atom can remain stable for a longer duration of time (≈ 5milliseconds).



(a) The system of atoms in the ground state are illuminated by radiation such that they get excited and move to excited state (E_2) by absorbing photons of energy $E_2 - E_1 = h\gamma'$. This is called optical pumping.

(b) Since the life of excited atoms is very small, they jump to metastable state (E_3) by non-radiative transition. The atoms can remain in this metastable state for longer time. Thus, there will be more atoms in metastable state than in the ground state. Thus, population inversion is said to be achieved.

(c) The atoms in the metastable state are bombarded by photons each of energy $E_3 - E_1 = h\gamma$. The atoms make transition to the ground state by stimulated emission. This results in emission of photons each of energy $E_3 - E_1 = h\gamma$. These photons along with the bombarding photons have same energy and are in same phase. Thus, the number of photons is multiplied by a factor of two. This process repeats and light amplification by stimulated emission of radiation or LASER occurs.

TYPES OF LASERS:

Based on the type of active medium, Laser systems are broadly classified into the following categories.

S.No	TYPES OF LASER	EXAMPLES
1.	Solid State laser Ruby Laser	Nd:YAG laser
2.	Gas laser He-Ne Laser,	CO_2 Laser, Argon – ion laser
3.	Liquid Laser	$SeOCL_2$ Laser, Europium Chelate Laser
4.	Dye laser	Rhodamine 6G laser, Coumarin dye laser
5	Semiconductor Laser	GaAs laser, GaAsP laser

1) **Solid State Laser:**

The solid-state laser is a type of laser where the medium used is solid. The solid material used in these lasers is either glass or crystalline materials. Glass or crystalline materials used in a solid-state laser are used as impurities in the form of ions along with the host material. Doping is the term used for describing the process of addition of impurities to the substance.

2) **Gas Laser:**

A gas laser is a laser in which an electric current is sent through a gas to generate light through a process known as population inversion. Gas lasers are of different types: they are, Helium (He) – Neon (Ne) gas lasers, argon ion lasers, carbon dioxide lasers (CO2 lasers), carbon monoxide lasers (CO lasers) are molecular gas, excimer lasers, nitrogen lasers, hydrogen lasers, etc. The type of gas used to construct the laser medium can determine the lasers wavelength or efficiency.

3) Liquid Lasers or Dye lasers:

Liquid lasers are also known as dye lasers. This is a type of laser in which liquids are used as an active medium. The active material used in the liquid laser is known as a dye and the commonly used dyes are sodium fluorescein, rhodamine B and rhodamine 6G.

4) Semiconductor laser:

It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased, it causes electrons and holes to recombine at the junction, releasing energy as photons. These photons then stimulate further photon emissions, resulting in a directional and monochromatic laser source. The semiconductor laser is a type of laser that is small in appearance and size. The operation of this laser is similar to LED but the characteristics of the output beam are of laser light.

There are two types of semiconductor lasers. They are,

1. Homo-junction Semiconductor laser

2. Hetero-junction Semiconductor laser

1. Homo-junction Semiconductor laser: Definition: If the p-n junction is formed in a single crystalline material, then it is called as homo-junction laser. Ex: Single crystal of Gallium Arsenide (GaAs).

2. Hetro-junction semiconductor laser: Definition: If the p-n junction is made up of the different material with two regions, n-type and p-type is called as hetero-junction laser. Ex: hetero-junction laser can be formed between GaAs and GaAlAs.

Semiconductor Diode Laser: Principle, Construction, Working, & Applications:

Definition:

It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

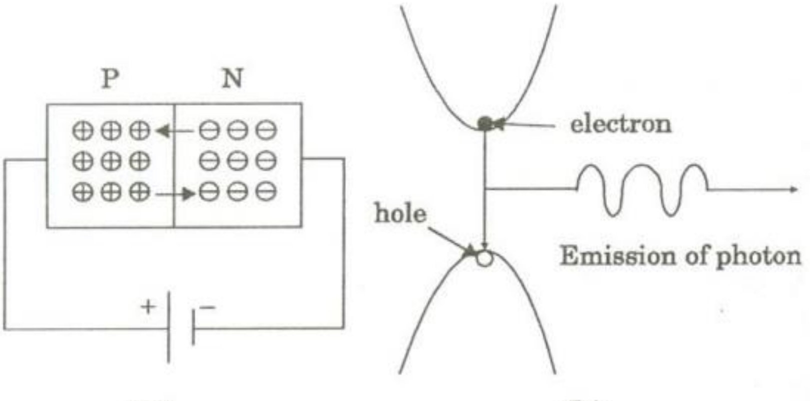
Principle:

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other.

During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.

Construction:

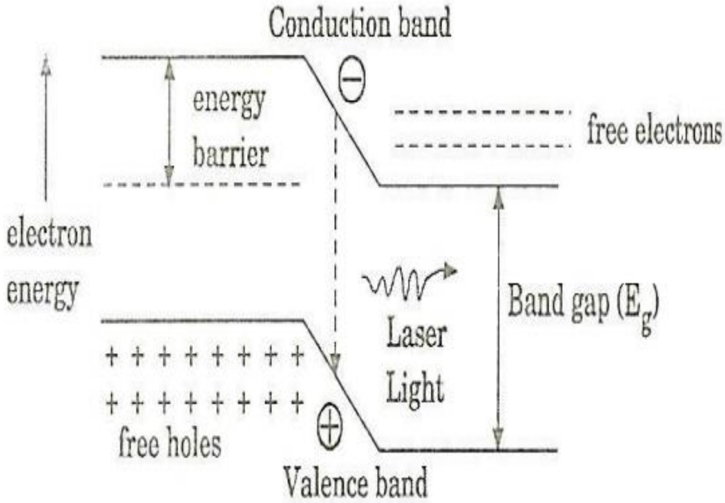


(a) (b)

Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5μmm.

The plates consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).

The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The electrical voltage is applied to the crystal through the electrode fixed on the upper surface.



The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out. Figure shows the energy level diagram of semiconductor laser.

When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration

The region around the junction contains a large amount of electrons in the conduction band and a large amount of holes in the valence band.If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

After gaining enough strength, it gives out the laser beam of wavelength 8400Å . The wavelength of laser light is given by

$$E_g = h\gamma = h\frac{c}{\lambda} \qquad \text{Or} \qquad \lambda = \frac{hc}{E_g}$$

Where, Eg is the band gap energy in joule.

CHARACTERISTICS:

1) **Type**: It is a solid-state semiconductor laser.
2) **Active medium**: A PN junction diode made from single crystal of gallium arsenide is used as an active medium.
3) **Pumping method**: The direct conversion method is used for pumping action
4) **Power output**: The power output from this laser is 1mW.
5) **Nature of output**: The nature of output is continuous wave or pulsed output.
6) **Wavelength of Output**: Gallium Arsenide laser gives infrared radiation in the wavelength 8300 to 8500Å.

ADVANTAGES:

1. It is very small in dimension. The arrangement is simple and compact.
2. It exhibits high efficiency.
3. The laser output can be easily increased by controlling the junction current
4. It is operated with lesser power than ruby and CO_2 laser.
5. It requires very little auxiliary equipment
6. It can have a continuous wave output or pulsed output.

DISADVANTAGES:

1) It is difficult to control the mode pattern and mode structure of laser.
2) The output is usually from 5 degree to 15 degree i.e., laser beam has large divergence.
3) The purity and monochromacity are power than other types of laser
4) Threshold current density is very large ($400 A/mm^2$).
5) It has poor coherence and poor stability.

APPLICATIONS:

1) It is widely used in fiber optic communication
2) It is used to heal the wounds by infrared radiation
3) It is also used as a pain killer
4) It is used in laser printers and CD writing and reading.

Attenuators:

An attenuator is a device or circuit that reduces the power of a signal without distorting its waveform, acting as the opposite of an amplifier. It is a passive, two-port electronic component designed using resistors to control the signal's strength, typically measured in decibels. Attenuators are used to prevent high-power signals from overwhelming sensitive circuits, ensure proper signal levels for devices like antennas, and provide isolation between components in a system.

Single-photon source – Definition: A **single-photon source** is a light source that emits light as single particles or photons. Single-photon sources are distinct from coherent light sources (lasers) and thermal light sources such as incandescent light bulbs.

Use of Attenuators for Single Photon Sources:

Attenuators are used with single photon sources to reduce the signal power to a level manageable and detectable by the sensitive, but often saturated, single-photon detectors. By blocking a controlled fraction of photons, an attenuator dynamically extends the detector's operating range, allowing for accurate measurements even when the raw signal is too intense.

This is crucial for testing photodetector linearity, calibrating single-photon experiments, and performing other tasks at the few-photon level that would otherwise be impossible due to detector saturation.

Attenuators are used to extend the effective range of detectors, allowing them to be calibrated and used in situations where the signal is too strong for their normal operating range.

Optical Modulators:

Optical modulators convert data from the electrical to the optical domain by altering light's properties, such as amplitude, phase, polarization, or frequency. They are classified by the effect used (e.g., electro-optic, acousto-optic) or the property altered (e.g., amplitude, phase). Common types include electro-optic modulators for phase/polarization changes and acousto-optic modulators for amplitude/frequency shifts, used in communications and laser control.

Electro-optic modulator (EOM):

Electro-optic modulator (EOM) is an optical device in which a signal-controlled element exhibiting the electro-optic effect is used to modulate a beam of light. The modulation may be imposed on the phase, frequency, amplitude, or polarization of the beam. Modulation bandwidths extending into the gigahertz range are possible with the use of laser- controlled modulators.

The electro-optic effect is the change in the refractive index of a material resulting from the application of a DC or low frequency electric field. This is caused by forces that distort the position, orientation, or shape of the molecules constituting the material.

Explanation:

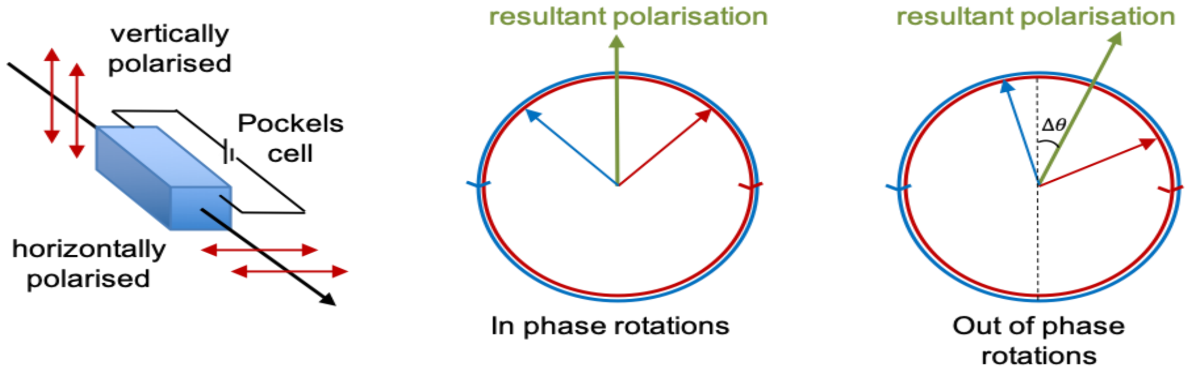
Generally, a nonlinear optical material (organic polymers have the fastest response rates, and thus are best for this application) with an incident static or low frequency optical field will see a modulation of its refractive index The simplest kind of EOM consists of a crystal, such as lithium niobate, whose refractive index is a function of the strength of the local electric field. That means that if lithium niobate is exposed to an electric field, light will travel more slowly through it. But the phase of the light leaving the crystal is directly proportional to the length of time it takes that light to pass through it.

Therefore, the phase of the laser light exiting an EOM can be controlled by changing the electric field in the crystal Note that the electric field can be created by placing a parallel plate capacitor across the crystal. Since the field inside a parallel plate capacitor depends linearly on the potential, the index of refraction depends linearly on the field (for crystals where Pockels effect dominates), and the phase depends linearly on the index of refraction, the phase modulation must depend linearly on the potential applied to the EOM. The voltage required for inducing a phase change of is called the half-wave voltage ( ). For a Pockels cell, it is usually hundreds or even thousands of volts, so that a high-voltage amplifier is required. Suitable electronic circuits can switch such large voltages within a few nanoseconds, allowing the use of EOMs as fast optical switches

Pockels effect:

Discovered by Friedrich Pockels in 1893, the effect requires non-centrosymmetric materials and is used in devices like Pockels cells to modulate light for high-speed optical communication and laser intensity control.

The Pockels effect is a phenomenon in certain crystals where an applied electric field changes the material's refractive index linearly. This change in refractive index leads to optical birefringence, allowing for the manipulation of light's polarization and phase.



Kerr effect:

The Kerr effect is a nonlinear phenomenon where the intense light of the signal itself changes the fiber's refractive index, leading to distortions like self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). This intensity-dependent refractive index alters the speed of light within the fiber, causing signal degradation and limiting the capacity and reach of long-haul communication systems, especially at high data rates and power levels.

The Kerr effect is a phenomenon that occurs when a material's refractive index changes in response to an electric field. A Scottish physicist named John Kerr in 1875 discovered the Kerr effect and it was named after him. This effect is a type of electro-optic effect, which refers to the interaction between light and an electric field.

When a strong electric field is applied to a transparent substance in a direction transverse to the beam of light, double refraction is induced in it. So, the refractive index of the material is varied with the electric field and it behaves like a crystal with its optic axis parallel to the electric field.

In general, the Kerr effect can be observed in all materials. But some liquids tend to

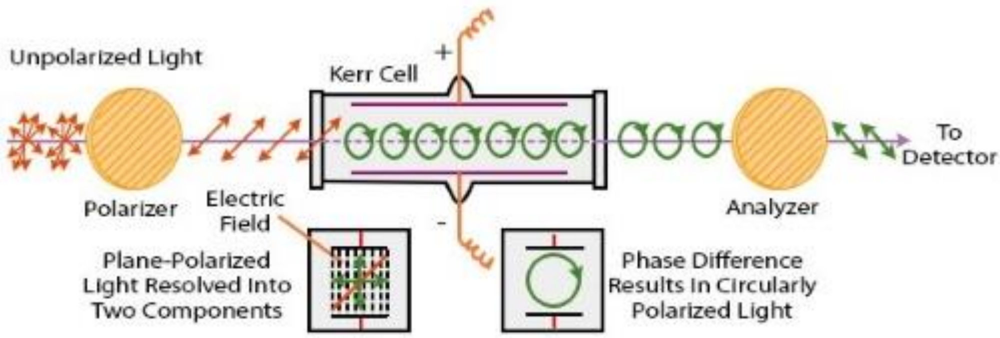
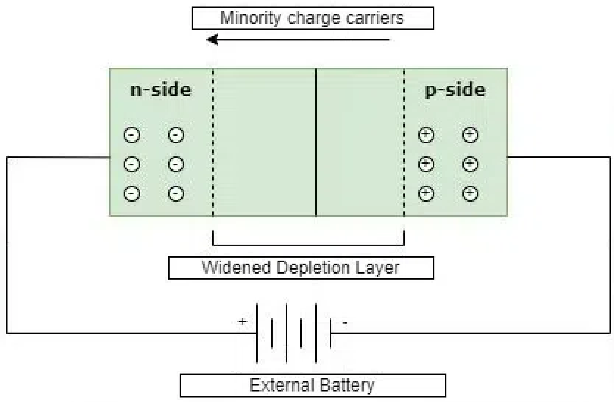


Figure 1: Working of Kerr Cell

exhibit a stronger Kerr effect compared to others. The material that exhibits the Kerr effect is called the Kerr cell, also known as the Kerr electro-optical shutter. It employs the Kerr effect to interrupt a light beam up to 10^{10} times per second. The working of the Kerr cell is shown in Figure 1.

Photodetectors:

A photodetector can be defined as a device that is used to detect light radiations by absorption. It converts light pulses (or radiations) energy into electrical signals in the form of current & voltage. Sometimes, it is also called photosensors. As the name implies, it detects incident photons or radiations by absorbing the incident lights. The principle behind this process is known as photo detections.



Working:

When photons (light particles) hit the photodetector's semiconductor material, they are absorbed. The absorbed energy excites electrons, causing them to jump to a higher energy band (conduction band), leaving behind a positively charged "hole" in the lower energy band (valence band). These newly created electron-hole pairs are then separated by an internal electric field. The separation of these charge carriers results in a measurable electric current, or photocurrent, which is proportional to the intensity of the incident light.

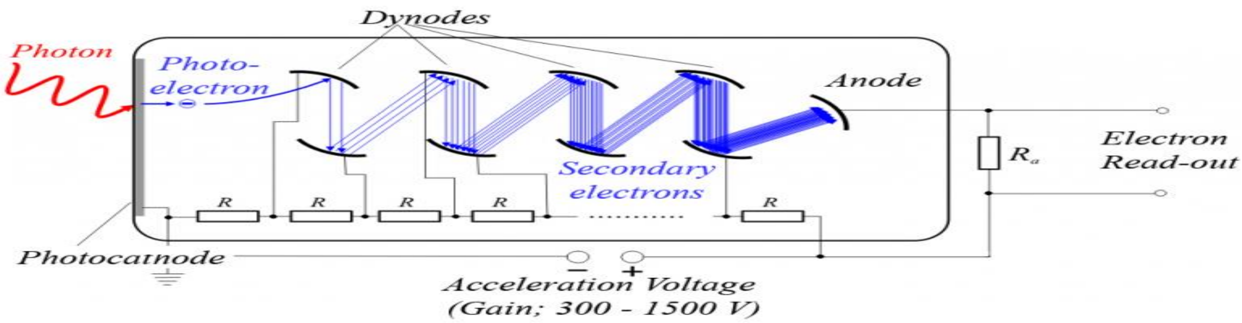
Applications:

- **Fiber Optic Communication:** Detecting light signals transmitted through optical fibers.
- **Consumer Electronics:** In remote controls to detect infrared signals from a device.
- **Safety & Security:** Used in various sensor systems for detection and monitoring.

- **Scientific Instrumentation**: Essential for process control, environmental sensing, and light measurement.
- **Imaging**: Found in image sensors like CMOS (Complementary Metal-Oxide-Semiconductor) to capture images electronically.

Photomultipliers:

A photomultiplier tube (PMT) is an extremely sensitive vacuum tube that detects very faint light by converting photons into an electrical current. It works by using a photocathode to convert incoming photons into electrons, then amplifying these electrons through a series of dynodes via secondary emission to create a strong, measurable electrical signal at the anode. PMTs offer high sensitivity, low noise, and fast response times, making them useful in applications like spectroscopy, radiation detection, and astronomy for sensing even single photons.



Photomultiplier Tube

Working:

Light enters the PMT and strikes the photocathode, a photo emissive surface. When a photon hits the photocathode, it ejects one or more electrons, known as photoelectrons. These photoelectrons are then accelerated by an electric field to a series of positively charged dynodes. Each time an accelerated electron strikes a dynode, it causes the dynode material to emit multiple secondary electrons. This process repeats through the entire chain of dynodes, resulting in an "electron avalanche" and an enormous amplification of the initial signal. The amplified cloud of electrons is collected at the anode, creating a measurable electrical current or pulse.

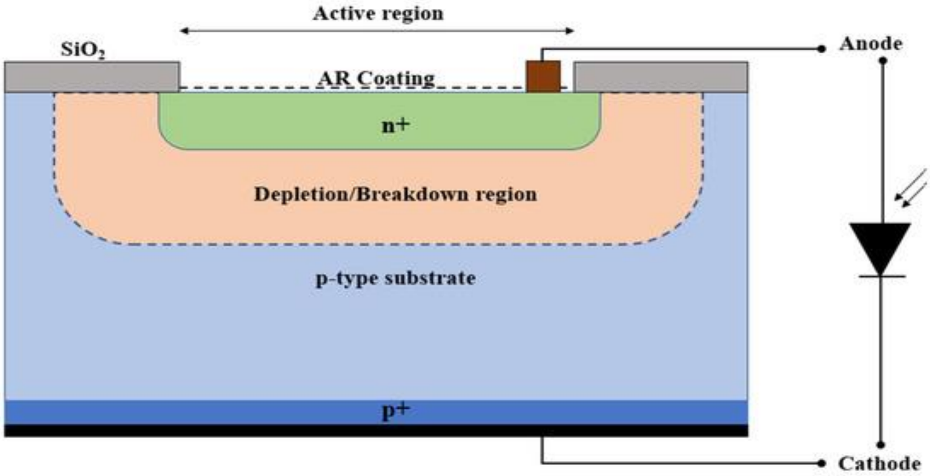
Applications:

PMTs are used in a wide range of scientific and industrial fields:

- **Life Sciences**: Fluorescence spectroscopy and microscopy.
- **Astronomy**: Detecting faint celestial objects.
- **Radiation Detection**: In scintillation detectors to detect radiation particles like gamma rays or beta particles.
- **Industrial Inspection**: X-ray inspection in industries like automotive and security.
- **Spectroscopy**: Measuring light intensity in various analytical applications.

Single-Photon Avalanche Diode (SPAD):

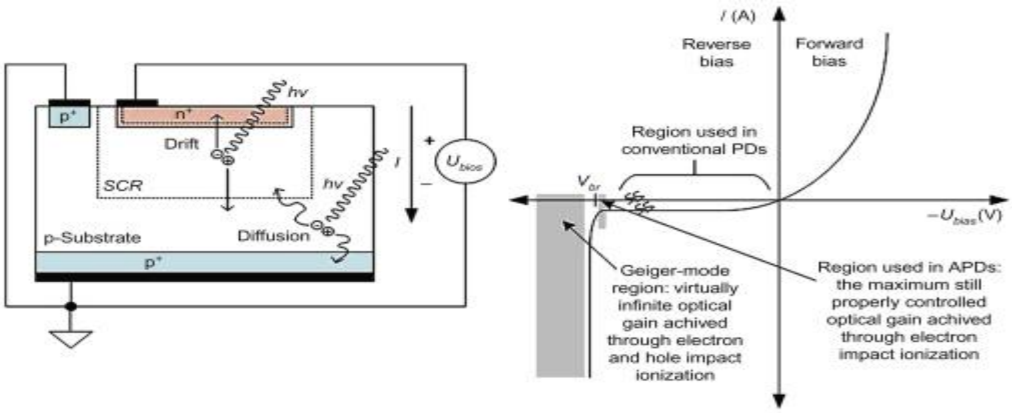
A single-photon avalanche diode (SPAD) works by operating a p-n junction in Geiger mode, biased above its breakdown voltage, to create an intense electric field. A single incident photon generates a carrier, which, under the high electric field, triggers a self-sustaining impact ionization avalanche of current.



Working:

A SPAD is a semiconductor diode (a p-n junction). It is reverse-biased with a voltage that exceeds its breakdown voltage. This creates an extremely high electric field within the depletion layer. A single photon hitting the SPAD's depletion layer generates a primary charge carrier (an electron or hole). This carrier is accelerated by the intense electric field. As the carrier accelerates, it gains enough energy to collide with the semiconductor lattice atoms. These collisions cause impact ionization, creating more electron-hole pairs.

This process continues, leading to a cascade or "avalanche" of carriers, which produces a detectable, macroscopic current pulse. The avalanche current would continue to flow indefinitely if not interrupted. A quenching circuit (often a resistor or more complex active circuit) is used to reduce the voltage across the SPAD. When the voltage drops below the breakdown voltage, the electric field is no longer strong enough to sustain the avalanche, and the current ceases. After quenching, the bias voltage is restored by the circuit, allowing the SPAD to be ready for another photon detection. The time during which the SPAD is unable to detect another photon is known as the "dead time".



Superconducting nanowire single photon detectors (SNSPD's):

Superconducting nanowire single photon detectors (SNSPD's) are the advanced devises for single photon detection. They work on the principle that when a photon is incident it breaks cooper pairs and reduces the local critical current. By measuring, the changes in the current can detect the photon.

Construction:

The SNSPD consists of a thin and narrow superconducting wire. The wire is arranges in a curved fashion (called Meander geometry) to achieve high detection efficiency. The wire is kept at a temperature below the critical temperature and connected to DC source. The biasing current (I_B) in the wire is maintained just below its critical current (I_C). The whole arrangement is connected to a special type of electronic circuit called as readout.

Working:

When a photon is incident on the wire, it breaks the cooper pairs and local critical current decreases (fig i). If the critical current decreases below the bias current then the superconductivity is spoiled and a local non-superconducting region or 'Hotspot' is created. The resistance of the hotspot is larger than the resistance of the readout (about1Kilo-ohm). As a result bias current flows through the readout. (In fact the readout acts as a shunt for the current). This produces a measureable voltage pulse (fig ii) such that one photon pulse. By measuring this voltage, we can detect the incident photon.

With most of the bias current flowing through the readout, the non superconducting region rapidly cools and returns to the superconducting state, ready to detect another photon. (fig iii).

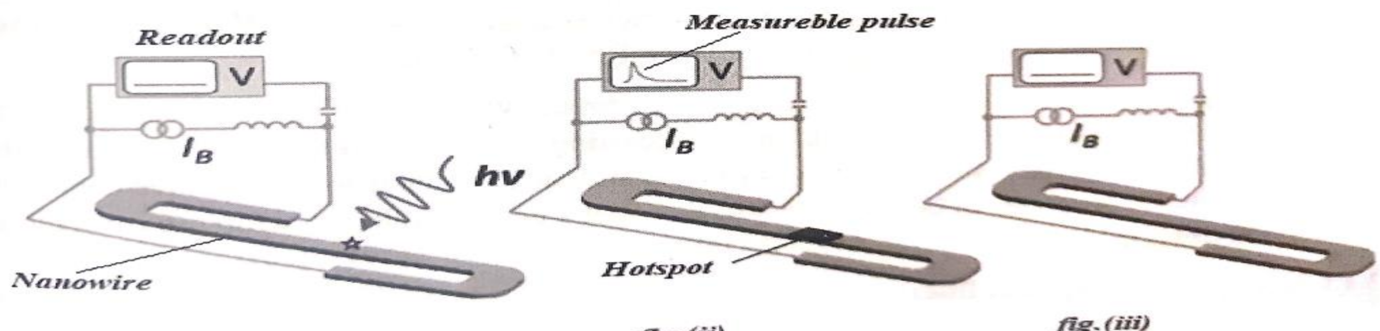


fig.(i) fig.(ii) fig.(iii)

Advantages:

SNSPD's offers many important advantages over SPADs. Some of them are

1. Unparalleled detection efficiency and timing precision.
2. Negligible intrinsic dark counts.
3. Ultrafast detection rates.
4. Broadband operation.

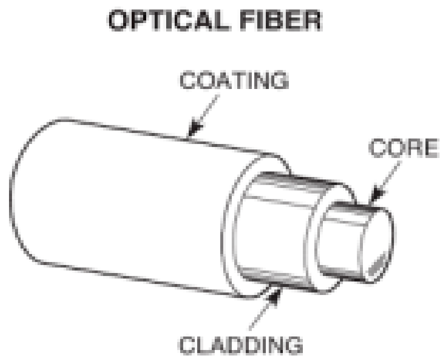
Uses:

They are becoming more popular in the applications of bio photonics, quantum optics and quantum computing.

Introduction:

FIBER OPTICS

Optical fibers are the light guides used in optical communications as wave-guides. They are thin, cylindrical, transparent flexible dielectric fibers. They are able to guide visible and infrared light over long distances. The working structure of optical fiber consists of three layers.



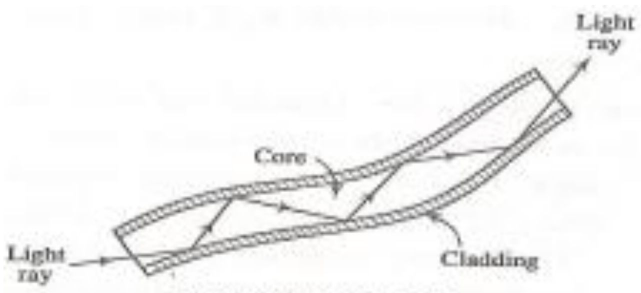
Core: the inner cylindrical layer that is made of glass or plastic.

Cladding: which envelops the inner core. It is made of the same material of the core but of lesser refractive index than core.

The core and the cladding layers are enclosed in a polyurethane jacket called sheath which safeguards the working structure of fiber against chemical reactions, mechanical abrasion and crushing etc.

Propagation mechanism in Optical fibre:

In optical fibres light waves can be guided through it, hence are called light guides. The cladding in an optical fibre always has a lower refractive index (RI) than that of the core. The light signal that enters into the core can strike the interface of the core and the cladding at angles greater than critical angle of incidence because of the ray geometry. The light signal undergoes multiple total internal reflections within the fibre core. Since each reflection is a total internal reflection, the signal sustains its strength and also confines itself completely within the core during propagation. Thus, the optical fibre functions as a wave-guide.



FIBER AS A WAVEGUIDE

Propagation mechanism:

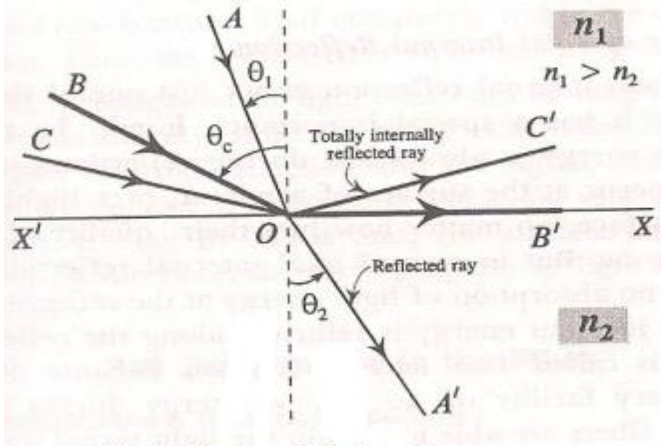
- The cladding in an optical fiber always has a lower refractive index than that of the core.
- The light signal which enters into the core and strikes the interface of the core and cladding with an angle greater than the critical angle will undergo total internal reflection.
- Thus the light signal undergoes multiple reflections within the core and propagates through the fiber.
- Since each reflection is a total internal reflection, there is no absorption of light energy at the reflecting surface
- Therefore the signal sustains its strength and also confines itself completely within the core during the propagation.

- After series of such total internal reflection, it emerges out of the core. Thus the optical fiber works as a waveguide. Care must be taken to avoid very sharp bends in the fiber because at sharp bends, the light ray fails to undergo total internal reflection.

Total Internal Reflection:

When a ray of light travels from denser to rarer medium it bends away from the normal.

As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the "critical angle" (θ_c), the refracted ray grazes the surface separating the media or the angle of refraction is equal to 90°.



Total Internal Reflection

If the angle of incidence is further increased beyond the critical angle, the light ray is reflected back to the same medium. This is called "**Total Internal Reflection".**

In total internal reflection, there is no loss of energy. The entire incident ray is reflected back.

Let XX^l is the surface separating medium of refractive index n_1 and medium of refractive index n_2, $n_1 > n_2$. AO and OA^l are incident and refracted rays. θ_1 and θ_2 are angle of incidence and angle of refraction, $\theta_2 > \theta_1$. For the ray BO, θc is the critical angle. OB^l is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θc is totally reflected back along OC^l .

From Snell's law, $n_1 sin\theta_1 = n_2 sin\theta_2$ $\theta_1 = \theta_c \; and \; \theta_2 = 90°$

$$n_1 sin\theta_c = n_2 \qquad (\because \sin 90° = 1)$$

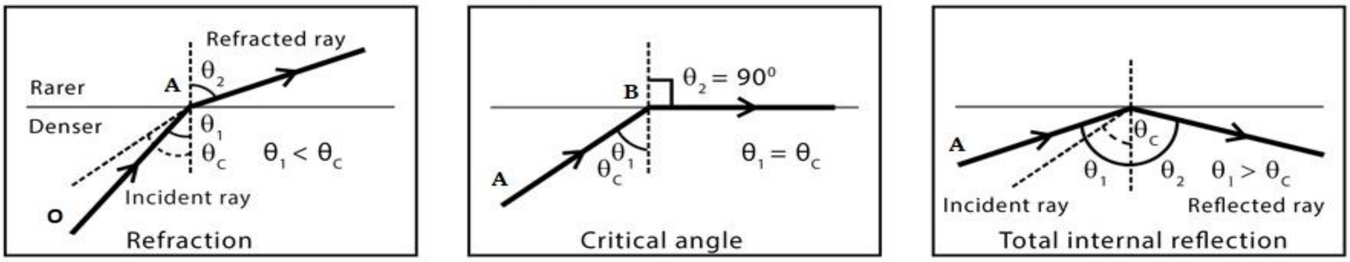
$$\theta_0 = sin^{-1}\frac{n_2}{n_1}$$

Expression for Numerical aperture and condition for propagation:

Consider a light ray AO incident at an angle 'θ_0' enters into the fiber. Let 'θ_1' be the angle of refraction for the ray OB. The refracted ray OB incident at a critical angle ($90° - \theta_1$) at B grazes the interface between core and cladding along BC. If the angle of incidence is greater than critical angle, it undergoes total internal reflection. Thus θ_0 is called the waveguide acceptance angle and $sin\theta_0$ is called the numerical aperture.

n1= refractive index of core medium n2 =refractive index of cladding

θ_1 = angle of incidence θ_2 = angle of refraction θ_c = critical angle



Snell's law of refraction $n_1\sin\theta_1 = n_2\sin\theta_2$

For critical angle, $\theta_2 = 90^0$ $n_1\sin\theta_1 = n_2\sin 90^0 = n_2 \times 1$

For total internal reflection to occur, $\theta_1 > \theta_c$

Let n_0, n_1 and n_2 be the refractive indices of the surrounding medium, core and cladding respectively.

Applying Snell's law at O→A,

$n_o \sin\theta_0 = n_1 \sin\theta_1$

$sin\ \theta_0 = \frac{n_1}{n_0} sin\ \theta_1 \ldots\ldots\ldots\ldots\ldots\ldots (1)$

Applying Snell's law at A→B,

$n_1 \sin(90\text{-}\theta_1) = n_2 \sin 90°$

$n_1 \cos\theta_1 = n_2$ $(\because \sin 90° = 1)$

$\Rightarrow cos\ \theta_1 = \frac{n_2}{n_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$

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

Substituting for $cos\ \theta_1$ from (2)

$$sin\ \theta_0 = \frac{n_1}{n_0}\sqrt{1 - \left[\frac{n_2}{n_1}\right]^2}$$

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

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

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

If $n_0 = 1$ $i.e., surrounding\ medium\ if\ it\ is\ air$

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

Where, $sin\ \theta_0$ is called numerical aperture

$$NA\ = sin\ \theta_0 = \sqrt{n_1^2 - n_2^2} ----(3)$$

$Equation\ (3)\ is\ the\ required\ expression\ of\ Numerial\ Aperture.$

$$Acceptance\ angle, \theta_0 = sin^{-1}\sqrt{n_1^2 - n_2^2}$$

Condition for propagation:

If θi is the angle of incidence of the incident ray, then the ray will be able to propagate,

if $\theta i < \theta 0$

$\Rightarrow if\ sin\ \theta i < sin\ \theta 0$

$or\ sin\ \theta i < \sqrt{}n1\ 2 - n2\ 2$

$i.e.\ ,\ sin\ \theta i < N.\ A$

Acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fiber and propagate through the fiber.

Numerical aperture indicates the ability of the optical fiber to accept light i.e. the light gathering capability of the optical fiber. The sign of the acceptance angle also called numerical aperture.

Fractional index change (Δ):

The ratio of the difference in refractive index of core and cladding to the refractive index of core of an optical fiber.

$i.e., \Delta\ = \frac{n_1 - n_2}{n_1}$

Mode of Propagation:

The number of light signals passing through an optical fiber is called mode of propagation. If only one light wave passing through an optical fiber then it is single mode fiber, if more than one light wave passing through an optical fiber then it is call multimode fiber.

V- Number:

The number of modes supported for propagation in the fiber is determined by a parameter called V-number. If the surrounding medium is air, then V-number is given by,

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

Where, d is the core diameter,

n_1 and n_2 are refractive indices of core and cladding respectively,

λ is the wavelength of light propagating in the fiber.

Attenuation in optical fibers: (Losses)

Attenuation is the loss of optical power suffered by the optical signal as it propagates through a fiber also called as the fiber loss.

Attenuation Co-Efficient

The attenuation of a fiber optic cable is expressed in decibels.

i.e., $$\alpha = -\frac{10}{L}\log\left[\frac{P_{out}}{P_{in}}\right] \, dB/km$$

The main reasons for the loss in light intensity over the length of the cable is due to light absorption, scattering and due to bending losses.

Attenuation takes place through three mechanisms.

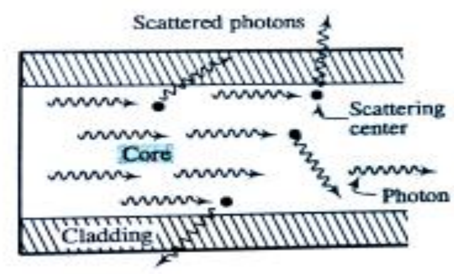
(i) **Absorption losses:**
(ii) **Scattering losses:**
(iii) **Radiation losses:**

(i) Absorption losses:

Absorption of photons by impurities like metal ions such as iron, chromium, cobalt and copper in the silica glass of which the fiber is made of. During signal propagation photons interact with electrons of impurity atoms and the electrons are excited to higher energy levels. Then the electrons give up their absorbed energy either in the form of heat or light energy. The re-emission of light energy will usually be in a different wavelength; hence it is referred as loss of energy.

The other impurity such as hydroxyl (OH) ions, which enters into the fiber at the time of fabrication, causes significant absorption loss. The absorption of photons by fiber itself assuming that there are no impurities and in-homogeneities in it is called as intrinsic absorption.

(ii) Scattering losses:



Scattering of light waves occurs whenever a light wave travels through a medium having scattering objects whose dimensions are smaller than the wavelength of light.

Similarly, when a light signal travels in the fiber, the photons may be scattered due to the sharp changes in refractive index values inside the core over distances and due to the structural impurities present in the fiber material.

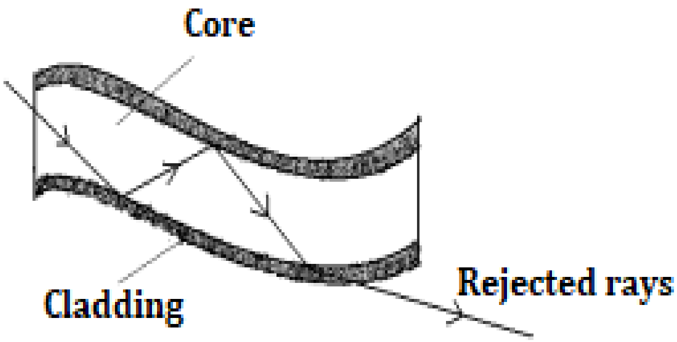
This type of scattering is called as Rayleigh scattering. Scattering of photons also takes place due to trapped gas bubbles, which are not dissolved at the time of manufacturing. A scattered photon moves in random direction and leaves the fiber.

(iii) Radiation losses:

Radiation losses occur due to macroscopic bends and microscopic bends.

Macroscopic bending:

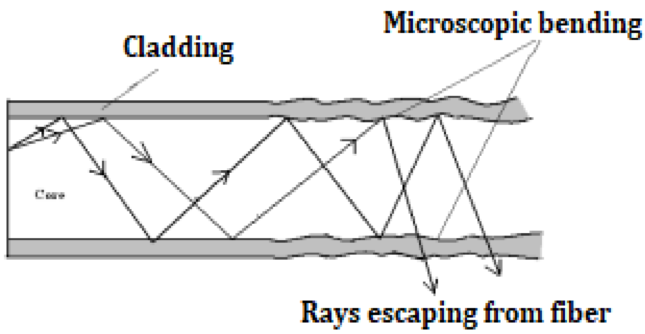
All optical fibers are having critical radius of curvature provided by the manufacturer. If the fiber is bent below that specification of radius of curvature, the light ray incident on the core cladding interface will not satisfy the condition of total internal reflection. This causes loss of optical power.



Radiation Leaks

Microscopic bending:

Microscopic bends are repetitive small scale fluctuations in the linearity of the fiber axis. They occur due to non-uniformities in the manufacturing and also lateral pressure built up on the fiber. They cause irregular reflections and some of them leak through the fiber. The defect due to non-uniformity (micro-bending) can be overcome by introducing optical fiber inside a good strengthen polyurethane jacket.



Microscopic Bending Loss

Mach-Zehnder Interferometer:

In the Michelson and Twyman–Green interferometers, the same beam splitter is used to first split the incident beam and then to combine the split beams after introducing the desired path difference between them. The Mach–Zehnder interferometer, on the other hand, uses two beam splitters – one for splitting the incident beam and the other for combining the split-beams (Fig.).

Mirrors M_1 and M_2 steer the beams appropriately. The centers of the beam splitters and mirrors lie on the corners of a parallelogram. The split-beams travel widely separated paths before they are combined by the second beam splitter. This interferometer is particularly useful for plasma diagnostics and gas flow studies (in a wind tunnel, for example).

One arm of the interferometer contains the test chamber and compensating elements (not shown in the figure) are kept in the other arm to equalize the optical path lengths. The refractive index changes associated with the density changes in the test chamber can be accurately determined in terms of the fringe displacements. The contours of the fringes determine local density changes within the test chamber under different experimental conditions. The fringes can be localized at any convenient region in the test chamber by appropriately tilting one of the mirrors.

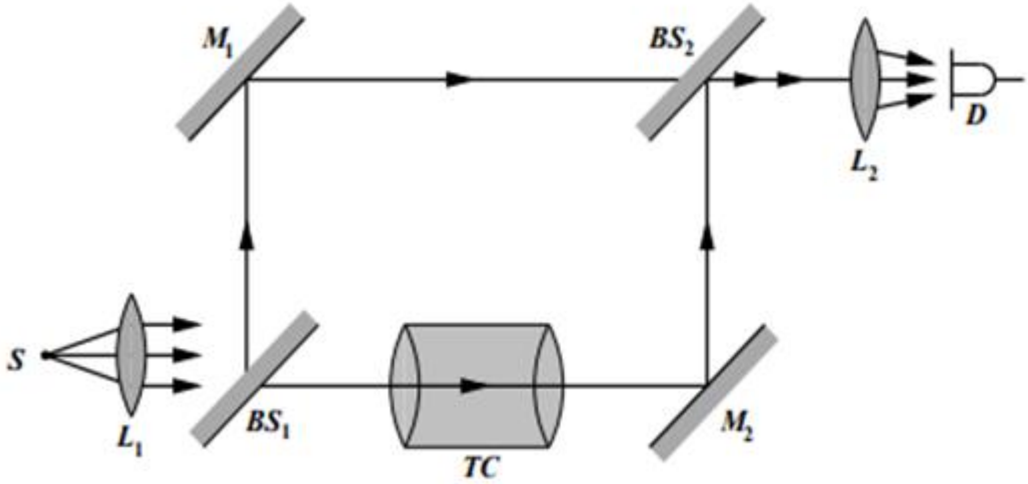


Fig. Mach–Zehnder interferometer; BS_1 and BS_2 are beam splitters, M_1 and M_2 are mirrors, TC is test chamber, D is detector.

LASER:

1. A pulsed laser emits photon of wavelength 780nm with 20mW average power/pulse. Calculate the number of photons contained in each pulse if the pulse duration is 10 ns. **(Jan 2019-18S)**

Data: Wavelength of photon, λ = 780nm = $780 \times 10^{-9}m$

Power of each pulse $P = 20mW = 20 \times 10^{-3}W$

Duration of Each Pulse, $t = 10ns = 10 \times 10^{-9}sec$

To find: No. of photons in each pulse, N=?

Solution: wavelength of photon, λ = 780nm = $780 \times 10^{-9}m$

$$\therefore Energy\ of\ each\ photons, \Delta E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{780 \times 10^{-9}} = 2.55 \times 10^{-19}J$$

$$Now, we\ have\ the\ energy\ of\ each\ pulse\ E = Power\ \times duration\ of\ pulse$$

$$E = P \times t = 20 \times 10^{-3} \times 10 \times 10^{-9} = 2 \times 10^{-10}J$$

If N is the number of photons (each of energy ΔE) in the pulse, then $N \times \Delta E = E$

$$\therefore N = \frac{E}{\Delta E} = \frac{2 \times 10^{-10}}{2.55 \times 10^{-19}} = 7.86 \times 10^{8}$$

$$\therefore \boldsymbol{Number\ of\ photons\ in\ each\ pulse\ is}\ 7.86 \times 10^{8}.$$

2. The average output of laser source emitting a laser beam of wavelength 632.8nm is 5mW. Find the number of photons emitted per second by the laser source. **(July 2019 | Aug 2021 | Feb 2022–18S)**

Data : Wavelength of laser, λ = 632.8nm = $632.8 \times 10^{-9}m$

Power of each pulse $P = 5mW = 5 \times 10^{-3}W$

To find : No. of photons in each pulse, N=?

Solution: we have $N = \frac{E}{\Delta E}$ $(\therefore E = P \times t,\ \Delta E = \frac{hc}{\lambda})$

$$N = \frac{P \times t}{\frac{hc}{\lambda}}\ or\quad N = \frac{P \times t \times \lambda}{hc} = \frac{5 \times 10^{-3} \times 632.8 \times 10^{-9}}{6.63 \times 10^{-34} \times 3 \times 10^{8}} = 1.59 \times 10^{16}$$

$$\therefore \boldsymbol{Number\ of\ photons\ in\ each\ pulse\ is\ 1.59 \times 10^{16}}$$

3. The ratio of population of two energy levels is $1.059x10^{-30}$. Find the wavelength of light emitted by spontaneous emission at 330K. **(Jan 2020, Feb 2021 | July 2022-18S)**

Data: *The ratio of population,* $(N_2/N_1) = 1.059x10^{-30}$

Ambient temperature, $T = 330K$

To find : *Wavelength of light emitted,,* λ = ?

Solution: we have Boltzmann factor, $\frac{N_2}{N_1} = e^{\frac{-\Delta E}{kT}}$

By Taking natural log on both sides, we have

$$In\left(\frac{N_2}{N_1}\right) = \frac{-\Delta E}{kT} = \frac{-hc}{\lambda kT} = -\left(\frac{hc}{k}\right)\left(\frac{1}{\lambda T}\right)$$

$$since\ \left(\frac{hc}{k}\right) = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.38 \times 10^{-23}} = 0.014413$$

$$\lambda = -\left(\frac{hc}{k}\right)\left(\frac{1}{In\left(\frac{N_2}{N_1}\right)T}\right) = \frac{0.014413}{In(1.059x10^{-30}) \times 330} = 632 \times 10^{-9}m = 632nm$$

$$\therefore \boldsymbol{The\ wavelength\ of\ light\ emitted\ by\ spontaneous\ emission\ is\ 632nm.}$$

4. A pulse from laser with power 1mW lasts for 10nS, if the number of photons emitted per pulse is 3.491x10[7]. Calculate the wavelength of the laser. **(Mar 2022–18S)**

   Data: *Power per pulse* $P = 1mW = 1 \times 10^{-3}W$

   No. of photons in each pulse, N= $3.491x10^7$

   Duration of Each Pulse, $t = 10ns = 10 \times 10^{-9}sec$

   To find: wavelength of laser, λ =?

   Solution: $N = \frac{E}{\Delta E}$ $\quad (\therefore E = P \times t,\ \Delta E = \frac{hc}{\lambda})$

$$N = \frac{P \times t}{\frac{hc}{\lambda}} \quad or \quad N = \frac{P \times t \times \lambda}{hc}$$

   Rearranging this, we get $\lambda = \frac{N \times h \times c}{P \times t} = \frac{3.491x10^7 \times 6.63 \times 10^{-34} \times 3 \times 10^8}{1 \times 10^{-3} \times 10 \times 10^{-9}} = 6943 \times 10^{-10}m = 6943Å$

$$\therefore \boldsymbol{Wavelength\ of\ laser, \lambda = 6943}\text{Å}$$

5. How many photons of yellow light of wavelength 5500x10[-10]m constitutes 1.5J of energy.

   Data: $Wavelength\ of\ yellow\ light, \lambda = 5500 \times 10^{-10}m$ **(Aug 2022–21S)**

   Energy, E = 1.5J

   To find: No of photons n =?

   Solution. $E = \frac{N \times hc}{\lambda}$ *or by rearranging,* $N = \frac{E \times \lambda}{hc} = \frac{1.5 \times 5500 \times 10^{-10}}{6.63 \times 10^{-34} \times 3 \times 10^8} = 4.1478 \times 10^{18}$.

$$\boldsymbol{No. of\ photons\ emitted\ N\ is\ 4.1478 \times 10^{18}.}$$

6. A He-Ne laser is emitting a beam with an average power of 4.5mW. Find the number of photons emitted per second by the laser. The wavelength of the light is 6328Å.
   (Refer problem no.2 same type) **(Answer $\boldsymbol{N = 1.43 \times 10^{16}}$)**
7. A Ruby laser a pulse of 20ns duration with average power per pulse being 100KW. If the number of photons in each pulse is 6.981×10^{15}. Calculate the wavelength of photons.
   (Refer problem No.4 same type) **(Answer $\boldsymbol{\lambda = 6943 \times 10^{-10} m}$)**
8. Find the ratio of population of two energy levels in a laser if the transition between them produced a wavelength of 694.3nm. Assume the ambient temperature is 27°C.

   Data: wavelength of light emitted,, λ = 694.3nm *or* $\lambda = 694.3 \times 10^{-9}m$

   Ambient temperature, T = 27°C *or (27+273) = 300K*

   To find: The ratio of population, (N₂/N₁) =?

   Solution: we have Boltzmann factor, $\frac{N_2}{N_1} = e^{\frac{-\Delta E}{kT}}$ ***(note: use*** **[shift + In] for *e* in calculator)**

$$\left(\frac{N_2}{N_1}\right) = e^{\frac{-hc}{\lambda kT}} = e^{\left(\frac{-6.63 \times 10^{-34} \times 3 \times 10^8}{694.3 \times 10^{-9} \times 1.38 \times 10^{-23} \times 300}\right)} = 8.87 \times 10^{-31}$$

$$\therefore \boldsymbol{The\ ratio\ of\ population, \left(\frac{N2}{N1}\right) = 8.87 \times 10^{-31}}$$

9. A laser beam at thermal equilibrium temperature 300K has two energy levels with a wavelength separation of 1μm. find the ratio of population densities of the upper and lower levels. **(Jan 2018-17S)**

(Refer problem no.8 same type) $\left(\textbf{Answer } \left(\frac{N2}{N1}\right) = 1.365 \times 10^{-21}\right)$

10. A semiconductor has a peak emission radiation of wavelength 0f 1.24μm. what is the band gap energy value in eV?

Data: wavelength of light emitted,, $\lambda = 1.24\mu m$ *or* $\lambda = 1.24 \times 10^{-6} m$

To find : *Band gap value* $E_g = ?$

Solution: *Band gap value* $E_g = E_2 - E_1 = h\gamma = \frac{hc}{\lambda}$

$$E_g = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{1.24 \times 10^{-6}}$$

$$E_g = 1.6 \times 10^{-19}\, J = 1.eV$$

$$\therefore \textbf{Band gap value } E_g \textbf{ is } 1.eV$$

FIBER OPTICS

11. The refractive indices of core and cladding are 1.50 and 1.48 respectively in an optical fiber. Find the numerical aperture and angle of acceptance.

(Jan 2019-18S)

Data: *Refractive index of core* , $n_1 = 1.50$

Refractive index of cladding , $n_2 = 1.48$

To find: Numerical aperture, N.A=? *and* *Angle of acceptance, θ =?*

Solution: *we have the relation for N.A* $= \sqrt{(n_1^2 - n_2^2)} = \sqrt{1.50^2 - 1.48^2} = 0.244$

Angle of acceptance , $\theta = sin^{-1}\sqrt{(n_1^2 - n_2^2)} = sin^{-1}(0.244) = 14.1°$

$\therefore$ ***The values of numerical aperture and angle of Accceptance angle are 0.244 and 14.1° respectively.***

12. An optical fiber has core of refractive indices and cladding are 1.50 and 1.45 respectively in an opticalfiber. Find the numerical aperture and angle of acceptance.
(Sep 2020-18S) **(Refer problem no.11 same type)**

13. Calculate the refractive indices of core and cladding of a given optical fiber with numerical aperture of 0.22 and fractional index change variation 0.012.

Data : *Numerical Aperture , NA=0.22* **(Aug 2022–21S)**

Fractional index change, $\Delta = 0.012$

To find: *Refractive index of core* , n_1 =?

Refractive index of claddding , n_2 =?

Solution: *we have the relation for N.A* $= n_1\sqrt{2\Delta}$

$$or\ n_1 = \frac{NA}{\sqrt{2\Delta}} = \frac{0.22}{\sqrt{2 \times 0.012}} = 1.42$$

$$we\ have\ the\ relation\ for\ N.A = \sqrt{(n_1^2 - n_2^2)}$$

$$or\ (NA)^2 = n_1^2 - n_2^2$$

$$Or\ n_2^2 = n_1^2 - (NA)^2$$

$$n_2^2 = 1.42^2 - (0.22)^2$$

$$n_2^2 = 1.968 \quad or\ n_2 = 1.40$$

$$\therefore \boldsymbol{Refractive\ index\ of\ core\ , n_1 = 1.42\ and\ Refractive\ index\ of\ core\ , n_2 = 1.40}$$

14. The acceptance angle of an optical fiber is 30° when kept in an air find the angle of acceptance when it is in a medium of refractive index 1.33. **(Jan 2018-17S)**

Data: $Refractive\ index\ of\ core\ , n_0' = 1.33$

$Angle\ of\ acceptance\ , \theta = 30°$

To find: *Angle of acceptance while the fiber is in the refracting medium,* $\theta_0' = 1.33$

Solution: *we have the equation,* $sin\theta_0 = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0'}$ ....*(1)*

When the surrounding medium is air, then $n_0 = 1\ and\ \theta_0 = 30°$

$$sin30° = \sqrt{(n_1^2 - n_2^2)}$$

$$0.5 = \sqrt{(n_1^2 - n_2^2)} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

When the surrounding medium is of the refractive index 1.33, let θ_0' be the acceptance angle.

Now eqn(1) becomes, $\sin\ \theta_0' = \frac{\sqrt{(n_1^2 - n_2^2)}}{n_0'} = \frac{\sqrt{(n_1^2 - n_2^2)}}{1.33}$

$$1.33\ \sin\ \theta_0' = \sqrt{(n_1^2 - n_2^2)} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$\therefore from\ equation (2) and\ (3),$ $\quad 1.33\ \sin\ \theta_0' = 0.5$

$$\theta_0' = sin^{-1}\left(\frac{0.5}{1.33}\right) = 22°$$

$$\therefore \boldsymbol{The\ Acceptance\ angle\ when\ the\ fiber\ is\ in\ the\ medium\ of\ refractive\ index\ 1.33\ is\ 22°}$$

15. Calculate the V-number for a fiber of core of diameter 40µm and with refractive indices of 1.55 and 1.50 respectively for core and cladding. When the wavelength of the propagating wave is 1400nm. Also calculate the number of modes that the fiber can support for propagation. Assume that the fiber is in air. **(July 2019– 18S)**

Data: $Refractive\ index\ of\ core\ , n_1 = 1.55$

$Refractive\ index\ of\ cladding\ , n_2 = 1.50$

$Diamter\ of\ core\ , d = 40\mu m = 40 \times 10^{-6} m$

$Wavelength\ of\ the\ propagating\ light, \lambda = 1400nm = 1400 \times 10^{-9} m$

To find: *Numerical aperture, N.A=? and V-number , V=?*

Solution: $we\ have\ the\ relation\ for\ N.A\ = \sqrt{(n_1^2 - n_2^2)} = \sqrt{1.55^2 - 1.50^2} = 0.3905$

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

$$V = \frac{\pi \times 40 \times 10^{-6}}{1400 \times 10^{-9}} \times 0.3905 = 35$$

$$\therefore \boldsymbol{The\ number\ of\ modes\ of\ the\ fiber\ support, N = \frac{V^2}{2} = \frac{35^2}{2} = 612}$$

16. Estimate the attenuation in an optical fiber of length light 500m when a light signal of power 100mW emerges out of fiber with a power 90mW.

(Jan 2020,Sep 2020, Aug 2021,Mar 2022–18S)

Data: $Length\ of\ the\ optical\ fiber = 500m = o.5km$

$Input\ power\ of\ the\ signal\ , P_{in} = 100mW = 100 \times 10^{-3}W.$

$Output\ power\ of\ the\ signal\ , P_{out} = 90mW = 90 \times 10^{-3}W.$

To find: $Fiber\ attenuation, \alpha$=?

Solution: $The\ fiber\ attenuation\ \alpha\ is\ given\ by, \alpha = -\frac{10}{L}\ Log_{10}\left(\frac{P_{out}}{P_{in}}\right)$ *dB/km*

$$\alpha = -\frac{10}{L}\ Log_{10}\left(\frac{90\times10^{-3}}{100\times10^{-3}}\right) = 0.915\ dB/km$$

$$\therefore \boldsymbol{Fiber\ Attenuation = \ 0.915\ dB/km}$$

17. Calculate the number of modes that can propagate inside an optical fiber with the given data below. Refractive of index of core is 1.53 and cladding is 1.50. Radius of core is 50μm. Wavelength of the light propagating through the optical fiber is 1μm. **(Feb 2021-18S)**

Data: $Refractive\ index\ of\ core\ , n_1 = 1.53$

$Refractive\ index\ of\ cladding\ , n_2 = 1.50$

$Diamter\ of\ core, d = 2\ times\ of\ radius, i.e., = 2 \times 50\mu m = 100\mu m = 100 \times 10^{-6}m$

$Wavelength\ of\ the\ propagating\ light, = 1\mu m = 1 \times 10^{-6}m$

To find: Numerical aperture, N.A=? And V-number, V=?

Solution: $we\ have\ the\ relation\ for\ N.A\ = \sqrt{(n_1^2 - n_2^2)} = \sqrt{1.53^2 - 1.50^2} = 0.3014$

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

$$V = \frac{\pi \times 100 \times 10^{-6}}{1 \times 10^{-6}} \times 0.3014 = 94.63$$

$$\therefore \boldsymbol{The\ number\ of\ modes\ of\ the\ fiber\ support, N = \frac{V^2}{2}}$$

$$\boldsymbol{N = \frac{94.63^2}{2} = 4478.3}$$

$$\therefore \boldsymbol{The\ number\ of\ modes\ of\ the\ fiber\ support, N = 4478.3}$$

18. The attenuation of light in an optical fiber is 3.6 dB/km, what fraction of its initial intensity remains after: i) 1 km ii) 3km? **(Dec 2014,Aug 2022-18S)**

Data: $Fiber\ attenuation, \alpha$=3.6 dB/km

To find: (i) $After\ 1\ km\ distance,\ \left(\frac{P_{out}}{P_{in}}\right)$ =?

(ii) $After\ 3\ km\ distance,\ \left(\frac{P_{out}}{P_{in}}\right)$ =?

Solution: $we\ have, , \alpha = -\frac{10}{L}\ Log_{10}\left(\frac{P_{out}}{P_{in}}\right)$

Where, L the length of the fiber is expressed in km.

$$\therefore\ Log_{10}\left(\frac{P_{out}}{P_{in}}\right) = -\left(\frac{\alpha L}{10}\right)$$

$$or\left(\frac{P_{out}}{P_{in}}\right) = \ 10^{-\left(\frac{\alpha L}{10}\right)}$$

$\boldsymbol{(i)\ At\ 1km\ distance\ , L = 1}$ $\left(\frac{P_{out}}{P_{in}}\right) = \ 10^{-\left(\frac{3.6}{10}\right)} = 0.436$

$(\boldsymbol{i})$ ***At 3km distance , L = 3*** $\left(\frac{P_{out}}{P_{in}}\right) = 10^{-\left(\frac{3.6\times3}{10}\right)} = 0.0832$

$$\therefore (\boldsymbol{i})\boldsymbol{After\ 1\ km\ distance,}\ \left(\frac{P_{out}}{P_{in}}\right) = \mathbf{0.436}$$

$$\boldsymbol{and}\ (\boldsymbol{ii})\boldsymbol{After\ 3\ km\ distance,}\ \left(\frac{\boldsymbol{P_{out}}}{\boldsymbol{P_{in}}}\right) = \mathbf{0.0832}$$

19. Calculate the NA, Relative RI, V number and the number of modes in an optical fiberof core diameter of 50µm and the core and cladding R.I are 1.41 and 1.40 respectively. Given wavelength of source 820nm. **(Mar 2022–18S)**

Data: $Refractive\ index\ of\ core\ , n_1 = 1.41$

$Refractive\ index\ of\ cladding\ , n_2 = 1.40$

$Diamter\ of\ core\ , d = 50\mu m = 50 \times 10^{-6} m$

$Wavelength\ of\ the\ propagating\ light, \lambda = 820nm = 820 \times 10^{-9} m$

To find: Numerical aperture, N.A=? and V-number , V=?

Solution: $we\ have\ the\ relation\ for\ N.A = \sqrt{(n_1^2 - n_2^2)} = \sqrt{1.41^2 - 1.40^2} = \mathbf{0.1676}$

Relative refractive index, $\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.41 - 1.40}{1.41} = 0.00709$

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

$$V = \frac{\pi \times 50 \times 10^{-6}}{820 \times 10^{-9}} \times 0.1676 = 32$$

$$\therefore \boldsymbol{The\ number\ of\ modes\ of\ the\ fiber\ support,\ N} = \frac{\boldsymbol{V^2}}{\mathbf{2}} = \frac{\mathbf{32^2}}{\mathbf{2}} = \mathbf{512}$$

20. The attenuation of light in an optical fiber is estimated at 2.2db/Km. What fractional intensity remains after 2Km and 6Km?

Data: $Fiber\ attenuation, \alpha$ =2.2 dB/km

To find: *(i)* $After\ 2\ km\ distance,\ \left(\frac{P_{out}}{P_{in}}\right)$ =?

(ii) $After\ 6\ km\ distance,\ \left(\frac{P_{out}}{P_{in}}\right)$ =?

Solution: *we have, ,* $\alpha = -\frac{10}{L} Log_{10}\left(\frac{P_{out}}{P_{in}}\right)$

Where, L the length of the fiber is expressed in km.

$$\therefore\ Log_{10}\left(\frac{P_{out}}{P_{in}}\right) = -\left(\frac{\alpha L}{10}\right)$$

$$or \left(\frac{P_{out}}{P_{in}}\right) = 10^{-\left(\frac{\alpha L}{10}\right)}$$

$(\boldsymbol{i})$ ***At 1km distance , L = 2*** $\left(\frac{P_{out}}{P_{in}}\right) = 10^{-\left(\frac{2.2\times2}{10}\right)} = 0.363$

$(\boldsymbol{i})$ ***At 3km distance , L = 6*** $\left(\frac{P_{out}}{P_{in}}\right) = 10^{-\left(\frac{2.2\times6}{10}\right)} = 0.0478$

$$\therefore (\boldsymbol{i})\boldsymbol{After\ 2\ km\ distance,}\ \left(\frac{P_{out}}{P_{in}}\right) = 0.363$$

$$\boldsymbol{and}\ (\boldsymbol{ii})\boldsymbol{After\ 6\ km\ distance,}\ \left(\frac{\boldsymbol{P_{out}}}{\boldsymbol{P_{in}}}\right) = 0.0478$$