UNIT 5

OPTICAL FIBER TRANSMISSION MEDIA

Syllabus

OPTICAL FIBER TRANSMISSION MEDIA: Optical Fiber types, Light Propagation, Optical fiber Configurations, Optical fiber classifications, Losses in Optical Fiber cables, Light Sources, Optical Sources, Light Detectors, LASERS, WDM Concepts, Optical Fiber System link budget.

LEARNING OBJECTIVES

- **Define optical communications and Present an Overview of the optical fibers and optical fiber communications.**
- **Describe optical fiber construction.**
- **Explain the physics of light and the following terms: velocity of propagation, refraction, refractive index, critical angle, acceptance angle, acceptance cone, and numerical aperture.**
- **What is a mode? What are the different modes of propagation? and What is index profile?**
- **Describe the three types of optical fiber configurations: single-mode step index, multimode step index, and multimode graded index.**
- **Describe the various losses incurred in optical fiber cables**
- **Explain the light sources: light-emitting diodes and injection diodes**
- **Explain the light detectors: PIN diodes and avalanche photodiodes**
- **Explain the operation of a laser**
- **Explain how to calculate a link budget for an optical fiber system.**

INTRODUCTION

Optical fiber cables are the latest and perhaps the most encouraging kind of guided transmission medium for almost any type of digital and data communications applications. Optical fibers guide electromagnetic waves without using electrical current flow. Electromagnetic waves in the form of light propagate through the optical fibers almost similar to the radio signals propagating over the Earth's atmosphere. In essence, an optical communications system uses light as the carrier of information.

Propagating light waves over Earth's atmosphere is complex and usually impractical. So, optical fiber communications systems use glass or plastic fiber cables to "encompass" the light waves and guide them in a method similar to the way electromagnetic waves are guided through a metallic transmission medium.

The information-carrying capacity of any electronic communications system is directly proportional to bandwidth. Optical fiber cables have an infinite bandwidth. Hence, they have the ability to transfer much greater information than their metallic counterparts and even the most sophisticated wireless communications systems.

PART-A SHORT QUESTIONS WITH SOLUTIONS

Q1. What is Snell's law?

(Model Paper, Q1(e) | Nov./Dec.-17, (R13), Q1(a))

Ans:

The Snell's law states the behaviour of light ray, when it strikes the interface of two media having different refractive indexes.

According to Snell's law,

$$\boxed{n_1 \sin\phi_1 = n_2 \sin\phi_2} \quad \dots (1)$$

Where, n_1, n_2 are refractive indexes of two media's and $n_1 > n_2$. ϕ_1 and ϕ_2 are the angle of incidence and angle of refraction respectively.

From equation (1),

$$\frac{n_1}{n_2} = \frac{\sin\phi_2}{\sin\phi_1}$$

From the above expression, it is clear that the ratio of refractive index of two media is inversely proportional to the sine of refractive and incident angles.

Q2. Define the terms,

1. **Acceptance Angle**
2. **Numerical aperture**

Ans:

1. **Acceptance Angle**

The maximum angle at which the light ray may incident on fiber to propagate down the fiber is known as "Acceptance angle". The maximum acceptance angle can be derived from the numerical aperture equation as,

Numerical aperture, NA = $\sin\theta_a = n_1\sqrt{2\Delta}$

$$\theta_a = \sin^{-1}\left(n_1\sqrt{2\Delta}\right)$$

$$\theta_a = \sin^{-1}(NA)$$

2. **Numerical Aperture**

The numerical aperture is a figure of merit, which is used to explain the angles associated with light propagation in fiber optics. The sine of half-angle of acceptance angle is referred as 'numerical aperture'. Usually for optical lens, numerical aperture ranges from 0.3 to 1.3.

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

Where,

n_1 – Refractive index of core

n_2 – Refractive index of cladding.

Q3. Classify optical fibers based on the refractive index profile.

Ans:

The classification of optical fibers based on the refractive index of the core is,

1. **Step-index Fiber**

In step-index optical fiber, the refractive index of the core is uniform and undergo a step change at the boundary of cladding.

2. **Graded-index Fiber**

In graded-index optical fiber, the refractive index of the core varies with the radial distance from the center of fiber.

Q4. List the advantages of SMFs over MMFs.

Ans:

The advantages of single mode fibers (SMFs) over multimode fibers (MMFs) are,

1. Low fiber attenuation
2. Low joint and coupling losses
3. Simple parameter dependence
4. Low dispersion than in MMF
5. High bandwidth
6. SMF can integrate easily with other devices to function in integrated optics.

Q5. What is attenuation of a signal?

Ans:

Attenuation can be defined as the decrease in the power of light signals during their propagation along the optical fiber. It is also known as signal loss or fiber loss and determines the maximum distance between transmitter and receiver of a communication system.

Mathematically, the attenuation loss can be expressed in decibels as,

$$\text{Attenuation } (\alpha) = 10 \log \frac{P_i}{P_o} \text{ dB}$$

Where,

P_i – Input (Transmitted) power

P_o – Output (Received) power.

Alternatively, attenuation per unit length of the fiber is expressed as,

$$\alpha_{dB} L = 10 \log \frac{P_i}{P_o}$$

Q6. Define dispersion and classify its different types.

Ans:

Dispersion

Dispersion is defined as an optical phenomenon in which light pulses get broadened (or) spreaded as they travel along the fiber length.

Intramodal dispersion is further divided into material dispersion and waveguide dispersion.

Figure illustrates the classification of dispersion in optical fibers.

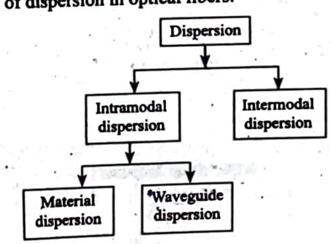


Figure: Classification of Dispersion

Q7. List the difference between intramodal and intermodal dispersion.

Ans:

The differences between intermodal and intramodal dispersions are mentioned in table below:

	Intermodal Dispersion		Intramodal Dispersion
1.	Intermodal dispersion means the dispersion that occurs in different fibers.	1.	Intramodal dispersion means the dispersion that occurs in same fiber.
2.	It occurs primarily due to the different times consumed by different propagating modes of optical fiber.	2.	It occurs due to the propagation delay differences between various spectral components of transmitted signal.
3.	This type of dispersion occurs only in multi-mode fibers.	3.	This type of dispersion occurs both in single-mode and multi-mode fibers.
4.	It causes more broadening of light pulses in optical fibers.	4.	It causes less spreading of light when compared to intermodal dispersion.
5.	It is also known as modal delay.	5.	It is also known as chromatic dispersion.

Table

Q8. List and define the different types of light source materials.

Ans:

The different types of light source materials used in optical fibers are

1. LED
2. LASER

1. LED

Light emitting diode is a light sensitive diode, which emits light when it is forward biased.

2. LASER

LASER is an acronym for light amplification by simulated emission of radiation. Its light beam has directionality coherence and monochromaticity.

Q9. What is meant by hetero junction? List out the advantages of hetero junction.

Ans:

Heterojunction

It is an interface formed by joining two semiconductor materials having dissimilar band-gap energies.

Advantages

1. Excellent injection efficiency
2. Better ohmic contact
3. Carrier and optical constraint.

Q10. Draw the block diagram of WDM system.

Ans:

The block diagram of WDM system is shown in below figure:

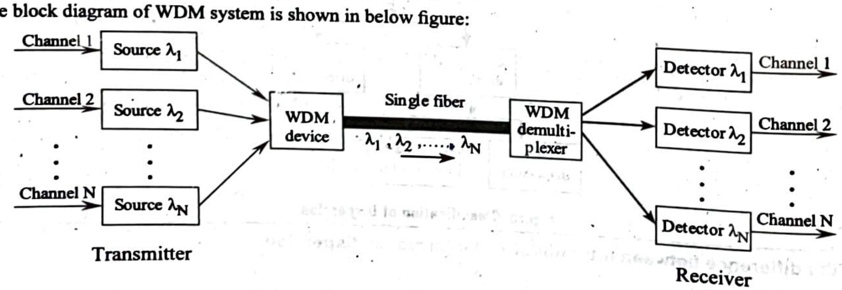


Figure.

Q11. Illustrate interchannel crosstalk that occurs in WDM networks.

Ans:

In WDM networks if an interference is caused by a noise i.e., unwanted signal of some wavelength which is different from that of the transmitted signal, then the interference is known as "interchannel cross talk". This affects the capacity of WDM systems. Since the capacity depends on minimal channel spacing which is limited by this cross talk.

Q12. What are the advantages of WDM.

Ans:

The advantages of WDM are,

1. It has greater transmission capacity.
2. Duplex transmission.
3. Simultaneous transmission of various signals.
4. Easy system expansion.
5. Lower cost.
6. Faster access to new channels.

Q13. Define Jitter.

Ans:

Timing jitter or edge jitter or phase distortion is defined as the distortion due to noise in the receiver and pulse distortion in the optical fiber.

$$\text{Timing jitter (\%)} = \frac{\Delta T}{T_b} \times 100\%$$

Where,

ΔT – Distortion at the threshold level

T_b – Bit interval.

Q14. How do you ensure that the required system performance is met or not?

Ans:

The performance requirements of a system are met or not is ensured on carrying out link power budget and rise time budget analyses.

1. Link power budget analysis determines the power margin required for a specified bit error rate, losses occurred in a system and the power penalties required to compensate for the losses.
2. Rise time budget analysis is carried out to ensure that the dispersion limit is confined with in the bounded value.

Q15. What are the system considerations in design of a fiber optic link. Model Paper, Q1(l)

Ans:

The system considerations in the design of fiber optic link are,

1. The transmitter and the receiver sources.
2. Operating range based on the coverage distance.
3. Performance characteristics.
4. Fiber configuration of optic cable.
5. Cost and reliability of system etc.
6. Modifications in fiber parameters if required.

PART-B ESSAY QUESTIONS WITH SOLUTIONS

5.1 OPTICAL FIBER TYPES, LIGHT PROPAGATION, OPTICAL FIBER CONFIGURATIONS, OPTICAL FIBER CLASSIFICATION, LOSSES IN OPTICAL FIBER CABLES

Q16. Explain optical fiber communication system with neat block diagram.

Ans:

The simplified block diagram of an optical fiber communication system, that encompasses transmitter, receiver and the optical fiber cable is as illustrated in figure (a).

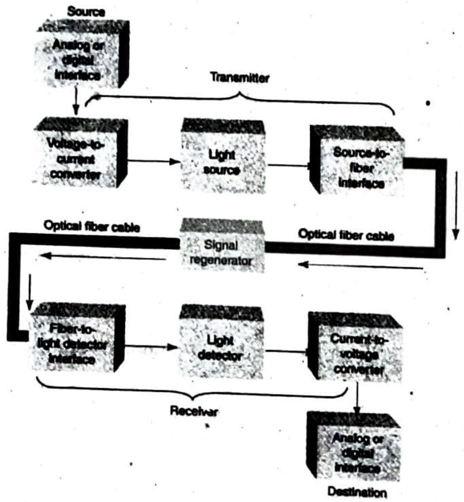


Figure (a)

Transmitter

As illustrated in figure (a), the transmitter encompasses three blocks.

1. Voltage to current converter
2. Light source
3. Source-to-fiber interface.

Initially the information in the form of voltage is converted into current using the voltage to current converter circuit. The current thus produced is applied to the light source. The light source converts the current into light and the intensity of light is directly proportional to the magnitude of the input signal. We can use an LED (Light Emitting Diode) or ILD (Injection Laser Diode) as the light source. Next, the light emitted by the light source is coupled into the optical fiber cable using a source-to-optical fiber coupler. An example of source-to-fiber coupler is an optical lens.

Optical Fiber Cable: As illustrated in figure (b), an optical fiber cable contains a glass or plastic fiber at its core that is surrounded by a cladding and then enclosed's in a protective jacket.

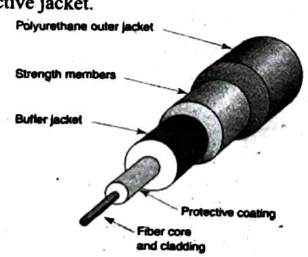


Figure (b)

Depending on the distance of seperation between the transmitter and receiver it is essential to include one or more signal regenerators to the optical fiber cable transmission.

Receiver

The function of receiver is exactly opposite to transmitter. It contains a fiber-to-light detector interface, a photo detector and a current-to-voltage converter.

The light detector is a mechanical-coupler that couples light from the optical fiber to the photo detector. Usually, we use a PIN diode or avalanche photodiode or photo transistor as the photo detector. The photo detector converts the information in the form of light into current. The current is converted into voltage using a current to voltage converter. The output voltage thus produced is proportional to the original source information.

Q17. What are the advantages and disadvantages of optical fiber cable.

Ans:

Advantages

1. Optical fibers have wide bandwidth upto several thousand gigahertz. Due to this they have greater information carrying capacity. An optical fiber can transmit several gigabits per second across thousands of kilometers. Further, it favors to combine and transmit millions of individual voice and data channels through a single optical fiber cable.
2. As glass and plastic fiber do not conduct current, fiber cables are not enclosed by a varying magnetic fields (primary source of cross talk). Therefore, optical fiber cables are immune to cross talk.
3. Optical fiber cables have good resistance to environmental calamities. They are immune to extreme weather conditions compared to metallic cables. We can use them in extreme temperature ranges and the influence of corrosive liquids and gases is very less on them.
4. There is no fear of explosion or fires with optical fibers so we can use them in volatile liquids and gases without any concern.
5. The fiber is made up of either glass or plastic. Thus, it is a non conductor of electric current. So, they are immune to static noise caused by electromagnetic interference (EMI) and do not radiate electromagnetic energy. Therefore, they are much safer than metallic cables.
6. Optical fibers are small in size, light-in-weight and are closely and firmly packed together. As a result, they require very less storage space and are cheaper to transport, easier to work and easier to install and maintain.
7. When compared with metallic cables, optical fibers provide significantly less signal loss. Today, optical fibers are produced with signal loss of a few-tenths-of-a decible per kilometer. Because of this the optical regenerators and amplifiers can be spaced much farther apart.

Disadvantages

1. Practically, optical fibers are useful only when they are connected to conventional electronic equipment. But to connect equipment to fiber we need costly interfaces.
2. The tensile strength of optical fibers is much less compared to coaxial cable. We enhance its strength by coating it with standard kevlar (protective covering) and using PVC as a protective jacket.
3. Sometimes, in few applications we need to supply electrical power to distant regenerating equipment. In such case, metallic cables are incorporated together with optical fibers in the cable assembly.
4. Optical fiber are delicate and more sensitive to twist or bend. We encounter losses due to twist or bend in optical fiber. The light passing through the fiber either by reflection or refraction encounter's irregularity in its path and results in loss of signal power.

Q18. What are the different types of optical fiber's. Explain there construction, advantages and disadvantages.

Ans: Model Paper, Q10(a)

At present we have three types of optical fiber's that are in use today.

Type 1: Plastic core and cladding

Type 2: Glass core with plastic cladding called PCS fiber

Type 3: Glass core and glass cladding called SCS fiber.

Construction

The primary single optical fiber cable contains the following,

1. Core
2. Cladding
3. Coating
4. Buffer jacket
5. Strength member
6. Outer jacket

❖ The different layers surrounding an optical fiber cable are as illustrated in figure (a).

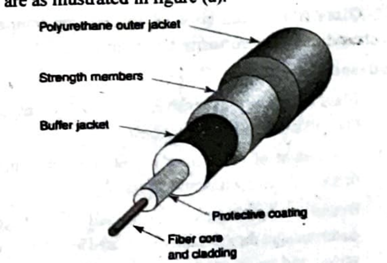


Figure (a)

- The core and cladding are built using either plastic or glass or by combining both the plastic and glass.
- The core and cladding are regarded as the effective part of the optical fiber because they cause the light to propagate through them.
- Next the exterior of cladding is coated with acrylate. The coating acts as a plastic layer and reinforce (strengthens) and protects the fiber core.
- The protective coating is surrounded by a buffer jacket that provides added protection to the core against crushing forces, excessive tension and shock during installation.
- The buffer jacket is then enclosed in a strength member that enhances the tensile strength of the entire optical fiber cable group.
- Finally, the entire cable is enclosed in an polyurethane jacket. This is the outer layer of any cable.

Plastic Fiber

Advantages

- Plastic fibers are cost-effective, more flexible and more stronger than glass fibers.
- Also, the weight of plastic fibers is 60% less than glass fibers and can withstand stress.
- These makes the installation of plastic fiber cable easy.

Disadvantages

- We can't use plastic fibers in extreme temperature conditions and corrosive environments.
- Plastic fibers offer higher attenuation and low light transmissivity compared to glass fiber's.

Because of the above mentioned advantages and disadvantages the plastic fiber usage is restricted to small distances (areas) like within a building.

Glass Fiber

Advantages

- Glass fiber's offer very low attenuation and high light transmissivity compared to plastic fiber's.
- Glass fiber's can be used in extreme temperature conditions and corrosive environment.

Disadvantages

- Glass fiber's are expensive, less flexible and delicate than plastic fibers.
- The weight of glass fiber's is 60% more than plastic fibers and can't withstand stress.
- Because of the above mentioned advantages and disadvantages the glass fiber's are used in communication, sensor and measurement systems. Also, they are good choice for long distance transmission.

Q19. Explain refraction and refractive index of light.

Ans:

Refraction is the bending of light wave when it moves from one transparent medium to another transparent medium. In fact, the light wave is not bent instead it alters its direction at the interface of the two mediums.

Refraction occurs whenever light enters a medium of different refractive index at an angle to the normal. Normal is an imaginary line drawn at 90° to the surface of two mediums.

Figure (a) illustrates the refraction of light, when it moves from a less denser medium to a more denser medium.

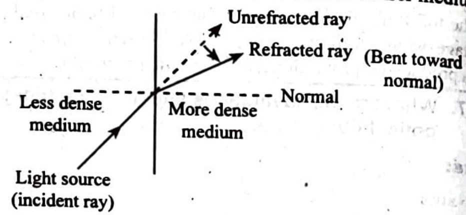


Figure (a)

The change in direction of light wave is due to the change in speed of light in the second medium. The amount of refraction depends on two things.

1. **Change in Speed**

(a) If the medium makes the light to speed up, it will refract more towards the normal.

(b) If the medium makes light to slowdown, it will refract more away from the normal.

2. **Angle of Incidence**

(a) If light enters the medium at a greater angle then refraction is more

(b) If light enters the medium straight on without making any angle, the light slows down but it won't changes its direction.

Refractive Index: Refractive index forecast the extent of refraction at the interface of two mediums. It is defined as the ratio of the velocity of propagation of light in free space to the velocity of propagation of light in a given medium. It is denoted as 'n' and mathematically expressed as,

$$n = \frac{c}{v} \quad \text{... (1)}$$

Where,

n is refractive index (unitless)

c is speed of light

v is speed of light in a given medium.

Q20. Explain in brief about physics of light.

Ans:

Light has dual nature, that is, sometimes it behaves as wave and sometimes it behaves as particle.

The wave nature of light was explained through diffraction and interference experiments. The wave nature explain is how light bends around an object.

The particle of light is known as photon. The particle nature was evident from photo electric effect. The particle nature explains how light travels in a straight line.

Light is a part of electromagnetic wave spectrum that propagates with a speed of approximately 3×10^8 m/s in free space. But, the speed reduces (compared with free space) when light enters a denser (thick) medium. Further, in the denser medium the speed of different frequencies of light is different. For instance, when white light passes through a prism the violet wavelength is refracted more whereas red wavelength is refracted less.

Light is produced either by incandescence method or by luminescence. Incandescence is emission of light from hot matter while luminescence is the emission of light when excited electrons fall to lower energy levels.

Q21. What is Snell's law? Explain.

Ans:

Snell's law describes the response of light wave when it encounters two mediums of different refractive indexes.

Figure (a) illustrates a refractive index prototype for Snell's law. When light incident (touches) the interface of the two medium's, it makes an angle with the normal called angle of incidence (θ). After entering the second medium the light (wave) refracts (bends) and the angle made by the refracted wave with normal is called angle of refraction (θ_2).

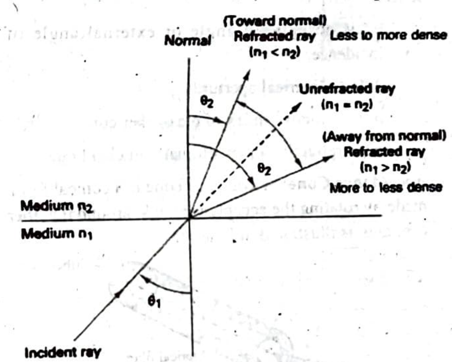


Figure (a)

If n_1 and n_2 are refractive indexes of medium 1 and medium 2 respectively, then Snell's law states that

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \text{... (1)}$$

Where,

θ_1 is angle of incidence

θ_2 is angle of refraction

The angle of refraction θ_2 can be larger than angle of incidence θ_1 or θ_2 can be smaller than θ_1, it depends on the refractive indexes of the two mediums.

If $n_1 < n_2$, then $\theta_1 > \theta_2$

if $n_1 > n_2$, then $\theta_1 < \theta_2$

In other words, if $n_1 < n_2$ then the refracted wave moves towards the normal. If $n_1 > n_2$ then the refracted wave move away from the normal.

Equation (1), can be written as,

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \quad \text{... (2)}$$

From equation (1), it is evident that refractive index and its respective angle are inversely proportional to each other.

Q22. Determine the angle of refraction for an angle of incidence of 30°. When light moves from medium 1 (of glass with refractive index 1.5) to medium 2 (of ethyl alcohol with refractive index 1.36).

Ans:

Given data,

$n_1 = 1.5$

$n_2 = 1.36$

$\theta_1 = 30°$

and $\theta_2 = ?$

'θ_2' is obtained using snell's law, which is given as,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \text{... (1)}$$

$$\Rightarrow \sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} \quad \text{... (2)}$$

Substituting the values of n_1, θ_1 and n_2 in equation (2), we get,

$$\sin\theta_2 = \frac{1.5 \sin 30}{1.36}$$

$$\Rightarrow \sin\theta_2 = \frac{1.5}{1.36} \times \frac{1}{2}$$

$$\Rightarrow \sin\theta_2 = 0.5514$$

$$\theta_2 = \sin^{-1}(0.5514)$$

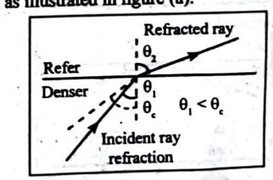
$$\boxed{\therefore \theta_2 = 33.46°}$$

Therefore, the angle of refraction, $\theta_2 = 33.46°$.

Q23. What is critical angle? With neat diagram explain the critical angle phenomenon.

Ans:

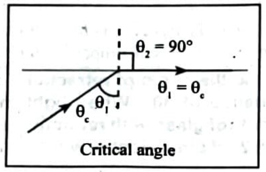
When light travels from a denser medium (n_1) to a rarer medium (n_2) {$n_1 > n_2$} then the refracted wave bends away from the normal as illustrated in figure (a).



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

Figure (a)

As the angle of incidence increases, the refracted wave bends more away from the normal and approaches near the surface (interface) of the two mediums as illustrated in figure (b). When the refracted wave makes an angle of 90° with the normal (figure (b)), at this point the angle of incidence 'θ_1' is called the critical angle 'θ_c'.



For critical angle, $\theta_2 = 90°$
Therefore, $n_1 \sin\theta_1 = n_2 \sin 90° = n_2$
$\Rightarrow \theta_1 = \theta_c = \arcsin(n_2/n_1)$

Figure (b)

Critical angle is obtained from snell's law as follows,

From snell's law we have,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \text{... (1)}$$

Equation (1) can be written as,

$$\sin\theta_1 = \frac{n_2}{n_1}\sin\theta_2 \quad \text{... (2)}$$

When θ_1 becomes critical angle θ_c, then $\theta_2 = 90°$. Using this equation (2) is written as,

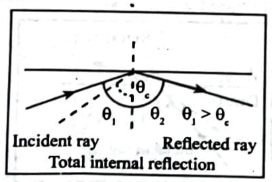
$$\sin\theta_c = \frac{n_2}{n_1}\sin 90 = \frac{n_2}{n_1}(1)$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\boxed{\therefore \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)} \quad \text{... (3)}$$

This is the expression for critical angle. From equation (3), it is evident that every single pair of transmissive mediums [with different refractive indexes (n_1 & n_2)] is associated with a specific critical angle value.

For incident angle values (θ_1) greater then critical angle the light is totally reflected back into the denser medium as illustrated in figure (c). This phenomenon is known as total internal reflection.



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

Figure (c)

Q24. Explain the following,

(a) Acceptance angle

(b) Numerical aperture

(c) Acceptance cone.

Ans:

(a) **Acceptance Angle:** The maximum angle with which the light can strie the fiber to transmit through it by total internal reflection is called "Acceptance Angle". The acceptance angle is denoted as 'θ_a'. The acceptance angle 'θ_a' is expressed as a function of numerical aperture as,

$$NA = (n_1^2 - n_2^2)^{1/2} = \sin\theta_a \quad \text{... (1)}$$

(b) **Numerical Aperture:** Numerical aperture is a dimensionless number that describes the angular region over which the fiber can accept or emit light. A fiber with greater numerical aperture value will allow to couple a greater amount of external light into it. The expression for numerical aperture (NA) of a glass fiber that receives light from an air is given as,

$$NA = \sin\theta_{in} \quad \text{... (1)}$$

and $$NA = \sqrt{n_1^2 - n_2^2} \quad \text{... (2)}$$

$$\therefore \theta_{in} = \sin^{-1}(NA) \quad \text{... (3)}$$

Where,

θ_{in} is acceptance angle or external angle of incidence.

NA is numerical aperture

n_1 is refractive index of glass fiber core

n2 is refractive index of quartz in cladding.

(c) **Acceptance Cone:** Acceptance cone is a conical form made by rotating the acceptance angle around the fiber core axis as illustrated in figure (a).

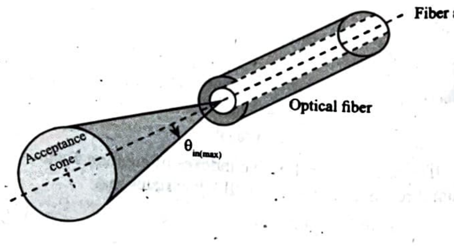


Figure (a)

If light enter the fiber from within the cone then light propagation takes place by total internal reflection in fiber. If light enters the fiber from outside the cone then light propagation takes place by consecutive sets of reflection and refraction. This results in energy loss and light attenuation. Figure (b) illustrates the relationship between acceptance angle and critical angle.

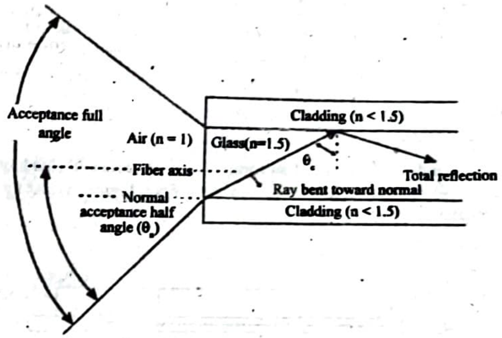


Figure (b)

Q25. What is mode of propagation and index profile of the fiber?

Ans:

Mode of propagation and index profile of the fiber determines how light travels down the fiber. In other words, light travels either by reflection or refraction this is determined by the mode of propagation and index profile of the fiber.

Mode of Propagation: In optical fiber communication language mode means path (road).

An optical fiber is known as single mode fiber, if it has only one path for the light to propagate down the cable. Figure (a) illustrates a single mode optical fiber, it has only one path for the light to propagate and the path passes through the center of the fiber.

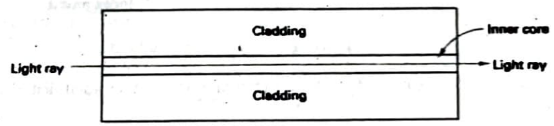


Figure (a)

An optical fiber is known as multimode fiber, if it has more than one path for the light to propagate down the cable figure (b) illustrates a multimode optical fiber, it has many paths for the light to propagate and the light travels in several paths in a zig-zag style.

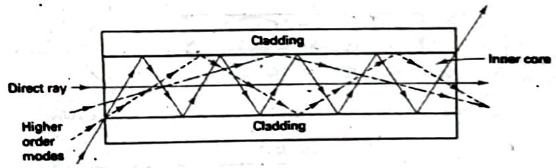


Figure (b)

The number of modes (or paths) supported by a multimode fiber is decided by the wavelength of the light (passing through it), refractive indexes of the core and cladding and the diameter of the core.

Mathematically, the number of modes supported by a multimode fiber is given as,

$$N = \left\{\frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}\right\}^2$$

Where,

N is number of propagating modes

d is diameter of core

λ is wavelength of light

n_1 is refractive index of core

n_2 is refractive index of cladding

Index Profile

Index profile is a graphical illustration of distribution of refractive index across the core and cladding of a fiber. We have two types of index profiles.

1. Step index fiber
2. Graded index fiber

Step Index Fiber

A fiber in which the refractive index is distributed uniformly across its core and cladding. And also, the refractive index of cladding is less than the core then such a fiber is known as step index fiber. Figure (a) and figure (b) illustrates a single mode and multimode step index fiber respectively.

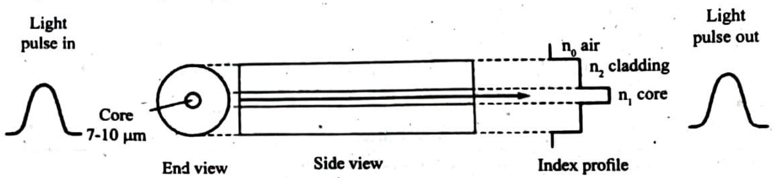


Figure (a)

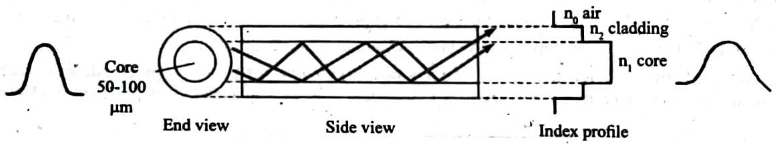


Figure (b)

In the above figures, refractive index is plotted on the horizontal axis and the radial distance from the center of core is plotted on the vertical axis.

Graded Index Fiber

A fiber in which there is no cladding and the refractive index is distributed non-uniformly across the core, such a fiber is known as graded index fiber. Figure (c) illustrates a graded index fiber that has maximum refractive index at its center and decreases slowly when we move towards outer edge.

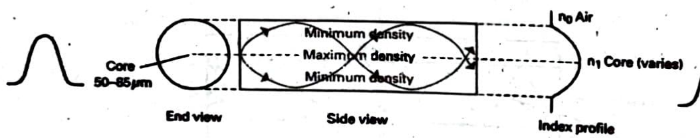


Figure (c)

Q26. Give the classification of optical fibers in practice.

Model Paper, Q10(b)

Ans:

Based on the number of modes and the index profile the optical fibers can be classified into several types.

But, in practice we have only three types of fibers they are

1. Single mode step index optical fiber
2. Multimode step index optical fiber
3. Multimode graded index optical fiber.

1. Single Mode Step Index Optical Fiber

A fiber that has only one mode (or path) for the light to propagate down its length and has an index profile of step index is known as single mode step index optical fiber.

The index profile of step index fiber resembles a step, that is, the refractive index (distribution) makes a step change at the core-cladding interface as illustrated in figure (a).

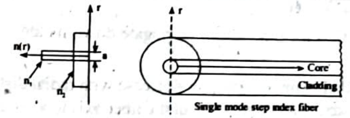


Figure (a)

Mathematically, the index profile of step index fiber is given as,

$$n(r) = \begin{cases} n_1 \text{ for } r < a(\text{core}) \\ n_2 \text{ for } r \geq a(\text{cladding}) \end{cases}$$

Where

n_1 is refractive index of core

n_2 is refractive index of cladding

a is radius of core

r is radius from center of core to outer edge of cladding

In single mode step index, the diameter of the core is made considerably small so that there is only one path for the light to propagate down the fiber length.

In this light travels either straight down the core or by rare reflection. As a result, all the light waves entering the fiber follow the same path down the cable and take same amount of time to travel down the cable.

This mode allows only the lowest order (low frequency) light wave to pass through it. Hence the pulse dispersion effect is minimized. Therefore this fiber is very useful in long distance communication systems.

Nowadays, the telecommunication and data networking industries uses single mode step index fiber's largely for inter connectivity.

2. Multimode Step Index Optical Fiber

A fiber that has many modes (or paths) for the light to propagate down its length and has an index profile of step index is known as multimode step index fiber.

The index profile of step index fiber resembles a step, that is, the refractive index (distribution) makes a step change at the core-cladding interface as illustrated in figure (b).

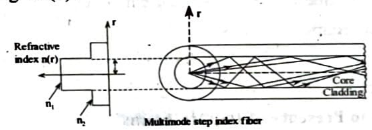


Figure (b)

In multimode step index fiber, the diameter of the core is made larger so that it allows more external light to enter the cable and propagate down the fiber length.

From figure (c), it is evident that the light can follow many paths to propagate down the fiber. Figure (c) illustrates 3 modes,

(a) Lower order mode, in this light propagates along the axis of the core

(b) Middle order mode, in this light propagates by reflecting twice at the core-cladding interface.

(c) Higher order mode in this light propagates by reflecting many times across the core-cladding interface. This is known as total internal reflection phenomenon. This results in pulse broadening and dispersion.

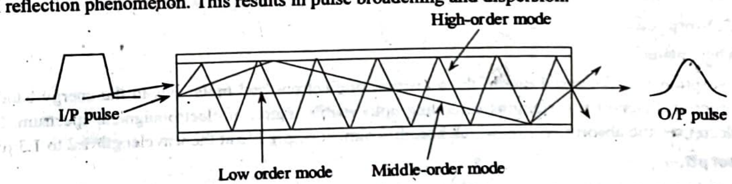


Figure (c) : Configuration of Multimode Step Index Fiber

Because of pulse broadening and dispersion effects, multimode step index fiber's are used rarely in telecommunication industries.

3. **Multimode Graded Index Optical Fiber**

A fiber that has many modes (or palls) for the light to propagate down its length and has an index profile of graded index is known as multimode graded index fiber.

The index profile of graded index fiber is not constant, it decrease with radial distance from the center of core to edge of the cladding. In other words, it varies from a maximum value of n_1 at the fiber axis to a minimum value of n_2 till the edge of cladding.

Figure (d) illustrates the index profile and light propagation in multimode graded index fiber.

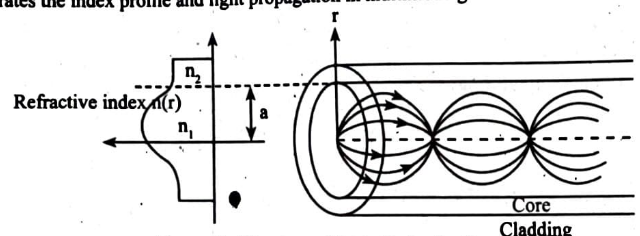


Figure (d) : Structure of Graded Index Profiles

In this light travels down the fiber by means of refractive. As light is propagating across a core that has nonuniform refractive index the light is refracted continuously and constantly as illustrated in figure (d).

Due to the varying refractive index profile multimode graded index fiber's experience less inter modal dispersion compared to multimode step index fiber.

Q27. What is absorption loss? Briefly explain different types of absorption losses occuring in optical fiber.

Ans:

Absorption Loss

Conversion of optical power into heat causes absorption loss. In other words whenever a photon from light beam (having energy equal to energy band gap is absorbed by the material) optical fiber suffers an absorption loss. This absorption loss is primarily caused due to the following three mechanisms.

1. **Absorption Loss due to Atomic Defect**

Absorption by atomic defect in the glass composition. This absorption is caused due to the imperfections in the atomic structure of fiber material. The major imperfections in structure include,

(i) High-density clusters of atom groups

(ii) Missing molecules

(iii) Oxygen defects in glass structure.

2. **Extrinsic Absorption Losses due to Presence of Impure Atoms**

Extrinsic absorption is primarily caused due to the unintentional injection of impurities into the optical fiber. These impurities may combine with the fiber materials during their fabrication process. Metal ions are the most common sources of impurities that significantly vary the transmission characteristics of optical fibers. If the concentration of these ions exceeds one parts per billion (ppb), it results in unacceptable loss in optical power thereby causing attenuation in the fiber.

3. **Intrinsic Absorption Losses**

Intrinsic absorption occurs when the fiber material has zero impurities i.e., in pure state. The two major causes that contribute for intrinsic absorption are,

(i) Ultraviolet absorption

(ii) Infrared absorption

(i) **Ultraviolet Absorption**

Ultraviolet absorption loss is caused due to the transition of electrons and molecules in the energy band. This type of absorption occurs at different wavelengths extending upto visible region of electromagnetic spectrum. Increase in the wavelength, decreases the absorption loss which becomes almost negligible at the wavelength 1.2 to 1.3 μm.

(ii) **Infrared Absorption**

Infrared absorption (IR absorption) is caused due to the vibration of chemical bonds in the fiber material. These vibrations occur because of the absorption of light energy (or photons) by glass atoms which gets transformed into random mechanical vibrations.

Q28. Write notes on "scattering losses in fiber".

Ans:

Scattering Loss

Scattering is an optical process, in this a part or all of the optical power propagating in a particular mode is transferred into another mode. In other words, if the light beam propagating through the fiber encouters an obstacle, it changes the direction and fails to achieve total internal reflection. Like this light scatter's (spreads) in different directions, causing scattering losses in the fiber.

The major causes for scattering losses in a glass material are,

(i) Microscopic variations in the material density

(ii) Compositional fluctuations.

(iii) Structural in homogeneities.

(iv) Manufacturing defects.

Light propagating thorugh the fiber encounters diffrent types of scattering losses among them the most predominant is Rayleigh scattering losses.

Rayleigh Scattering

Rayleigh scattering is caused when the physical variations in the optical fiber is equal to or less than $\frac{1}{10}^{th}$ of the diameter of the operating wavelength. It is the dominant loss mechanisms which results from inhomogeneities such as density, compositional variations and refractive index fluctuations. The scattering loss caused due to density fluctuations is spilled in all direction, thereby resulting in an attenuation which is proportional to $\frac{1}{\lambda^4}$.

Q29. Discuss how bending introduces attenuation in optical fibers.

(or)

Write short notes on bending losses and explain how to overcome the losses?

Ans:

Bending Losses

The loss that exists when an optical fiber is subjected to bending is known as bending loss. In other words, loss induced by physical stress on the fiber is referred to as bending loss.

Whenever a light beam is made to propagate along a straight fiber axis, it achieves total internal reflection and travels smoothly along the fiber. On the other hand, if the same light beam travelled along a bend fiber axis, it forms a propagation angle greater than critical angle. Due to this, it fails to attain total internal reflection, thereby causing bending loss in the fiber. Bending losses can be classified into two types namely,

1. **Macroscopic Bends**

Macroscopic bending losses (or bending losses) occur when the fiber is subjected to excessive bendings. Due to this sharp bending, the light cannot propagate at the turns resulting in the lost of signal within the classing. Figure (1) illustrates the diagrammatic representation of macrobend losses.

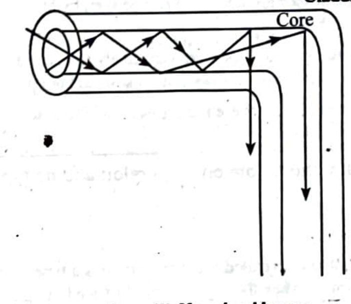


Figure (1): Macrobend Losses

Minimum bending of optical fiber which is marked as safe is nearly 20 times the total diameter of fiber. This minimum bending radius of fiber depends on the attenuation and strength of the optical fiber. The point at which large bending losses occur are termed as critical radius of curvature.

2. **Microbending Losses**

The bending which represents the repetitive small scale fluctuations in the radius of curvature of the fiber axis is known as microbending. These type of losses are caused due to the following reasons,

(i) Non-uniformities that occur during the manufacturing of the fiber.

(ii) Non-uniform lateral pressures generated during fiber cabling.

Figure (2) illustrates the diagrammatic representation of microbending losses.

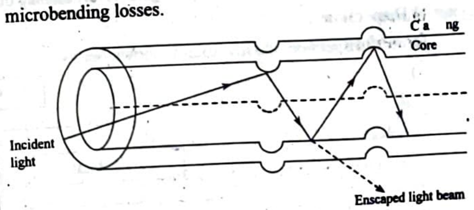


Figure (2): Microbending Losses

These losses are very difficult to avoid, but can be reduced to a considerable extent by forcing out a compressible jacket over the fiber.

Q30. Distinguish between macro bending and micro bending losses in brief.

Ans:

The following are the differences between macro bending and micro bending losses,

	Macro Bending Losses		Micro Bending Losses
1.	Macro bending losses generally occur at the bends of the fiber.	1.	Micro bending losses generally occur randomly through out the fiber.
2.	These losses are large and can be seen by human eye.	2.	These losses are repetative and can't be seen by naked human eye.
3.	Macro bending losses are very likely to occur during field installation, transportation and packing process.	3.	Micro bending losses are very likely to occur during fabrication and installation process.
4.	Multimode fibers are more susceptible to macro bending losses.	4.	Single mode fibers are more susceptible to micro bending losses.

Q31. Write a short note on dispersion and its types.

Ans:

Dispersion

Dispersion also called pulse spreading is a type of distortion caused in both digital and analog transmission in an optical fiber. For example when the digital data illustrated in figure (a) is transmitted over an optical fiber, the individual pulses broaden (or spread) and overlap with the neighbouring pulses as illustrated in figure (2). This is due to dispersion.

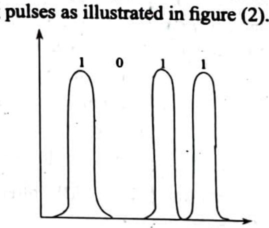


Figure (1): Fiber Input

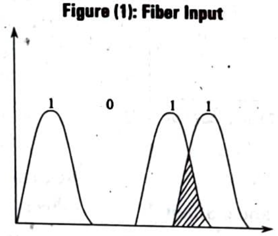
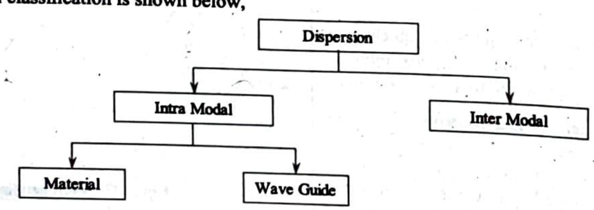


Figure (2): Broadening Output of Fiber Input Given

Types of Dispersion

General dispersion classification is shown below,



The description is as follows,

1. Inter Modal Dispersion
2. Intra Modal Dispersion

Intra Modal Dispersion

Intramodal dispersion also known as chromatic dispersion is caused due to the finite spectral linewidth of optical sources. This type of dispersion occurs in all types of optical fibers. The optical sources emit band of frequencies which travel along the fiber with different propagation delays. This causes differences in propagation delays between different spectral components of the transmitted signal. As a result, light pulses of each transmitted mode gets broadend, thereby causing intramodal dispersion in optical fibers.

The depending on the causes of delay differences, intramodal dispersion can be classified into two types namely,

(a) Material Dispersion – Caused due to dispersive properties of waveguide material

(b) Waveguide Dispersion – Caused due to guidance effects in fiber structure.

Material Dispersion

A material undergoes material dispersion when the second derivative of refractive index with respect to wavelength $\left(\frac{d^2n}{d\lambda^2}\right)$ is not equal to zero.

i.e., $\frac{d^2n}{d\lambda^2} \neq 0$

In other words, the variation of refractive index of core material as a function of wavelength results in material dispersion.

Waveguide Dispersion

Waveguide dispersion is primarily caused due to the difference in the speeds of optical energy travelling in both core and cladding of the fiber. The major reason for this difference is because of different refractive indices of the core and cladding materials. Moreover, the lower refractive index of cladding results in the faster propagating of light power in it when compared to that in the fiber core. This type of dispersion is predominant in single-mode fibers and is almost negligible in multi-mode fibers.

Intermodal Dispersion

Intermodal dispersion also known as modal delay is caused due to different group velocities of modes at a single operating frequency of optical fiber. This type of dispersion appears only in multimode fibers.

The broadening of pulse due to intermodal dispersion depends on the transmission times on both the fastest and the slowest modes propagating in the fiber. Due to this, multimode fibers exhibit large amount of pulse spreading and thereby causing large dispersion in an optical fiber.

The above mentioned material, waveguide and inter modal dispersions, waveguide dispersion can be ignored in multimode fibers.

5.2 Light Sources, Optical Sources, Light Detectors, LASERS

Q32. What are the requirements of an optical source to be used in optical communication systems?

Ans:

The advancement in semiconductor technology led to design of optical sources with very high efficiency and with very low losses. Implementation of semiconductor optical sources in fiber optic communication improved the quality of output. These sources constitute desired physical and performance characteristics necessary for efficient fiber optic system. These includes,

1. Size compatibility of source to a low-loss optical fiber. The source may be an LED or laser that can launch light into the fiber.
2. Capability of launching adequate power so that it can compensate fiber attenuation and connection losses and detects the signal at the receiver.
3. Optimized wavelengths that reduce fiber loss and dispersion
4. A narrow spectral width to reduce the dispersion.
5. It supports direct modulation of output power.

Optical sources are independent to environmental changes, i.e., the rise and fall of the temperature doesn't effect the operation of optical system. These are more accurate compared to electrical devices.

The basic light sources used in fiber optic communication system are,

1. Semiconductor LED
2. Laser diodes,

Q33. Draw the schematic of edge emitting double hetro junction LED and explain its working in detail. Model Paper, Q11(a)

(or)

Explain the working of hetero structure LED.

(Refer Only Edge Emitting LED)

Ans:

The basic LED structures used in optical communication system are namely,

1. Surface emitting LED
2. Edge emitting LED.

1. Surface Emitting LED

A high radiance etched well Double Heterostructure (DH) surface emitting LED is depicted in figure (1).

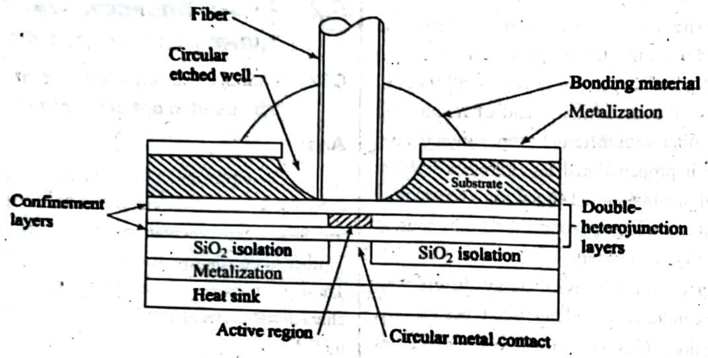


Figure (1): Surface-Emitting LED

It is also called burrus type or front emitting LED. In order to acquire high radiance, the emission of light must be constrained to a small active region within the device. Hence, a well is etched in a GaAs substrate such that the absorption of emitted light can be reduced and a fiber is incorporated into it for transmission of radiant light. Here, the plane of the active light emitted region is perpendicular to the fiber axis.

Because of large band gaps, the internal absorption becomes negligible and has high reflection coefficient at the crystal. This enhances the forward radiation.

In surface emitting LED, the wavelength of emission ranges from 0.8 to 0.9 μm. The diameter and thickness of active region is 50 μm and 2.5 μm respectively. Since, the thermal impedance of this structure is low, the coupling of light into the fiber is easy. The emitted light has isotropic radiation pattern with 120° half power beam width. This isotropic pattern is called lambertian pattern.

The brightness of light source is equal in all directions, but the power reduces by a factor cosϕ. Here, ϕ is the angle between viewing direction and normal axis. At $\phi = 60°$, the power is decreased to 50%. Hence, the total half power beam width becomes 120°.

The power coupled into a multimode step index fiber can be written as,

$$P_C = \pi(1 - r) AR_D (NA)^2 \quad \text{... (1)}$$

Where,

P_C – Power coupled into fiber

r – Fresnel reflection coefficient

A – Emission area of source

R_D – Radiance of the source

NA – Numerical Aperture.

The coupling power relies on the following aspects,

1. Distance and alignment between emission area and the fiber.
2. Medium between the emitting area and the fiber.
3. Emission pattern of SLED.

By adding the expoxy resin in the etched well, the mismatch of refractive index can be minimized and the efficiency of external power is improved. Therefore, the coupling power in DH surface emitting LED increases and becomes greater than the coupling power P_C.

2. **Edge Emitting LED**

The structure of a high radiance stripe geometry Double Heterojunction (DH) edge emitting LED is as shown in figure (2)..

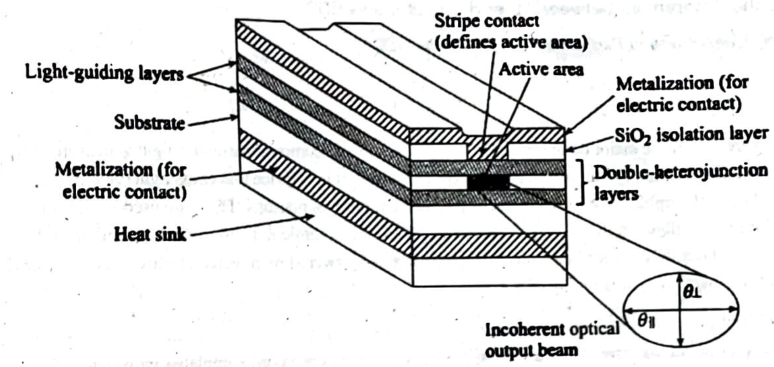


Figure (2): Edge-Emitting LED

The structure incorporates with an incoherent light source (active area) and a pair of guiding layers as shown in figure (2). The refractive index of guiding layers is greater than that of coating material (ex:SiO_2) and is smaller than that of active region. One face of LED is coated with a reflector and other end face coated with antireflector so that, the radiation pattern emits from one face (i.e., from the edge coated with antireflector). A waveguide channel is formed in LED to guide the optical radiation towards the fiber core. The contact stripes having the diameter 50-70 μm are used to attain proper matching of fiber-core of diameters (50 - 100 μm).

The emission pattern in edge emitter is highly directional than that in surface emitter. Also, the edge emitters efficiently couple the optical power into the fiber of small Numerical Aperture (NA). In the absence of waveguide effect, the emission pattern coming out from the plane parallel to the junction is lambertain pattern, the half power beamwidth is of 120° (i.e., $\theta_{11} = 120°$). At the plane perpendicular to the junction the half power beamwidth ranges between 25° and 35°.

Q34. With respect to LED why heterojunction devices are suitable for optical fiber communication systems?

Ans:

The two single crystal semiconductors having distinct bandage energies are placed adjacently to from a heterojunction and the devices having these junctions are called as heterojunction devices which have heterostructure. The two heterojunction techniques are,

(i) Isotope heterojunction

(ii) An-isotope heterojunction.

Isotope Heterojunction (n–n or p–p)

The confinement of minority carriers to small active region is carriedout by the potential barrier, which is provided by the isotope heterojunction with in the structure.

Thus, diffusion of carrier length diffusion length of carrier and volume are decreased with in the structure at the radiative recombination.

Applications of Isotope Heterojunction Technique

1. In fabricating the high radiance LED's and injection lasers
2. LED's

An Isotope Heterojunction (p-n)

An-isotope heterojunction technique provides confinement of radiation to a small active region and also improves the efficiency of either holes or electrons, where the efficiency of confinement can be calculated by using the differences in band gap and wavelength.

Q35. What is LASER diode? Compare its performance with that of LED.

(or)

What are the differences between laser diode and an LED?

(Refer Only Comparison of Performance of Laser with LED)

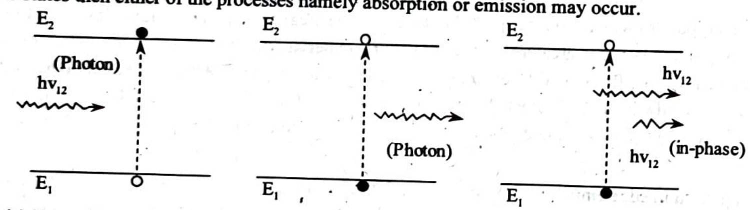
Ans:

Laser Diode

Laser diodes are one of the major optical sources, used in the optical communication for light generating purpose. Laser is an acronym for 'light amplification by stimulated emission of radiation'. It is a device that emits light (electro magnetic radiation) through a process of optical amplification based on the stimulated emission of photons. These are used as amplifiers to attain high gain and for avoiding oscillations. In these diodes, the active medium is a semiconductor, which is similar to that in LED. The most common type of a laser diode is formed from a P-N junction and powered by injected electric circuit. Laser diodes output assures that the beam generated by it is highly directional.

Principle of Operation

The operating principle of laser involves absorption, spontaneous emission, stimulated emission. Consider figure (a), which has two energy levels say E_1 and E_2, where E_1 is the ground state level and E_2 is the excited state. If a transition is executed between these two states then either of the processes namely absorption or emission may occur.



(a) Absorption (b) Spontaneous Emission (c) Stimulated Emission

Figure

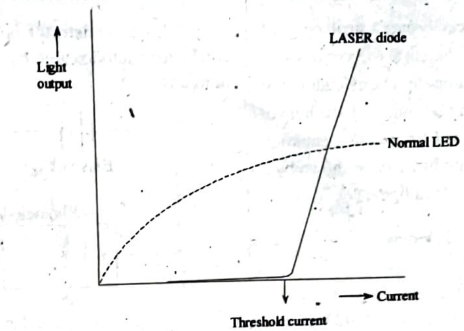
The photon is absorbed by an electron and transits to excited level. But this level is unstable, so electron returns to the by emitting a photon spontaneously as shown in figure (b). Sometimes after absorption, the electron still remains in excited level, it can be made to jump to the ground-state level by applying an energy hv_{12}, which is known as stimulated emission.

This emission has two photons, one is absorbed to transit from excited level to ground level and other one is emitted while performing the above process. These both photons maintain in-phase with each other.

Comparison of Performance of Laser with LED

	LED		LASER Diode
1.	Spontaneous emission is possible in LEDs.	1.	Stimulated emission is possible in LASER diodes.
2.	The output beam of an LED is non-coherent.	2.	The output beam of laser diode is coherent.
3.	Data rate is low.	3.	Data rate is very high.
4.	Transmission distance is smaller.	4.	Transmission distance is greater.
5.	Less sensitive to temperature.	5.	LASER diodes are more temperature sensitive.
6.	Simple design.	6.	Complex design.
7.	Output power is linearly proportional to drive current.	7.	Output power is proportional to current above threshold.
8.	Coupling efficiency is very low.	8.	Coupling efficiency is high.
9.	Best suited for low distance transmission.	9.	Used for long distance transmission.
10.	Available wavelengths are between 0.66 to 1.65 μm.	10.	Available wavelengths are between 0.78 to 1.65 μm.
11.	Life time is about 10^5 hours.	11.	Life time is about 10^4 hours.

The spectral comparison between LASER diode and LED is shown in following figure.



Figure

Q36. Establish a relation between the separation between resonating modes of an injection laser diode for a given dimensions of Fabry-Perot cavity and a specified source spectral width.

Ans:

Fabry Perot Resonator Cavity

The light amplification in LASER occurs when a photon colliding with an atom in excited energy state causes stimulated emission of second photon and these two photons release two more and so on. Thus, amplified coherent emission is acquired as the avalanche multiplication and EM waves linked with photons are in phase.

Laser action can be achieved by obtaining the conditions for coherence in two ways,

1. Laser medium must contain photons
2. Must sustain the circumstances.

In semiconductor lasers, the stimulated emission of photons occurs due to the optical transition between the energy states. Whereas, in gas and solid-state lasers, radiative transition arises between the isolated atomic and molecular levels. The radiation is generated inside the cavity of the laser diode. This cavity is called Fabry Perot resonator cavity.

The schematic of Fabry Perot resonator cavity is as shown in figure (1).

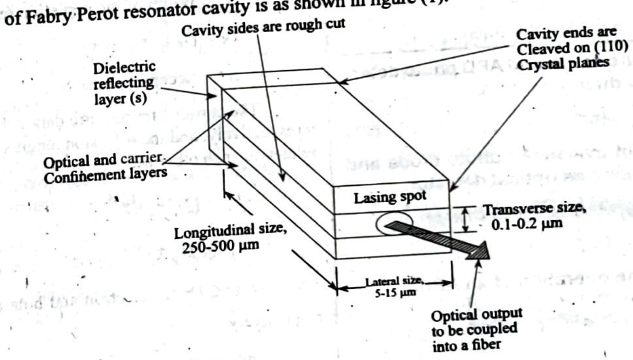


Figure (1): Fabry Perot Resonator Cavity

The Fabry Perot cavity consists of two highly reflecting parallel plane mirrors which are arranged parallel to each other and the spacing between the mirrors is 'L'.

The resonator cavity is very small with dimensions 250-500 μm long, 5-15 μm wide and 0.1 – 0.2 μm thickness.

The positive feed back of photons can be obtained from an optical cavity by the process called reflection, carried out at mirrors.

Generation of Optical Radiations

Oscillations occur in the laser cavity over a small range of frequencies where the cavity gain is sufficient to overcome losses such as absorption, scattering, diffraction etc. The calculation of central frequency of spectral band can be done with the help of difference in energy levels in process of stimulated emission transition. The broader laser transition line can be shown by a relative amplification factor as is shown in figure (2).

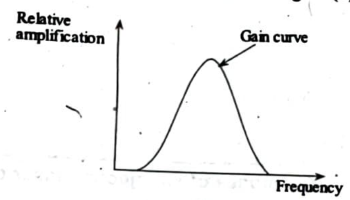


Figure (2)

The frequency range represented by the gain curve determines the spectral emission from the device.

As the structure forms a resonant cavity, the radiation builds up. The established frequencies are found only at the frequencies, where the distance between mirrors is equal to integral multiple of half wavelengths. Thus, when the spacing between the mirrors is L, the resonance condition along the axis of cavity is,

$$L = \frac{\lambda q}{2n}$$

Where,

λ – Emission wavelength

n – Refractive index of medium.

Q37. Draw the structure of PIN and APD photo detectors and explain their operation.

(or)

Draw structure of avalanche photo diode and describe its working as optical detector.

(Refer Only APD (Avalanche Photo Diode))

(or)

Briefly explain the operation of an APD.

(Refer Only APD (Avalanche Photo Diode))

Ans:

Physical Principle of Photo Diode

The physical principles of photodiodes are briefly illustrated by explaining following photo detectors i.e.,

1. PIN photo detector
2. Avalanche Photo Diode (APD).

1. PIN Photo Detector

Pin photodetector is the most commonly used semiconductor photodetector. Its schematic representation is shown in figure (1).

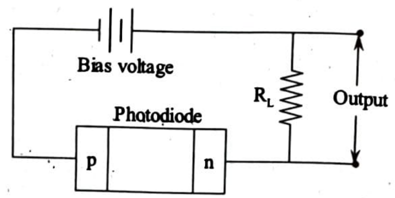


Figure (1)

It consists of p and n regions. The width of the depletion layer may be increased artificially by adding an intermediate intrinsic region. As the intrinsic region has high resistance, a small reverse bias is good enough to increase the width of the depletion region, so that it extends into the n-layer.

A further advantage of the pin diode is that the charge separation in the active region is larger, which leads to smaller junction capacitance.

The electric field in the intrinsic region is uniform and has a magnitude 'E_o'. Whereas, in the case of the p-n photodiode.

$$E_o = \frac{N_a q x_p}{\epsilon_o k}$$

Where,

q – Magnitude of electronic charge

x_p – Width of the depletion region in the P-side,

k – Dielectric constant

N_a – Acceptor density.

The carrier lifetimes are denoted by τ_n and τ_p for n and p respectively, and the diffusion lengths as L_n and L_p. They are related to each other as,

$$L_n = (D_n \tau_n)^{1/2}$$

$$L_p = (D_p \tau_p)^{1/2}$$

D_n and D_p are electron and hole diffusion coefficients respectively.

The cut-off wavelength can be calculated depending on the bandgap energy (E_g) of the material.

i.e., $\lambda_c = \frac{hc}{E_g}$ or $\lambda_c = \frac{1.24}{E_g}$

$$\lambda_c(\text{mm}) = \frac{1.24}{E_g(\text{eV})}$$

2. APD (Avalanche Photo Diode)

APD is a special PIN diode which is shown in figure (2),

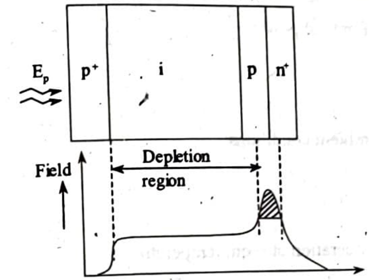


Figure (2)

It works as follows,

The incident photon generates an electron hole pair, as they do in a general PD, but here relatively high reverse voltage is applied as a result the generated e^- hole pairs acquires more energy and gets accelerated. These generated e^- hole pairs strike neutral atoms and create new carriers called secondary and the impact ionization creates avalanche breakdown in diodes with reverse bias in APD, photons are made to heavily doped p^+ region. Compared to energy of incident photons, the energy gap of this layer is very large and is transparent to the incident light. So the photons enter the intrinsic layer, where they produce e^- hole pairs. The reverse voltage separates these e^- hole pairs and moves them towards the pn^+ junction, since the electric field exists there is very high (in the order of 10^5 V/cm). And this electric field accelerates the carriers and results in impact ionization. So in pn^+ region the carrier multiplication (impact ionization) takes place.

The average number of e^- hole pairs generated by a carrier per unit distance travelled is called ionization factor. Diodes with different materials pursues different electron and hole ionization rates i.e., α and β respectively. Eventhough both electrons and holes can be involved in the ionization process, but practically the devices constructed of materials in which one type of carrier largely dominates exhibits low noise and large gain-band width products.

Q38. Explain the importance of semiconductor photo diode in fiber optic communications.

Ans:

Specifications of a Semiconductor Photo Diode

The important performance parameters of a semiconductor photodiode are described below:

1. **Responsivity**

   The ratio of generated photocurrent to incident light power, typically expressed in A/W when used in photoconductive mode. The responsivity may also be expressed as a quantum efficiency or the ratio of the number of photo generated carriers to incident photons and thus, a unitless quantity. The typical values for responsivity are, 0.65 A/W for silicon at 900 nm, 0.45 A/W for germanium at 1.3 μm and 0.9 A/W for InGaAs at 1.3 μm.

2. **Dark Current**

   The current through the photodiode in the absence of light, when it is operated in photoconductive mode. The dark current includes photocurrent generated by background radiation and the saturation current of the semiconductor junction. Dark current must be accounted for calibration if a photodiode is used to make an accurate optical power measurement. It is also a source of noise when a photo diode is used in an optical communication system.

3. **Noise Equivalent Power (NEP)**

   The minimum input optical power to generate photocurrent, equal to the r.m.s noise current in a 1 Hz bandwidth. The related characteristic directivity D is the inverse of NEP i.e., $\frac{1}{NEP}$ and the specific directivity D^* is the directivity normalized to the area, A of the photodiode i.e.,

   $$\boxed{D^* = D\sqrt{A}}$$

   The NEP is roughly the minimum detectable input power of a photodiode.

4. **Quantum Efficiency**

   The photodiode's capability to convert light energy to electrical energy is referred as quantum efficiency. It can be also described as the ratio of number of electron-hole pairs generated to the number of incident photons. In a practical photodiode, the quantum efficiency of the detector ranges from 30 to 95%.

5. **Sensitivity**

   It is a measure of the effectiveness of a detector in producing an electrical signal at the peak sensitivity wavelength.

6. **Rise Time**

   The time required for a detector output to reach from 10 to 90% of its final value.

Q39. What is the function of photo detector? Compare various photo detectors.

(or)

Compare PIN and APD.

(Refer Only Comparison of Photo Detectors)

(or)

Compare and contrast PIN diode and APD.

(Refer Only Comparison of Photo Detectors)

Ans:

Photo-detector

Photo-detector is an essential component of an optical fiber communication system. Its function is to convert the received optical signal into an electrical signal which is amplified before further processing. The requirements for photo detector can be given as follows,

1. They should have high sensitivity at operating wavelength.
2. It should have high fidelity to reproduce the original waveform effectively.
3. It should produce maximum electrical signal for a given amount of optical power.
4. It should have short response time to obtain a suitable bandwidth.
5. Dark currents, leakage currents, shunt conductance should be low.
6. Performance characteristics should be independent of changes in ambient conditions.
7. The physical size of detector must be small for effective coupling.
8. Detector should not require excessive bias voltages or currents.
9. It must be highly reliable and must be capable of continuous stable operation at room temperature.
10. It should be economical.

The detector must satisfy the above requirements of performance and compatibility.

Comparison of Photodetectors

The most commonly used photo detectors for fiber optic systems are the photodiodes. These photodiodes are divided into two types they are,

(i) PIN photodetector

(ii) Avalanche photodetector.

Table below illustrates the differences between these photodiodes by assuming that the semiconductor is 'silicon (Si)'.

	PIN Photodiode		Avalanche Photodiode
1.	The range of the wavelength (λ) when 'Si' is used as the semiconductor is 400 – 1100 nm.	1.	The range of the wavelength (λ) when 'Si' is used as the semiconductor is given as 400 - 1100 nm.
2.	The dark current (I_p) for pin photodiode ranges from 1 nA to 10 nA.	2.	The dark current (I_p) for avalanche photodiode ranges from 0.1 to 1 nA.
3.	The range of rise time (τ_r) is given as 0.5 ns to 1 ns.	3.	The range of rise time (τ_r) is given as 0.1 ns to 2 ns.
4.	The bandwidth of pin photodiode ranges from 0.3 GHz to 0.7 GHz.	4.	The gain-bandwidth of avalanche photodiode ranges from 100 GHz to 400 GHz.
5.	The biasing voltage (V_B) of pin photodiode is '5V'.	5.	The biasing voltage (V_B) of avalanche photodiode ranges from 150 V to 400 V.

Table

Q40 Explain different structures of lasers with neat sketches.

Ans:

The two different types of confinements by which structures of lasers are classified are,

1. **Optical Confinement**

An efficient operation of laser requires optical confinement to achieve lasing in single confined filament, stabilizing the lateral gain and achieving a low threshold current in lasers.

There are three types of optical confinement methods listed out below:

(i) The first type of structure is used in devices called gain-guided laser. The optical power is in excess of 100 mW but have strong instabilities and two peak beams. The structure (shown below) consists of a narrow electrode strip (<< 8 μm) placed along the length of diode.

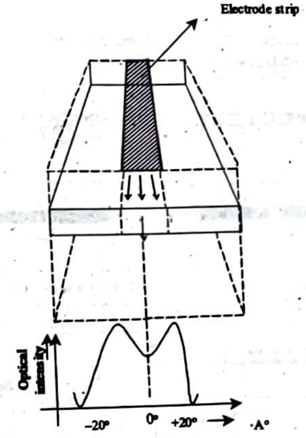


Figure (1)

Refractive index of the layer below the strip changes due to injection of electrons and holes into the device. Due to injection of electrons and holes a waveguide is created which confines the light laterally.

(ii) The second type of structure is positive index-guided lasers. A dielectric waveguide is created at the time of fabrication in the lateral direction. The central region has a higher refractive index than the outer region (shown below). The guided light is reflected at the dielectric boundary and the device emits a single, well-collimated beam of light that has a bell shaped intensity profile.

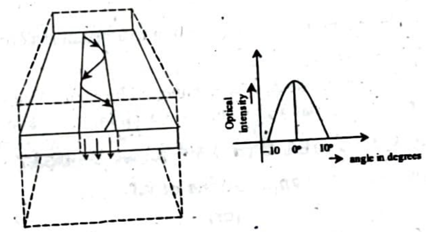


Figure (2)

(iii) The third type of structure used for optical confinement is negative index guided laser or negative index waveguide. Compared to outer region of laser, the central region of laser has lower refractive index.. Hence at the dielectric boundary some of the light rays get reflected while the remaining part of light gets refracted and is lost in the outer region forming side lobes to the main beam of radiation pattern. At fundamental mode, lasing occurs.

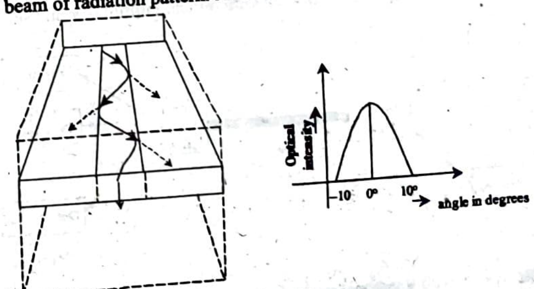


Figure (3)

2. **Current Confinement**

There are four methods of current confinement in laser diode as listed below,

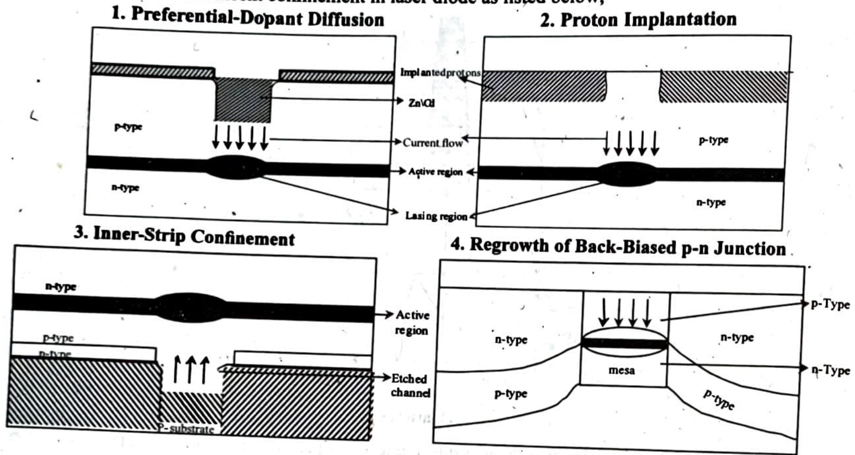


Figure (4)

(i) **Preferential-Dopant Diffusion Method**

A narrow has path is formed for the current by diffusing p-type material over n-type material.

(ii) **Proton Implantation Method**

High resistive regions, restricting current to a narrow path between these regions.

(iii) **Inner-Strip Confinement**

In this method, on the channel, a lasing structure is inscribed in to a planal material.

(iv) **Regrowth of Back-Biased p-n Junction**

A back-biased p-n junction is reconstructed. The current on either of the channel has active layer and is discontinuous. The current flow is blocked on either sides of mesa by grouping p-n junctions that are reverse biased when device is working.

5.3 WDM CONCEPTS, OPTICAL FIBER SYSTEMS LINK BUDGET

Q41. Discuss the principle, requirement and applications of WDM.

(or)

Discuss the following, WDM networks.

(Refer Only Excluding Applications)

Model Paper, Q11(b)

Ans:

In fiber optic communication, WDM is a technology, which multiplexes more than one optical carrier signal on a single optical fiber by using different wave lengths of laser light to carry different signals. 'N' independent optically formatted information streams, each transmitted at a different wavelength are combined with optical multiplexer and sent over the same fiber as shown in below figure.

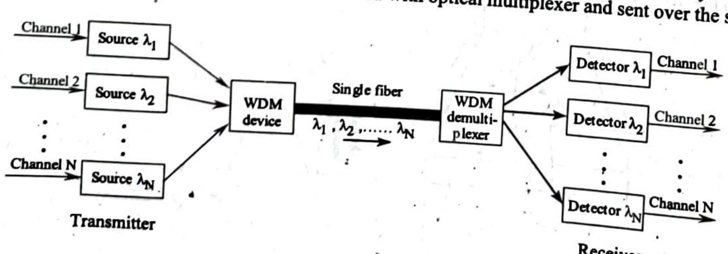


Figure: WDM System with N Independent Input Signal for Transmission Over a Single Fiber

Each of the streams could be a different data rate. Each information stream maintains its individual data rate after being multiplexed with other streams and operates at its unique wavelength.

The key feature of WDM is that the discrete wavelengths form an orthogonal set of carriers that can be separated, routed and switched without interfering with each other as shown in figure.

The optical bandwidth can be expressed in terms of wavelength deviation "$\Delta\lambda$",

$$|\Delta\nu| = \left|\left[\frac{c}{\lambda^2}\right]\Delta\lambda\right|$$

Since the spectral width of a high quality source occupies only a narrow optical bandwidth. The two loss windows provide many additional operating regions. The light sources, each emitting at different peak wavelengths is sufficiently spaced to avoid interference. Fixed frequency spacing is selected because the operating mode of laser is locked, which means the frequency of the laser is fixed.

At the transmitter end, there are several modulated light sources which emit signals at different wavelength. A multiplexer is used to combine these signals into a spectrum of closed wavelength signals and mix them into a single fiber. At the receiver, the demultiplexer separates the optical signal into appropriate detection channels for signal processing.

A variety of active and passive devices are required to implement WDM networks. The passive devices require no external control for their operation. The active devices can be controlled electronically. Hence they provide a degree of network flexibility.

Applications

Wavelength division multiplexing finds its application in,

1. Synchronous Optical Network (SONET)
2. Dense Wave-length Division Multiplexing (DWDM).

Q42. List the features of WDM.

Ans:

The features of Wavelength Division Multiplexing (WDM) are,

1. **Capacity Upgrade**

   The classical application of WDM is to upgrade the capacity of existing point-to-point fiber optic transmission links. If each wavelength supports an independent network signal of a few gigabits per second, then WDM can increase the capacity of a fiber network dramatically.

2. **Transparency**

   An important aspect of WDM is that each optical channel can carry any transmission format. Any type of information i.e., analog or digital can be sent simultaneously over the same fiber.

3. **Wavelength Routing**

   In addition to the usage of multiple wavelengths to increase link capacity and flexibility, the use of wavelength-sensitive optical routing devices, in designing communication meteorology and switches has an very important role. Wavelength routed networks use the final address.

4. **Wavelength Switching**

   Wavelength routed networks are based on a rigid fiber structure, wavelength switched architectures allow re-configurations of the optical layer.

Q43. Write wavelength division multiplexing for optical communication system.

Ans:

Wavelength Division Multiplexing (WDM)

A unidirectional WDM network is as shown in figure (1).

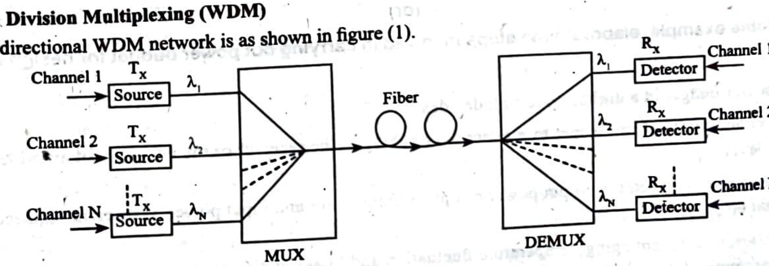


Figure (1): Unidirectional WDM Network

In unidirectional WDM technique, optical signals from different light sources each comprising of a channel are simultaneously transmitted through, the same optical fiber. Each light source is operating at different carrier frequency or light wavelength using LED or laser. The light from each source is combined using a device called optical multiplexer. As the signal transmits through the fiber and reaches the far end, a device called optical demultiplexer sends signal of each channel to its own receiver. At the receiver, photodetectors convert light signals into corresponding electrical signals. When N channels at bit rates $B_1, B_2, ...B_N$ are transmitted simultaneously over a fiber of length L, the total bit rate-distance product, BL is given by,

$$BL = (B_1+B_2+.....+B_N)L$$

If $B_1 = B_2 = B_3 = ... = B_N = B$, we get,

$$BL = NBL$$

Therefore, the system capacity is enhanced by a factor N.

The capacity of WDM depends on minimum channel spacing ΔV_{ch} which is limited by inter-channel cross talk. Minimum channel spacing is $\Delta V_{ch} \geq 2B$ where B is bit rate. The spectral efficiency, η_s of WDM is given by,

$$\eta_s = \frac{B}{\Delta V_{ch}}$$

Common used channel spacing for most commercial WDM systems is 100 GHz with only 10% efficiency at 10 bit rate of 10 Gb/s. However, to improve the efficiency up to 80% lower channel spacing of 50 GHz and bit rate of 40 Gb/s is used.

Bi-directional WDM System

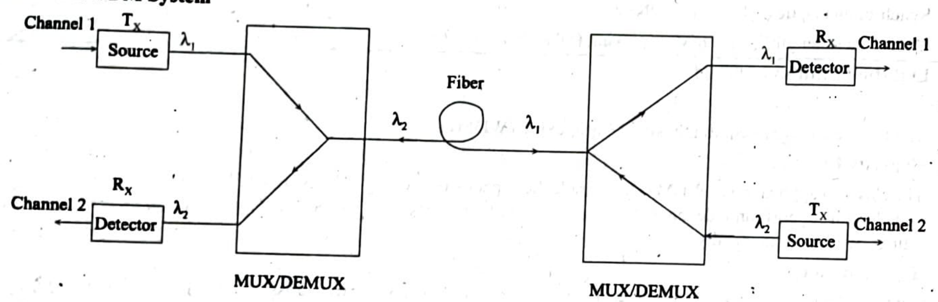


Figure (2): Bidirectional WDM Network

In bi-directional WDM system, the multiplexing device operates in two directions i.e., they work as MUX/DEMUX at the same time. The device acts as multiplexer for the light source of channel 1 and as a demultiplexer for the received light signal of channel 2. The device present at the far end acts in reverse fashion i.e., it acts as demultiplexer for signal of channel 1 and multiplexer for the signal of channel 2 from the light source. Thus, light signal travels simultaneously along the fiber in opposite direction in two channels. The important use of WDM systems are in loop and trunk system applications.

Q44. Describe optical fiber link power budget for a repeater less system.

(or)

Discuss in detail about power budget analysis.

(or)

With suitable example, elaborate the steps involved in carrying out power budget for design of a FO link.

Ans:

The link power budget in a digital optic link decides,

1. If the power attenuation level is met to prevent overloading in the receiver or the necessity of amplifier to increase the power level.
2. The power margin between the output power of optical transmitter and input power of receiver required to realize a specified bit error rate (BER).
3. Besides losses, component aging, temperature fluctuation and losses arising from the components are also analyzed with the parameter link power margin in the analysis.

The power loss model for a point-to-point link is shown in the figure below.

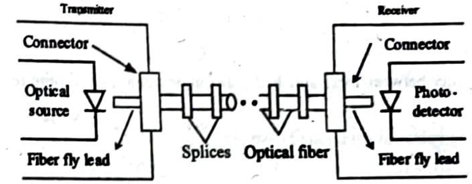


Figure: Optical Power Loss Model for a Point-to-point Digital Link

The optical power received at the detector is dependent on the light coupled into the fiber and losses incurred in the fiber and at connectors and splices.

1. The loss occured in each element in the link is given as,

$$\text{loss} = 10 \log \frac{P_{out}}{P_{in}}$$

Where,

P_{in} – Input optical power to loss element

P_{out} – Output optical power from loss element.

The total optical power 'P_T' that is allotted to cable attenuation, connector loss, splicing loss and system margin occurred between the light source and photo detector is considered in digital link loss budget.

Total power loss in the digital link is formulated by the expression,

$$P_T = P_S - P_R$$
$$= 2l_c + \alpha_f L + \text{system margin}$$

Here,

P_S – Optical power produced at the end of fiber fly lead

P_R – Receiver sensitivity

l_C – Connector loss

α_f – Fiber attenuation in dB/km

L – Transmission distance in km

Margin of 6 dB to 8 dB is usually used for those systems which are assumed to have no further addition of components into the digital link.

Q45. A single-mode cascaded fiber communication link is specified by:

Operating wavelength: 1.30 μm | **Total system length: 80 km**
Power launched at transmitter : 2 dBm | **Fiber cable loss: 0.40 dB km⁻¹**
Fiber splice losses: 0.02 dB per splice | **No. of splices in the link = 8**
No. of connectors = 2 (at ends) | **Connector loss = 1 dB.**
Estimate the minimum power received for a system margin of 6 dB.

Ans:

Given that,

For a single mode fiber,

Operating wavelength, $\lambda = 1.30\ \mu m$

Total system length, $L = 80$ km

Power launched at transmitter, $P_s = 2$ dB m

Fiber cable loss, $\alpha_f = 0.40$ dB km^{-1}

Fiber splice losses, $l_s = 0.02$ dB per splice

Number of splices in the link, $N_s = 8$

Number of connectors, $N_c = 2$

Connector loss, $l_c = 1$ dB

System or power margin, $P_m = 6$ dB

Minimum received power, $P_R = ?$

The relation between transmit power and received power is expressed as,

$$P_T = P_S - P_R \quad \text{... (1)}$$

$$= 2l_c + \alpha_f L + P_m \quad \text{... (2)}$$

From equation (1), the difference between total launched transmit power and minimum received power is equal to the total power loss (P_T).

On substituting corresponding values in equation (2), we get,

$$P_T = (2 \times 1) + (0.40 \times 80) + 6$$

$$= 2 + 32 + 6$$

$$\Rightarrow \boxed{\therefore P_T = 40 \text{ dB}}$$

On substituting the values of P_T and P_S is equation (1), we get,

$$40 = 2 - P_R$$

$$\Rightarrow P_R = 2 - 40$$

$$= -38 \text{ dB m}$$

$\therefore$ Minimum received power or received power sensitivity is,

$$\boxed{P_R = -38 \text{ dB m}}$$

Q46. A transmitter has an output power of 0.1 mW. It is used with a fiber having NA = 0.25, attenuation of 6 dB/km and length 0.5 km. The link contains two connectors of 2 dB average loss. The receiver has a minimum acceptable power (sensitivity) of 35 dBm. The designer has allowed a 4 dB margin. Calculate the link power budget.

Ans:

Given that,

For a link,

The output power of transmitter, $P_s = 0.1$ mW

Numerical aperture of fiber, $NA = 0.25$

Attenuation of fiber, $\alpha_f = 6$ dB/km,

Length of fiber = 0.5 km

Average loss of the link containing two connectors = 2 dB

Minimum acceptable power of receiver = –35 dBm

Allowed system power margin, $P_m = 4$ dB

Link power budget = ?

The link power budget determines the power attenuation level of power loss.

Total power loss in the analog link is formulated by the expression.

$$P_T = P_S - P_R$$

$$= 2\,l_c + \alpha_f L + \text{System margin}$$

The power losses include coupling loss, fiber loss and total connector loss and are determined as,

$$\text{Coupling loss} = -10 \log(N.A)^2$$

$$= -10 \log(0.25)^2$$

$$= 12.04 \approx 12 \text{ dB}$$

$$\text{Fiber loss, } l_f = \alpha_F L$$

$$= (6 \text{ dB/km})\,(0.5)\text{km}$$

$$l_f = 3 \text{ dB}$$

Total connector loss of two connectors, $2l_c = 2 \times$ Average loss of connectors

$$= 2 \times 2 \text{ dB}$$

$$= 4 \text{ dB}$$

$\therefore$ Total power loss = Σlosses + Power margin

$$= 12 \text{ dB} + 3 \text{ dB} + 4\text{dB} + 4\text{dB}$$

$$= 23 \text{ dB}$$

$\therefore$ Actual output power, P_{out} = Transmitter power (P_s) – Power loss

$$= -10 \text{ dBm} - 23 \text{ dBm} \quad [\because P_s = 0.1 \text{ mw} = -10 \text{ dBm}]$$

$$= -33 \text{ dBm}$$

As the minimum acceptable power i.e., sensitivity = –35 dBm

$$\Rightarrow P_{min} = -35 \text{ dBm}$$

Since $P_{out} > P_{min}$, the system performance is optimum over its operating life.

Important Questions

Q1. Explain optical fiber communication system with neat block diagram.

Important Question

Ans: Refer Q16.

Q2. What are the different types of optical fiber's. Explain there construction, advantages and disadvantages.

Important Question

Ans: Refer Q18.

Q3. What is Snell's law? Explain.

Important Question

Ans: Refer Q21.

Q4. What is critical angle? With neat diagram explain the critical angle phenomenon.

Important Question

Ans: Refer Q23.

Q5. Explain the following,

(a) Acceptance angle (b) Numerical aperture (c) Acceptance cone.

Important Question

Ans: Refer Q24.

Q6. Give the classification of optical fibers in practice.

Important Question

Ans: Refer Q26.

Q7. Draw the schematic of edge emitting double hetro junction LED and explain its working in detail.

Important Question

Ans: Refer Q33.

Q8. Establish a relation between the separation between resonating modes of an injection laser diode for a given dimensions of Fabry-Perot cavity and a specified source spectral width.

Important Question

Ans: Refer Q36.

Q9. Draw the structure of PIN and APD photo detectors and explain their operation.

Important Question

Ans: Refer Q37.

Q10 Explain different structures of lasers with neat sketches.

Important Question

Ans: Refer Q40.

Q11. Discuss the principle, requirement and applications of WDM.

Important Question

Ans: Refer Q41.

Q12. Describe optical fiber link power budget for a repeater less system.

Important Question

Ans: Refer Q44.