1 UNIT

Introduction to Optical Communication

CONTENTS

PART-1

Optical Spectral Band with Operating Windows, General Communication System, Optical Communication System with its Advantages.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.1. What are optical spectral band designations used in optical fiber communication ? Also state different ways to measure the physical properties of a wave in various region.

Answer

A. Optical spectral band :

1. The International Telecommunications Union (ITU) has designated six spectral bands for use in optical fiber communications within the 1260 to 1675 nm region.
2. These long-wavelength band designations arose from the attenuation characteristics of optical fibers and the performance behaviour of an erbium doped fiber amplifier (EDFA).
3. Fig. 1.1.1 shows and Table 1.1.1 defines the regions which are known by the letters *O*, *E*, *S*, *C*, *L* and *U*.

Table 1.1.1. Spectral band designations used in optical fiber communications

Name	Designation	Spectrum (nm)	Origin of name
Original band	O-band	1260 to 1360	Original (first) region used for single mode fiber links
Extended band	E-band	1360 to 1460	Link use can extend into this region for fibers with low water content
Short band	S-band	1460 to 1530	Wavelengths are shorter than the C-band but higher than the E-band

Conventional	C-band	1530 to 1565	Wavelength region used by a conventional EDFA
Long band	L-band	1565 to 1625	Gain decreases steadily to 1 at 1625 nm in this longer wavelength band
Ultra long band	U-band	1625 to 1675	Region beyond the response capability of an EDFA

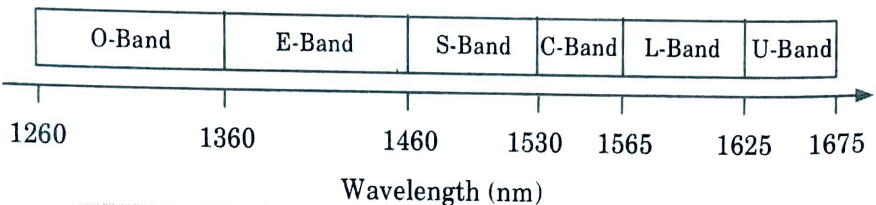


Fig. 1.1.1. Designations of spectral bands used for optical fiber communications.

4. The 770 to 910 nm band is used for shorter wavelength multimode fiber systems. Thus this region is designated as the short wavelength or multimode fiber band.

B. Physical properties :

1. There are three different ways to measure the physical properties of a wave in various regions in the EM spectrum.
2. These measurement units are related by some simple equations. First of all, in a vacuum the speed of light c is equal to the wavelength λ times the frequency ν, so that

$$c = \lambda\nu$$

where, the frequency ν is measured in cycles per second or hertz (Hz).

3. The relationship between the energy of a photon and its frequency (or wavelength) is determined by the equation known as Planck's Law.

$$E = h\nu$$

where, the parameter $h = 6.63 \times 10^{-34}$ J-s = 4.14 eV-s is Planck's constant. The unit J means joules and the unit eV stands for electron volts.

4. In terms of wavelength (measured in units of μm), the energy in electron volts is given by

$$E(\text{eV}) = \frac{1.2406}{\lambda(\mu m)}$$

5. The optical spectrum ranges from about 5 nm in the ultraviolet region to 1 mm for far-infrared radiation.

6. In between these limits is the 400 to 700 nm visible band. Optical fiber communications use the near-infrared spectral band ranging from nominally 770 to 1675 nm.

Que 1.2. **Draw a block diagram of fiber optic communication system and describe the function of each component.**

AKTU 2019-20, Marks 07

Answer

1. Fig. 1.2.1 shows the block diagram of optical fiber communication.

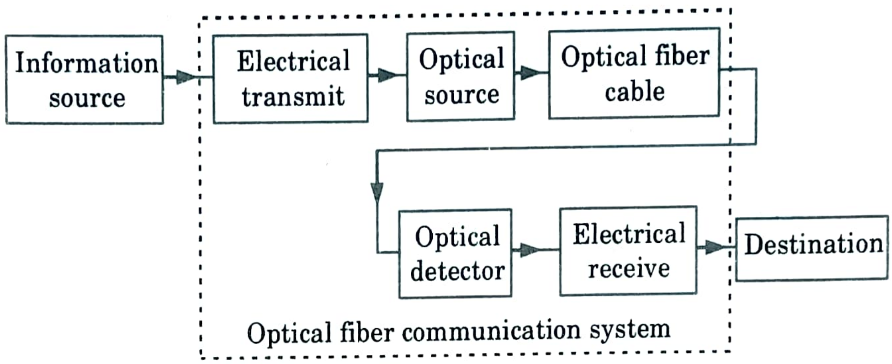


Fig. 1.2.1. The optical fiber communication system.

2. The information source provides an electrical signal to the transmitter, comprising of an electrical stage which drives an optical source to give modulation of the light wave carrier.
3. The optical source is used to provide an electrical optical conversion. It may be either a semiconductor Laser or LED.
4. The transmission medium consists of an optical fiber cable and the receiver is an optical detector which drives the further electrical stage and hence provides the demodulation of the optical carrier.
5. Photodiodes and in some instances photo transistors and photo conductors may be utilized for the detection of the optical signal and its conversion to electrical signal.
6. Thus, electrical interfacing at either end of the optical link is needed.

Que 1.3. **What are the various advantages of optical fiber communication system ?**

AKTU 2017-18, Marks 10

Answer

Advantages of optical fiber communication system :

1. **Enormous potential bandwidth :** The optical carrier frequency in the range 10^{13} Hz to 10^{16} Hz yields a far greater potential transmission

bandwidth than metallic cable system. Thus, the information-carrying capacity of optical fiber systems has proved far superior to the best copper cable systems.

2. **Small size and weight :** The optical fiber have very small diameter which are often no greater than the diameter of human hair. Even when such fibers are covered with protective coatings, they are far smaller and much lighter than corresponding copper cable.
3. **Electrical isolation :** Optical fibers which are fabricated from glass or polymer are electrical insulators and therefore do not exhibit earth loop and interface problems.
4. **Signal security :** The light from optical fibers does not radiate significantly and thus provide a high degree of signal security.
5. **Low transmission loss :** Optical fibers have been developed in which losses are as low as 0.2 dB km^{-1}. Therefore, repeater links will be required after hundreds of km.
6. **Ruggedness and flexibility :** Although protective coatings are essential, optical fibers may be manufactured with very high tensile strength.
7. **System reliability and ease of maintenance :** As less number of repeaters or line amplifiers are required, therefore reliability is high and is easy to maintain.
8. **Potential low cost :** The glass which generally provides the optical fiber transmission medium is made from sand, not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low cost line communication.

PART-2

Optical Fiber Waveguides : Ray theory of Transmission with TIR, Acceptance Angle, Numerical Aperture and Skew Rays.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.4. **Explain the structure of optical waveguide.**

Answer

1. Optical fiber consists of mainly three regions. The central region is known as the core. The middle region is called the cladding. The outer region is a protective sheath.

2. The refractive index of cladding *i.e.*, n_2 is always lower than that of core *i.e.*, n_1.
3. Cladding keeps the light waves within the core. It also provides some strength to the core.

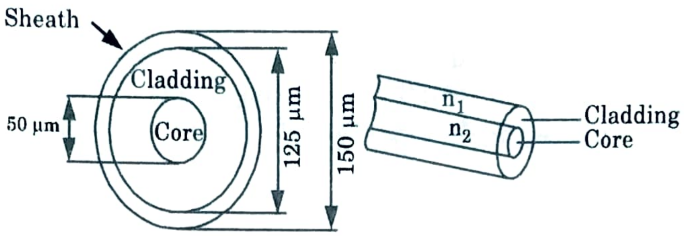


Fig. 1.4.1. Cross sectional view of an optical fiber.

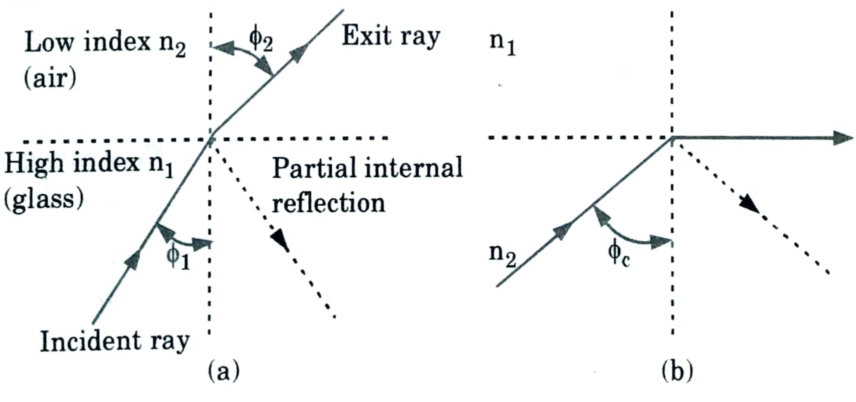
4. The outer most protective sheath protects the cladding and core from moisture, contamination and abrasions.
5. Optical fiber is made from glass or plastic which are transparent to optical frequencies.
6. With these materials three major type of fibers are made :
i. Plastic core with plastic cladding.
ii. Glass core with plastic cladding.
iii. Glass core with glass cladding.

Que 1.5. **Explain Snell's law. What is total internal reflection? Explain with suitable diagram.**

AKTU 2019-20, Marks 07

Answer

1. The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in a medium *i.e.*, $n = c/v$.
2. When a ray is incident on the interface between two dielectric of different refractive indices (*e.g.*, glass-air), refraction occurs as shown in Fig. 1.5.1.
3. The angle of incidence ϕ_1 and refraction ϕ_2 are related to each other and to the refractive indices of dielectrics by Snell's law of refraction.



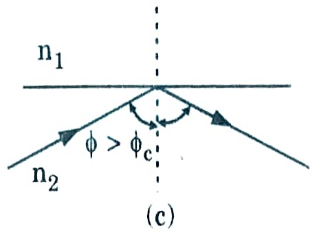


Fig. 1.5.1. Light rays incident on high to low refractive index interface (e.g., glass-air) : (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle f$_c$; (c) total internal reflection where f > f$_c$.

4. It states that

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

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

5. From Fig. 1.5.1(a), it is observed that a small amount of light is reflected back into the originating dielectric medium, this phenomenon is partial internal reflection.
6. As $n_1 > n_2$, the angle of refraction is always greater than angle of incidence.
7. From Fig. 1.5.1(b), it is observed that when angle of refraction ϕ_2 is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°.
8. Thus the angle of incidence in denser medium for which angle of refraction in rarer medium is 90° is called critical angle.
9. It is given as,

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

10. If the angle of incidence is greater than the critical angle then the light is reflected back into the originating dielectric medium then this process is known as total internal reflection as shown in Fig. 1.5.1(c).
11. Fig. 1.5.2 explains the transmission of a light ray in an optical fiber via a series of total internal reflection. The ray has an angle of incidence ϕ at the interface which is greater than the critical angle and is reflected at the same angle to the normal. This light ray is known as meridional ray.

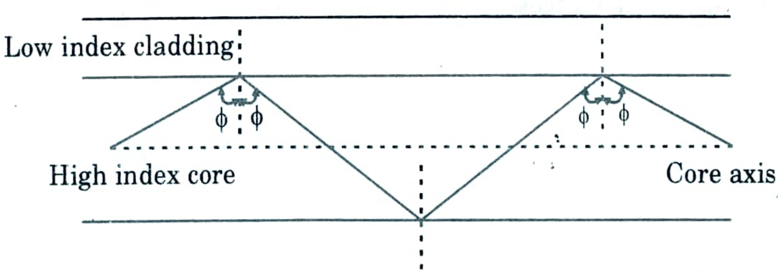


Fig. 1.5.2. The transmission of a light ray in a perfect optical fiber.

Que 1.6. **What do you mean by acceptance angle of an optical fiber ? Derive an expression for numerical apeı ture of optical fiber.**

Answer

A. Acceptance angle :

1. The geometry concerned with launching a light ray into an optical fiber is shown in Fig. 1.6.1.

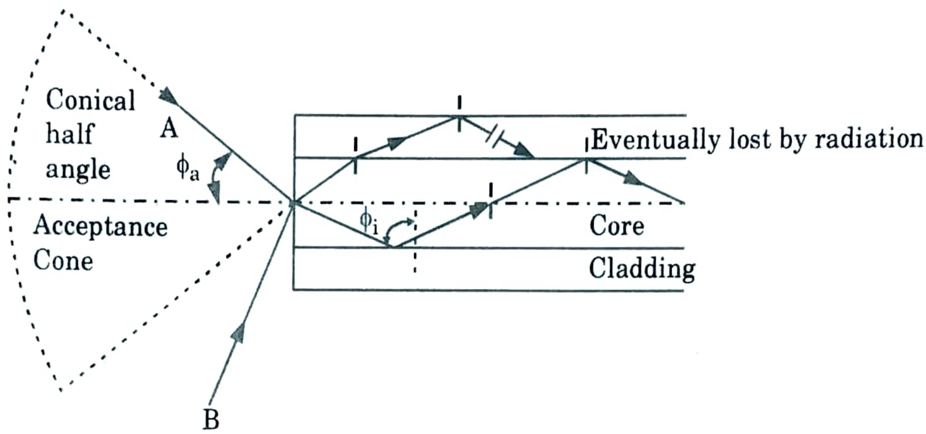


Fig. 1.6.1. The acceptance angle θ_a when launching light into an optical fiber.

2. In this, it is observed that the meridional ray '*A*' enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air core interface before transmission to the core-cladding interface at the critical angle.
3. Thus, any ray which is incident into the fiber core at an angle greater than θ_a will be transmitted to the core-cladding interface at an angle less than θ_c, and will not be totally internally reflected.
4. In the Fig. 1.6.1, it is observed that incident ray *B* at an angle greater than θ_a is refracted into the cladding and eventually lost by radiation.
5. Thus θ_a is the maximum angle to the axis at which light may enter the fiber in the order to be propagated, and is referred as acceptance angle.

B. Numerical aperture :

1. In the Fig. 1.6.2, it is observed that a light ray incident on the fiber core at an angle θ_1 is less than the acceptance angle θ_a .
2. The ray enters into the fiber from a medium of air having refractive index n_0, and the fiber core has refractive index n_1.
3. The refractive index n_1 is greater than the cladding refractive index n_2.
4. By considering the refraction at the air-core interface and using Snell's law, we get

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \quad ...(1.6.1)$$

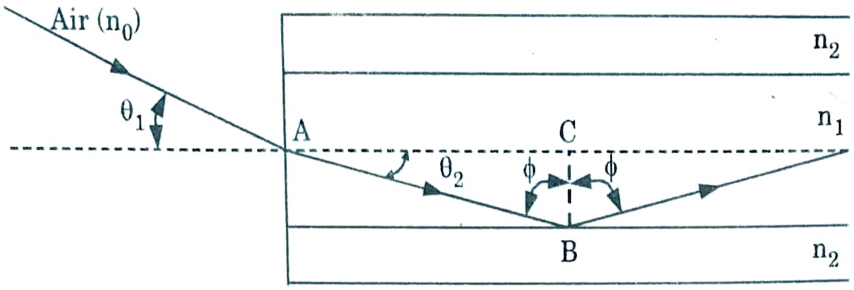


Fig. 1.6.2. The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber.

5. Considering the right-angled triangle ABC, the

$$\phi = \frac{\pi}{2} - \theta_2 \quad ...(1.6.2)$$

Here ϕ is greater than the critical angle at core-cladding interface.

6. Eq. (1.6.1) can be written as

$$n_0 \sin \theta = n_1 \cos \phi \quad ...(1.6.3)$$

7. By using relationship $\sin^2 \phi + \cos^2 \phi = 1$, then eq. (1.6.3) can be written as

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{1/2} \quad ...(1.6.4)$$

8. When the limiting case of total internal reflection is consider, ϕ becomes equal to critical angle for core cladding interface. In this case θ_1 becomes the acceptance angle θ_a. Therefore

$$n_0 \sin \theta_a = n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \quad ...(1.6.5)$$

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2} \quad ...(1.6.6)$$

9. Thus the *NA* is defined as the light capturing capability that can be accepted by a fiber.

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2} \quad ...(1.6.7)$$

10. The numerical aperture may also be given in terms of relative refractive index difference Δ between the core and cladding

i.e.,
$$\Delta = \frac{n_1^2 - n_2^2}{2 n_1^2} \quad ...(1.6.8)$$

$$\simeq \frac{n_1 - n_2}{n_1} \text{ for } \Delta << 1 \quad ...(1.6.9)$$

11. Hence combining eq. (1.6.7) with eq. (1.6.8), we get

$$NA = n_1 (2\Delta)^{1/2}$$

Que 1.7. **What are skew rays ?**

Answer

1. The rays which outnumber the meridional rays and follow a helical path through the fiber are called skew rays.
2. This type of ray is transmitted without passing through fiber axis.
3. It is very difficult to visualize the skew ray paths in two dimension.
4. From Fig. 1.7.1, it is observed that the helical path traced through the fiber gives a change in direction of 2γ at each reflection where γ is the angle between the projection of the ray in two dimensions and radius of fiber core at the point of reflection.

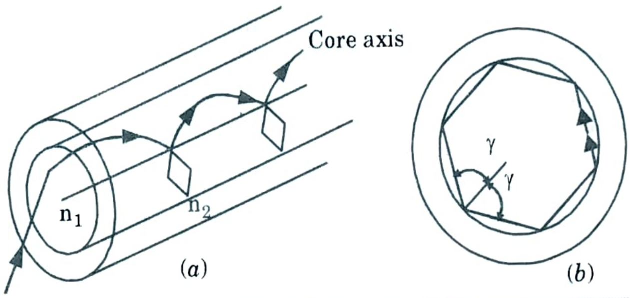


Fig. 1.7.1. The helical path taken by a skew ray in an optical fiber: (*a*) skew ray path down the fiber (*b*) cross-sectional view of the fiber.

5. The point of emergence of skew rays from the fiber in air will depend upon the number of reflections they undergo rather than the input condition to the fiber.
6. When the light input to the fiber is non-uniform, skew rays will tend to have smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output.
7. The amount of smoothing is dependent on the number of reflections encountered by the skew rays.
8. The acceptance conditions for skew rays are :

$$n_0 \sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{1/2} = NA$$

9. When

$$n_0 = 1$$

$$\sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{1/2} = NA$$

Que 1.8. **An optical fiber in air has an *NA* of 0.4. In that fiber, skew rays which change direction by 100° at each reflection. Find out the acceptance angle of skew rays.**

AKTU 2016-17, Marks 05

OR

Discuss skew rays. An optical fiber in air has an *NA* of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

AKTU 2015-16, Marks 05

Answer

A. **Screw rays :** Refer Q. 1.7, Page 1–9D, Unit-1.

B. **Numerical :**

Given : $NA = 0.4$

To Find : Acceptance angle.

1. As $$NA = n_0 \sin \theta_a$$
   Here $$n_0 = 1$$
   $$NA = \sin \theta_a$$
   $$\theta_a = \sin^{-1} NA$$
   $$\theta_a = \sin^{-1} 0.4 = 23.58°$$
2. The skew rays change direction by 100° at each reflection, therefore
   $$\gamma = 50°$$
3. Acceptance angle for skew rays is
   $$\theta_{as} = \sin^{-1}\left[\frac{NA}{\cos \gamma}\right] = \sin^{-1}\left[\frac{0.4}{\cos 50°}\right]$$
   $$= 38.32°$$
4. In this, the acceptance angle for the skew rays is about 15° greater than meridional rays.

Que 1.9. **Derive expression of acceptance angle for skew rays. An optical fiber has numerical aperture of 0.344. What is the acceptance angle for meridional rays ? Calculate the acceptance angle for skew rays which change direction by 100^0 at each reflection.**

AKTU 2017-18, Marks 10

Answer

A. **Derivation of acceptance angle for screw rays :** Refer Q. 1.6, Page 1–8D, and Refer Q. 1.7, Page 1–9D, Unit-1.

B. **Numerical :**

Given : $NA = 0.344$

To Find : Acceptance angle.

1. As $$NA = n_0 \sin \theta_a$$
   Here $$n_0 = 1$$
   $$NA = \sin \theta_a$$
   $$\theta_a = \sin^{-1} NA$$
   $$\theta_a = \sin^{-1} 0.344$$
   $$= 20.13°$$
2. The skew rays change direction by 100° at each reflection, therefore
   $$\gamma = 50°$$
3. Acceptance angle for skew rays is

$$\theta_{as} = \sin^{-1}\left[\frac{NA}{\cos\gamma}\right] = \sin^{-1}\left[\frac{0.344}{\cos 50^\circ}\right]$$

$$= 32.3°$$

4. In this, the acceptance angle for the skew rays is about 12° greater than meridional rays.

Que 1.10. **Sketch the block diagram of optical fiber communication system. With the suitable ray diagram, explain the propagation of skew rays in the optical waveguide and compare it with meridional rays.**

AKTU 2018-19, Marks 10

Answer

A. **Block diagram of optical fiber communication :** Refer Q. 1.2, Page 1–4D, Unit-1.
B. **Screw rays :** Refer Q. 1.7, Page 1–9D, Unit-1.
C. **Comparison between skew rays and meridional rays :**

S. No.	Skew rays	Meridional rays
1.	This type of ray transmitted without passing through fiber axis.	This type of ray enters the core and passes through its axis.
2.	These types of rays are not confined to single plane, but instead tend to follow a helical type path alone the fiber.	These rays are confined to meridian planes of the fiber which are the planes that contain the axis of symmetry of the fiber.
3.	These rays are difficult to locate as they are confined to single plane.	As these rays lies in a single plane its path is easy to track as it travels along the fiber.

Que 1.11. **A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47.**
Determine :
a. **The critical angle at the core-cladding interface ;**
b. **The *NA* for the fiber ;**
c. **The acceptance angle in air for the fiber.**

AKTU 2015-16, Marks 05

OR

What do you mean by acceptance angle of an optical fiber ? Derive an expression for numerical aperture of optical fiber. A silica optical fiber with a core diameter large enough to be considered by ray

theory analysis has a core refractive index of 1.5 and cladding refractive index of 1.47. Determine critical angle at core cladding interface, *NA* (Numerical aperture) for the fiber and Acceptance angle.

AKTU 2018-19, Marks 10

Answer

A. **Acceptance angle :** Refer Q. 1.6, Page 1–8D, Unit-1.

B. **Derivation of numerical aperture :** Refer Q. 1.6, Page 1–8D, Unit-1.

C. **Numerical :**

Given : $n_1 = 1.5$, $n_2 = 1.47$
To Find : Critical angle, *NA*, acceptance angle.

i. Critical angle to core cladding interface,

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.5}\right) = 78.52°$$

ii. $$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.47)^2} = 0.298$$

iii. Acceptance angle, $\theta_A = \sin^{-1}(NA) = \sin^{-1}(0.298) = 17.36°$

PART-3

Electromagnetic Mode Theory for Optical Propagation, Modes in a Planar Guide, Phase and Group Velocity.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.12. State electromagnetic wave theory. Describe Maxwell's equation for electromagnetic wave propagation.

Answer

1. There are two approaches which describe the guiding of light in optical fiber. The first one is geometrical or ray optics approach and the second one is wave optics approach.
2. In wave optics approach the light is considered as an electromagnetic wave. To obtain an improved model for the propagation of light in an optical fiber, electromagnetic wave theory must be considered.
3. The basis for the study of electromagnetic wave propagation is provided by Maxwell's equations. Maxwell's equations give the relationships between the electric and magnetic fields.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad ...(1.12.1)$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \quad ...(1.12.2)$$

$$\nabla \cdot \vec{D} = 0 \text{ (no free charges)} \quad ...(1.12.3)$$

$$\nabla \cdot \vec{B} = 0 \text{ (no free poles)} \quad ...(1.12.4)$$

where $\vec{D} = \varepsilon \vec{E}$ and $\vec{B} = \mu \vec{H}$. The parameter ε is the permittivity (or dielectric constant) and μ is the permeability of the medium.

4. A relationship defining the wave phenomena of the electromagnetic fields can be derived from Maxwell's equations.
5. Taking the curl of eq. (1.12.1), we have

$$\nabla \times (\nabla \times \vec{E}) = -\frac{\partial}{\partial t}(\nabla \times \vec{B}) = -\mu \frac{\partial}{\partial t}(\nabla \times \vec{H})$$

$$\nabla(\nabla . \vec{E}) - \nabla^2 \vec{E} = -\mu \frac{\partial^2 \vec{D}}{\partial t^2}$$

$$-\nabla^2 \vec{E} = -\mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2}$$

or

$$\nabla^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad ...(1.12.5)$$

6. Similarly, by taking the curl of eq. (1.12.2) it can be shown that

$$\nabla^2 \vec{H} = \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \quad ...(1.12.6)$$

7. Eq.(1.12.5) and eq.(1.12.6) are known as standard wave equations.
8. For rectangular cartesian and cylindrical polar coordinates, the above wave equations satisfying the scalar wave equation :

$$\nabla^2 \psi = \frac{1}{v_p^2} \frac{\partial^2 \psi}{\partial t^2} \quad ...(1.12.7)$$

where ψ may represent a component of the $\vec{E}$ or $\vec{H}$ field and v_p is the phase velocity (velocity of propagation of a point of constant phase in the wave) in the dielectric medium.

9. It follows that

$$v_p = \frac{1}{\sqrt{\mu\,\varepsilon}} = \frac{1}{\sqrt{(\mu_r\,\mu_0)\,(\varepsilon_r\,\varepsilon_0)}} \quad ...(1.12.8)$$

where μ_r and ε_r are the relative permeability and permittivity for the dielectric medium and μ_0 and ε_0 are the permeability and permittivity of free space.

10. The velocity of light in free space is

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad ...(1.12.9)$$

11. In planar waveguides, described by rectangular cartesian coordinates (x, y, z) or circular fibers, described by cylindrical polar coordinates (r, ϕ, z) are considered, then the Laplacian operator takes the form :

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} \quad ...(1.12.10)$$

or

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\Psi}{\partial z^2} \quad ...(1.12.11)$$

12. The basic solution of the wave equation is a sinusoidal wave, that varies with t and it is a function of only one position variable, which in our case we will initially assume, is z.

13. Thus,

$$\psi = \psi_0 \exp\ j(\omega t - \vec{k}\,.\,\vec{z}) \quad ...(1.12.12)$$

where ω is the angular frequency of the field, t is the time, $\vec{k}$ is the propagation vector which gives the direction of propagation and the rate of change of phase with distance.

14. The vacuum phase propagation constant k (where $k = |\vec{k}|$) is given by

$$k = \frac{2\pi}{\lambda}$$

15. The complete expression for electric field and magnetic field when there is no loss,

$$E(z, t) = E_0 \exp j(\omega t \pm kz) \quad ...(1.12.13)$$

and

$$H(z, t) = H_0 \exp j(\omega t \pm kz) \quad ...(1.12.14)$$

16. For this condition, $\vec{E}$ and $\vec{H}$ are inphase to determine the directions of $\vec{E}$ and $\vec{H}$ and the ratio of their magnitudes. This ratio is called the intrinsic wave impedance.

17. From equation $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$, we have,

$$\hat{j}\frac{\partial E_x}{\partial z} - \hat{i}\frac{\partial E_y}{\partial z} = -\hat{i}\frac{\partial B_x}{\partial t} - \hat{j}\frac{\partial B_y}{\partial t} - k\frac{\partial B_z}{\partial t} \quad ...(1.12.15)$$

because ε is a function of z only. The terms $\hat{i}$, $\hat{j}$ and $\hat{k}$ are unit vectors.

18. If we arbitrarily choose the x direction to be parallel to E, $B_x = B_z = 0$

and

$$\frac{\partial E_x}{\partial z} = -\frac{\partial B_y}{\partial t}$$

$$E_{0x} = \pm \frac{\omega}{k} \mu H_{0y}$$

$$\frac{E_{0x}}{H_{0y}} = \pm \sqrt{\frac{\mu}{\varepsilon}}$$

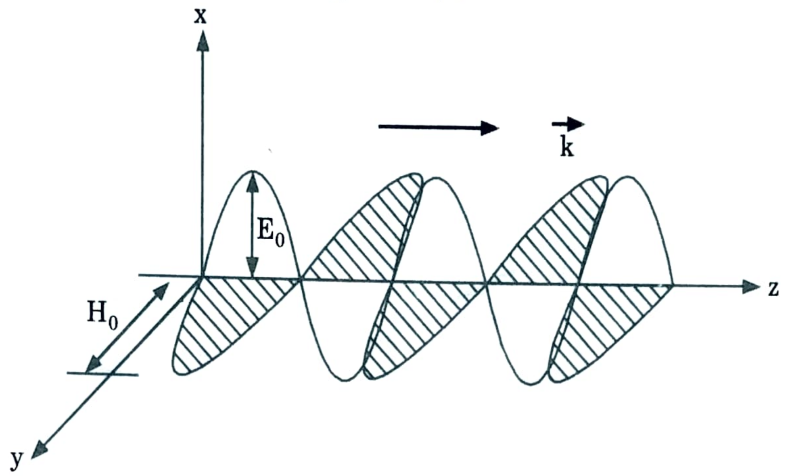


Fig. 1.12.1. A plane electromagnetic wave propagating in the + z direction.

19. The plus sign is for a wave moving in the + z direction and the minus sign is for a wave moving in the – z direction. One can see that $\vec{E} \perp \vec{H} \perp \vec{k}$ (Fig. 1.12.1) and the vector $\vec{E} \times \vec{H}$ is parallel to the direction of propagation.

Que 1.13. **Explain modes in a planar guide. Also state the formation of modes in a planar dielectric guide.**

OR

Analyze the light propagation in dielectric slab waveguide.

AKTU 2016-17, Marks 10

Answer

1. The planar guide is the simplest form of optical waveguide. We may assume it consists of a slab of dielectric with refractive index n_1 sandwiched between two regions of lower refractive index n_2.
2. In order to obtain an improved model for optical propagation it is useful to consider the interference of plane wave components within this dielectric waveguide.
3. A plane monochromatic wave propagating in the direction of the ray path within the guide as shown in Fig. 1.13.1(a).
4. As the refractive index within the guide is n_1, the optical wavelength in this region is reduced to λ/n_1, while the vacuum propagation constant is increased to n_1k.
5. When θ is the angle between the wave propagation vector or the equivalent ray and the guide axis, the plane wave can be resolved into

two component plane waves propagating in the z and x directions, as shown in Fig. 1.13.1.

6. The component of the phase propagation constant in the z direction β_z is given by :

$$\beta_z = n_1 k \cos\theta \quad ...(1.13.1)$$

7. The component of the phase propagation constant in the x direction β_x is

$$\beta_x = n_1 k \sin\theta \quad ...(2.13.2)$$

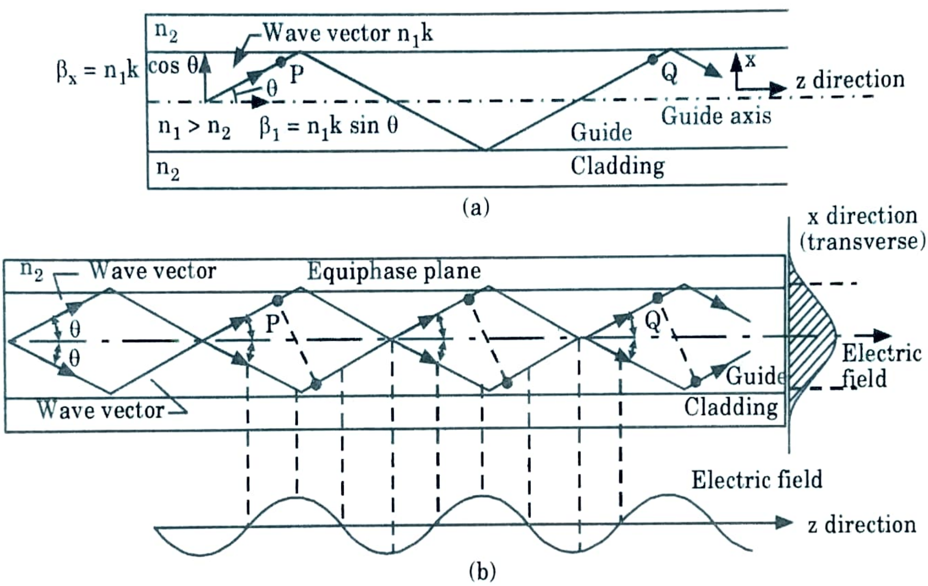


Fig. 1.13.1. The formation of a mode in a planar dielectric guide.

8. The component of the plane wave in the x-direction is reflected at the interface between the higher and lower refractive index media.
9. When the total phase change after two successive reflections at the upper and lower interfaces (between the points P and Q) is equal to $2m\pi$ radians, where m is an integer, then constructive interference occurs and a standing wave is obtained in the x-direction.
10. This situation is illustrated in Fig. 1.13.1(b), the optical wave is effectively confined within the guide and the electric field distribution in the x-direction does not change as the wave propagates in the z-direction.
11. The sinusoidally varying electric field in the z-direction is also shown in Fig. 1.13.1(b).
12. The stable field distribution in the x-direction with only periodic z dependence is known as a mode.
13. A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface have a particular value, as indicated in Fig. 1.13.1(b).
14. In effect, eq. (1.13.1) and eq. (1.13.2) define a group or congruence of rays which in the case described represents the lowest order mode.
15. Hence the light propagating within the guide is formed into discrete modes, each specified by a distinct value of θ.

16. These modes have a periodic z dependence of the form $\exp(-j\beta_z z)$ where β_z becomes the propagation constant for the mode as the modal field pattern is invariant except for a periodic z dependence.

Que 1.14. What is phase velocity and group velocity ? Derive the relation between group velocity and group index of the guide.

AKTU 2018-19, Marks 10

Answer

1. A monochromatic light wave propagates along a waveguide in the z-direction these points of constant phase travel at a phase velocity v_p given by :

$$v_p = \frac{\omega}{\beta} \quad ...(1.14.1)$$

where ω is the angular frequency of the wave.
2. A group of waves with closely similar frequencies propagate so that their resultant forms a packet of waves.
3. This wave packet does not travel at the phase velocity of the individual waves but is observed to move at a group velocity v_g given by

$$v_g = \frac{\delta\omega}{\delta\beta} \quad ...(1.14.2)$$

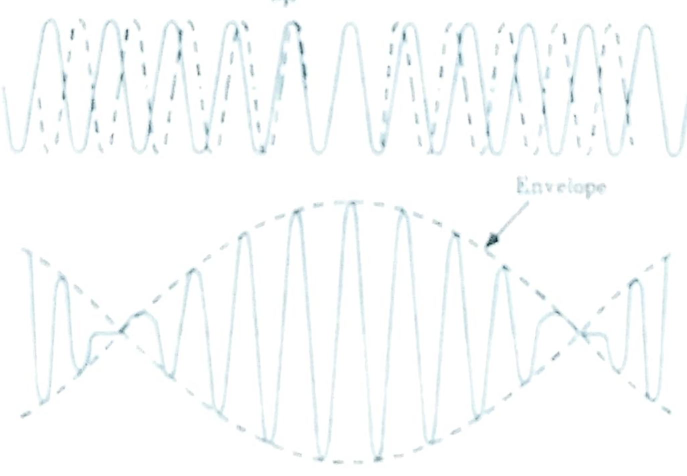


Fig. 1.14.1. Combination of two waves with nearly equal frequencies. The envelope travels at a group velocity v_g.

4. The group velocity is of greatest importance in the study of the transmission characteristics of optical fibers as it relates to the propagation characteristics of observable wave groups or packets of light.
5. If propagation in an infinite medium of refractive index n_1 is considered, then the propagation constant

$$\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1\omega}{c} \quad ...(1.14.3)$$

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where c is the velocity of light in free space.

6. We assume propagation in the z direction only and hence $\cos\theta$ is equal to unity. Using eq. (1.14.3) we obtain the following relationship for the phase velocity.

$$v_p = \frac{c}{n_1} \quad ...(1.14.4)$$

7. Similarly, employing eq. (1.14.4), where in the limit $\frac{\delta\omega}{\delta\beta}$ becomes $\frac{d\omega}{d\beta}$, the group velocity :

$$v_g = \frac{d\lambda}{d\beta}\cdot\frac{d\omega}{d\lambda}$$

$$= \frac{d}{d\lambda}\left(n_1\frac{2\pi}{\lambda}\right)^{-1}\left(\frac{-\omega}{\lambda}\right) = \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1}$$

$$= \frac{c}{\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)} = \frac{c}{N_g}$$

The parameter N_g is known as the group index of the guide.

PART-4

Phase Shift with Total Internal Reflection, Evanescent Field, Goos-Haenchen Shift.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.15. Explain in detail the phase shift with total internal reflection.

Answer

1. The wave equation in cartesian coordinates for the electric field in a lossless medium is :

$$\nabla^2 E = \mu\varepsilon\frac{\partial^2 E}{\partial t^2} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} \quad ...(1.15.1)$$

2. As the guide-cladding interface lies in the y-z plane and the wave is incident in the x-z plane on the interface, then $\partial/\partial y$ may be assumed to be zero.

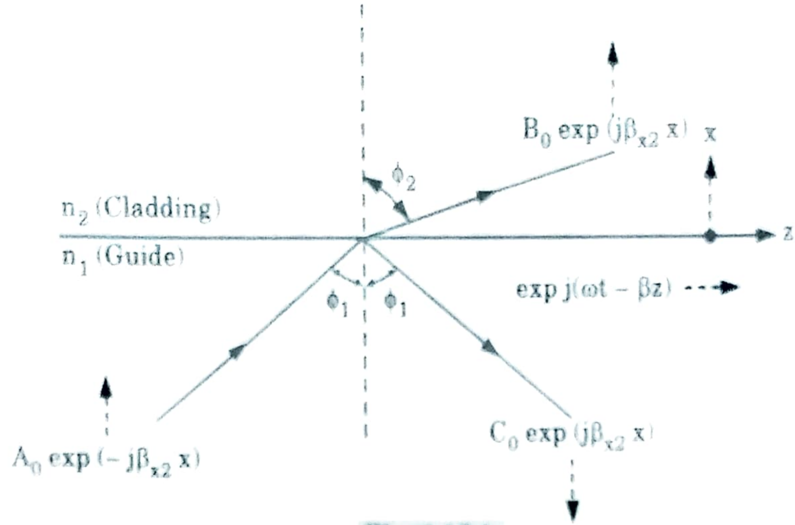


Fig. 1.15.1.

3. There the wave propagation in the z-direction may be described by $\exp j(\omega t - \beta z)$. In addition, there will also be propagation in the x-direction.
4. When the components are resolved in this plane :

$$\beta_{x1} = n_1 k \cos \phi_1 \qquad \text{...(1.15.2)}$$

$$\beta_{x2} = n_2 k \cos \phi_2 \qquad \text{...(1.15.3)}$$

where β_{x1} and β_{x2} are propagation constants in the x-direction for the guide and cladding respectively.

5. Thus, the three waves in the waveguide indicated in Fig. 1.15.1. The incident, the transmitted and the reflected, with amplitudes A_0, B_0 and C_0, respectively, will have the forms :

$$A = A_0 \exp - (j\beta_{x1}\, x) \exp j(\omega t - \beta z) \qquad \text{...(1.15.4)}$$

$$B = B_0 \exp - (j\beta_{x2}\, x) \exp j(\omega t - \beta z) \qquad \text{...(1.15.5)}$$

$$C = C_0 \exp - (j\beta_{x1}\, x) \exp j(\omega t - \beta z) \qquad \text{...(1.15.6)}$$

6. Using the simple trigonometrical relationship $\cos^2 \phi + \sin^2 \phi = 1$:

$$\beta_{x1}^2 = (n_1^2 k^2 - \beta^2) = -\xi_1^2 \qquad \text{...(1.15.7)}$$

$$\beta_{x2}^2 = (n_2^2 k^2 - \beta^2) = -\xi_2^2 \qquad \text{...(1.15.8)}$$

7. When an electromagnetic wave is incident upon an interface between two dielectric media, Maxwell's equation require that both the tangential components of E and H and the normal components of D ($= \varepsilon E$) and B ($= \mu H$) are continuous across the boundary.
8. The normal components of the E and H fields at the interface may be equated giving

$$A_0 + C_0 = B_0 \qquad \text{...(1.15.9)}$$

9. An electric field component in the y direction is related to the tangential magnetic field component H_z following

$$H_z = \frac{J}{\mu r\, \mu_0 \omega} \frac{\partial E_y}{\partial x} \qquad \text{...(1.15.10)}$$

10. Applying the tangential boundary conditions and equating H_z by differentiating E_y gives :

$$-\beta_{x1}A_0 + \beta_{z2}C_0 = -\beta_{x2}B_0 \quad ...(1.15.11)$$

11. Algebraic manipulation of eq. (1.15.9) and (1.15.10) provides the following results :

$$C_0 = A_0\left(\frac{\beta_{x1}-\beta_{x2}}{\beta_{x1}+\beta_{x2}}\right) = A_0 r_{ER} \quad ...(1.15.12)$$

$$B_0 = A_0\left(\frac{2\beta_{x1}}{\beta_{x1}+\beta_{x2}}\right) = A_0 r_{ET} \quad ...(1.15.13)$$

12. If f_1 is further increased the component β_{x2} becomes imaginary and we may write it in the form $-j\xi_2$. Under the conditions of total internal reflection eq. (1.15.12) may therefore be written as :

$$C_0 = A_0\left(\frac{\beta_{x1}+j\xi_2}{\beta_{x1}+j\xi_2}\right) = A_0 \exp 2j\delta_E \quad ...(1.15.14)$$

13. Where we observe there is a phase shift of the reflected wave relative to the incident wave. This is signified by δ_E which is given by :

$$\tan \delta_E = \frac{\xi_2^2}{\beta_{x1}} \quad ...(1.15.15)$$

Que 1.16. **Write a short note on evanescent field.**

Answer

1. The phenomenon of interest under conditions of total internal reflection is the form of the electric field in the cladding of the guide.
2. Before the critical angle for total internal reflection is reached, and hence when there is only partial reflection, the field in the cladding is of the form given by

$$B = B_0 \exp -(j\beta_{x2}\, x) \exp j(\omega t - \beta z) \quad ...(1.16.1)$$

3. However, as indicated previously, when total internal reflection occurs, β_{x2} becomes imaginary and may be written as $-j\xi_2$. Substituting for β_{x2} in eq. (1.16.1) gives the transmitted wave in the cladding as :

$$B = B_0 \exp(-\xi 2x) \exp j(\omega t - \beta z) \quad ...(1.16.2)$$

4. Thus the amplitude of the field in the cladding is observed to decay exponentially in the x direction.
5. Such a field, exhibiting and exponentially decaying amplitude, is often referred to as evanescent field.
6. Fig. 1.16.1 shows a diagrammatic representation of the evanescent field.
7. A field of this type stores energy and transports it in the direction of propagation (z) but does not transport energy in the transverse direction (x).
8. Nevertheless, the existence of an evanescent field beyond the plane of reflection lower index medium indicates that optical energy is transmitted into the cladding.

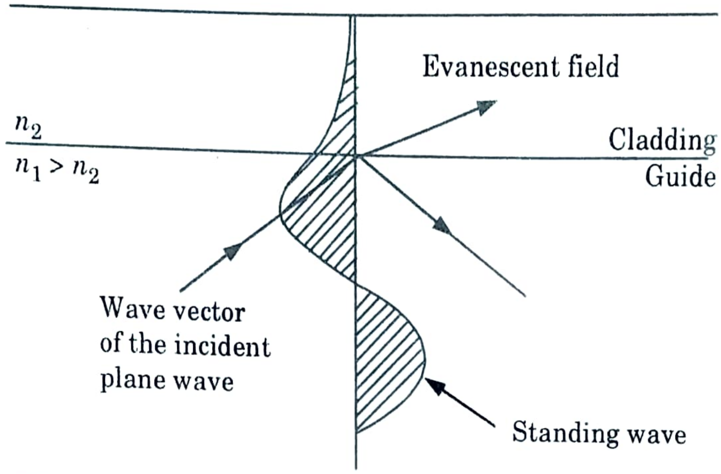


Fig. 1.16.1. The exponentially decaying evanescent field in the cladding of the optical waveguide.

Que 1.17. **Explain Goos-Hanchen shift.**

Answer

1. The phase change incurred with the total internal reflection of a light beam on a planar dielectric interface may be understood from physical observation.
2. Careful examination shows that the reflected beam is shifted laterally from the trajectory predicted by simple ray theory analysis, as illustrated in Fig. 1.17.1.
3. This lateral displacement is known as the Goos-Hanchen shift, after its first observer.

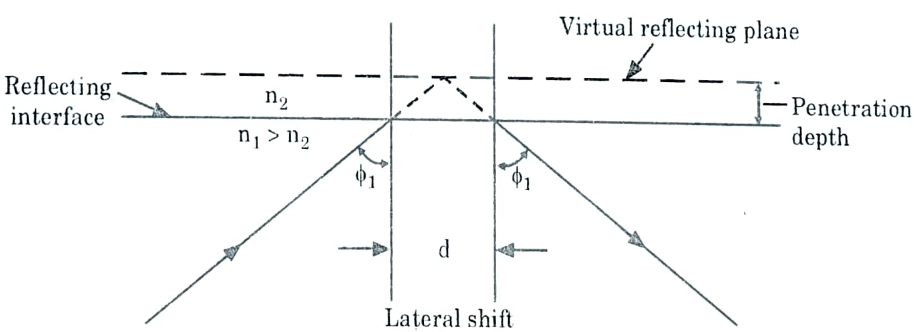


Fig. 1.17.1. The lateral displacement of a light beam on reflection at a dielectric interface (Goos-Haenchen shift).

PART-5

Cylindrical Fiber Modes, Mode Coupling, Step Index Fibers vs Graded Index Fibers, Single Mode Fibers-Cut-off Wavelength, MFD and Spot Size.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.18. **Explain the modes in cylindrical fiber and derive an expression for normalised frequency.**

Answer

1. The cylindrical waveguide is bounded in two dimensions rather than one. Thus two integers, l and m, are necessary in order to specify the modes.
2. For cylindrical waveguide we therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays travelling within the fiber.
3. However, hybrid modes where E_z and H_z are non-zero also occur within the cylindrical waveguide.
4. For the cylindrical homogeneous core waveguide the scalar wave equation can be written in the form :

$$\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} + \frac{1}{r^2}\frac{d^2\psi}{d\phi^2} + (n_1^2k^2 - \beta^2)\psi = 0 \qquad ...(1.18.1)$$

where ψ is the field (E or H), n_1 is the refractive index of the fiber core, k is the propagation constant for light in a vacuum, and r and ϕ are cylindrical coordinates.
5. The propagation constants of the guided modes β lie in the range :

$$n_2k < \beta < n_1k$$

where n_2 is the refractive index of the fiber cladding.
6. Solutions of the wave equation for the cylindrical fiber are separable, having the form:

$$\psi = E(r)\left\{\begin{matrix}\cos l\phi \\ \sin l\phi\end{matrix}\exp(\omega t - \beta z)\right\} \qquad ...(1.18.2)$$

where in this case ψ represents the dominant transverse electric field component.
7. The periodic dependence on ϕ following $\cos l\phi$ or $\sin l\phi$ gives a mode of radial order l. Hence the fiber supports a finite number of guided modes of the form of eq. (1.18.2).
8. Introducing the solutions given by eq. (1.18.1) into eq. (1.18.2) results in a differential equation of the form :

$$\frac{d^2E}{dr^2} + \frac{1}{r}\frac{dE}{dr} + \left[(n_1k^2 - \beta^2) - \frac{l^2}{r^2}\right]E = 0 \qquad ...(1.18.3)$$

9. For a step index fiber with a constant refractive index core, eq. (1.18.1) is a Bessel differential equation and the solutions are cylinder functions.

10. In the core region, the solutions are Bessel functions denoted by J_l. A graph of these gradually damped oscillatory functions (with respect to r) is shown in Fig. 1.18.1.

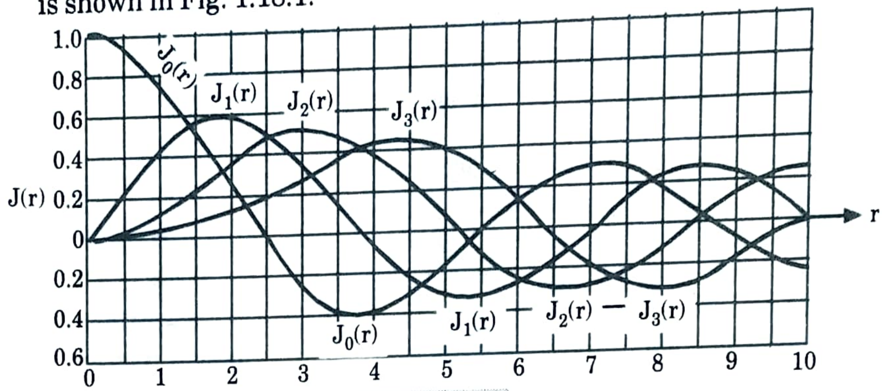


Fig. 1.18.1.

11. The electric field may therefore be given by :

$$E(r) = GJ_l(UR) \quad \text{...(1.18.4)}$$

For $R < 1$ (core)

$$= GJ_l(U)\frac{K_l(WR)}{K_l(W)}$$

For $R > 1$ (cladding)

where G is the amplitude coefficient and $R = r/a$ is the normalized radial coordinate when a is the radius of the fiber core.

12. U and W which are the eigen values in the core and cladding respectively, are defined as

$$U = a(n_1^2k^2 - \beta^2)^{1/2} \quad \text{...(1.18.5)}$$

$$W = a(b^2 - n_2^2k^2)^{1/2} \quad \text{...(1.18.6.)}$$

13. The normalized frequency V where

$$V = (U^2 + W^2)^{1/2}$$

$$V = ka(n_1^2 - n_2^2)^{1/2} \quad \text{...(1.18.7)}$$

14. The normalized frequency may be expressed in terms of the numerical aperture (NA) and the relative refractive index difference (Δ), respectively, as :

$$V = \frac{2\pi}{\lambda}a(NA) \quad \text{...(1.18.8)}$$

$$V = \frac{2\pi}{\lambda}an_1(2\Delta)^{1/2} \quad \text{...(1.18.9)}$$

15. The normalized frequency is a dimensionless parameter and hence is also sometimes simply called the V number or value of the fiber.

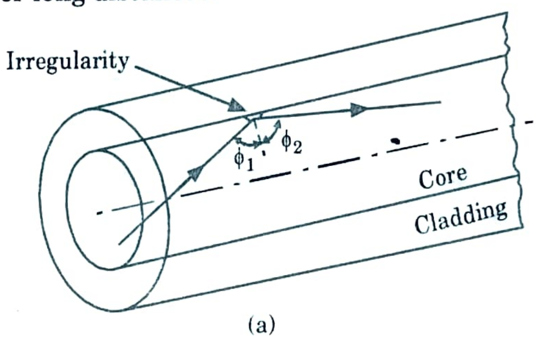
Que 1.19. Define mode coupling in cylindrical fiber.

Answer

1. Waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core

cladding interface and refractive index variations may change the propagation characteristics of the fiber.

2. These will have the effect of coupling energy travelling in one mode to another depending on the specific perturbation.
3. Ray theory aids the understanding of this phenomenon, as shown in Fig. 1.19.1, which illustrates two types of perturbation. It may be observed that in both cases the ray no longer maintains the same angle with the axis.
4. In electromagnetic wave theory this corresponds to a change in the propagating mode for the light.
5. Thus individual modes do not normally propagate throughout the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing.
6. Mode coupling affects the transmission properties of fibers in several important ways, a major one being in relation to the dispersive properties of fibers over long distances.



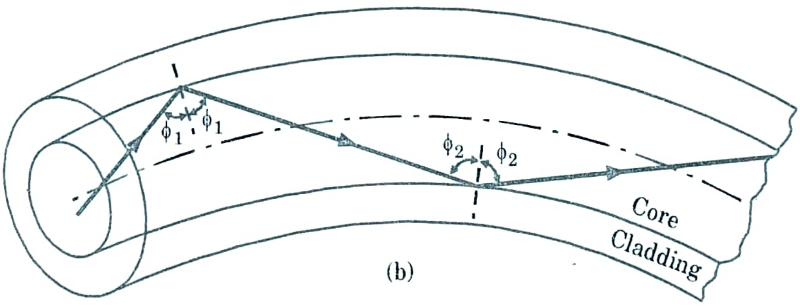


Fig. 1.19.1. (a) irregularity at the core-cladding interface; (b) fiber bend.

Que 1.20. **Describe with simple ray diagram the step index fiber.**

OR

What is mode coupling ? Describe step index fiber with its refractive index profile and ray transmission through it.

AKTU 2015-16, Marks 7.5

Answer

A. **Mode Coupling :** Refer Q. 1.19, Page 1–24D, Unit-1.

B. **Step Index Fiber :**

1. A step index fiber is one for which the refractive index of core n_1 is constant and is larger than the refractive index of the cladding n_2.
2. The refractive index profile for this type of fiber makes a step change at the core-cladding interface that's why it is named as step index fiber.
3. The refractive index profile may be defined as :

$$n(r) = \{n_1, \quad r < a \text{ (core)}$$
$$= \{n_2, \quad r \geq a \text{ (cladding)}$$

4. There are two major types of step index fiber
   a. Multimode step index fiber
   b. Single mode step index fiber.
5. The Fig. 1.20.1 shows a multimode step index fiber and single mode step fiber. In multimode step index fiber core diameter is around 50 μm or greater, which is large enough to allow the propagation of many modes within the fiber whereas single mode step index fiber has a very fine thin core, so that only one mode can be propagated.

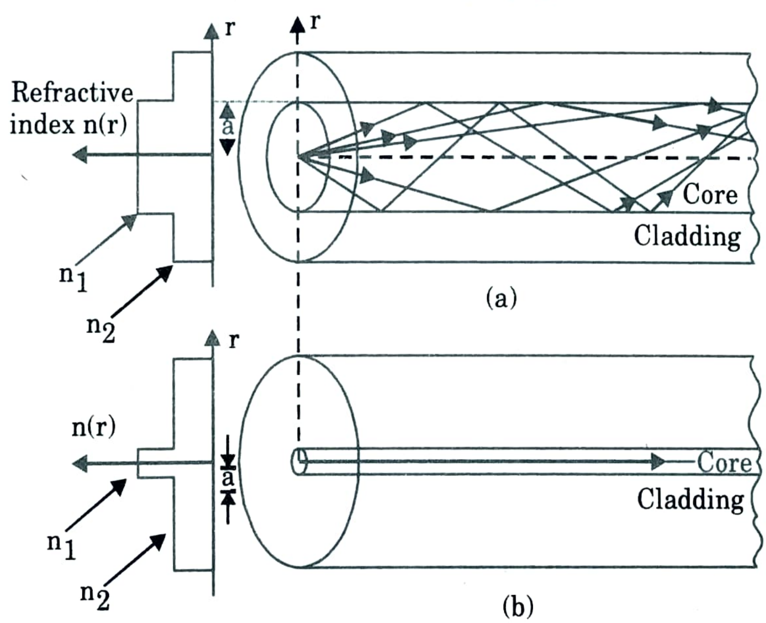


Fig. 1.20.1. The refractive index profile and transmission in step index fibers : (a) multimode step index fiber ; (b) single-mode step index fiber.

6. Multimode step index fiber allows the propagation of finite number of guided modes along the channel.
7. The number of guided modes is dependent upon the physical parameters of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency V of fiber.

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \quad ...(1.20.1)$$

where a = Radius of the core,

λ = Free space wavelength.

8. The eq. (1.20.1) can also be written in form

$$V = \frac{2\pi a}{\lambda} NA$$

or
$$V = \frac{2\pi a}{\lambda} n_1\sqrt{2\Delta}$$

9. Guided modes are important in optical fiber communications as these are confined to fiber over its full length.
10. The total number of guided modes is also known as mode volume (M_S).
11. For step index fiber, $M_S \approx \dfrac{V^2}{2}$
12. For single mode fiber $V < 2.405$ and for multimode fiber $V > 2.405$.

Que 1.21. **How does the ray of light propagate in a graded index fiber ?**

OR

Draw the structures of single and multimode step index fibers and graded index fiber with their typical dimensions.

AKTU 2019-20, Marks 07

Answer

A. Single and multimode step index fiber : Refer Q. 1.20, Page 1–25D, Unit-1.

B. Graded index fiber :

1. Graded index fibers do not have a constant refractive index in the core but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius 'a' in the cladding.
2. The index variation may be represented as

$$n(r) = \{n_1 (1 - 2\,\Delta\,(r/a)^{\alpha})^{1/2} \qquad r < a \text{ (core)}$$
$$= \{n_1 (1 - 2\,\Delta)^{1/2} = n_2 \qquad r \geq a \text{ (cladding)}$$

where Δ is relative refractive index difference and α is a profile parameter which gives the refractive index profile of the fiber core.

3. The equations above is a convenient method of expressing the refractive index profile of the fiber core as a variation of α allows representation of the step index profile when $\alpha = \infty$, a parabolic profile when $\alpha = 2$ and a triangular profile when $\alpha = 1$.

4. The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with $\alpha \approx 2$.

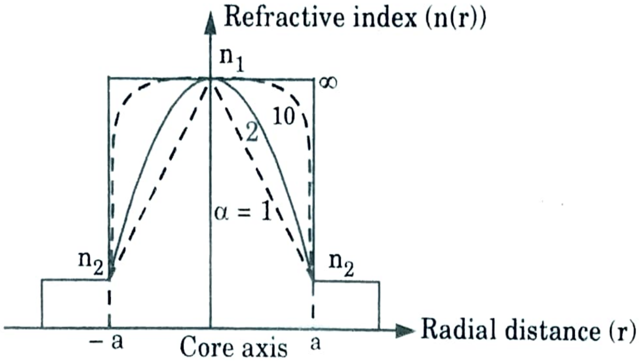


Fig. 1.21.1. Possible fiber refractive index profiles for different values of α.

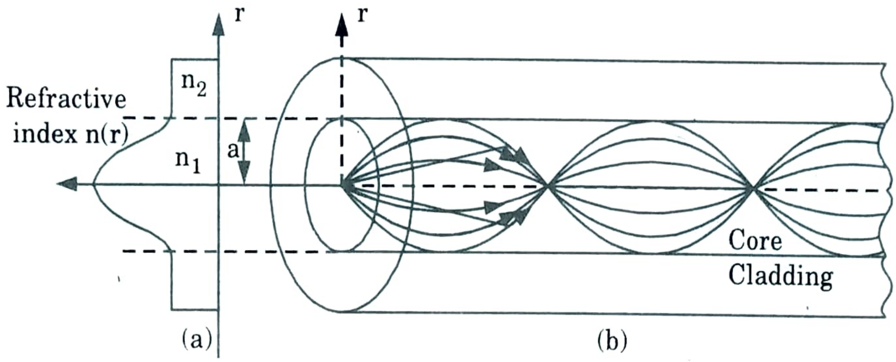


Fig. 1.21.2. The refractive index profile and ray transmission in a multimode graded index fiber.

5. A multimode graded index fiber with a parabolic index profile core is shown in Fig. 1.21.2. It is observed that meridional rays appear to follow a curved path through the fiber core.
6. Using the idea of geometric optics, the gradual decrease in refractive index from the center of the core creates much refraction of the rays as they are effectively incident on a large number of the high to low index interface.
7. The rays travelling close to the fiber axis have shorter paths when compared with rays which travel into outer regions.
8. The near axial rays are transmitted through a region of higher refractive index and therefore travel with a lower velocity than the more extreme rays.

Que 1.22. **Describe with the aid of simple ray diagrams :**

i. The multimode step index fiber,

ii. The single mode step index fiber.

Compare the advantages and disadvantages of these two types of fiber for use as an optical channel. **AKTU 2018-19, Marks 10**

OR

Compare the step index fiber and graded index fiber on their performance parameters. **AKTU 2016-17, Marks 10**

Answer

A. **Simple ray diagram :** Refer Q. 1.20, Page 1–25D, Unit-1.

B. **Comparison :**

S. No.	Step index fiber	Grade index fiber
1.	A step index fiber has a central core with uniform refractive index. The core is surrounded by an outside cladding with a uniform refractive index less than that of central core.	In graded index fiber, there is no cladding and the refractive index of the core is non-uniform. It is highest at the center and decreases gradually towards the outer edge.
2.	Data rate is slow.	Data rate is higher.
3.	Coupling efficiency is higher.	Coupling efficiency is lower.
4.	$\Delta = \dfrac{n_1 - n_2}{n_1}$	$\Delta = \dfrac{n_1^2 - n_2^2}{2n_1^2}$
5.	Pulse spreading by fiber length is more.	Pulse spreading is less.

Que 1.23. **A graded index fiber with a parabolic refractive index profile core has a refractive index at the core axis of 1.5 and a relative refractive index difference of 1 %. Estimate the maximum possible core diameter which allows single mode operation at a wavelength of 1.3 μm.** **AKTU 2015-16, Marks 05**

Answer

1. The maximum value of normalized frequency for single-mode operation is

$$V = 2.4\left(1 + \frac{2}{\alpha}\right)^{\frac{1}{2}} = 2.4\left(1 + \frac{2}{2}\right)^{\frac{1}{2}} = 2.4\sqrt{2}$$

2. The maximum core radius is given as

$$a = \frac{V\lambda}{2\pi\, n_1\,(2\Delta)^{1/2}},$$

$$a = \frac{2.4\sqrt{2} \times 1.3 \times 10^{-6}}{2\pi \times 1.5 \times (0.02)^{1/2}}, \quad a = 3.3\ \mu\text{m}$$

Hence the maximum core diameter which allows single-mode operation is 6.6 μm.

Que 1.24. **Write a short note on following :**

a. Cut-off wavelength

b. Mode field diameter.

OR

What do you mean by spot size ?

Answer

a. Cut-off wavelength :

1. Single mode operation only occurs above a theoretical cut-off wavelength λ_C which is given as :

$$\lambda_C = \frac{2\pi\, an_1}{V_C}(2\Delta)^{1/2} \quad ...(1.24.1)$$

where V_C is the cut-off normalized frequency and λ_C is the wavelength above which a particular fiber becomes single mode.

2. For the same fiber inverse relationship also exist *i.e.* obtained by dividing eq. (1.24.1) by $V = \frac{2\pi}{\lambda} an_1 (2\Delta)^{1/2}$. It is given as

$$\frac{\lambda_C}{\lambda} = \frac{V}{V_C}$$

3. Thus for step index fiber where $V_C = 2.405$, the cut-off wavelength is given by :

$$\lambda_C = \frac{V\lambda}{2.405}$$

4. An effective cut-off wavelength has been defined by the CCITT which is obtained from a 2 m length of fiber containing a single 14 cm radius loop. This definition was produced because the first higher order LP_{11} mode strongly affected by fiber length and curvature near cut-off.

b. Mode field diameter :

1. The mode field diameter is an important parameter for characterizing single mode fiber properties which takes into account the wavelength dependent field penetration into the fiber cladding.

2. For step index and graded single mode fibers operating near cut off wavelength λ_C, the field is approximated by a gaussian distribution.

3. MFD is generally taken as the distance between the opposite $1/e = 0.37$ times the near field strength (amplitude) and the power $1/e^2 = 0.135$ points in relation to corresponding values on the fiber axis as shown in Fig. 1.24.1.

4. Spot size is half the MFD. Thus the spot size ω_0 is,

$$\omega_0 = \frac{MFD}{2}$$

OR

$$MFD = 2\omega_0$$

where ω_0 is the nominal half width of the input excitation.

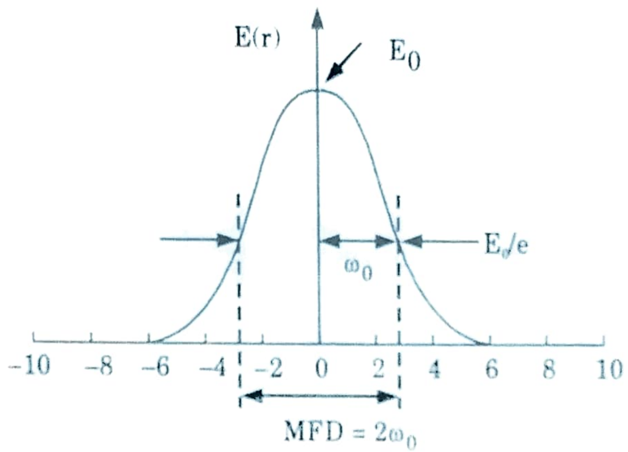


Fig. 1.24.1. Field amplitude distribution $E(r)$ of the fundamental mode in single mode fiber illustrating the mode-field diameter (MFD) and spot size (ω_0).

2

UNIT

Signal Loss in Optical Fiber

CONTENTS

PART-1

Attenuation, Material Absorption Losses (Intrinsic and Extrinsic Absorption), Types of Linear and Non-linear Scattering Losses, Fiber Bending Losses, Kerr Effect.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.1. **Write a short note on attenuation.**

Answer

1. Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.
2. Signal attenuation within optical fibers is usually expressed in the logarithmic unit of decibel (dB).
3. dB is used to compare two power levels, may be defined for a particular optical wavelength in the ratio of the input power p_i into a fiber to the output optical power p_0 from the fiber as

$$\text{Number of dB} = 10 \log_{10} \frac{p_i}{p_o}$$

4. In optical fiber communication the attenuation usually expressed in dB per km.

$$\alpha_{dB} l = 10 \log_{10} \frac{p_i}{p_0}$$

where α_{dB} is signal attenuation per unit length in dB and l is the length of the fiber.

Que 2.2. **Explain absorption loss mechanisms with their causes in the silica glass fibers in detail.** AKTU 2015-16, Marks 10

OR

Explain absorption losses. AKTU 2017-18, Marks 10

Answer

Absorption loss is related to the material composition and fabrication process of fiber. The absorption of the light may be intrinsic or extrinsic.

i. Intrinsic absorption :

1. This type of absorption occurs when material is in absolutely pure state, no density variation and inhomogeneities. This is the natural property of the glass.
2. An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near infrared region.
3. Intrinsic absorption results from electronic absorption bands in UV regions and from atomic vibration bands in the near infrared region.
4. The electronic absorption bands are associated with the band gaps of the amorphous glass materials.
5. Absorption occurs when a photon interacts with an electron in the valence band and excites it to higher energy level.
6. Intrinsic losses are mostly insignificant in a wide region where fiber systems can operate, but these losses inhibit the extension of fiber systems towards the ultraviolet as well as toward longer wavelengths.

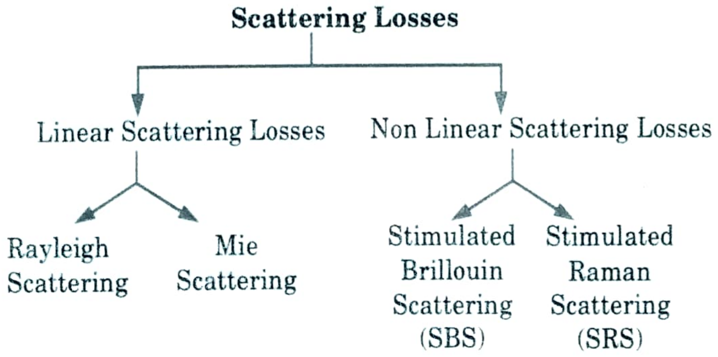
ii. Extrinsic absorption :

1. Extrinsic absorption occurs due to electronic transitions between the energy levels and because of charge transitions from one ion to another.
2. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper.
3. The presence of impurities in the fiber material is the major source of loss in practical fibers.
4. Another major extrinsic loss mechanism is caused by absorption due to water dissolved in the glass.
5. These hydroxyl groups are bonded into the glass structure and have fundamental stretching vibrations which occur at wavelengths between 2.7 and 4.2 μm depending on group position in the glass network.

Que 2.3. **What do you understand by scattering loss ? Describe its types with expressions.**

Answer

1. Scattering losses in glass arise from microscopic variations in the material density, from compositional fluctuations, and defects occurring during fiber manufacture.
2. The scattering losses can be classified as :



A. Linear Scattering losses :

1. Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly into a different mode.
2. There are two types of linear scattering losses.

i. Rayleigh scattering :

1. Rayleigh scattering is the dominant loss mechanism in the low absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with wavelength of light.
2. For single-component glass the scattering loss at a wavelength λ resulting from density fluctuations is given by :

$$\alpha_{scatt} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_T K_B T_F \quad ...(2.3.1)$$

where : α_{scatt} is the Rayleigh scattering co-efficient,
λ is the optical wavelength,
n is the refractive index of medium,
p is the average photoelastic coefficient,
β_T is the isothermal compressibility,
T_F is fictive temperature, and
K is Boltzmann's constant.

3. Rayleigh scattering co-efficient is related to the transmission loss factor of the fiber T by

$$T = e^{-\alpha_{scatt} L}$$

where L is the length of fiber

ii. Mie Scattering :

1. Linear scattering may also occur at inhomogeneities which are comparable in size to the guided wavelength.
2. When the scattering inhomogeneity size is greater than $\lambda/10$, the scattered intensity which has an angular dependence can be made very large.
3. Thus the scattering which is mainly created by such inhomogeneities is mainly in the forward direction and is called mie scattering. This type of scattering depends upon the fiber material, design and the manufacture.
4. Following are the method to reduce inhomogeneities :
   a. Removing imperfection due to glass manufacturing process.
   b. By fiber coating.
   c. Increasing the fiber guidance by increasing the relative refractive index difference.

B. Non-Linear Scattering loss :

1. The non-linear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same or other modes at a different frequency.
2. This type of scattering are of two types :

i. Stimulated Brillouin Scattering (SBS) :

1. SBS may be regarded as the modulation of light through thermal molecular vibrations within the fiber.

2. The scattered light appears as upper and lower side bands which are separated from the incident light by the modulation frequency.
3. Brillouin scattering is only significant above threshold power density.
4. The threshold power P_B is given by :

$$P_B = 4.4 \times 10^{-3}\, d^2 \lambda^2 \,\alpha_{dB} \nu \text{ watts}$$

where d and λ are fiber core diameter and operating wavelength,
α_{dB} is the fiber attenuation in decibels per kilometer, and
ν is the source bandwidth in gigahertz.

ii. Stimulated Raman Scattering (SRS) :

1. This type of scattering is similar to Stimulated Brillouin Scattering (SBS) except that a high frequency optical phonon rather than an acoustic phonon is generated in scattering process.
2. The threshold optical power for *SRS i.e.* P_R in a long single-mode fiber is given by :

$$P_R = 5.9 \times 10^{-2}\, d^2 \lambda^2 \,\alpha_{dB} \text{ watts.}$$

Que 2.4. **Silica has an estimated fictive temperature of 1400 K with an isothermal compressibility of 7×10^{-11} m^{2}N^{-1}. The refractive index and the photoelastic co-efficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometers due to the fundamental Rayleigh scattering in silica at optical wavelength of 0.63, 1.00, 1.30 μm. Boltzmann's constant is 1.38×10^{-23} J/K.**

Answer

Given : $T_F = 1400$ K, $\beta_T = 7 \times 10^{-11}$m^{2}N^{-1}, $n = 1.46, p = 0.286$,
$K = 1.381 \times 10^{-23}$, $\lambda_1 = 0.63$ μm, $\lambda_2 = 1.00$ μm, $\lambda_3 = 1.30$ μm
To Find : Attenuation in dB.

1. The Rayleigh's scattering co-efficient is given by :

$$\alpha_{scatt} = \frac{8\pi^3 n^8 p^2 \beta_T K T_F}{3\lambda^4} \quad ...(2.4.1)$$

2. At a wavelength $\lambda_1 = 0.63$ μm

$$\alpha_{scatt} = \frac{8 \times (3.14)^3 \times (1.46)^8 \times (0.286)^2 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3 \times (0.63 \times 10^{-6})^4}$$

$$= 1.199 \times 10^{-3} \text{ m}^{-1}$$

$$T = e^{-\alpha_{scatt} L} = e^{-(1.199 \times 10^{-3}) \times 1000} = 0.301$$

$$\text{Attenuation} = 10 \log_{10}\left(\frac{1}{T_{km}}\right)$$

$$= 10 \log_{10} 3.322 = 5.2 \text{ dB km}^{-1}$$

3. At a wavelength $\lambda_2 = 1.00$ μm

$$\alpha_{scatt} = \frac{8 \times (3.14)^3 \times (1.46)^8 \times (0.286)^2 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3 \times (1.00 \times 10^{-6})^4}$$

$$= 1.895 \times 10^{-4}\ \text{m}^{-1}$$

$$T = e^{-\alpha_{scatt} L} = e^{-(1.895 \times 10^{-4} \times 1000)}$$
$$= e^{-0.1895}$$
$$= 0.827$$
$$\text{Attenuation} = 10 \log_{10} 1.209$$
$$= 0.8\ \text{dB km}^{-1}$$

4. At wavelength of 1.30 μm

$$\alpha_{scatt} = \frac{8 \times (3.14)^3 \times (1.46)^8 \times (0.286)^2 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3 \times (1.30 \times 10^{-6})^4}$$
$$= 0.664 \times 10^{-4}\ \text{m}^{-1}$$
$$T = e^{-(0.664 \times 10^{-4}) \times 103}$$
$$= 0.936$$
$$\text{Attenuation} = 10 \log_{10} 1.069$$
$$= 0.3\ \text{dB km}^{-1}.$$

Que 2.5. **With a neat diagram, enumerate the different mechanisms that contribute to attenuation in optical fibers.**

AKTU 2016-17, Marks 12

OR

What are the losses on signal attenuation mechanisms in a fiber ? Explain in detail. **AKTU 2019-20, Marks 07**

OR

Discuss the fiber bend loss.

Answer

The losses on signal attenuation mechanisms in fiber are :

i. **Material absorption loss :** Refer Q. 2.2, Page 2–2D, Unit-2.
ii. **Scattering loss :** Refer Q. 2.3, Page 2–3D, Unit-2.
iii. **Fiber bend loss :**

1. Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber.
2. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained.
3. Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium.
4. The loss can generally be represented by the radiation attenuation coefficient which is given as :

$$\alpha_r = C_1 \exp(-C_2 R) \quad ...(2.5.1)$$

where R is the radius of curvature of the fiber bend, C_1 C_2 are constants and are independent of R.

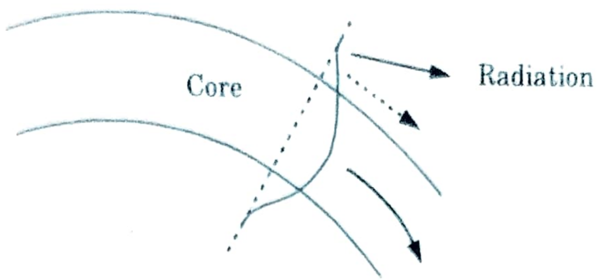


Fig. 2.5.1. An illustration of the radiation loss at a fiber bend.

5. Large bending losses tend to occur in multimode fibers at a critical radius of curvature R_C, which is given by

$$R_C \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{3/2}} \quad ...(2.5.2)$$

6. From eq. (2.5.2), it is observed that potential macro bending losses may be reduced by :
   a. Designing fibers with large relative refractive index difference.
   b. Operating at the shortest wavelength possible.
7. The critical radius of curvature for a single mode fiber R_{CS} is given by :

$$R_{CS} \simeq \frac{20\lambda}{(n_1 - n_2)^{3/2}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3} \quad ...(2.5.3)$$

where λ_c is the cut-off wavelength for the single mode fiber.
8. Thus, for single mode fiber, the critical wavelength of the radiated light becomes progressively shorter as the bend radius is decreased. The critical radius is called critical bending radius.

iv. Losses due to leaky modes.

Que 2.6. **A 8 micrometer core diameter single mode fiber with a core refractive index of 2, and relative refractive index difference of 0.3 % and operating wavelength of 1.55 micrometer. Determine critical radius of curvature. Explain bending losses.**

AKTU 2017-18, Marks 10

Answer

A. Numerical :

Given : Diameter = 8μm, $n_1 = 2$, $\Delta = 0.003$, $\lambda = 1.55 \times 10^{-6}$ m
To Find : Critical radius of curvature

1. Given $n_2^2 = n_1^2 - 2\Delta n_1^2$
   $n_2^2 = 4 - (0.006 \times 4) = 3.976$
2. The cut-off wavelength for single mode fiber is given as :

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{2.405}$$

$$\lambda_c = \frac{2\pi \times 4 \times 10^{-6} \times (2 \times 0.003)^{1/2} \times 2}{2.405} = 1.62\ \mu m$$

3. The critical radius of curvature for the single mode fiber gives,

$$R_c = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c}\right)^{-3}$$

$$= \frac{20 \times 1.55 \times 10^{-6}}{(0.043)^{3/2}} \left(2.748 - \frac{0.996 \times 1.55 \times 10^{-6}}{1.62 \times 10^{-6}}\right)^{-3} = 34\ mm$$

B. Bending losses : Refer Q. 2.5, Page 2–6D, Unit-2.

Que 2.7. What is self phase modulation ? Explain Kerr effect.

Answer

1. The refractive index n of many optical materials has a weak dependence on optical intensity I (equal to the optical power per effective area in the fiber) given by

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{eff}} \quad ...(2.7.1)$$

where n_0 is the ordinary refractive index of the material and n_2 is the non-linear index coefficient. In silica, the factor n_2 is about $2.6 \times 10^{-8}\ \mu m^2$ W.

2. The non-linearity in the refractive index is known as the Kerr non-linearity. This non-linearity produces a carrier induced phase modulation of the propagating signal, which is called the Kerr effect.
3. In single wavelength links, this gives rise to self phase modulation (SPM), which converts optical power fluctuations in a propagating light wave to spurious phase fluctuations in the same wave.
4. The main parameter γ which indicates the magnitude of the non-linear effect for SPM is given by,

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}} \quad ...(2.7.2)$$

where λ is the free space wavelength and A_{eff} is the effective core area.

5. The value of γ ranges from 1 to 5 $W^{-1}\ km^{-1}$ depending on the fiber type and the wavelength. For example, $\gamma = 1.3\ W^{-1}\ km^{-1}$ at 1550 nm for a standard single mode fiber that has an effective area equal to 72 μm^2.
6. The frequency shift $\Delta\varphi$ arising from SPM is given by

$$\Delta\varphi = \frac{d\varphi}{dt} = \gamma L_{eff} \frac{dP}{dt} \quad ...(2.7.3)$$

Here L_{eff} is the effective length given by eq. (2.7.3) and $\frac{dP}{dt}$ is the derivative of the optical pulse power, that is, it shows that the frequency shift occurs when the optical pulse power is changing in time.

PART-2

Dispersion : Introduction with its Types : Chromatic / Intramodal Dispersion (Material and Waveguide Dispersion), Intramodal Dispersion (for MSI and MGI Fibers).

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.8. **Explain the phenomenon of dispersion and pulse broadening.**

Answer

1. Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fiber.

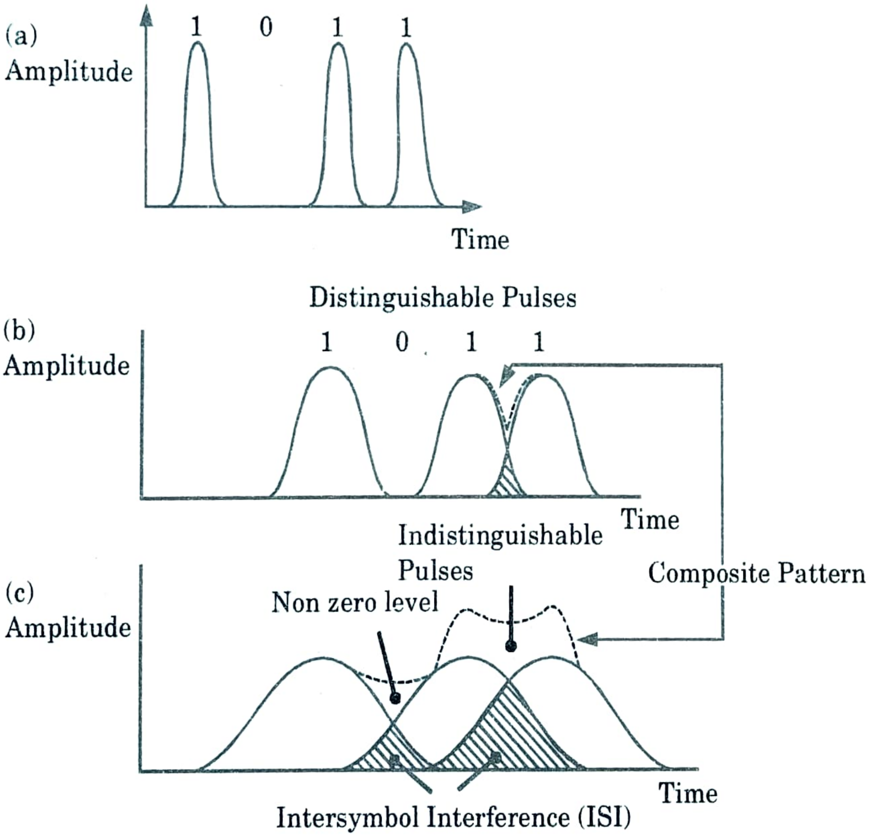


Fig. 2.8.1. An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted.

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2. The major implementation of optical fiber transmission involves some form of digital modulation then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. This phenomenon is shown in the Fig. 2.8.1.
3. From Fig. 2.8.1 it may be observed that each pulse broadens and overlaps with its neighbors, eventually becomes indistinguishable at the receiver input the effect is known as intersymbol interference (ISI).
4. For no overlapping of light pulses down on an optical fiber link the digital bit rate B_T must be less than the reciprocal of the broadened pulse duration (2τ)

Hence,
$$B_T \leq \frac{1}{2\tau} \quad ...(2.8.1)$$

5. The eq. (2.8.1) gives a conservative estimate of maximum bit rate that may be obtained as an optical fiber link as $1/2\tau$.
6. Another more accurate estimate of the maximum bit rate for an optical channel with dispersion may be obtained by considering the light pulses at the output to have a gaussian shape with an rms width of σ.
7. The maximum bit rate is given by

$$B_T\,(\text{max}) \leq \frac{0.2}{6} \text{ bit per sec} \quad ...(2.8.2)$$

8. Fig. 2.8.2 shows the three common optical fiber structures, multimode step index, multimode graded index and single mode step index and also shows pulse broadening associated with each fiber type.

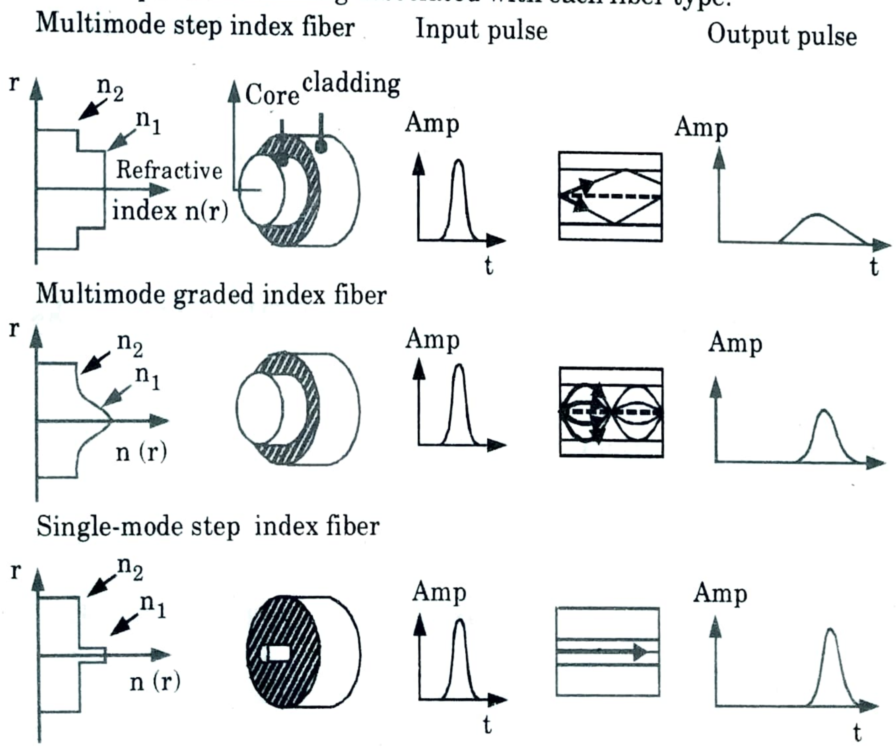

Fig. 2.8.2. An illustration showing the pulse broadening due to inter model dispersion in each fiber type.

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9. It is seen that multimode step index fiber exhibits the greatest dispersion of transmitted light pulse and the multimode graded index fiber gives a considerable improved performance.
10. The single mode fiber gives the minimum pulse broadening and thus is capable of the greatest transmission bandwidths which are currently in gigahertz range whereas transmission via multimode step index fiber is limited to bandwidths of a few tens of megahertz.
11. The amount of pulse broadening is dependent upon the distance the pulse travels within the fiber, and for a given optical fiber link the restriction on usable bandwidth is dictated by the distance between regenerative repeaters.

Que 2.9. **Define graded index fibers. A multimode graded index exhibits the total pulse broadening of 0.1 μm over a distance of 15 km. Estimate :**

a. Maximum possible BW without ISI.
b. Pulse dispersion per unit length.
c. Information carrying capacity. **AKTU 2015-16, Marks 7.5**

OR

A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km and dispersion is 6.67 ns. km^{-1}. Estimate
i. The maximum possible bandwidth on the link.
ii. The bandwidth length product for the fiber.

AKTU 2016-17, Marks 03

OR

What do you understand by Inter Symbol Interference (ISI) ? A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 15 km.
Estimate :
i. The maximum possible bandwidth without ISI.
ii. Pulse dispersion per unit length. **AKTU 2019-20, Marks 07**

Answer

A. Graded index fibers : Refer 1.21, Page 1–27D, Unit-1.
B. ISI : Refer Q. 2.8, Page 2–9D, Unit-2.
C. Numerical :

Given : $\tau = 0.1\ \mu s$, $L = 15$ km
To Find : B_T, Pulse dispersion per unit length, bandwidth length product.

i. Maximum possible bandwidth without ISI :

$$B_T = \frac{1}{2\tau} = \frac{1}{2 \times 0.1 \times 10^{-6}} = 5 \text{ MHz}$$

ii. Pulse dispersion per unit length :

$$\frac{\tau}{L} = \frac{0.1 \times 10^{-6}}{15} = 0.67 \times 10^{-8} \text{ s/km}$$

iii. Bandwidth length product :

$$B_T \times L = 5 \times 15 = 75 \text{ MHz-km.}$$

Que 2.10. **A multimode graded index fiber exhibit total pulse broadening of 0.1 microsecond over a distance of 10 km. Determine maximum possible bandwidth on the link assuming no inter symbol interference. Pulse dispersion per unit length and bandwidth length product for the fiber.**

AKTU 2017-18, Marks 10

Answer

Given : $\tau = 0.1\ \mu s$, $L = 10$ km

To Find : B_T, Pulse dispersion per unit length, bandwidth length product.

i. Maximum possible bandwidth without ISI :

$$B_T = \frac{1}{2\tau} = \frac{1}{2 \times 0.1 \times 10^{-6}} = 5 \text{ MHz}$$

ii. Pulse dispersion per unit length :

$$\frac{\tau}{L} = \frac{0.1 \times 10^{-6}}{10} = 1 \times 10^{-8} \text{ s/km}$$
$$= 5 \text{ MHz}$$

iii. Bandwidth length product :

$$B_T \times L = 5 \times 10 = 50 \text{ MHz-km.}$$

Que 2.11. **What is Intramodal (chromatic) dispersion ? Explain material dispersion and waveguide dispersion in brief.**

OR

Discuss the waveguide dispersion with relevant mathematical treatment.

AKTU 2016-17, Marks 10

OR

Explain material dispersion and waveguide dispersion in detail.

AKTU 2019-20, Marks 07

Answer

Intramodal dispersion :

1. Intramodal or chromatic dispersion is a pulse spreading that occurs within a single mode.
2. This dispersion is due to the fact that group velocity of guided mode is a function of the wavelength.
3. It depends upon the wavelength and therefore, its effect on signal distortion increases with the spectral width of the optical source.

4. The spectral width of the optical source is defined as the band of wavelengths over which the optical source emits light.
5. The intramodal dispersion has two main regions :

a. Material dispersion :

1. Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source.
2. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies non-linearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero $\left(i.e., \dfrac{d^2n}{d\lambda^2} \neq 0\right)$.
3. The pulse spread due to material dispersion may be obtained by considering the group delay τ_g in the optical fiber which is the reciprocal of the group velocity v_g. Hence the group delay is given by :

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad ...(2.11.1)$$

when n_1 is the refractive index of the core material.

4. The pulse delay τ_m due to material dispersion in a fiber of length L is therefore :

$$\tau_m = \frac{L}{C}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right) \qquad ...(2.11.2)$$

5. For a source with rms spectral width σ_λ and a mean wavelength λ, the rms pulse broadening due to material dispersion σ_m may be obtained from the expansion of equation in a Taylor series about λ where :

$$\sigma_m = \sigma_\lambda\frac{d\tau_m}{d\lambda} + \sigma_\lambda\frac{2d^2\tau_m}{d\lambda^2} + ... \qquad ...(2.11.3)$$

6. As the first term in eq. (2.11.3) usually dominates, especially for sources operating over the 0.8 to 0.9 μm wavelength range, then :

$$\sigma_m = \delta_\lambda\frac{d\tau_m}{d\lambda} \qquad ...(2.11.4)$$

7. Hence the pulse spread may be evaluated by considering the dependence of τ_m on λ, where from eq. (2.11.3).

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c}\left[\frac{dn_1}{d\lambda} - \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right]$$

$$= \frac{-L\lambda}{c}\frac{d^2n_1}{d\lambda^2} \qquad ...(2.11.5)$$

8. Therefore, substituting the expression obtained in the rms pulse broadening due to material dispersion is given by,

$$\sigma_m = \frac{\sigma_\lambda L}{c}\left|\lambda\frac{d^2n_1}{d\lambda^2}\right| \qquad ...(2.11.6)$$

9. The material dispersion for optical fibers is sometimes quoted as a value for $\left|\lambda^2\left(\frac{d^2n_1}{d\lambda^2}\right)\right|$ or $\left|\frac{d^2n_1}{d\lambda^2}\right|$
10. However, it may be given in terms of a material dispersion parameter M with is defined as :

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| \qquad ...(2.11.7)$$

and which is often expressed in units of ps nm^{-1} km^{-1}.

b. Waveguide dispersion :

1. The waveguiding of the fiber may also create intramodal dispersion. This results from the variation in group velocity with wavelength for a particular mode.
2. Considering the ray theory approach it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, and hence dispersion.
3. For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion when $\frac{(d^2\beta)}{(d\lambda^2)} \neq 0$.
4. Multimode fibers, where the majority of modes propagate far from cut-off, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion ($\approx$ 0.1 to 0.2 ns km^{-1}).
5. However, with single mode fibers where the effects of the different dispersion mechanisms are not easy to separate, waveguide dispersion may be significant.

Que 2.12. Discuss various dispersion mechanisms.

Answer

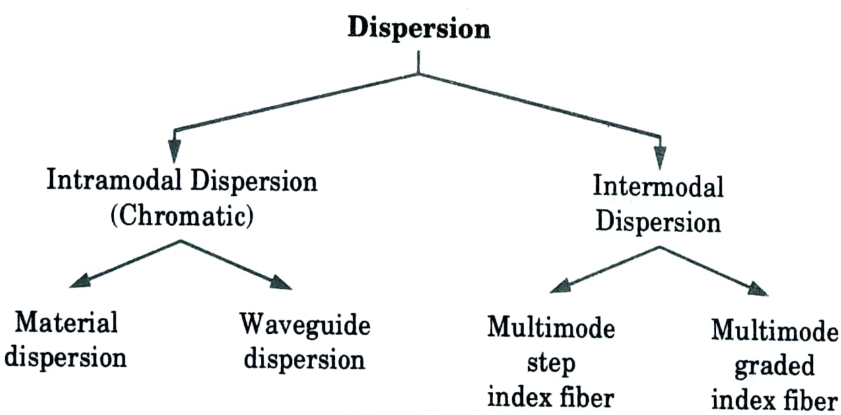


Fig. 2.12.1.

i. **Intramodal dispersion :** Refer Q. 2.11, Page 2–13D, Unit-2.

ii. Intermodal dispersion :

1. Pulse broadening due to intermodal dispersion results from propagation delay difference between modes within a multimode fiber.
2. The different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes.
3. Thus multimode step index fibers exhibit a large amount of intermodal dispersion which gives a great pulse broadening.

Que 2.13. Describe the mechanism of intermodal dispersion in a multimode step index fiber. Show that the total broadening of light pulse δT_S due to intermodal dispersion in a multimode step index fiber may be given by $\delta T_S = \dfrac{L(NA)^2}{2\ cn_1}$ where L is the fiber length, NA is numerical aperture, n_1 is the core refractive index and c is the velocity of light.

AKTU 2018-19, Marks 10

Answer

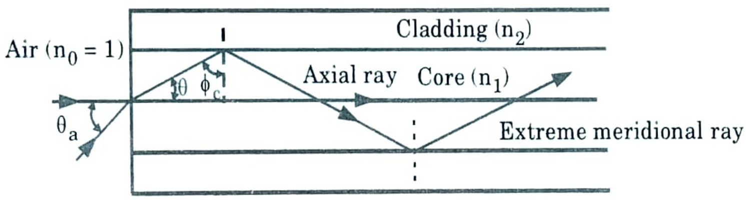


Fig. 2.13.1. The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber.

1. Let us consider a ray diagram showing the axial and an extreme meridional ray in a perfect multimode step index fiber.
2. The delay difference between these two rays when travelling in the fiber core allows estimation of the pulse broadening resulting from intermodal dispersion within the fiber.
3. As both rays are travelling at the same velocity within the constant refractive index fiber core, then the delay difference is directly related to their respective path lengths within the fiber.
4. The time taken for the axial ray to travel along a fiber of length L gives the minimum delay time T_{min} as

$$T_{min} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c} \qquad ...(2.13.1)$$

where n_1 is the refractive index of the core and c is the velocity of light in vacuum.

5. The extreme meridional ray exhibits the maximum delay time T_{max} where

$$T_{max} = \frac{L / \cos\theta}{c / n_1} = \frac{Ln_1}{c\cos\theta} \qquad ...(2.13.2)$$

6. Using Snell's law of refraction at core-cladding interface

$$\sin\phi_c = \frac{n_2}{n_1} = \cos\theta \qquad ...(2.13.3)$$

where n_2 = refractive index of cladding

7. Putting the value of eq. (2.13.3) in eq. (2.13.2)

$$T_{max} = \frac{Ln_1}{c(n_2/n_1)} = \frac{Ln_1^2}{cn_2} \qquad ...(2.13.4)$$

8. The delay difference δT_S between the extreme meridional ray and axial ray may be obtained as,

$$\delta T_S = T_{max} - T_{min}$$

$$= \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c} = \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right) \qquad ...(2.13.5)$$

$$\simeq \frac{Ln_1^2\Delta}{cn_2} \quad \text{when } \Delta << 1$$

where Δ is the relative refractive index difference

9. When $\Delta << 1$, the relative refractive index difference may be given as :

$$\Delta = \frac{n_1 - n_2}{n_2}$$

Thus $$\delta T_S = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{Ln_1\Delta}{c}$$

And $$\delta T_S = \frac{L(NA)^2}{2n_1c}$$

where NA is the numerical aperture for the fiber.

10. The expression of delay difference is usually employed to estimate the maximum pulse broadening in time due to intermodal dispersion in multimode step index fibers.
11. The rms pulse broadening due to intermodal dispersion is given as :

$$\sigma_S = \frac{Ln_1\Delta}{2\sqrt{3}c}.$$

Que 2.14. **Describe the mechanism of intermodal dispersion in multimode graded index fiber.**

Answer

1. Intermodal dispersion in multimode fibers is minimized with the use of graded index fibers.
2. By using multimode graded index fiber, bandwidth is improved as compared to multimode step index fibers. The reason for the improved performance of the fibers may be observed by considering a ray diagram.

3. The index profile is given as

$$n(r) = n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right]^{1/2} \qquad r < a \text{ (core)}$$

$$n_1(1 - 2\Delta)^{1/2} = n_2 \qquad r \geq a \text{ (cladding)}$$

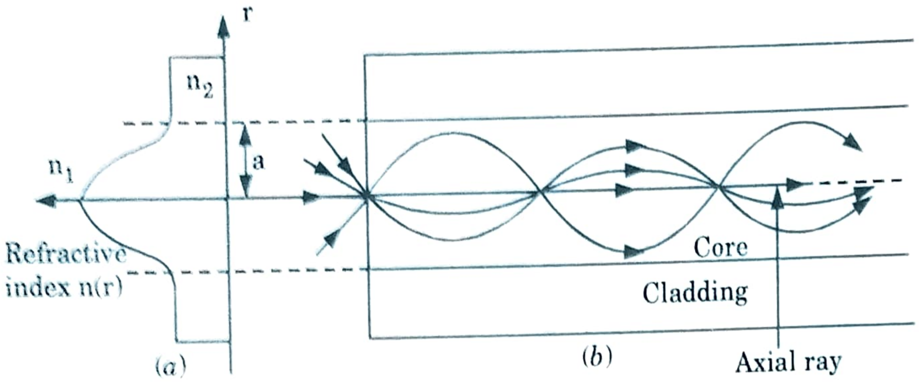


Fig. 2.14.1. A multimode graded index fiber : (*a*) parabolic refractive index profile ; (*b*) meridional ray paths within the fiber core.

4. From Fig. 2.14.1, it is shown that from the axial ray the meridional rays follow sinusoidal trajectories of different path lengths which result from index grading.
5. As group velocity is inversely proportional to the local refractive index and therefore the longer sinusoidal paths are compensated for by higher speeds in lower index medium away from the axis.
6. Multimode fiber bandwidth is improved by using a parabolic refractive index profile. This can be explained by considering reduced delay difference between the fastest and slowest modes for this graded index fiber δT_g.
7. Ray theory gives an expression for delay difference as :

$$\delta T_g = \frac{L n_1 \Delta^2}{2c} = \frac{(NA)^4}{8 n_1^3 c}$$

8. The electromagnetic mode theory gives an expression as :

$$\delta T_g = \frac{L n_1 \Delta^2}{8c}$$

9. The rms pulse broadening of a near parabolic index profile graded index fiber is related to the rms pulse broadening of step index fiber by the expression as

$$\sigma_g = \frac{\Delta}{D}\sigma_S$$

where D is the constant between 4 and 10 depending on the precise evaluation.

10. The best theoretical intermodal rms pulse broadening for a graded index fiber is given as

$$\sigma_g = \frac{L n_1 \Delta^2}{20\sqrt{3}c}$$

PART-3

Overall (Total) Fiber Dispersion in Multimode and Single Mode Fiber, Dispersion Modified Single Mode Fibers, Polarization and Fiber Birefringence.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.15. **Discuss overall fiber dispersion in multimode fibers.**

Answer

1. The overall dispersion in multimode fibers consists of both intramodal and intermodal terms.
2. The total rms pulse broadening σ_T is given as :

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{1/2}$$

where σ_c = Intramodal or chromatic broadening

σ_n = Intermodal broadening caused by delay differences between the modes.

Que 2.16. **Explain overall fiber dispersion in single mode fiber.**

Answer

1. The pulse broadening in single mode fiber consist of only intramodal or chromatic dispersion as only single mode is allowed to propagate.
2. The transit time or specific group delay τ_g for a light pulse propagating along a unit length of single mode fiber may be given as :

$$\tau_g = \frac{1}{c}\frac{d\beta}{dr}$$

where c = Velocity of light in vacuum

β = Propagation constant for a mode within the fiber core of refractive index n_1

k = Propagation constant for the mode in the vacuum.

3. The total first order dispersion parameter of a single mode fiber is given as :

$$D_T = \frac{d\tau_g}{d\lambda}$$

4. When the variable λ is replaced by ω,

then $$D_T = \frac{-\omega}{\lambda}\frac{d\tau_g}{d\omega} = \frac{-\omega}{\lambda}\frac{d^2\beta}{d\omega^2}$$

5. The total rms pulse broadening $= \sigma_\lambda L \left|\frac{d\tau_g}{d\lambda}\right| = \frac{\sigma_\lambda L 2\pi}{c\lambda^2}\frac{d^2\beta}{dk^2}$

where σ_λ is the source rms spectral line width centered at a wavelength λ.

6. This showed that pulse broadening depends upon material properties and normalized propagation constant and give rise to three interrelated effects which involve complicated cross product terms.

Que 2.17. **Define dispersion modified single mode fiber.**

Answer

1. The dispersion characteristics of single mode fibers are modified by the tailoring of specific fiber parameters. However, the major trade off which occurs in this process between material dispersion and waveguide dispersion may be expressed as :

$$D_T = D_M + D_W$$

$$= \underbrace{\frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right|}_{\text{material dispersion}} - \underbrace{\left[\frac{n_1 - n_2}{\lambda c}\right]\frac{Vd^2(Vb)}{dV^2}}_{\text{waveguide dispersion}}$$

2. At wavelengths longer than the zero material dispersion (ZMD) point in most common fiber designs, the D_M and D_W components are of opposite sign and can therefore be made to cancel at some longer wavelength.
3. Hence the wavelength of zero first order chromatic dispersion can be shifted to the lowest loss wavelength for silicate glass fibers at 1.55 µm to provide both low dispersion and low loss fiber.
4. This may be achieved by such mechanisms as a reduction in the fiber core diameter with an accompanying increase in the relative or fractional index difference to create so called dispersion shifted (DS) single mode fibers.

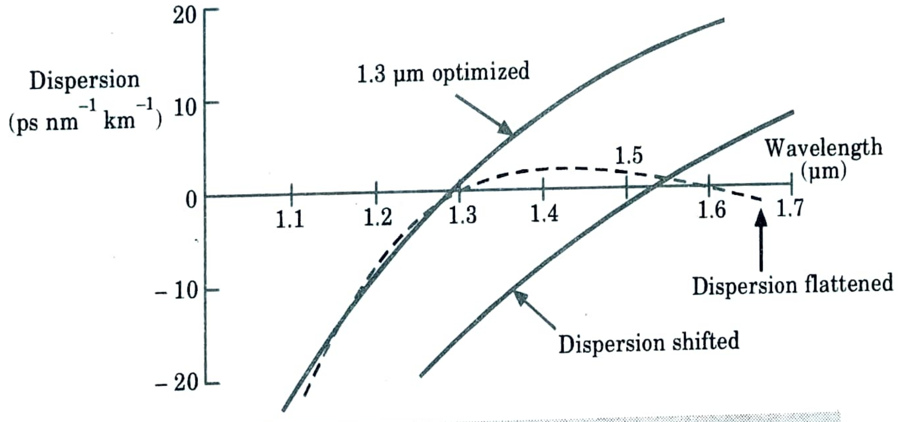


Fig. 2.17.1. Total dispersion characteristics for the various types of single-mode fiber.

Que 2.18. **Describe the scheme for realizing the dispersion shifted fiber.**

AKTU 2016-17, Marks 10

Answer

1. Single mode fiber refractive index profiles are capable of modification in order to tune the zero dispersion wavelength point λ_0 to a specific wavelength within a region adjacent to the zero material dispersion (ZMD) point.

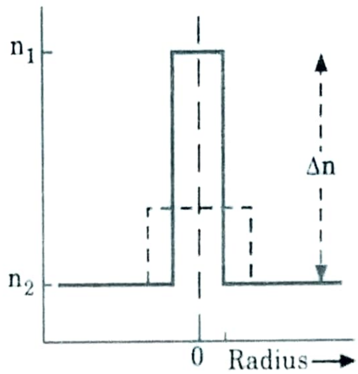
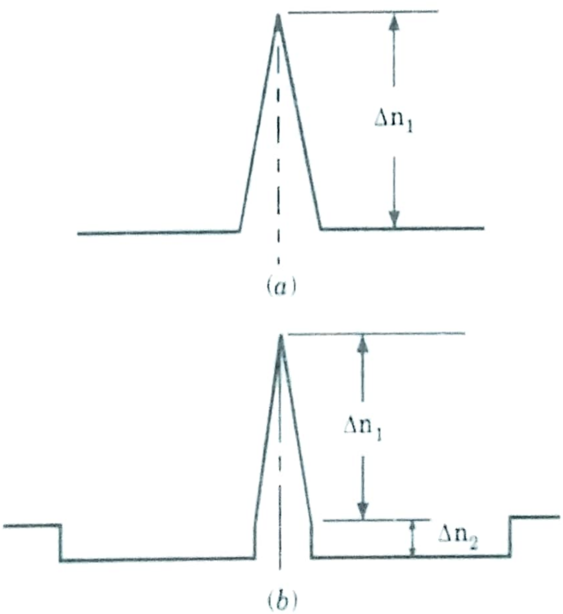


Fig. 2.18.1. Refractive index profile of a step index dispersion shifted fiber (solid) with a conventional non-shifted profile design (dashed).



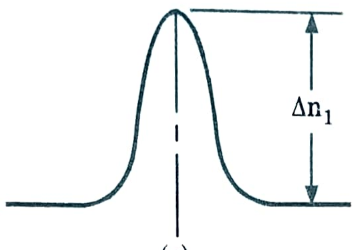


Fig. 2.18.2. Refractive index profiles for graded index dispersion shifted fibers; (a) triangular profile; (b) depressed-cladding trianglar profile, (c) Gaussian profile.

2. The step index profile gives a shift to longer wavelength by reducing the core diameter and increasing the fractional index difference. Typical values for the two parameters are 4.4 μm and 0.012 μm respectively.
3. λ_0 could be shifted to longer wavelength by altering the material composition of the single mode fiber.
4. For suitable power confinement of the fundamental mode, the normalized frequency V should be maintained in the range 1.5 to 2.4 μm and the fractional index difference must be increased as a square function while the core diameter is linearly reduced to keep V constant.

Que 2.19. **Explain dispersion flattened fibers.**

Answer

1. To modify the dispersion characteristics of single mode fibers in order to give two wavelengths of zero dispersion. A typical W fiber index profile (double clad) is shown in Fig. 2.19.1(a).
2. The first practical demonstration of dispersion flattening using the W structure was reported in 1981.
3. However, drawbacks with the W structural design included the requirement for a high degree of dimensional control so as to make reproducible DF fibers.
4. To reduce the sensitivity to bend losses associated with the W fiber structure the light which penetrates into the outer cladding area can be retrapped by introducing a further region of raised index into the structure.

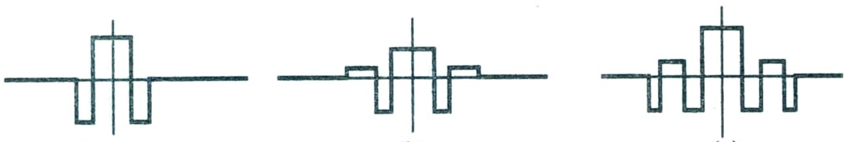


Fig. 2.19.1. Dispersion flattened fiber refractive index profiles: (a) double clad fiber (W fiber); (b) triple clad fiber; (c) quadruple clad fiber.

Que 2.20. **Explain modal birefringence and state of polarization.**

Answer

1. When the light propagates through cylindrical optical fibers, the state of polarization of the light input does not remain same.
2. There are some applications for which the state of polarization of input light should be maintained over significant distance.
3. Thus the phenomenon of maintaining the state of polarization is known as modal birefringence.
4. When the fibre cross-section is independent of the fibre length L in the z direction the modal birefringence B_F for fiber is given as :

$$B_F = \frac{(\beta_x - \beta_y)}{(2\pi / \lambda)} \quad ...(2.20.1)$$

where β_x and β_y are propagation constants for two modes along x and y direction.

5. The difference in phase velocities causes the fiber to exhibit a linear retardation $\psi_{(z)}$ assuming that the phase coherence of two modes components maintained is given by :

$$\psi_{(z)} = (\beta_x - \beta_y) L \quad ...(2.20.2)$$

6. The condition for the birefringent coherence to be maintained over a length of fiber L_C is known as coherence length

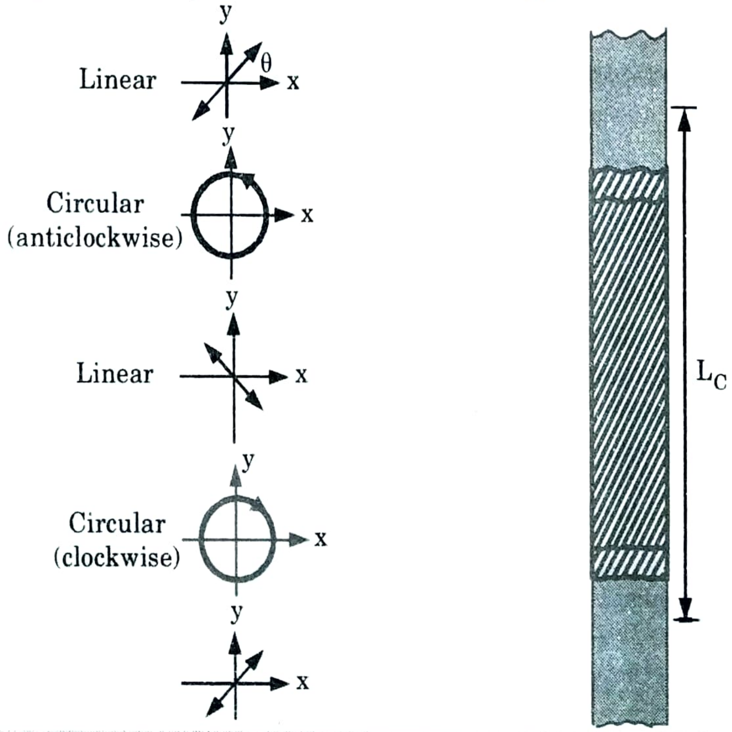


Fig. 2.20.1. An illustration of the beat length in a single mode optical fibre.

$$L_C = \frac{c}{B_F \, \delta f} = \frac{\lambda}{B_F \, \delta\lambda} \quad ...(2.20.3)$$

where δf = Source frequency width

$\delta\lambda$ = Source line width

7. When phase coherence is maintained, then

$$\beta = k n_1 [1 - 2\Delta (1 - b)^{1/2}] \quad ...(2.20.4)$$

leads to polarization state which is generally elliptical which varies periodically along the fiber. This situation is shown in Fig. 2.20.1.

8. The incident linear polarization which is at 45° with respect to the x-axis circular polarization at $\psi = \pi/2$ and linear at $\psi = \pi$. This process continues through another circular polarization at $\psi = 3\pi/2$ before returning to initial linear polarization at $\psi = 2\pi$.

9. The characteristic length L_B corresponding to this process known as beat length.

$$L_B = \frac{\lambda}{B_F}$$

$$L_B = \frac{\lambda \times 2\pi}{(\beta_x - \beta_y)\lambda} = \frac{2\pi}{\beta_x - \beta_y}$$

Que 2.21. **What is Modal Birefringence ? The beat length in a single-mode optical fiber is 9 cm when light from an injection laser with a spectral line width of 1 μm and a peak wavelength of 0.9 μm is launched into it. Determine the modal birefringence and estimate the coherence length in this situation. In addition calculate the difference between the propagation constants for the two orthogonal modes and check the result.** **AKTU 2018-19, Marks 10**

Answer

A. **Modal birefringence :** Refer Q. 2.20, Page 2–22D, Unit-2.

B. **Numerical :**

Given : L_B = 9 cm = 0.09 m, $\delta\lambda$ = 1 nm, λ = 0.9 μm

To Find : Modal birefringence, and coherence length.

1. Modal birefringence is given by,

$$B_F = \frac{\lambda}{L_B} = \frac{0.9 \times 10^{-6}}{0.09} = 10^{-5}$$

2. Coherence length,

$$L_C = \frac{\lambda^2}{B_F\,\delta\lambda} = \frac{(0.9 \times 10^{-6})^2}{10^{-5} \times 10^{-9}} = 81 \times 10^2 = 8.1 \text{ km}$$

Que 2.22. **Two polarization maintaining fibers operating at a wavelength of 1.3 μm have beat lengths of 0.7 mm and 80 m. Determine the model birefringence in each case.** **AKTU 2016-17, Marks 05**

Answer

Numerical :

Given : Wavelength, $= \lambda 1.3 \mu$ m, Beat length of fiber 1, $L_{B1} = 0.7$ mm,
Beat length of fiber 2, $L_{B2} = 80$ m
To Find : Modal birefringence.

1. Modal birefringence of fiber 1,

$$B_{F1} = \frac{\lambda}{L_{B1}} = \frac{1.3 \times 10^{-6}}{0.7 \times 10^{-3}} = 1.857 \times 10^{-3}$$

2. Modal birefringence of fiber 2,

$$B_{F2} = \frac{\lambda}{L_{B2}} = \frac{1.3 \times 10^{-6}}{80} = 1.625 \times 10^{-8}$$

3 UNIT

Optical Sources

CONTENTS

PART-1

LEDs-Introduction to LEDs and Materials used for Fabrication, LED Power and efficiency, LED Structures, LED Characteristics, Modulation Bandwidth.

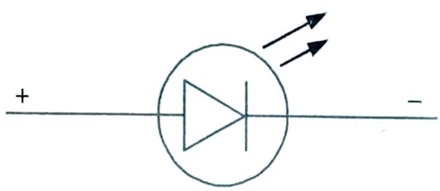
Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. **Write a short note on LEDs. Explain its working.**

Answer

1. LEDs are special diodes that emit light when connected in a circuit.
2. Light Emitting Diodes (LEDs) are semiconductor *p-n* junction operating under proper forward biased conditions and are capable of emitting external spontaneous radiations in the visible range (370 nm to 770 nm) or the nearly ultraviolet and infrared regions of the electromagnetic spectrum.
3. The circuit symbol of LED is shown in Fig. 3.1.1.



Circuit symbol

Fig. 3.1.1.

Working :

1. The negative side of an LED is indicated in two ways

i. By the flat side of the bulb and

ii. By the shorter of the two wires extending from the LED.

2. The negative lead should be connected to the negative terminal of a battery. LED's operate at relative low voltages between about 1 and 4 volts, and draw currents between about 10 and 40 milliamperes.
3. Voltages and current substantially above these values can melt a LED chip.
4. The most important part of a light emitting diode (LED) is the semiconductor chip located in the center of the bulb and is attached to the top of the anvil.

5. The chip has two regions separated by a junction. The *p*-region is dominated by positive electric charges, and the *n*-region is dominated by negative electric charges.

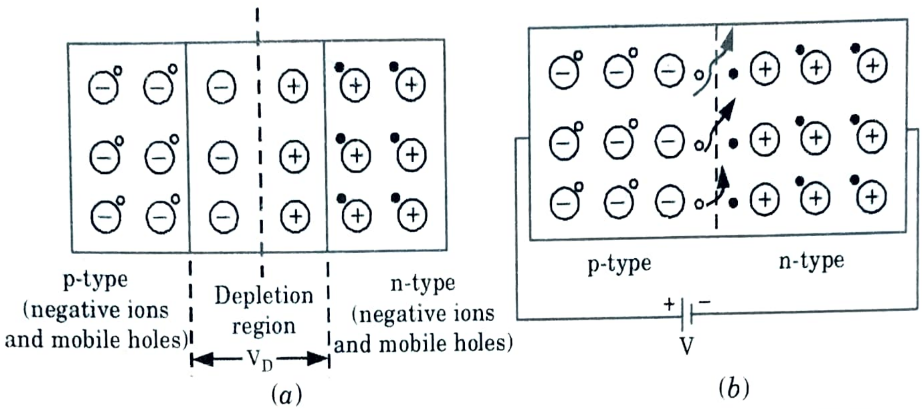


Fig. 3.1.2. Light radiation by the *p-n* junction of a semiconductor (*a*) Depletion region and Depletion voltage V_D; (*b*) Light radiation as the result of electron-hole recombinations.

6. The junction acts as a barrier to the flow of electrons between the *p* and *n*-regions.
7. Only when sufficient voltage is applied to the semiconductor chip, can the current flow and the electrons cross the junction into the *p*-region.
8. In the absence of a large enough electric potential difference (voltage) across the LED, the junction presents an electric potential barrier to the flow of electrons.

Que 3.2. **Discuss the advantages and disadvantages of LED.**

Answer

Advantages :

1. It has a simple fabrication since there are no mirror facets and in some structures no striped geometry.
2. The simple construction of LED leads to much reduced cost.
3. It is reliable as it does not exhibit catastrophic degradation.
4. It has simple drive circuitry due to generally lower drive currents and reduced temperature dependence.
5. The LED has a linear light output against current characteristics.

Disadvantages :

1. Lower optical power coupled into a fiber.
2. Usually lower modulation bandwidth.
3. Harmonic distortion.

Que 3.3. **Explain the structure of double heterojunction LED.**

OR

Discuss heterojunction in LED diodes.

Answer

1. The principle of operation of the DH LED is shown in Fig. 3.3.1
2. The device consists of a *p*-type GaAs layer sandwiched between a *p*-type AlGaAs and an *n*-type AlGaAs layer.
3. When a forward bias is applied, electrons from *n*-type layer are injected through the *p*-*n*-junction into the *p*-type GaAs layer where they become minority carriers.
4. These carriers diffuse away from the junction, recombining with majority carriers. Photons are therefore produced with energy corresponding to the bandgap energy of the *p*-type GaAs layers.
5. The injected electrons are inhibited from diffusing into the *p*-type AlGaAs layer because of the potential barrier presented by the *p–p* heterojunction.
6. Hence electroluminescence only occurs in GaAs junction layer, providing both good internal quantum efficiency and high radiance emission.

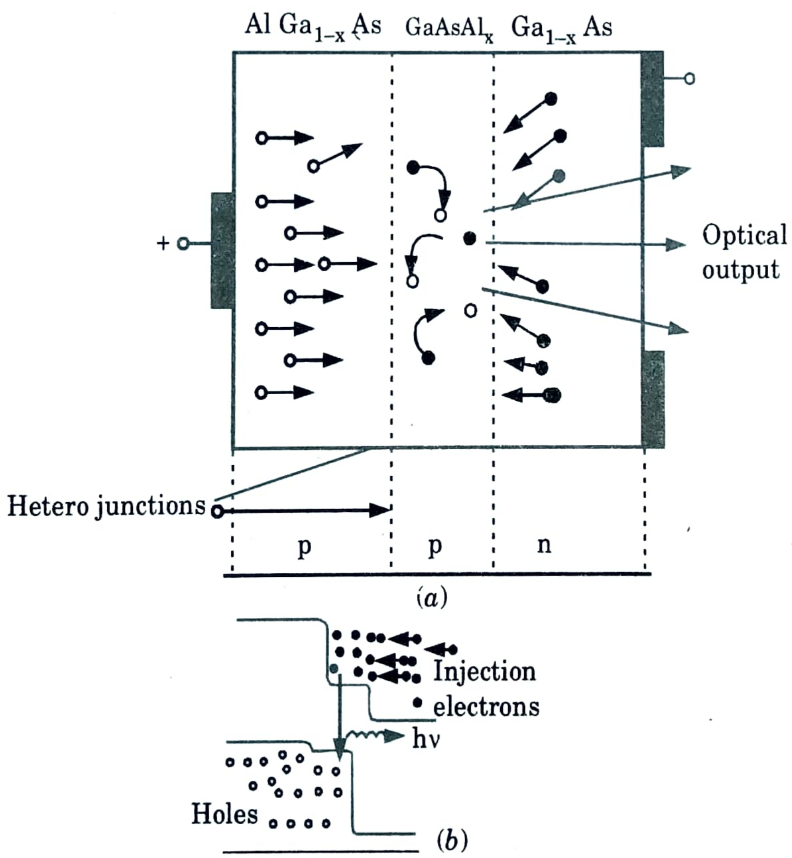


Fig. 3.3.1. (*a*) The double heterojunction LED, layer structure. (*b*) The corresponding energy band diagram.

Que 3.4. **What are the types of LED structures ? Explain each of them.**

Answer

Types of LED structure :

a. **Planar LED :**

1. The planar LED is the simplest structure that is available and fabricated by either liquid or vapour phase epitaxial processes over the whole surface of GaAs substrate.
2. This involves a *p*-type diffusion into the *n*-type substrate in order to create the junction as shown in Fig. 3.4.1. Forward current flow through the junction gives Lambertian spontaneous emission and the device emits light from all surfaces.

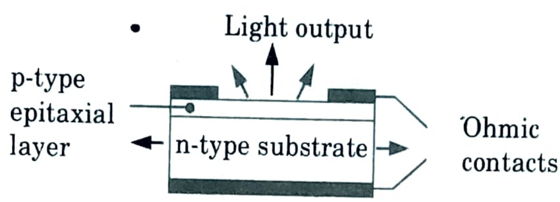


Fig. 3.4.1. The structure of a planar LED showing the emission of light from all surfaces.

b. **Dome LED :**

1. A hemisphere of *n*-type GaAs is formed around a diffused *p*-type region.
2. The diameter of the dome is chosen to maximize the amount of internal emission reaching the surface within the critical angle of GaAs – air interface.
3. Hence this device has higher external power efficiency than the planar LED.

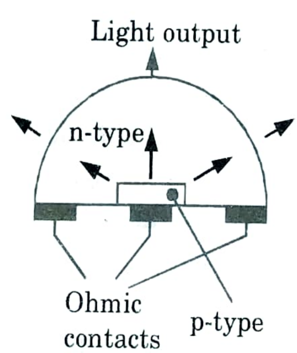


Fig. 3.4.2. Dome LED.

c. **Surface emitter LEDs :**

1. The structure of a high radiance etched well DH surface emitter for the 0.8 to 0.9 mm wavelength band is shown in Fig. 3.4.3.

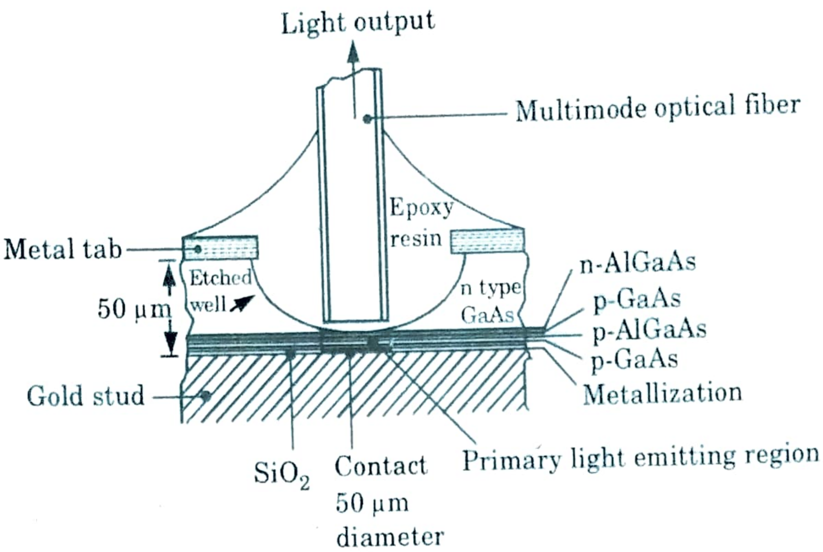


Fig. 3.4.3. The structure of an AlGaAs DH surface–emitting LED (Burrus type).

2. The internal absorption of this device is very low due to large bandgap confining layers, and the reflection coefficient at the back crystal face is high giving good forward radiance. The power coupled P_C into a multimode step index fiber may be estimated as :

$$P_C = \pi(1-r)AR_D(NA)^2$$

where r = Fresnel reflection coefficient.
A = Fiber cross section emission area of the source.
R_D = Radiance of the source.

3. The addition of epoxy resin in the etched well tends to reduce the refractive index mismatch and increase the external power efficiency of device.

d. Edge emitter LEDs :

1. The basic high radiance structure currently used in fiber communication is stripe geometry DH edge emitter LED (ELED).
2. The edge emitter depicted in Fig. 3.4.4 consists of active junction region, which is the source of incoherent light and two guiding layers.
3. The guiding layers both have a refractive index which is lower than that of active region but higher than the index of surrounding material.
4. This structure forms a waveguide channel that directs the optical radiation towards the fiber core.
5. To match the typical fiber core diameter (50 – 100 mm), the contact stripes for the edge emitter are 50 – 70 mm wide.
6. The emission pattern of the edge emitter is more directional than that of the surface emitter.

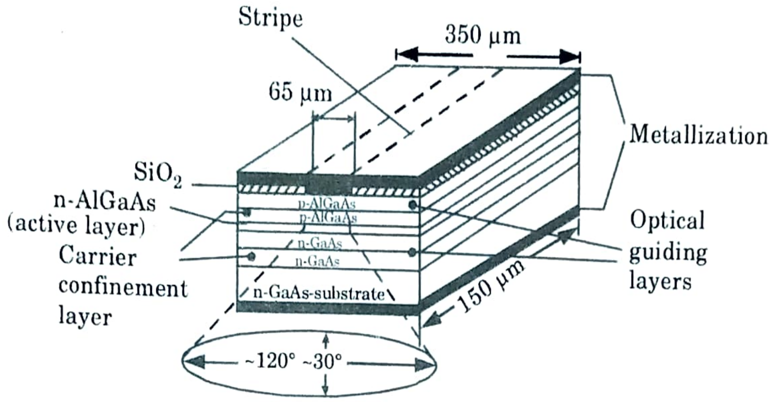


Fig. 3.4.4. Schematic illustration of the structure of a stripes geometry DH AlGaAs edge emitting LED.

e. Superluminescent LEDs :

1. The third device geometry which provides significant benefits over SLED and ELED in communication applications is the superluminescent diode or SLD.
2. This device gives :
   i. More output power
   ii. A directional output beam
   iii. A narrow spectral bandwidth

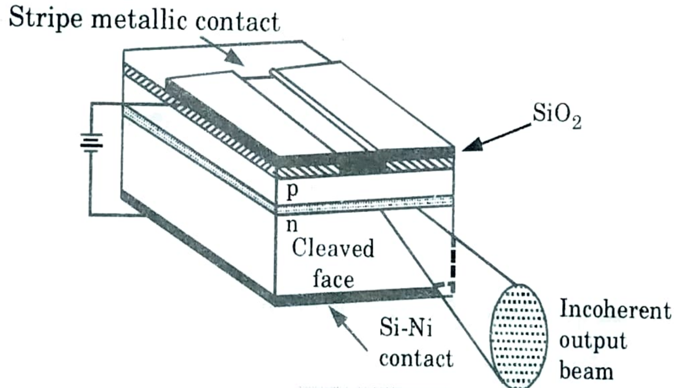


Fig. 3.4.5.

3. The structure of SLD is a long rectangular stripe, a ridge waveguide or a buried heterostructure.
4. One end of the device is made optically lossy to prevent reflections and thus suppress lasing, the output being from the opposite end.
5. Fig. 3.4.5 employs a contact stripe together with an absorbing region at one end to suppress laser action.
6. Such device provides peak power of 60 mW at a wavelength of 0.87 mm in pulsed mode.
7. AR coating is applied to the cleaved facets of SLDs in order to suppress lasing action.

Que 3.5. **Explain the working principle of LED. How the quantum efficiency of LED is defined ? List out various parameters which are needed to be optimized for getting maximum output power from the LED.**

AKTU 2018-19, Marks 10

AKTU 2019-20, Marks 07

OR

What do you understand by the term external quantum efficiency and internal quantum efficiency of a LED ?

AKTU 2019-20, Marks 07

Answer

A. Working principle of LED : Refer Q. 3.1, Page 3–2D, Unit-3.

B. Quantum efficiency

1. The internal quantum efficiency (η_{int}) is defined as the ratio of radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$

where,

R_r = Radiative recombination rate, and
R_{nr} = Non-radiative recombination rate.

2. If n are the excess carriers, then radiative life time, $\tau_r = \frac{n}{R_r}$, and non-radiative life time,

$$\tau_{nr} = \frac{n}{R_{nr}}.$$

3. The internal quantum efficiency is given as,

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}}$$

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$

4. The recombination time of carriers in active region is t. It is also known as bulk recombination life time.

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Therefore, internal quantum efficiency is given as,

$$\eta_{int} = \frac{\tau}{\tau_r}$$

5. If the current injected into the LED is I and q is electron charge, then total number of recombination per second is,

$$R_r + R_{nr} = \frac{I}{q}$$

$$\eta_{int} = \frac{R_r}{I / q}$$

$$R_r = \eta_{int} \times \frac{I}{q}$$

6. Optical power generated internally in LED is given as,

$$P_{int} = R_r \, . \, h\nu$$

$$P_{int} = \left(\eta_{int} \times \frac{I}{q}\right) h\nu$$

$$P_{int} = \left(\eta_{int} \times \frac{I}{q}\right) h\frac{c}{\lambda}$$

$$P_{int} = \eta_{int} \cdot \frac{hcI}{q\lambda}$$

7. The external quantum efficiency is used to calculate the emitted power. The external quantum efficiency is defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation,

$$\eta_{ext} = \frac{1}{n(n+1)^2}$$

8. The optical output power emitted from LED is given as,

$$P = h_{ext} \, . \, P_{int}$$

$$P = \frac{1}{n(n+1)^2} P_{int}$$

C. **Parameters :** The various parameters which are needed to be optimized for getting maximum output power from the LED are :

1. λ_{center}
2. $\Delta\lambda$
3. $d\lambda/dT$
4. dP_{opt}/dT
5. POF basic attenuation
6. Change of P_{opt}
7. Effect of wavelength drift
8. Effect of spectral width
9. Effective loss for 50 m POF
10. Change in received power

Que 3.6. **Discuss heterojunction in light emitting diode (LED). Explain the efficiency and modulation capability of LED.**

AKTU 2018-19, Marks 10

Answer

A. **Heterojunction LED :** Refer Q. 3.3, Page 3–3D, Unit-3.

B. **Efficiency :** Refer Q. 3.5, Page 3–8D, Unit-3.

C. **Modulation Capability :** The various characteristics of LED are as follows :

i. **Optical output power :**

1. The ideal light output power against current characteristics for an LED is shown in Fig. 3.6.1. It is linear corresponding to the linear part of injection laser optical power output characteristics before lasing occurs.

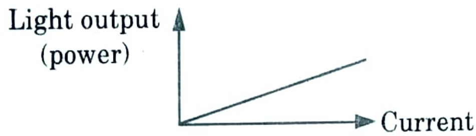


Fig. 3.6.1. An ideal light output against current characteristics for an LED.

2. The LED is a very linear device in comparison with the majority of injection Lasers and hence it tends to be more suitable for analog transmission where several constraints are put on the linearity of the optical source.

ii. **Modulation bandwidth :**

1. The modulation bandwidth in optical communication may be defined in either electrical or optical terms. It is more convenient to find the electrical signal power with the variation of modulated portion of the optical signal.

2. As the optical sources operate on DC, we consider the high frequency 3 dB point. The modulation bandwidth being the frequency range between zero and this high frequency 3 dB point.

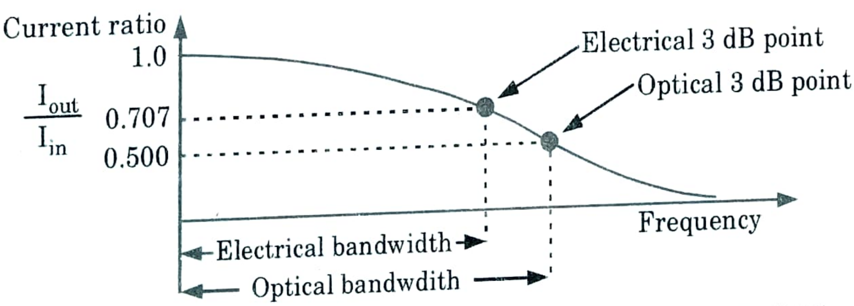


Fig. 3.6.2. The frequency response for an optical fiber system showing the electrical and optical bandwidths.

3. If 3 dB bandwidth of modulated optical carrier is considered, an increased value for the modulation bandwidth is obtained.
4. The modulation bandwidth of LEDs is generally determined by three mechanisms.

a. The doping level in the active layer.

b. The reduction in radiative lifetime due to the injection carrier.

c. The parasitic capacitance of device.

iii. Reliability :

1. LEDs are not affected by catastrophic degradation mechanisms which can severely affect injection Lasers.
2. Maximum LED operational time is expressed as

$$RF = B_F\, T_F\, E_F\, Q_F \times \frac{\text{failure}}{1 \times 10^6 \text{ hr}}$$

where
RF = Reliability factor
B_F = Base failure rate
E_F = Environment factor
Q_F = Quality factor

Que 3.7. Name the materials used for fabrication of LEDs. Explain the working principle of LED and how its efficiency can be defined ? Discuss the double heterojunction LED. **AKTU 2015-16, Marks 10**

OR

Name the material used for the fabrication of LED. What are basic requirement of optical sources to be used for optical fiber ?

AKTU 2017-18, Marks 10

Answer

A. Material used for fabrication of LEDs :

i. GaAS/AlGaAs : Operate in shorter wavelength region.

ii. InGaASP/InP : Operate in longer wavelength region.

B. Working of LED : Refer Q. 3.1, Page 3–2D, Unit-3.

C. Efficiency : Refer Q. 3.5, Page 3–8D, Unit-3.

D. Double heterojunction LED : Refer Q. 3.3, Page 3–3D, Unit-3.

E. Requirement of optical sources :

1. Physical dimensions to suit the optical fiber geometry.
2. Narrow radiation pattern.
3. Ability to be directly modulated by varying driving current.
4. Fast response time.
5. Adequate output power to couple into the optical fiber.

6. Narrow spectral width.
7. Driving circuit issue.
8. Stability, efficiency, reliability and cost.

Que 3.8. **What types of materials are used for optical sources? What are the advantages of double Hetro structure ? Compare surface emitting and edge emitting LED structures.**

AKTU 2019-20, Marks 07

Answer

A. Types of materials are used for optical sources :

i. Types of materials used for LED (Optical source) are :
1. Gallium Arsenide (GaAs)
2. Gallium Phosphide (GaP)

ii. Types of materials used for edge emitting semiconductor laser diode (Optical source) are :
1. Gallium Arsenide (GaAs)
2. Indium Phosphide (InP)
3. Gallium Antimonide (GaSb)
4. Gallium Nitride (GaN)

B. Advantages :
1. It offers higher efficiency with low to high radiance compare to single homojunction ($p - n$ +) LED type.
2. Emitting wavelength of GaAs/AlGaAs based DH LEDs range approx. between 0.8 to 0.9 μm.

C. Comparison :

S. No.	SLED structures	ELED structures
1.	Easy to fabricate.	Difficult to fabricate.
2.	Easy to mount and handle.	Difficult to mount and handle.
3.	Require less critical tolerances.	Need critical tolerance on fabrication.
4.	Less reliable.	Highly reliable.
5.	Low system performance.	High system performance.
6.	Less modulation Bandwidth.	Better Modulation. Bandwidth of the order of hundreds of MHz.

Que 3.9. **The radiative and non-radiative recombination lifetimes of the minority carriers in the active region of double heterostructure LED are 60 ns and 100 ns respectively. Determine the total carrier recombination lifetime and the power internally generated within the device when the peak emission wavelength is 0.87 μm at a drive current of 40 mA.**

Answer

Given : $\tau_r = 60$ ns, $\tau_{nr} = 100$ ns
To Find : Total carrier recombination lifetime, internal power.

1. The total carrier recombination lifetime is given as

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{60 \times 100}{(60 + 100)} = 37.5 \text{ ns}$$

2. The internal quantum efficiency is given as

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{37.5}{60} = 0.625 = 62.5\%$$

3. Internal power, $P_{int} = \eta_{int} \dfrac{hcI}{e\lambda}$

$$P_{int} = \frac{0.625 \times 6.626 \times 10^{-34} \times 2.998 \times 10^{8} \times 40 \times 10^{-3}}{1.602 \times 10^{-19} \times 0.87 \times 10^{-6}}$$

$$P_{int} = 35.6 \text{ mW}$$

PART-2

Laser Diodes : Introduction, Optical Feedback & Laser Oscillations, Resonant Frequencies.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.10. **Explain the principle of semiconductor lasers and draw the emission characteristics.**

Answer

A. Principle of semiconductor laser : The general operation of laser are as follows :

i. Absorption :

1. The interaction of light with matter takes place in discrete energy packets called quanta or photons.
2. The quantum theory suggests that atoms exist only in discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy state to another.
3. The frequency of the absorbed or emitted radiation f is related as the difference in energy between the higher energy state E_2 and lower energy state E_1 by the expression :

$$E = E_2 - E_1 = hf$$

where h = Planck's constant = 6.626×10^{-34} Js

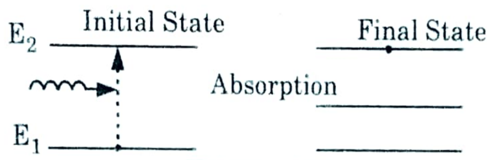


Fig. 3.10.1.

4. Fig. 3.10.1 illustrates a two energy state where an atom is initially in lower energy state E_1.
5. When a photon with energy $(E_2 - E_1)$ is incident on the atom it may be excited into the higher energy state E_2 through absorption of the photon. This process is referred as stimulated absorption of photon.

ii. Emission :

1. When the atom is initially in the higher energy state E_2 it can make a transition to the lower energy state E_1 providing the emission of a photon.
2. The emission process can occur in two ways :

a. Spontaneous emission

b. Stimulated emission

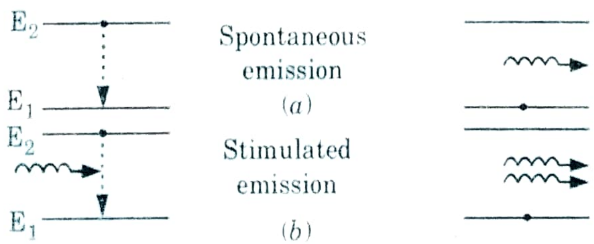


Fig. 3.10.2.

3. From Fig. 3.10.2, it is observed that in spontaneous emission atom from higher energy state returns to lower energy state in an entirely random manner whereas in stimulated emission, a photon having an energy equal to $(E_2 - E_1)$ interacts with the atom in the higher energy state causing it to return to the lower state with the creation of a second photon.

B. Emission characteristics :

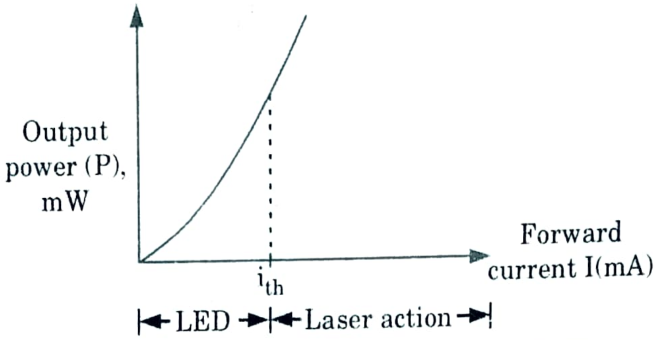


Fig. 3.10.3. Emission characteristics.

Que 3.11. **Discuss the working principle of Laser. The total efficiency of an injection Laser with a GaAs active region is 18 %. The voltage applied to the device is 2.5 V and the band gap energy for GaAs is 1.43 eV. Calculate the external power efficiency of the device.**

AKTU 2015-16, Marks 7.5

Answer

A. Working principle of laser : Refer Q. 3.10, Page 3–13D, Unit-3.

B. Numerical :

Given : $\eta_T = 18\ \% = 0.18$, $V = 2.5$, $E_g = 1.43$ eV

To Find : External power efficiency.

1. The external power efficiency is given as :

$$\eta_{ep} = \eta_T \left(\frac{E_g}{V}\right) \times 100\ \% = 0.18 \left(\frac{1.43}{2.5}\right) \times 100 = 10\ \%$$

2. This result indicates the possibility of achieving high overall power efficiencies from semiconductor Laser which are much larger than other Laser.

Que 3.12. **Explain and derive Einstein relation.**

Answer

1. Einstein described that the rates of three transition processes *i.e.*, absorption, spontaneous emission and stimulated emission were related mathematically.
2. This can be achieved by considering the atomic system to be in thermal equilibrium such that the rate of upward transitions must equal to the rate of downward transitions.
3. The population of two energy levels of such system are described by Boltzmann statistics as :

$$\frac{N_1}{N_2} = \frac{g_1 \exp(-E_1 / KT)}{g_2 \exp(-E_2 / KT)}$$

$$= \frac{g_1}{g_2} \exp (E_2 - E_1/KT)$$

$$= \frac{g_1}{g_2} \exp (hf/KT) \quad ...(3.12.1)$$

where,

N_1 and N_2 represent the density of atoms in energy levels E_1 and E_2,

g_1 and g_2 is corresponding degeneracies of levels,

K is Boltzmann constant,

T is absolute temperature.

4. As the density of atoms in the lower energy state E_1 is N_1, the rate of upward transition or absorption is proportional to both N_1 and the spectral density ρ_f of the radiation energy at transition frequency f. Hence the upward transition rate R_{12} may be given as :

$$R_{12} = N_1 \rho_f B_{12} \quad ...(3.12.2)$$

where B_{12} is known as Einstein coefficient of absorption.

5. If the density of atoms within the system with energy E_2 is N_2, then spontaneous emission rate is given by the product of N_2 and $\frac{1}{\tau_2}$, which is written as $N_2 A_{21}$ where A_{21} is Einstein coefficient of spontaneous emission, is equal to reciprocal of the spontaneous life time.

6. The rate of stimulated emission is given by $N_2 \rho_f B_{21}$, where B_{21} is Einstein coefficient of stimulated emission. Thus, the sum of spontaneous and stimulated contributions is given as:

$$R_2 = N_2 A_{21} + N_2 \rho_f B_{21} \quad ...(3.12.3)$$

7. In equilibrium condition

$$R_{12} = R_{21}$$

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

$$\rho_f = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} \quad ...(3.12.4)$$

and

$$\rho_f = \frac{A_{21} / B_{21}}{(B_{12} N_1 / B_{21} N_2) - 1} \quad ...(3.12.5)$$

8. Substituting the eq. (3.12.1) into eq. (3.12.5) the value will be

$$\rho_f = \frac{A_{21} / B_{21}}{[(g_1 B_{12} / g_2 B_{21}) \exp (hf / KT)] - 1} \quad ...(3.12.6)$$

9. Thus
$$\rho_f = \frac{8\pi h f^3}{c^3}\left(\frac{1}{\exp(hf/KT)-1}\right) \quad ...(3.12.7)$$

10. Comparing eq. (3.12.7) with eq. (3.12.6), the Einstein relation is obtained as
$$B_{12} = \left(\frac{g_2}{g_1}\right) B_{21}$$
and
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}$$

11. The ratio of the stimulated emission rate to the spontaneous emission rate is given by :
$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf/KT)-1}$$

Que 3.13. **Explain the process of population inversion.**

Answer

1. Under thermal equilibrium condition by Boltzmann's law, the lower energy level E_1 contains more atoms than upper energy level E_2.
2. Thus, to achieve optical amplification it is necessary to create a non-equilibrium distributions of atoms such that population of the upper energy level is greater than that of lower energy level ($N_2 > N_1$). This is known as population inversion.
3. Thus in order to achieve population inversion, it is necessary to excite atoms into upper energy level E_2 and hence obtain a non-equilibrium distribution. This process is achieved by using an external energy source referred as 'pumping'.

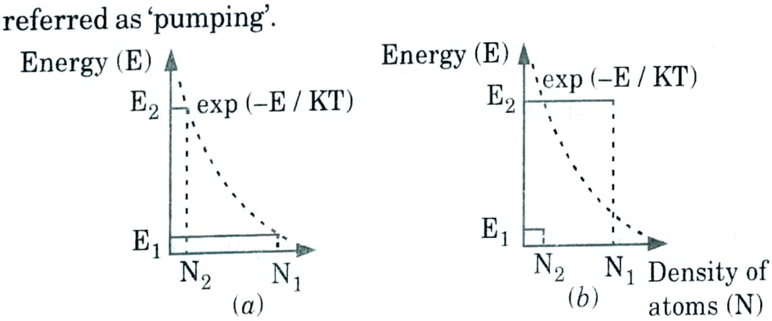


Fig. 3.13.1. Population in two energy level system : (*a*) Boltzmann distribution for a system in thermal equilibrium ; (*b*) a non-equilibrium distribution showing population inversion.

4. The population inversion may be obtained in three or four energy levels as shown in the Fig. 3.13.2.
5. In order to obtain population inversion both systems display a central metastable state in which atoms spend an unusual long time. It is from the metastable level that stimulated emission or lasing takes place.

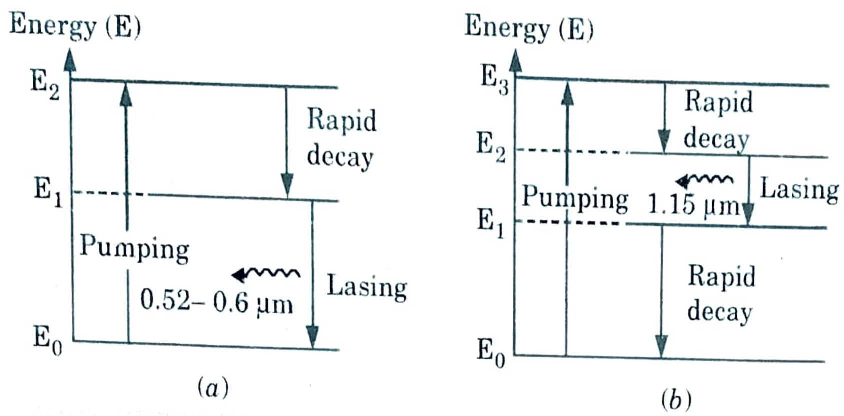


Fig. 3.13.2. Energy level diagrams showing population inversion and lasing for two non-semiconductor Lasers : (*a*) three level system – ruby (crystal) Laser ; (*b*) four level system – He–Ne (gas) Laser.

6. The three level system consist of ground level E_0, a metastable level E_1 and a third level E_2. With suitable pumping the electrons in some of the atoms is excited from ground state into higher level E_2.
7. As E_2 is normal level thus by non-radiative process, the electrons will rapidly decay to either E_1 or directly to E_0. Hence empty states will always be provided in E_2.
8. A drawback with three level system, ruby laser, is that it generally requires very high pump powers because the terminal state of the laser transition is the ground state whereas a four level system such as He – Ne Laser is characterized by lower pumping requirements.
9. In this the pumping excites the atoms from the ground state into energy level E_3 and then they decay rapidly to metastable state.
10. As the populations of E_3 and E_1 remain unchanged a small increase in the number of atoms in energy level E_2 creates population inversion, and lasing takes place between this level and E_1.

Que 3.14. **Explain Fabry–Perot Laser diode in detail.**

Answer

1. Fig. 3.14.1 shows a Laser diode which consists of two mirrors and the active medium between them. Two mirrors form a resonator with length *L*.
2. Let an arbitrary wave travel from the left hand mirror to the right hand one. At the right hand mirror, this wave is reflected, hence, the wave experiences a 180° phase shift.
3. As it is clear from Fig. 3.14.1(*b*) that the wave should have a break in its phase, which is impossible here. In other words, this resonator does not support this wave.
4. Now consider another wave travel inside a resonator, as shown in Fig. 3.14.1(*c*).

5. At the right hand mirror, the wave experiences a 180° phase shift and continues to propagate. At the left hand mirror, this wave again has the same phase shift and continues to travel. Thus, this wave yield a stable pattern called a standing wave.

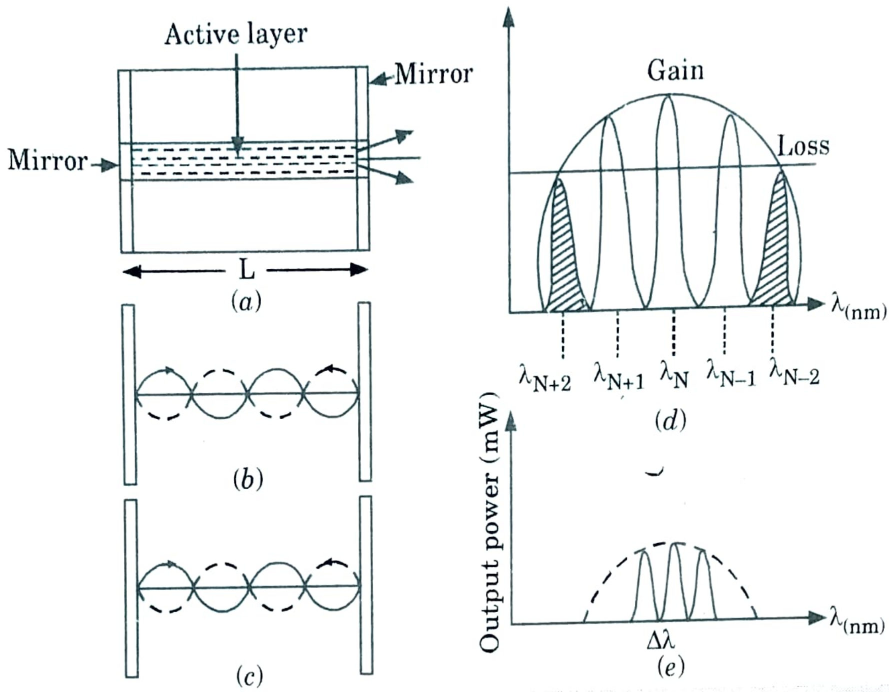


Fig. 3.14.1. Fabry–Perot Laser diode; (*a*) A Laser diode; (*b*) Fabry-Perot resonator with arbitrary wave; (*c*) Fabry–Perot resonator with standing wave; (*d*) Gain loss Curve and possible longitudinal modes; (*e*) Actual mulitmode radiation.

6. Two waves shown in Fig. 3.14.1(*b*) and 3.14.1(*c*) differs in their wavelength. Thus, a resonator can support only a wave with a certain wavelength, the wave that forms a standing wave pattern.

7. This physical requirement can be written as :

$$\frac{2L}{\lambda} = N \qquad ...(3.14.1)$$

where L is the distance between mirrors and N is an integer.

8. This resonator supports a wavelength equal to $\frac{2L}{N}, \frac{2L}{(N \pm 1)}, \frac{2L}{(N \pm 2)},$ $\frac{2L}{(N \pm 3)}$ and so forth. Wavelengths selected by a resonator are called longitudinal modes.

9. When the length of a resonator increases or decreases, the laser switches from one longitudinal mode to another. This is called mode hop.

10. A resonator can support an infinite number of waves whose wavelengths satisfy eq. (3.14.1.). However, the active medium provides gain within only a small range of wavelengths.

11. Since a laser is formed by a resonator and an active medium and since radiation is the result of their interaction, only several resonant wavelengths that fall within the gain curve might be radiated. This is shown in Fig. 3.14.1(*d*).
12. The light generates only when gain exceeds loss. Thus, eventually only those resonant wavelengths that are within the gain over loss curve will actually be radiated.
13. Waves with λ_N, $\lambda_{N\pm1}$ and $\lambda_{N\pm2}$, might be radiated, but only waves with λ_N and $\lambda_{N\pm1}$ will be the actual laser output. Modes $\lambda_{N\pm2}$, shown black, are not generated.
14. More specifically, we can explain this by introducing the spacing between two adjacent longitudinal modes, $\lambda_N - \lambda_{N+1}$.

$$\lambda_N - \lambda_{N+1} \approx \frac{2L}{N^2} = \frac{\lambda^2}{2L}$$

Que 3.15. **Explain distributed feedback (DFB) laser diode.**

Answer

1. A typical DFB laser configuration is shown in Fig. 3.15.1(*a*). A DFB laser diode has the Bragg grating incorporated into its heterostructure in the vicinity of an active region.
2. The Bragg grating works like a mirror, selectively reflecting only one wavelength, λ_B. This wavelength can be found from the Bragg condition given as :

$$2 \wedge n \sin q = \lambda_B.$$

where $\wedge$ is the period of grating and n is the refractive index of the medium.

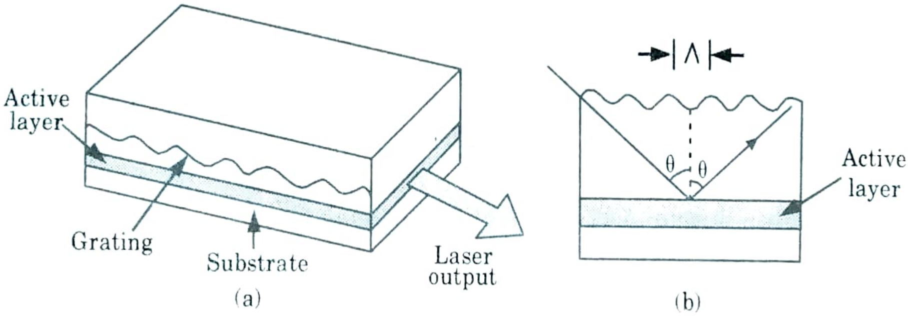


Fig. 3.15.1. Distributed feedback, (DFB) laser diode; (*a*) Structure of DFB laser diode; (*b*) Working of distributed feedback.

3. In distributed feedback laser diode, the meaning of the word, distributed, is that reflection takes place not a one point (as in Fabry Perot LDs), but at many points dispersed along the active region and the word feedback emphasizes that we have the means to return stimulated photons to an active medium.

4. This is done by reflecting a portion of the light at each slope of the grating as shown for one beam in Fig. 3.15.1.(*b*). All the portions reflected at each slope of this corrugated structure then combine so that most of the light will be reflected back provided that Bragg's condition is satisfied.
5. The final output of the DFB laser diode is the wave of wavelength λ_B containing the radiation of only single longitudinal mode and as a result, the spectral width of this radiation is extremely narrow, as shown in Fig. 3.15.2.

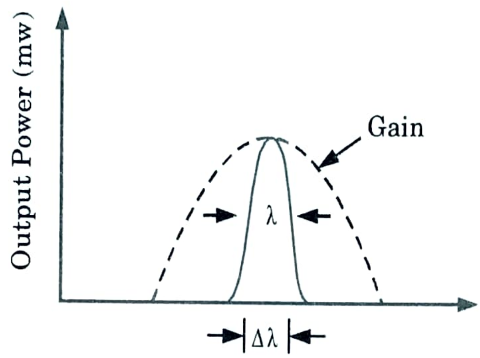


Fig. 3.15.2. Actual single mode radiation of DFB Laser diode.

Que 3.16. **Derive the formula for resonant frequency and plot the spectrum of gain verses frequency of a multimode laser.**

Answer

1. To examine the resonant frequencies of the laser, $e^{-j2\beta L} = 1$. The condition holds when,

$$2\beta L = 2\pi m \quad \text{...(3.16.1)}$$

where m is an integer. Using $\beta = \dfrac{2\pi n}{\lambda}$ for the propagation constant

$$m = \frac{L}{\lambda/2n} = \frac{2Ln}{c}\nu \quad \text{...(3.16.2)}$$

where $n = \nu\lambda$.

2. This states that the cavity resonates (*i.e.*, a standing wave pattern exists within it) when an integer number m of half wavelengths spans the region between the mirrors.
3. The relationship between gain and frequency can be assumed to have the gaussian form

$$g(\lambda) = g(0)\exp\left[-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right] \quad \text{...(3.16.3)}$$

where λ_0 is the wavelength at the center of the spectrum, σ is the spectral width of the gain, and the maximum gain $g(0)$ is proportional to the population inversion.

4. The frequency spacing, between two successive modes of frequencies ν_{m-1} and ν_m represented by the integers $m-1$ and m,

$$m - 1 = \frac{2Ln}{c}\nu_{m-1} \quad ...(3.16.4)$$

and

$$m = \frac{2Ln}{c}\nu_m \quad ...(3.16.5)$$

5. Subtracting eq. (3.16.4) from eq. (3.16.5) yields

$$1 = \frac{2Ln}{c}(\nu_m - \nu_{m-1}) = \frac{2Ln}{c}\Delta\nu$$

from which we have the frequency spacing

$$\Delta\nu = \frac{c}{2Ln} \quad ...(3.16.6)$$

6. This can be related to the wavelength spacing $\Delta\lambda$ through the relationship $\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda}$, yielding

$$\Delta\lambda = \frac{\lambda^2}{2Ln} \quad ...(3.16.7)$$

7. The output spectrum of a multimode laser follows the typical gain versus frequency plot given in Fig. 3.16.1 where the exact number of modes, their heights, and their spacing depend on the laser construction.

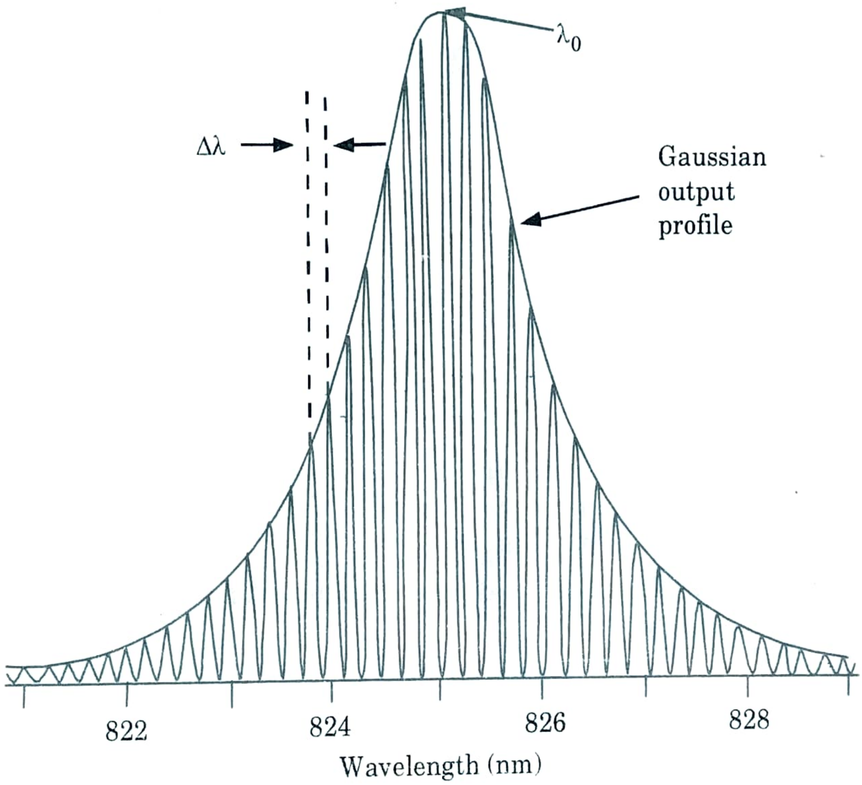


Fig. 3.16.1. Typical spectrum from a Fabry–Perot GaA/As / GaAs Laser diode.

Que 3.17. **Draw and discuss the basic laser structure using optical feedback for producing laser oscillations/laser modes at resonant frequencies.** **AKTU 2015-16, Marks 10**

Answer

1. Light amplification in a laser occurs when a photon colliding with an atom in the excited state causes stimulated emission of a second photon and then these photons release two more.
2. Continuation of this process causes avalanche multiplication and when these photons are in phase, amplified coherent emission is obtained.
3. To achieve laser action it is necessary to contain photons within the laser medium and maintain the condition for coherence. This is obtained by placing mirrors at either end of amplifying medium as shown in Fig. 3.17.1.

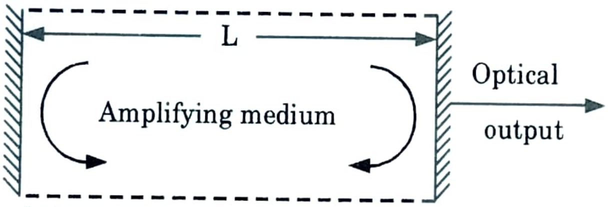


Fig. 3.17.1. The basic Laser structure incorporating plane mirrors.

4. The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity.
5. Hence the optical signal is fed back many times while receiving amplification therefore this structure act as Fabry Perot resonator.
6. A stable output is obtained at saturation when the optical gain is exactly matched by the losses experienced in the amplifying medium.

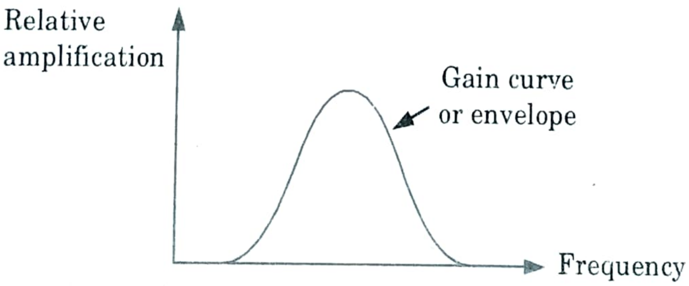


Fig. 3.17.2. The relative amplification in the Laser amplifying medium showing the broadened Laser transition line or gain curve.

7. The major losses occur from the factors such as absorption and scattering in the amplifying medium, absorption, scattering and diffraction at the mirrors and non-useful transmissions.

8. Oscillations in the laser cavity occur over a small range of frequencies where cavity gain is sufficient to overcome the losses. Thus the device is not a perfectly monochromatic source but emits over a narrow spectral band.
9. The central frequency of this spectral band is determined by the mean energy level difference. Other oscillation frequencies within the spectral band results from frequency variation due to thermal motion of atoms within amplifying medium.
10. Hence the amplification within the laser medium results in a broadened gain curve over a finite spectral width.
11. When the optical spacing between the mirrors is L the resonance condition along the axis of cavity is given as.

$$L = \frac{\lambda q}{2n} \quad \text{...(3.17.1)}$$

where λ = Emission wavelength
n = Refractive index of amplifying medium
q = Integer

12. This discrete emission frequency f is given as

$$f = \frac{qc}{2nL} \quad \text{...(3.17.2)}$$

where, c is velocity of light.

13. Since eq. (3.17.1) and (3.17.2) apply only when L is along the longitudinal axis of the structure, the frequency (f) given is known as longitudinal or axial modes.
14. These modes are separated by δf where

$$\delta f = \frac{c}{2nL} \quad \text{...(3.17.3)}$$

15. Assuming $\delta f << f$ and $f = \frac{c}{\lambda}$

$$\delta\lambda = \frac{\lambda \delta f}{f} = \frac{\lambda^2}{c}\delta f$$

$$\delta\lambda = \frac{\lambda^2}{2nL}$$

PART-3

Laser Modes and Threshold Condition for Laser Oscillations, Laser Diode Rate Equations.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.18. **Write a short note on laser mode.**

Answer

1. The typical output spectrum for a broad area injection laser is shown in Fig. 3.18.1. It does not consist of a single wavelength output but a series of wavelength peaks corresponding to different longitudinal (in the plane of the junction, along the optical cavity) modes within the structure.
2. The spacing of these modes is dependent on the optical cavity length as each one corresponds to an integral number of lengths. They are generally separated by a few tenths of a nanometer, and the laser is said to be a multimode device.

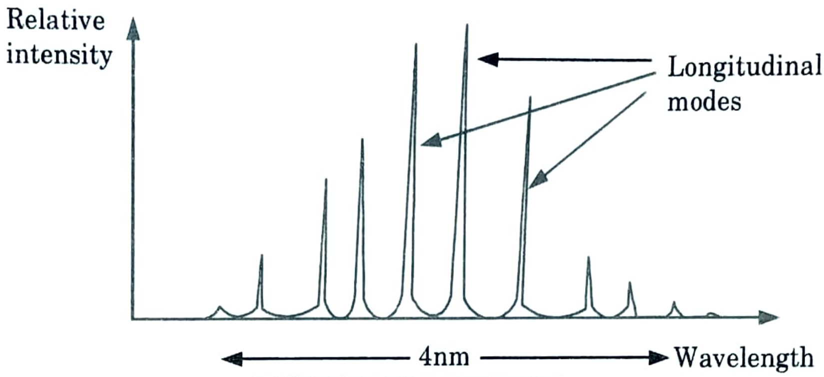


Fig. 3.18.1. Laser modes.

3. Some broadening of the longitudinal mode peaks due to subpeaks caused by higher order horizontal transverse modes.
4. These higher order lateral modes may exist in the broad area device due to the unrestricted width of the active region.
5. The correct stripe geometry inhibits the occurrence of the higher order lateral modes by limiting the width of the optical cavity leaving only a single lateral mode which gives the output spectrum.

Que 3.19. **Explain the working of semiconductor laser. What is threshold condition for lasing action ?** **AKTU 2017-18, Marks 10**

Answer

A. Working of semiconductor laser : Refer Q. 3.10, Page 3–13D, Unit-3.

B. Threshold condition for lasing action :

1. Steady state condition is reached when the gain in the amplifying medium exactly balances the losses.
2. Though population inversion is necessary for oscillation to be established, in addition a minimum or threshold gain is also required.
3. All losses due to transmission through the mirror may be included in a single loss coefficient α per cm.

4. Let assume the amplifying medium occupies a length L completely filling the region between the two mirrors which have reflectivities r_1 and r_2.
5. On each round trip beam passes through the medium twice. Hence the fractional loss experienced by the light beam is

$$\text{Fractional loss} = r_1 r_2 \exp(-2\alpha L) \quad \text{...(3.19.1)}$$

6. If the gain coefficient per cm is g, the fractional gain in the round trip is

$$\text{Fractional gain} = \exp(2gL) \quad \text{...(3.19.2)}$$

7. Hence $\exp(2gL) \times r_1 r_2 \exp(-2\alpha L) = 1$

and $r_1 r_2 \exp[2L(g - \alpha)] = 1$ ...(3.19.3)

8. Threshold gain g_{th} per cm may be obtained by rearranging the expression

$$g_{th} = \alpha + \frac{1}{2L} \ln \frac{1}{r_1 r_2}$$

9. The second term on RHS represents transmission loss through mirrors.

Que 3.20. **Explain laser diode rate equations.**

Answer

1. The relationship between optical output power and the diode drive current can be determined by examining the rate equations that govern the interaction of photons and electrons in the active region.
2. For a p-n junction with a carrier confinement region of depth d, the rate equations are given by

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}} \quad \text{...(3.20.1)}$$

= Stimulated emission + Spontaneous emission + Photon loss which governs the number of photons Φ,

and $$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi \quad \text{...(3.20.2)}$$

= injection + spontaneous recombination + stimulated emission

which governs the number of electrons n.

Here, C is a coefficient describing the strength of the optical absorption and emission interactions,

R_{sp} is the rate of spontaneous emission into the lasing mode (which is much smaller than the total spontaneous emission rate),

τ_{ph} is the photon lifetime,

τ_s is the spontaneous recombination lifetime, and

J is the injection current density.

4. The first term in eq. (3.20.1) is a source of photons resulting from stimulated emission.

5. The second term, describing the number of photons produced by spontaneous emission, is relatively small compared with the first term.
6. The third term indicates the decay in the number of photons caused by loss mechanisms in the lasing cavity.
7. In eq. (3.20.2), the first term represents the increase in the electron concentration in the conduction band as current flows into the device.
8. The second and third terms give the number of electrons lost from the conduction band owing to spontaneous and stimulated transitions, respectively.
9. The steady state is characterized by,

$$Cn - \frac{1}{\tau_{ph}} \geq 0 \qquad ...(3.20.3)$$

10. This shows that n must exceed a threshold value n_{th} in order for ϕ to increase.

$$\frac{n_{th}}{\tau_{sp}} = \frac{J_{th}}{qd} \qquad ...(3.20.4)$$

11. This expression defines the current required to sustain an excess electron density in the laser when spontaneous emission is the only decay mechanism.
12. Consider the photon and electron rate equations in the steady state condition at the lasing threshold. Respectively, eq. (3.20.1) and eq. (3.20.2) become

$$0 = Cn_{th}\Phi_s + R_{sp} - \frac{\Phi_s}{\tau_{ph}} \qquad ...(3.20.5)$$

and

$$0 = \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\Phi_s \qquad ...(3.20.6)$$

where Φ_s is the steady state photon density.

13. Adding eq. (3.20.5) and eq. (3.20.6), using eq. (3.20.4) for the term $\frac{n_{th}}{\tau_{sp}}$ and solving for Φ_s yields the number of photons per unit volume.

$$\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp} \qquad ...(3.20.7)$$

14. The first term in eq. (3.20.7) is the number of photons resulting from stimulated emission. The power from these photons is generally concentrated in one or a few modes.
15. The second term gives the spontaneously generated photons. The power resulting from these photons is not mode selective, but is spread over all the possible modes of the volume, which are on the order of 10^8 modes.

PART-4

Semiconductor Injection Laser : Laser Single Mode Operation Reliability of LED & ILD.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.21. **What is external quantum efficiency ?**

Answer

1. The external differential quantum efficiency η_{ext} is defined as the number of photons emitted per radiative electron hole pair recombination above threshold.
2. Under the assumption that above threshold the gain coefficient remains fixed at g_{th}, h_{ext} is given by

$$\eta_{ext} = \frac{\eta_i(g_{th} - \bar{\alpha})}{g_{th}} \quad ...(3.21.1)$$

3. Here, η_i is the internal quantum efficiency. This is not a well defined quantity in laser diodes, but most measurements show that $\eta_i \approx 0.6 - 0.7$ at room temperature.
4. Experimentally, η_{ext} is calculated from the straight line portion of the curve for the emitted optical power P versus drive current I, which gives

$$\eta_{\text{ext}} = \frac{q}{E_g}\frac{dP}{dI} = 0.8065\lambda\,(\mu\text{m})\frac{dP(\text{mW})}{dI(\text{mA})} \quad ...(3.21.2)$$

where E_g is the band gap energy in electron-volts, dP is the incremental change in the emitted optical power in milliwatts for an incremental change dI in the drive current (in milliamperes), and λ is the emission wavelength in micrometers.
5. For standard semiconductor Lasers, external differential quantum efficiencies of 15-20 percent per facet are typical. High quality devices have differential quantum efficiencies of 30-40 percent.

Que 3.22. **Elucidate the principle of operation of a laser diode and derive an expression for the lasing threshold current density. Find the external quantum efficiency for a $Ga_{1-x}Al_x$ As laser diode (with x = 0.03) which has an optical power versus drive current relationship of 0.5 mW/mA.**

AKTU 2016-17, Marks 15

Answer

A. **Principle of operation of laser diode :** Refer Q. 3.10, Page 3–13D, Unit-3.

B. Threshold current density : Refer Q. 3.19, Page 3–25D, Unit-3.

C. Numerical :

Given : $x = 0.03$.

To Find : External quantum efficiency.

1. We have, $$\eta_{ext} = 0.8065\,\lambda\,(\mu m)\,\frac{dP\,(mW)}{dI\,(mA)} \quad ...(3.22.1)$$
2. The band gap of $Ga_{1-x}Al_xAs$ is given by,
$$E_g(x) = 1.424 + 1.247x$$
$$= 1.424 + 1.247\,(0.03) = 1.46141\text{ eV}$$
$$\lambda(\mu m) = \frac{1.24}{E_g\,(eV)} = \frac{1.24}{1.46141} = 0.848\ \mu m$$
3. Substituting these values in eq. (3.22.1)
$$\eta_{ext} = 0.8065 \times 0.848 \times 0.5$$
$$= 0.34215 \simeq 34.22\ \%$$

Que 3.23. **Explain single mode operation of laser.**

Answer

1. For single mode operation, the optical output from a laser must contain only a single longitudinal and single transverse mode.
2. Hence the spectral width of the emission from the single mode device is far smaller than the broadened transition linewidth.
3. It was indicated that an inhomogeneously broadened laser can support a number of longitudinal and transverse modes simultaneously, giving a multimode output.
4. Single transverse mode operation, however, may be obtained by reducing the aperture of the resonant cavity such that only the TEM_{00} mode is supported.
5. To obtain single mode operation it is then necessary to eliminate all but one of the longitudinal modes.
6. One method of achieving single longitudinal mode operation is to reduce the length L of the cavity until the frequency separation of the adjacent modes is larger than the laser transition linewidth or gain curve.
7. Then only the single mode which falls within the transition linewidth can oscillate within the laser cavity.
8. It is clear that rigid control of the cavity parameters is essential to provide the mode stabilization necessary to achieve and maintain this single-mode operation.
   For example, the correct DH structure will restrict the vertical width of the waveguiding region to less than 0.4 μm allowing only the fundamental transverse mode to be supported and removing any interference of the higher order transverse modes on the emitted longitudinal modes.
9. The lateral modes (in the plane of the junction) may be confined by the restrictions on the current flow provided by the stripe geometry.

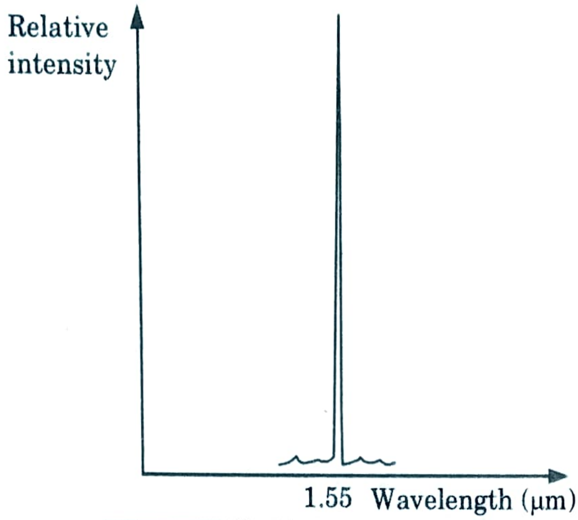


Fig. 3.23.1. Single mode laser.

10. In general, only the lower order modes are excited which appear as satellites to each of the longitudinal modes. Stripe contact devices often have instabilities and strong non-linearities in their light output against current characteristics.
11. Tight current confinement as well as good waveguiding are therefore essential in order to achieve only the required longitudinal modes which form between the mirror facets in the plane of the junction.
12. Finally, as indicated above, single mode operation may be obtained through control of the optical cavity length such that only a single longitudinal mode falls within the gain bandwidth of the device.
13. Fig. 3.23.1 shows a typical output spectrum for a single mode device. However, injection lasers with short cavity lengths (around 50 μm) are difficult to handle and have not been particularly successful.

Que 3.24. Explain the principle of semiconductor lasers and, draw the emission characteristic. A ruby laser contains a crystal length 4 cm with refractive index of 1.78. The peak emission wavelength from the device is 0.55 μm. Determine the number of longitudinal modes and their frequency separation.

AKTU 2018-19, Marks 10

Answer

A. Principle of semiconductor lasers and, draw the emission characteristic : Refer Q. 3.10, Page 3–13D, Unit-3.

B. Numerical :

Given : $L = 0.04$ m, $n = 1.78$, $\lambda = 0.55$ μm

To Find : Number of longitudinal modes, frequency.

1. The number of longitudinal modes supported within the structure is given by

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

$$q = \frac{2nL}{\lambda} = \frac{2 \times 1.78 \times 0.04}{0.55 \times 10^{-6}} = 0.258 \times 10^6$$

3. The frequency separation of modes is

$$\delta f = \frac{c}{2nL} = \frac{3 \times 10^8}{2 \times 1.78 \times 0.04} = 2.106 \text{ GHz}$$

Que 3.25. **Write down the difference between semiconductor diode and LED.**

Answer

S. No.	Semiconductor Diode	LED
1.	Semiconductor diode can be used for any application in both forward and reverse bias depending upon requirement.	LED can be used for any application only in forward bias direction.
2.	No semiconductor diode except LED can produce light for indication.	LED is used as indicator, it can produce light of different colours depends on the material used.
3.	It is not compulsion to sustain electron-hole pair recombination, if electron-hole pair recombination is sustained; it releases energy in the thermal form.	It is necessary to sustain electron-hole pair recombination to emit a quantum of electromagnetic energy (light) and this process is called electroluminescence.
4.	Here both (radiative and non-radiative) recombination takes place.	Only radiative recombination takes place.

4

UNIT

Power Launching in Fiber

CONTENTS

PART-1

Source to Fiber Power Launching, Source Output Patterns, Power Coupling Calculation, Power Launching Verses Wavelength, Equilibrium Numerical Aperture.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. **Write a short note on source to fiber power launching.**

Answer

1. Optical output from a source is measured in radiance.
2. Radiance is defined as the optical power radiated into a solid angle per unit emitting surface area.
3. Radiance is specified in watts/cm^2/steradian.

Source output pattern :

1. Spatial radiation pattern of source helps to determine the power accepting capability of fiber.
2. Fig. 4.1.1 shows three dimensional spherical co-ordinate systems for characterizing the emission pattern from an optical source. Where the polar axis is normal to the emitting surface and radiance is a function of θ and ϕ.

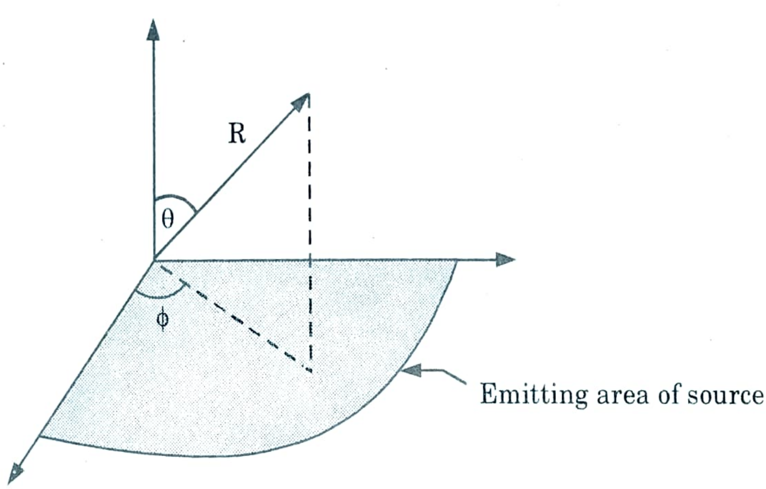


Fig. 4.1.1. Dimensional spherical co-ordinate system.

3. The Lambartian output by surface emitting LED is equally bright from any direction.

4. The emission pattern of Lambartian output is shown in Fig. 4.1.2 and its output is :

$$B(\theta, \phi) = B_0 \cos\theta$$

where, B_0 is the radiance along the normal to the radiating surface.

5. Both radiation in parallel and normal to the emitting plane are approximated by expression

$$\frac{1}{B(\theta,\phi)} = \frac{\sin^2\phi}{B_0 \cos^T \theta} + \frac{\cos^2\phi}{B_0 \cos^L \theta}$$

where, T and L are transverse and lateral power distribution coefficients.

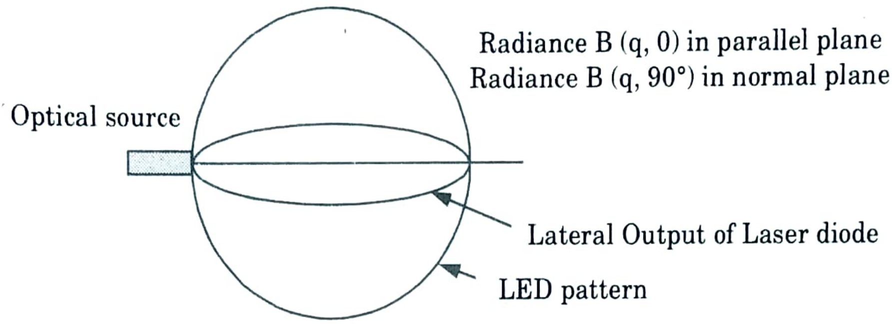


Fig. 4.1.2. Radiance pattern of Lambartian source.

Que 4.2. **How power coupling into the fiber can be calculated ?**

Answer

1. To calculate coupling into the fiber, let us consider an optical source launched into fiber as shown in Fig. 4.2.1.

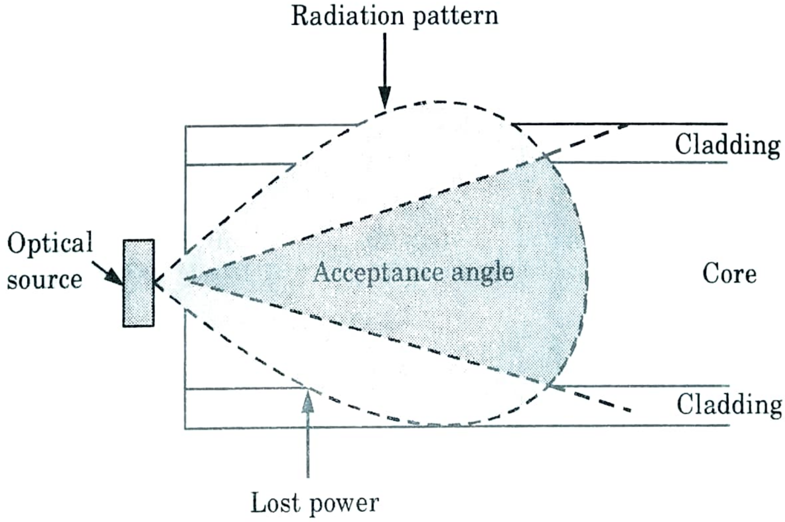


Fig. 4.2.1. Optical source coupled to fiber.

2. Let brightness of source is expressed as $B(A_s, \Omega_s)$ where A_s is area of source, and Ω_s is solid emission angle of source.

3. The coupled power P can be calculated as

$$P = \int_{A_f} dA_s \int_{\Omega_f} d\Omega_s B(A_s, \Omega_s)$$

$$P = \int_0^r \int_0^{2\pi} \left[\int_0^{2\pi} \int_0^{\theta_0 \max} B(\theta, \phi) \sin\theta \, d\theta \, d\phi \right] d\theta_s \, r dr \qquad ...(4.2.1)$$

4. The integral limits are area of source and solid acceptance angle ($\theta_{0\max}$).

Here $d\theta_s \, rdr$ is incremental emitting area.

5. Let us consider the radius of surface emitting LED is r_s and for Lambartian emitter,

$B(\theta, \phi) = B_0 \cos \theta$, then

$$P = \int_0^{r_s} \int_0^{2\pi} \left(2\pi \, B_0 \int_0^{2\pi} \int_0^{\theta_0 \max} \cos\theta \sin\theta \right) d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \int_0^{\theta_0 \max} (2 \sin\theta \cos\theta) \, d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \int_0^{\theta_0 \max} \sin 2\theta \, d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \left[\frac{-\cos 2\theta}{2} \right]_0^{\theta_{0\max}} d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \left[-\frac{1}{2} (\cos 2\theta_{0\max} - \cos 0) \right] d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \left[-\frac{1}{2} (\cos 2\theta_{0\max} - 1) \right] d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \left[\frac{1}{2} (1 - \cos 2\theta_{0\max}) \right] d\theta_s \, r dr$$

$$= B_0 \pi \int_0^{r_s} \int_0^{2\pi} \left[\frac{1}{2} (2 \sin^2 \theta_{0\max}) \right] d\theta_s \, r dr$$

$$= B_0\pi \int_0^{r_s} \int_0^{2\pi} \sin^2 \theta_{0\max}\, d\theta_s\, rdr = B_0\pi \int_0^{r_s} \int_0^{2\pi} NA^2\, d\theta_s\, rdr$$

Since, $NA = n_1\sqrt{2\Delta}$

Que 4.3. **Derive the expression for power coupling to a step index fiber by a surface emitting LED.**

Answer

1. For a step index fiber numerical aperture is not dependent on θ_s and r.
2. Thus LED power from step index fiber is

$$P_{\text{LED, step}} = \pi^2 r_s^2\, B_0 (NA)^2$$

$$P_{\text{LED, step}} = 2\pi^2 r_s^2\, B_0 (n_1^2 \Delta) \quad \text{...(4.3.1)}$$

3. Consider optical power P_s emitted from source area A_s into hemisphere $(2\pi\, S_r)$

$$P_s = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta, \phi) \sin\theta\, d\theta\, d\phi$$

$$P_s = \pi r_s^2\, 2\pi B_0 \int_0^{\pi/2} \cos\theta \sin\theta\, d\theta$$

$$P_s = \pi^2 r_s^2\, B_0 \quad \text{...(4.3.2)}$$

4. When source radius $r_s \le a$, the fiber core radius, the LED output power is given from eq. (4.3.1)

$$P_{\text{LED, step}} = P_S (NA)^2 \quad \text{...(4.3.3)}$$

where, $r_s > a$, Eq. (4.3.1) becomes

$$P_{\text{LED, step}} = \left(\frac{a}{r_s}\right)^2 P_s (NA)^2 \quad \text{...(4.3.4)}$$

Que 4.4. **Derive the expression for power coupling to a graded index fiber by a surface emitting LED.**

Answer

1. In graded index fiber, the index of refraction varies radially from fiber axis. Numerical aperture for graded index fiber is given by

$$NA\,(r) = [n^2(r) - n_2^{\,2}]^{1/2}$$

2. If source radius (r_s) is less than fiber core radius (a) *i.e.*, $r_s > a$, the power coupled from surface emitting LED is given as

$$P_{\text{LED, graded}} = 2\pi^2 B_0 \int_0^{r_s} [n^2(r) - n_2^2]\, r\, dr$$

$$P_{\text{LED, graded}} = 2\pi^2 r_s^2 B_0 n_1^2 \Delta \left[1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right]$$

3. For coupling maximum power to fiber, the refractive index of the medium separating source and fiber must be same, otherwise there will be loss of power.
4. The power coupled is reduced by factor

$$R = \frac{(n_1 - n)^2}{(n_1 + n)^2}$$

where, n is the refractive index of medium.
n_1 is the refractive index of fiber core.
R is the Fresnel reflection or reflectivity.

Que 4.5. **For a surface emitting LED has radiance of 150 W/(cm². Sr) and radius of emitting area is 35 μm. Calculate the optical power coupled to the fiber with**

i. $a_1 = 25\mu m$ **and** $NA = 0.20$ **step index**

ii. $a_2 = 50$ **and** $NA = 0.20$**, step index**

Answer

Given : $B_0 = 150$ W/cm².Sr, $r_s = 35$ μm $= 35 \times 10^{-4}$ cm, $a_1 = 25$ μm, $NA = 0.20$, $a_2 = 50$ μm, $NA = 0.20$
To Find : Optical power coupled.

i. For $r_s > a_1$, the power coupled to the fiber is given by,

$$P_{\text{LED, step}} = \left(\frac{a}{r_s}\right)^2 P_S (NA)^2$$

where, $P_S = \pi^2 r_s^2 B_0$

So, $$P_{\text{LED, step}} = \left(\frac{a}{r_s}\right)^2 (\pi^2 r_s^2 B_0)(NA)^2$$

$$P_{\text{LED, step}} = \left(\frac{25}{35}\right)^2 [\pi^2 \times (35 \times 10^{-4})^2 \times 150][0.20^2]$$

$$= 370\ \mu W$$

ii. For $r_s < a_2$, the power coupled to the fiber is given by,

$$P_{\text{LED, step}} = P_S (NA)^2$$

$$= \pi^2 r_s^2 B_0 (NA)^2$$
$$= [\pi^2 \times (35 \times 10^{-4})^2 \times 150] (0.20)^2$$
$$= 725.41 \ \mu W$$

Que 4.6. **Write short note on power launching versus wavelength.**

Answer

1. The optical power launched into a fiber does not depend on the wavelength of the source but only on its brightness that is, its radiance.
2. The number of modes that can propagate in a multimode graded index fiber of core size a and index profile α is

$$M = \frac{\alpha}{\alpha + 2}\left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta$$

3. Thus, for example, twice as many modes propagate in a given fiber at 900 nm than that at 1300 nm.
4. The radiated power per mode, $\frac{P_s}{M}$, from a source at a particular wavelength is given by the radiance multiplied by the square of the nominal source wavelength,

$$\frac{P_s}{M} = B_0 \lambda^2$$

5. Thus, twice as much power is launched into a given mode at 1300 nm than at 900 nm. Hence, two identically sized sources operating at different wavelength but having identical radiances will launch equal amounts of optical power into the same fiber.

Que 4.7. **Write a short note on equilibrium numerical aperture.**

Answer

1. The excess power loss must be analyzed carefully in any system design, since it can be significantly higher for some types of fiber than for others.
2. At the input end of the fiber, the light acceptance is described in terms of fiber numerical aperture.
3. If the light emitting area of the LED is less than the cross-sectional area of the fiber core, then at this point, the power coupled into the fiber is given by,

$$P_{\text{LED, step}} = P_s(NA)^2$$

where, $NA = NA_{in}$

4. When the optical power is measured in long multimode fibers after the launched modes have come to equilibrium the effect of the equilibrium numerical aperture NA_{eq} becomes apparent.
5. At this point, the optical power in the fiber scales as

$$P_{eq.} = P_{50}\left(\frac{NA_{eq}}{NA_{in}}\right)^2$$

where, P_{50} is the power expected in the fiber at the 50 m point based on the launch NA.

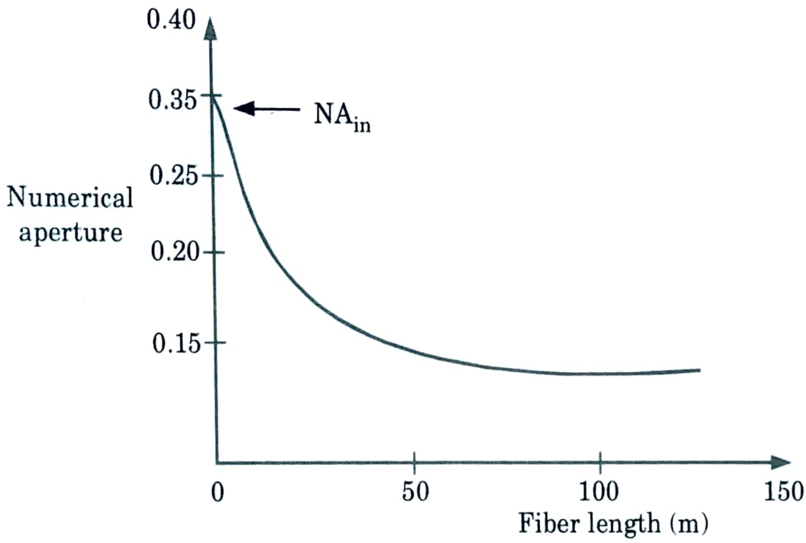


Fig. 4.7.1.

Que 4.8. **Discuss the various factors which effect the launching of optical signal into fiber. Determine the power coupled into step index fiber whose $n_1 = 1.48$, $n_2 = 1.46$, if surface emitting LED radiates 150 μW of power.**

AKTU 2018-19, Marks 10

Answer

A.

1. The launching of optical signal or optical power into a fiber depends on various factors like numerical aperture and size of core diameter, refractive index profile, radiance and angular power distribution of optical source.

i. Optical power launched into fiber does not depend on the wavelength of optical source, but only depends on its brightness that is, its radiance.

The radiated power per mode, P_s/M from a source at a particular wavelength is given by radiance multiplied by the square of nominal source wavelength,

$$\frac{P_s}{M} = B_0\lambda^2$$

Thus, twice as much power is launched into a given mode at 1300 nm than at 900 nm. Hence two identically sized sources operating at different wavelengths but having identical radiances will launch equal amounts of optical power into same fiber.

ii. A certain amount of optical power is lost during coupling of optical power from source to fiber. To achieve a low coupling loss, the light sources should be connected to a system fiber that has a nominally identical *NA* and core diameter. The fiber end face should be centered over the emitting surface of the source and is positioned as close to it as possible.

iii. For proper launching of optical power, there should be perfect coupling conditions between source and fiber. This can be achieved only if refractive index of medium separating the source and fiber end matches the refractive index n_1 of the fiber core. But if the refractive index n of this medium is different from n_1 then power coupled into fiber reduces by the factor

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

where R is Fresnel reflection.

B. Numerical :

Given : $P_{emitted} = 150\ \text{m}\Omega$, $n_1 = 1.48$, $n_2 = 1.46$
To Find : Coupled power.

1. The Fresnel reflection, $R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = \left(\frac{1.48 - 1.46}{1.48 + 1.46}\right)^2 = 4.63 \times 10^{-5}$

2. Coupled power, $P_{coupled} = (1 - R)\,P_{emitted}$
$= 1.499 \times 10^{-4} = 149.9\ \mu\text{W}$

PART-2

Photo Detectors : Introduction, Physical Principle of Photodiodes : The PIN Photo Detector, Avalanche Photodiodes, Temperature Effect on Avalanche Gain.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.9. **Explain the working of *p-i-n* photodiode. Also explain the factors that limit the speed of response of photodiode.**

OR

Explain the working principle of PIN photo detector in detail.

AKTU 2019-20, Marks 07

Answer

A. Working principle of photodiode (Photodetector) :

1. To allow the operation at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary.
2. For this purpose *n*-type material is doped so lightly that it can be considered intrinsic and to make a low resistance contact highly doped *n*-type (n^+) layer is added. This creates a *p-i-n* structure where all the absorption takes place in the depletion region.

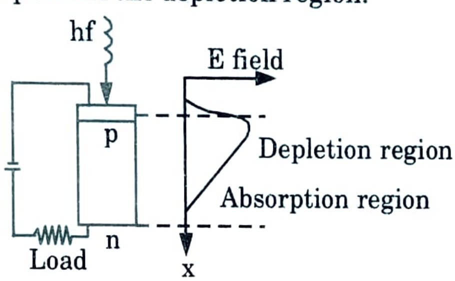


Fig. 4.9.1. *p-i-n* photodiode showing combined absorption and depletion region.

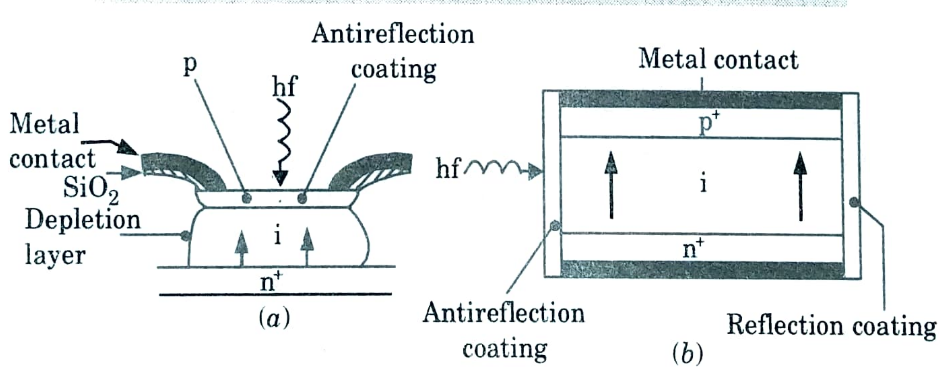


Fig. 4.9.2. (*a*) Structure of a front illuminated silicon *p–i–n* photodiode (*b*) Structure of a side illuminated (parallel to junction) *p–i–n* photodiode.

3. Fig. 4.9.2 shows the structure of two types of silicon *p-i-n* photodiode for operation in the shorter wavelength band below 1.09 μm.
4. The front illuminated photodiode when operating in the 0.8 to 0.9 μm band requires a depletion region of between 20 and 50 μm to attain high quantum efficiency together with fast response and low dark current.

B. Three main factors that limit the speed of response of a photodiode are :

a. Drift time of carriers through the depletion region :

1. The speed of response of a photodiode is limited by the time it takes photogenerated carriers to drift across the depletion region. When the field in the depletion region exceeds the saturation value then the carriers may assumed to travel at constant v_d.
2. The transit time t_{drift}, for carriers which must traverse the full depletion layer width w is given by

$$t_{drift} = \frac{w}{v_d}$$

b. Diffusion time of carriers generated outside the depletion region :

Carrier diffusion is a slow process where the time taken t_{diff}, for carriers to diffuse a distance d may be written as

$$t_{diff} = \frac{d^2}{2D_c}$$

where D_c is the minority carrier diffusion coefficient

c. Time constant incurred by the capacitance of the photodiode with its load :

1. A reverse biased photodiode exhibits a voltage dependent capacitance caused by the variation in the stored charge at the junction. The junction capacitance C_j is given by

$$C_j = \frac{\epsilon_S A}{W}$$

where ϵ_s = Permittivity of semiconductor material
A = Junction area
w = Small depletion layer width

2. The small depletion layer width w increases the junction capacitance. The capacitance of the photodiode C_d is that of junction together with the capacitance of the leads and packaging.
3. The maximum photodiode B_m is given by :

$$B_m = \frac{1}{2\pi\, t_{drift}} \frac{v_d}{2\pi w}$$

Significance :

1. The significance of intrinsic layer in PIN photodiode is that it is used for controlling the width of depletion region.
2. Appropriate width is chosen as a compromise between sensitivity and speed of response.
3. If width of depletion layer is large most of incident photon will be absorbed in depletion region, leading to high sensitivity and small junction capacitance thereby reducing RC time constant of detector circuit.

Que 4.10. **Explain various requirement of optical detector. Explain the working principle of PIN diode.**

AKTU 2017-18, Marks 10

Answer

A. **Various requirement of optical detector :** Photodetectors used for optical fibre communication must fulfill the following requirements for good performance :

1. Sensitivity at the operating wavelengths should be very high.
2. To reproduce the received signal waveform with fidelity, for analogy transmission the response of the photodetector must be linear with regard to the optical signal over a wide range.
3. The photodetector should produce a maximum electrical signal for a given amount of optical power *i.e.*, the quantum efficiency should be high.
4. In order to obtain a suitable bandwidth, response time should be as small as possible.
5. Dark currents, leakage currents and shunt conductance should be low. Noises in the circuitry must be low.
6. In an ideal detector, the performance characteristics should be independent of changes in ambient conditions.
7. The detector to be used must be of small size in order to have efficient coupling with fiber.
8. The detector should be reliable *i.e.*, it must be capable of continuous stable operation at room temperature for many years.
9. It must be of low cost.

B. **Working principle of PIN diode :** Refer Q. 4.9, Page 4–10D, Unit-4.

Que 4.11. **Explain the working of PIN photodiode. A PIN photodiode has a quantum efficiency of 55 % at a wavelength of 0.9 μm. Calculate :**

i. **Its responsivity at 0.9 μm.**
ii. **The received optical power if the mean photocurrent is 10^{-8} A.**
iii. **The corresponding number of received photons at this wavelength.**

AKTU 2017-18, 2018-19; Marks 10

Answer

A. **Working of PIN photodiode :** Refer Q. 4.9, Page 4–10D, Unit-4.

B. Numerical :

Given : $\eta = 55\ \% = 0.55$, $\lambda = 0.9\ \mu m$
To Find : Responsivity, received optical power, number of received photons.

i. Responsivity, $$R = \frac{\eta q}{h\nu} = \left(\frac{\eta}{1248}\right)\lambda(\text{nm})$$

$$R = \frac{0.55}{1248} \times 900 = 0.396\ \text{A/W}$$

ii. $$R = \frac{I_P}{P_{op}}$$

$\therefore$ $$P_{op} = \frac{I_P}{R} = \frac{10^{-8}}{0.396} = 2.52 \times 10^{-8}\ \text{W}$$

iii. $$P_{op} = n\frac{hc}{\lambda} = n\frac{6.62 \times 10^{-34} \times 3.0 \times 10^{8}}{0.9 \times 10^{-6}}$$

$$2.52 \times 10^{-8} = n \times 22.067 \times 10^{-20}$$

$\Rightarrow$ $$n = 1.14 \times 10^{11}$$

Que 4.12. **Enumerate the principle of operation of APD.**

AKTU 2016-17, Marks 10

Answer

1. The second major type of optical communication detector is avalanche photodiode.

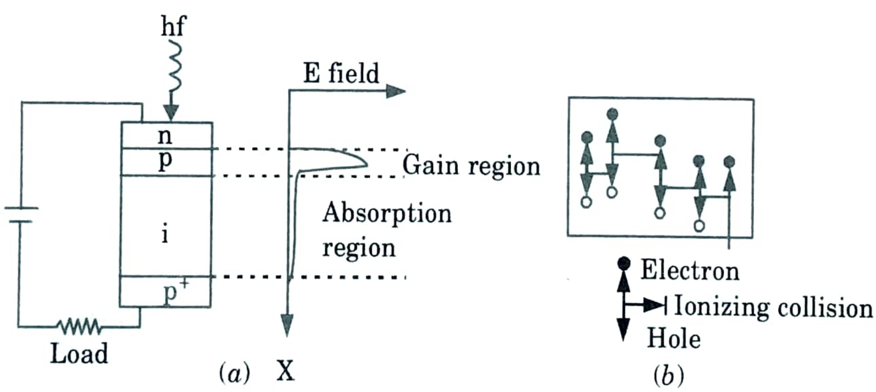


Fig. 4.12.1. (*a*) Avalanche photodiode showing high electric field (gain) region. (*b*) Carrier pair multiplication in the gain region.

2. The depletion region where most of the photons are absorbed and the primary carrier pairs generated there is a high field region in which holes and electrons can acquire sufficient energy to excite new electrons hole pairs.
3. This process is known as impact ionization and is the phenomenon that leads to avalanche breakdown in ordinary reverse biased diodes.

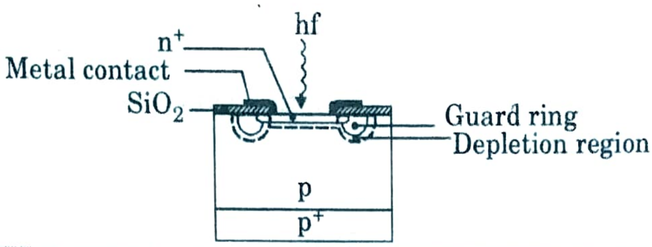


Fig. 4.12.2. Structure of a silicon avalanche photodiode with guard ring.

4. Carrier multiplication factors as great as 10^4 may be obtained using defect free materials to ensure uniformity of carrier multiplication over the entire area.
5. Operation of these devices at high speed requires full depletion in the absorption region.
6. When carriers are generated in undepleted material, they are collected somewhat slowly by the diffusion process.

Que 4.13. **Explain the structure of silicon reach through avalanche photodiode (RAPD) with its gain mechanism.**

AKTU 2015-16, Marks 05

Answer

1. The silicon reach through APD consist of p^+–π–p–n^+ layers as shown in a Fig. 4.13.1.
2. In the Fig. 4.13.1(b), the high field region where the avalanche multiplication takes place is relatively narrow and centred on the p-n^+ junction.

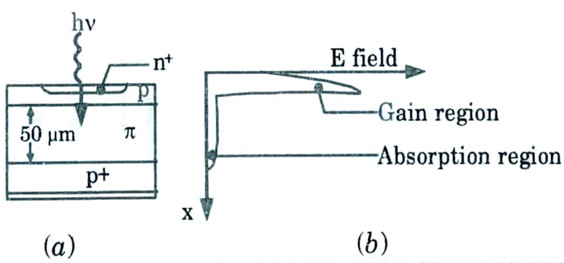


Fig. 4.13.1. (a) Structure of a silicon RAPD. (b) The field distribution in the RAPD showing the gain region across the p-n^+ junction.

3. When the reverse bias voltage is increased the depletion layer widens across the p-region until it reach through to the nearly intrinsic π-region.
4. Since the π-region is much wider than the p-region, the field in the π-region is much lower than the p-n^+ junction.
5. This has the effect of removing some of the excess applied voltage from the multiplication region to p-region giving a relatively slow increase in multiplication factor with applied voltage.

Que 4.14. **Describe the factors which limit the speed of response of a photodiode and show the impact of change in temperature over the avalanche multiplication factors/internal gain.**

AKTU 2015-16, Marks 10

OR

Explain avalanche photodiode and also explain effect of temperature on avalanche gain.

AKTU 2017-18, Marks 10

OR

Explain the physical principle of APD. What is the temperature effect on avalanche gain ? Describe automatic gain control using Op-Amp.

AKTU 2018-19, Marks 10

OR

Explain avalanche photodiode and also explain effect of temperature on avalanche gain.

AKTU 2019-20, Marks 07

Answer

A. **Principle of APD :** Refer Q. 4.12, Page 4–13D, Unit-4.

B. **Three main factors that limit the speed of response of a photodiode are :** Refer Q. 4.12, Page 4–13D, Unit-4.

C. **Temperature effect on avalanche gain :**

1. The gain mechanism of an avalanche photodiode is very temperature sensitive because of temperature dependence of the electron and hole ionization rates.
2. This temperature dependence is particularly critical at high bias voltage, where small changes in temperature can cause large variations in gain.
3. Let us consider an example for a silicon avalanche photodiode. If the operating temperature decreases and applied bias voltage is kept constant, the ionization rates for electrons and holes will increase and so will be the avalanche gain.
4. To maintain a constant gain as the temperature changes, the electric field in the multiplying region of the *p-n* junction must also be changed.
5. This requires that the receiver incorporate a compensation circuit which adjusts the applied bias voltage on the photodetector when the temperature changes.

$$M = \frac{1}{1-(V/V_B)^n}$$

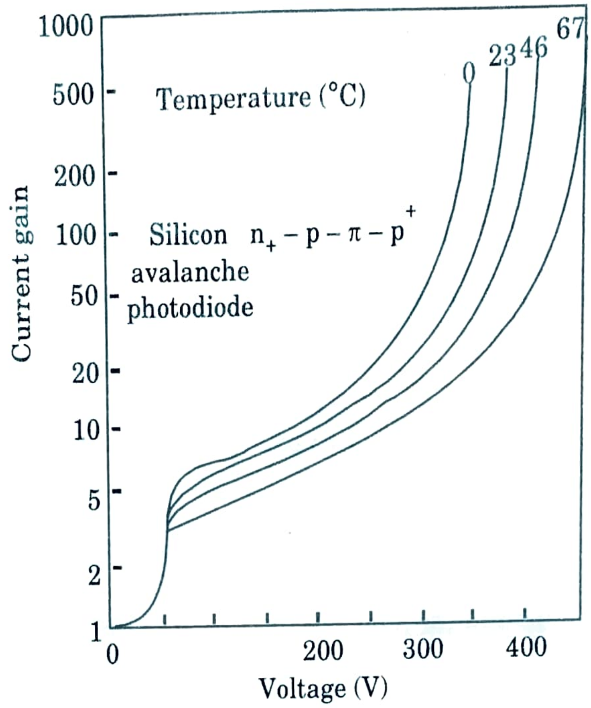


Fig. 4.14.1.

D. Automatic gain control using Op-Amp :

1. An AGC is a form by which multiplication factor can be held constant. The advantage of using AGC is that it reduces the dynamic range at the receiver input.
2. One simple method of providing AGC is to bias avalanche photodiode (APD) with a constant DC current source bias, as shown in Fig. 4.14.2.

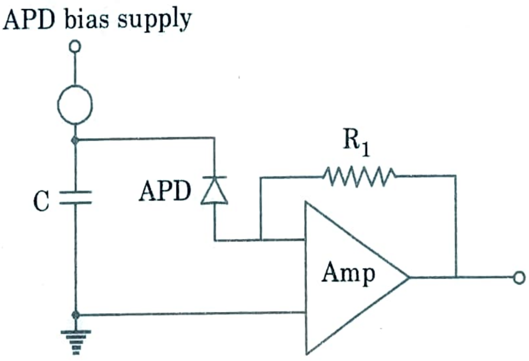


Fig. 4.14.2.

3. In this, constant current source is decoupled with capacitor C at all frequencies to prevent gain modulation.
4. When the mean optical input power is known, the mean current to the APD is defined by the bias which gives a constant multiplication factor at all temperatures.
5. Any variation in the multiplication factor will produce a variation in charge on C.

6. The output current from the photodetector is defined by input current from the constant current source giving full automatic gain control, thus this simple AGC technique is dependent on a constant, mean optical input power level and takes no account of dark current generated within detector.

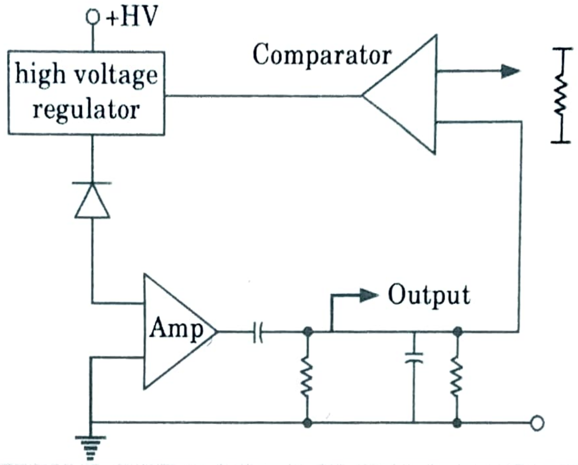


Fig. 4.14.3. Bias of an APD by peak detection and feedback to provide AGC.

PART-3

Detector Response Time, Photodetector Noise : Noise Sources, Signal to Noise Ratio, Comparison of Photodetector, Fundamental Receiver Operation With Digital Signal Transmission.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.15. **Explain detector response time.**

Answer

1. In order to determine detector response time, let us consider a reversed biased PIN photodiode.

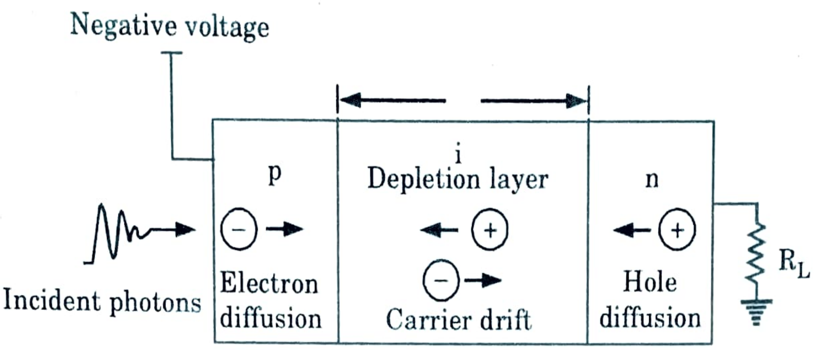


Fig. 4.15.1. Reverse biased PIN diode.

2. After observing Fig. 4.15.1 the total current density through depletion layer is $$J_{tot} = J_{dr} + J_{diff} \quad ...(4.15.1)$$
where
J_{dr} is drift current density due to carriers generated in depletion region.
J_{diff} is diffusion current density due to carriers generated outside depletion region.
3. The drift current density is expressed as :
$$J_{dr} = \frac{I_p}{A}$$
$$J_{dr} = q\,\phi_0(-e^{-\alpha_s W})$$
where, A is photodiode area and ϕ_0 is incident photon flux per unit area.
4. The diffusion current density is expressed as :
$$J_{diff} = q\phi_0 \frac{\alpha_s L_p}{1+\alpha_s L_p} e^{-\alpha_s W} + qP_{n_0} \frac{D_p}{L_p}$$
where, D_p is hole diffusion co-efficient, P_n is hole concentration in n-type material, and P_{n0} is equilibrium hole density.
5. Substituting in eq. (4.15.1), total current density through reversed biased depletion layer is $$J_{tot} = q\,\phi_0 \left[1 - \frac{e^{-\alpha_s W}}{1+\alpha_s L_p}\right] + q\,p_{n0} \frac{D_p}{L_p}$$
6. The factors that determine the response time of a photodiode are :
i. Transit time of photo carriers within the depletion region.
ii. Diffusion time of photo carriers outside the depletion region.
iii. RC time constant of diode and external circuit.

Que 4.16. What do you mean by photodetector noise ? Explain noise source.

Answer

1. The photodiode is generally required to detect very weak optical signals.

2. The power signal to noise ratio S/N at the output of an optical receiver is defined by :

$$\frac{S}{N} = \frac{\text{Signal power from photocurrent}}{\text{Photodetector noise power + Amplifier noise power}}$$

3. The noise sources in the receiver arise from the photodetector noises resulting from the statistical nature of the photon to electron conversion process and the thermal noise associated with the amplifier circuitry.
4. To achieve a high signal to noise ratio, the following conditions should be met :
   i. The photodetector must have a high quantum efficiency to generate a large signal power.
   ii. The photodetector and amplifier noises should be kept as low as possible.
5. The principal noise associated with photodetectors that have no internal gain are quantum noise, dark current noise generated in the bulk material of the photodiode, and surface leakage current noise.
6. The quantum or shot noise arises from the statistical nature of the production and collection of photoelectrons when an optical signal is incident on a photodetector.

$$\langle i_{\text{shot}}^2 \rangle = \sigma_{\text{shot}}^2 = 2qI_p B_e M^2 F(M)$$

7. The photodiode dark current is the current that continues to flow through the bias circuit of the device when no light is incident on the photodiode.
8. This is a combination of bulk and surface currents. The bulk dark current i_{DB} arises from electrons and/or holes which are thermally generated in the pn junction of the photodiode.
9. In an APD, these liberated carriers also get accelerated by the high electric field present at the pn junction, and are therefore multiplied by the avalanche gain mechanism.
10. The mean-square value of this current is given by

$$\langle i_{DB}^2 \rangle = \sigma_{DB}^2 = 2qI_D M^2 F(M) B_e$$

    where I_D is the primary (unmultiplied) detector bulk dark current.
11. The surface dark current is also referred to as a surface leakage current or simply the leakage current. It is dependent on surface defects, cleanliness, bias voltage, and surface area.
12. An effective way of reducing surface dark current is through the use of a guard ring structure which shunts surface leakage currents away from the load resistor.
13. The mean square value of the surface dark current is given by

$$\langle i_{DS}^2 \rangle = \sigma_{DS}^2 = 2qI_L B_e$$

    where I_L is the surface leakage current.

14. The surface dark current increases in proportion to the square root of the active area, and the bulk dark current is directly proportional to the area.

Que 4.17. **Draw and explain avalanche photodiode receiver and derive expression for SNR.** **AKTU 2018-19, Marks 10**

Answer

A. **APD :** Refer Q. 4.12, Page 4–13D, Unit-4.

B. **Expression for SNR :**

1. The origin of avalanche excess noise in APD is the difference in ionization of electrons and holes.
2. The ratio of the actual noise generated in an avalanche photodiode to the noise that would exist if all carrier pairs were multiplied by exactly M is called the excess noise factor F, which is determined by the following formula :

$$F = k_A M + (1 - k_A)\left(2 - \frac{1}{M}\right)$$

where k_A is the ratio of the electron and hole ionization rates.

3. The shot noise in an APD is

$$i_s^2\,(\text{APD}) = M^2\,[2eF\,(I^*_p)\,(BW)]$$

4. For dark-current noise the value of F is very small. Thermal noise, on the other hand, does not depend on current and, therefore, is not changed by the ionization process. This is because thermal noise is created on resistors.
5. As a result, then, for the formula for the RMS value of an APD's thermal-noise current is :

$$i_t(\text{APD}) = \sqrt{\left(\frac{4K_BT}{R_L}\right)(BW)}$$

6. Thus, the signal-to-noise ratio for an APD can be written as :

$$\text{SNR (APD)} = \frac{I_p^{*2}}{I^2_{\text{noise}}} = \frac{\left(M\,I_p^*\right)^2}{\left(i_s^2 + i_t^2\right)}$$

$$\text{SNR} = \frac{M^2\,I_p^{*2}}{\left(2eM^2\,I_p^* + \dfrac{4K_BT}{R_L}\right)BW}$$

Que 4.18. **Write a short note on noise sources in optical fiber communication.**

Answer

Noise sources in optical fiber communication are :

1. **Quantum or shot noise :** It arises from statistical nature of the production or collection of photoelectrons when optical signal is incident on a photodetector. The shot noise current has a mean square value in a receiver bandwidth B_e which is proportional to average value of photocurrent I_p.

$$\left\langle i_{\text{shot}}^2 \right\rangle = \sigma_{\text{shot}}^2 = 2qI_p B_e M^2 F(M)$$

2. **Dark current noise generated in bulk material of a photo diode :** The bulk dark current i_{DB} arises from electrons or holes which are thermally generated in the p-n junction photodiode. The mean square value of this current is given by

$$\left\langle i_{DB}^2 \right\rangle = \sigma_{DB}^2 = 2qI_D M^2 F(M) B_e$$

3. **Surface dark current/surface leakage current :** It depends on surface defects, cleanliness, bias voltage, and surface area. An effective way to reduce dark current is through guard ring structure which shunts surface leakage current away from load resistor.
The mean square value of dark current is

$$\left\langle i_{DS}^2 \right\rangle = \sigma_{DS}^2 = 2q\, I_L\, B_e$$

Que 4.19. **A silicon PIN photodiode incorporated into an optical receiver has a quantum efficiency of 60 % when operating at a wavelength of 0.9 mm. The dark current is 3 nA and the load resistance is 4 kΩ. The incident optical power is 200 nW and the post detection bandwidth of the receiver is 5 MHZ. Calculate the root mean square (rms) shot noise and thermal noise currents generated.**

AKTU 2019-20, Marks 07

Answer

Given : $\eta = 60\ \%$, $\lambda = 0.9$ mm, $I_d = 3$ nA, $R_L = 4$ kΩ, $P_0 = 200$ nW, $BW = 5$ MHz
To Find : Root mean square (rms) shot noise current, RMS thermal noise current.

1. The photocurrent is given by,

$$I_p = \frac{\eta P_0 e}{hf} = \frac{\eta P_0 e \lambda}{hc}$$

$$= \frac{0.6 \times 200 \times 10^{-9} \times 1.602 \times 10^{-19} \times 0.9 \times 10^{-3}}{6.626 \times 10^{-34} \times 3 \times 10^{8}} = 8.70 \times 10^{-5}\ \text{A}$$

$$= 87\ \mu\text{A} = 0.087\ \text{nA}$$

2. The total shot noise is,

$$\overline{i_{TS}^2} = 2eBW\,(I_d + I_p)$$

$$= 2 \times 1.602 \times 10^{-19} \times 5 \times 10^6 [(3 + 0.087) \times 10^{-9}]$$

$$= 49.45 \times 10^{-22} \text{ A}^2$$

And the root mean square (rms) shot noise current is

$$(\overline{i_{TS}^2})^{1/2} = 7.03 \times 10^{-11} \text{ A}$$

3. The thermal noise current is,

$$\overline{i_T^2} = \frac{4kTBW}{R_L}$$

$$= \frac{4 \times 1.381 \times 10^{-23} \times 293 \times 5 \times 10^6}{4 \times 10^3}$$

[∵ Assume T = 20 °C = 293° K]

$$= 2.02 \times 10^{-17} \text{ A}^2$$

4. Therefore, the rms thermal noise current is

$$(\overline{i_T^2})^{1/2} = 4.49 \times 10^{-9} \text{ A}$$

Que 4.20. Discuss the comparison between PIN and ADP photodetectors.

Answer

S. No.	Parameters	PIN	ADP
1.	Sensitivity	Less sensitive *i.e.*, form 0-12 dB	More sensitive *i.e.*, from 5 to 15 dB
2.	Biasing	Low reverse biased (5 to 10 V)	High reverse biased voltage (200–400 V)
3.	Wavelength region	300-1100 nm	400–100 nm
4.	Gain	No internal gain	Internal gain
5.	S/N ratio	Poor	Better
6.	Detector circuit	Simple	More complex
7.	Conversion efficiency	0.5 to 1.0 Amps/Watt	0.5 to 100 Amps/Watt
8.	Cost	Cheaper	More expensive

Que 4.21. Draw and explain the operation of optical receiver.

AKTU 2019-20, Marks 07

Answer

1. A block schematic of an optical fiber receiver is shown in Fig. 4.21.1.
2. The linear conversion of the received optical signal into an electrical current at the detector is amplified to obtain a suitable signal level.
3. Initial amplification is performed in the pre-amplifier circuit where it is necessary that additional noise is kept to minimum in order to avoid corruption of the received signal.

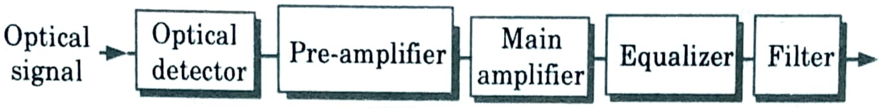


Fig. 4.21.1.

4. The main amplifier provides low noise amplification of the signal to give an increased signal level.
5. The transfer function of pre-amplifier-main amplifier combination may be such that the input signal becomes distorted.
6. Thus, to provide a suitable signal shape for the filter an equalizer is used in the receiver.
7. The function of the final element in the receiver, the filter, is to maximize the received signal to noise ratio.
8. In digital system, mainly the function of the filter is to reduce intersymbol interference whereas in analog system it is generally required to hold the amplitude and phase response of received signal.
9. The filter is also designed to reduce the noise bandwidth as well as inband noise levels.

Que 4.22. **What is the function of an optical detector ? Draw an optical receiver configuration with different possible structures for front-end amplifier. Explain the different types of error/noise sources in an optical receiver.** **AKTU 2015-16, Marks 10**

OR

Write a short note on front end amplifier.

AKTU 2017-18, Marks 10

AKTU 2019-20, Marks 3.5

OR

Explain the necessity of preamplifier in optical receiver. Mention the types of preamplifier and explain the working of any one of them. **AKTU 2017-18, Marks 10**

OR

Explain in detail with relevant circuit diagrams the different types of optical pre-amplifiers.

AKTU 2016-17, Marks 10

Answer

A. Function of optical detector :

1. The function of optical detector is to convert the received optical signal into an electrical signal, which is then amplified before further processing.
2. Therefore when considering signal attenuation along the link, the system performance is determined at the detector.

B. Necessity of preamplifier :

Initial amplification is performed in the preamplifier circuit where it is essential that additional noise is kept to a minimum in order to avoid corruption of the received signal.

C. Types of preamplifier :

a. Low impedance front end receiver :

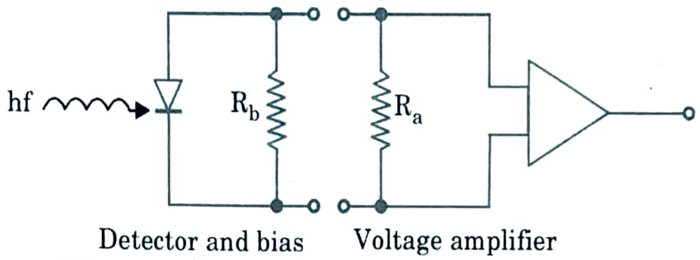


Fig. 4.22.1. Low impedance front end optical fiber receiver with voltage amplifier.

1. This configuration consists of a voltage amplifier together with a detector bias resistor. This is the simplest and most commonly used receiver.
2. In order to make the design suitable it is necessary to consider both bandwidth and noise.
3. The bandwidth is determined by the passive impedance which appears across the detector terminal taken as R_L.
4. However R_L may be modified to incorporate the parallel resistance of the detector bias resistor R_b and amplifier input resistance R_a.
5. The total resistance R_{TL} is given as :

$$R_{TL} = \frac{R_b R_a}{R_b + R_a}$$

6. To achieve an optimum bandwidth both R_b and R_a must be minimized.
7. This leads to low impedance front end design for the receiver amplifier.
8. This design allows thermal noise to dominate within the receiver which may severely limit its sensitivity.

b. High impedance front end receiver :

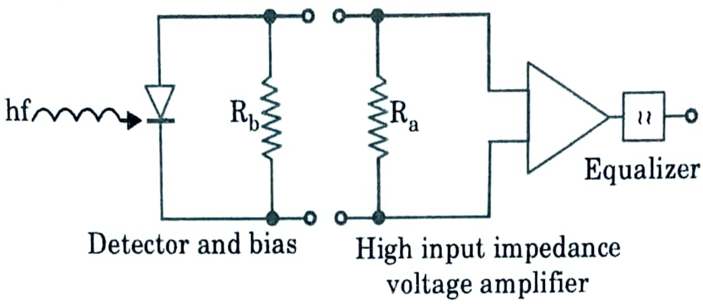


Fig. 4.22.2. High impedance integrating front end optical fiber receiver with equalized voltage amplifier.

1. This configuration consists of high input impedance amplifier together with a large detector bias resistor in order to reduce the effect of thermal noise.
2. This structure gives a degraded frequency response as bandwidth is not maintained for wideband operation.
3. The detector output is effectively integrated over a large time constant and must be restored by differentiation. This may be performed by correct equalization.
4. The high impedance front end structure provides a significant improvement in the sensitivity over a low impedance front end structure but it creates a heavy demand for equalization and has problems of limited dynamic range.
5. The limitations on dynamic range results from the attenuation of the low frequency signal components by the equalization process which causes the amplifier to saturate at high signal levels.

c. The transimpedance front end receiver :

1. This configuration mainly overcomes the drawbacks of the high impedance front end by utilizing a low noise, a high input impedance amplifier with negative feedback.

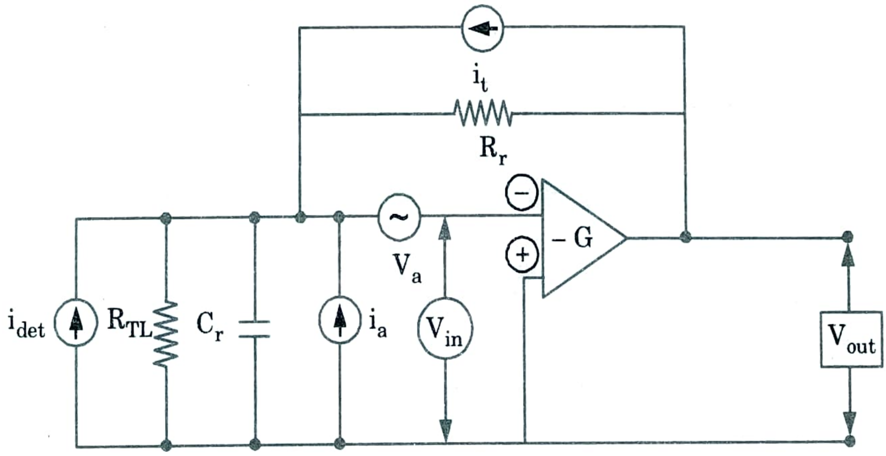


Fig. 4.22.3. An equivalent circuit for the optical fiber receiver incorporating a transimpedance (current mode) preamplifier.

2. This device operates as a current mode amplifier where the high input impedance is reduced by negative feedback.
3. In the above equivalent circuit, the parallel resistances and capacitances are combined into R_T and C_T.

D. Types of error / noise sources : Refer Q. 4.18, Page 4–20D, Unit-4.

Que 4.23. **Explain a digital signal transmission setup suitable for fiber optic communication.**

Answer

1. Transmitted signal is a two level binary data stream consisting of either a 0 or a 1 in a time slot of duration T_b. This time slot is referred as bit period.
2. Fig. 4.23.1, illustrates the shape of a digital signal at different points along an optical link.

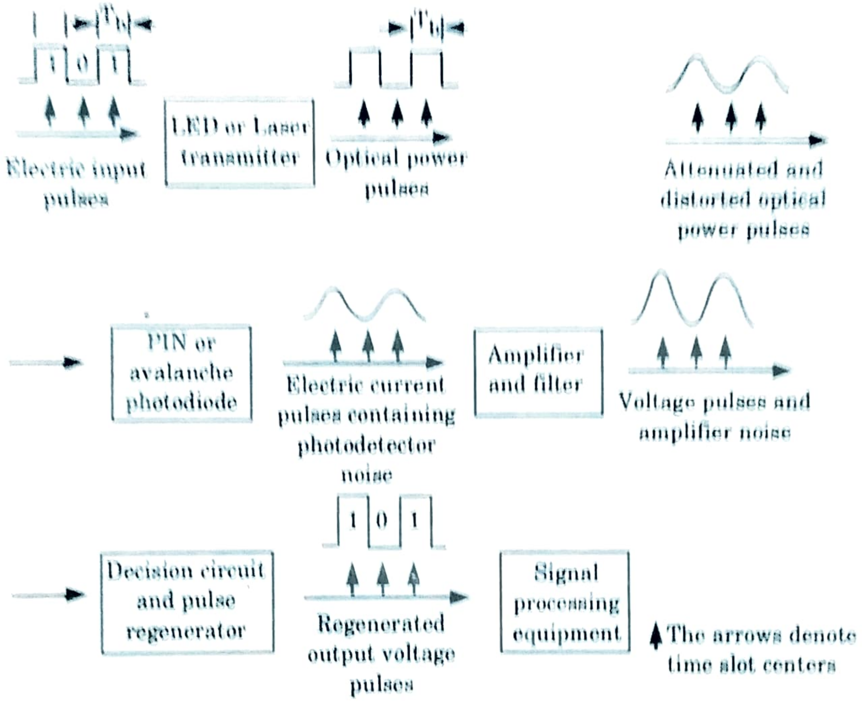


Fig. 4.23.1. Signal path through an optical data link.

3. One of the simplest techniques for sending binary data is amplitude shift keying or on-off keying wherein a voltage level is switched between two values, which are usually ON or OFF.
4. The resultant signal wave thus consists of voltage pulse of amplitude V relative to zero voltage level when a binary 1 occurs and zero voltage level space when a binary 0 occurs.
5. Depending on the coding scheme to be used, a binary 1 may or may not fill the time slot T_b.

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6. For simplicity here we assume that when 1 is sent, a voltage pulse of duration T_b occurs, whereas for 0 the voltage remains at its zero level.

5
UNIT

Digital Receiver Performance

CONTENTS

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PART-1

Probability of Error / BER, Receiver Sensitivity & The Quantum Limit, Error Control Techniques, Eye Diagram Pattern Features.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.1. **Write a short note on probability of error sensitivity.**

AKTU 2019-20, Marks 3.5

OR

Explain quantum limit.

Answer

The performance criterion for receivers is governed by the bit-error rate (BER), defined as the probability of incorrect identification of a bit by the decision circuit of the receiver.

BER :

1. Bit error rate (BER) is defined as the ratio of number of errors occurring over a time interval to the number of pulses transmitted during the interval.

$$BER = \frac{N_e}{N_t} \quad ...(5.1.1)$$

$$BER = \frac{N_e}{B_t} \quad ...(5.1.2)$$

where,

N_e is the number of errors occurring during the interval,

N_t is the number of pulses transmitted during the interval, and

B is the bit rate ($1/T_b$) or pulse transmission rate.

2. BER for optical fiber communication system is ranging between 10^{-9} and 10^{-12}. BER of receiver depends on S/N ratio.
3. To compute the BER at receiver probability distribution of output signal is considered.

$$P_e = \frac{1}{2}\left[1 - \text{erf}\left(\frac{V}{2\sqrt{2}\sigma}\right)\right]$$

where, V is the pulse amplitude and σ is standard deviation.

Quantum limit :

1. For an ideal photo detector quantum efficiency $\eta = 1$ and has zero dark current then the minimum received.
2. Power for a specific bit-error rate is known as quantum limit.
3. Let an optical pulse of energy E is incident on photo detector in time interval τ.
4. Then the probability of emitting zero electrons during the interval is τ

$$P_r(0) = e^{-\bar{N}} .$$

where, N is average number of electrons hole pair.

Que 5.2. **How to measure the BER and Q factor in digital transmission ?**

AKTU 2016-17, Marks 10

Answer

A. BER :

1. BER is a statistical parameter; its value depends on the measurement time and on the factors that cause the errors.
2. If the errors are due to Gaussian noise in a relatively stable transmission link, then a measurement time in which about 100 errors occur may be needed to ensure a statistically valid BER determination.
3. BER means that one bit error occurs every 100 seconds. Such a level may be unacceptable, so even lower bit error rates.
4. For example, to detect 100 errors for measuring a 10^{-12} BER in a 10 Gb/s link will require 2.8 hours. Thus test times on installed links could run anywhere from 8 to 72 hours. To reduce such costly and time consuming test periods, a Q-factor technique can be used.

B. Q-factor measurement :

1. In this method the receiver threshold is decreased, which increases the probability of errors and thus decreases test time.
2. Q-factor based measurements are more complex equipment also measure performance by using a degraded signal that more closely represents what is seen in fielded links.
3. This method is described in the IEEE 802.3 specification for testing 10-Gigabit Ethernet (10-GbE) devices.

Que 5.3. **Define bit error rate (BER) of digital optical receiver. Obtain its expression for binary receiver assuming noise distribution to be Gaussian.**

AKTU 2018-19, Marks 10

Answer

A. **BER :** Refer Q. 5.1, Page 5–2D, Unit-5.

B. **Derivation :**

1. We assume that the average received power is equal to P_1 when the symbol 1 is transmitted and to P_0 when the symbol 0 is transmitted. Since some noise contributions depend on the received optical power, the photocurrent fluctuations are also functions of the transmitted symbol.
2. The output photocurrent i fluctuates from one bit to another, around an average value μ_1 with the variance σ_1 when the symbol 1 is transmitted and μ_0 with the variance σ_0 when the symbol 0 is transmitted.
3. At the decision time t_D determined by the clock recovery circuit, the decision circuit compares the observed current value i with a threshold value i_D.
4. When i is found to be above the threshold value in the firm decision that a 1 is transmitted can be made.
5. When i is found to be below the threshold value i_D the firm decision can be made that a 0 is transmitted.
6. Fig. 5.3.1 shows the probability distributions of the photocurrent for the two transmitted symbols.

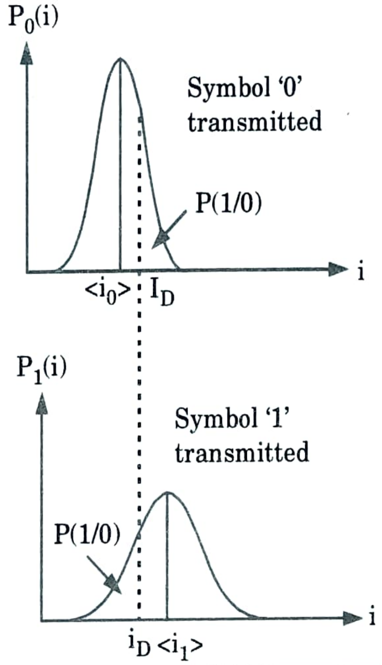

Fig. 5.3.1. Probability distributions of the photocurrent for the two transmitted symbols and selection of the decision thresholds.

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7. When, due to the signal and receiver noises, i is found above the threshold value i_D whereas the symbol 0 has been transmitted, an error occurs. In the same way, when i is found below the threshold value i_D whereas the symbol 1 has been transmitted, an error also occurs.
8. Both of these two error sources degrade the performance of the communication system.
9. The performance of a digital communication system is expressed in terms of bit error probability, also called the bit error ratio (BER), defined as the ratio of the number of wrong decisions to the number of transmitted bits :

$$BER = p(1)p(0/1) + p(0)p(1/0) \qquad ...(5.3.1)$$

10. In which $P(1)$ and $P(0)$ are the probabilities of transmitting 1 and 0 respectively and $P(0/1)$ is the probability of deciding that 0 is received when 1 is transmitted, and $P(1/0)$ is the probability of deciding 1 when 0 is transmitted.
11. The two products express the two joint probabilities to make a wrong decision. The bit error ratio is also frequently referred to as the bit error rate.
12. A binary message is more informative when the symbols 1 and 0 have the same probability to occur so that $P(1) = P(0) = \{1/2\}$. The BER is thus given by :

$$BER = \frac{1}{2}\,[P(0/1) + P(1/0)] \qquad ...(5.3.2)$$

13. Both the average and the variance of the photocurrent are different for bit 1 and bit 0. Using a Gaussian model, the probabilities $P(0/1)$ and $P(1/0)$ are written as :

$$p(0/1) = \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\infty}^{i_D}\exp\left[-\frac{(i-\mu_1)^2}{2\sigma_1^2}\right]di = \frac{1}{2}\,\text{erfc}\left(\frac{\mu_1 - i_D}{\sigma_1\sqrt{2}}\right) \qquad ...(5.3.3)$$

$$p(1/0) = \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\infty}^{i_D}\exp\left[-\frac{(i-\mu_0)^2}{2\sigma_0^2}\right]di = \frac{1}{2}\,\text{erfc}\left(\frac{i_D - \mu_0}{\sigma_0\sqrt{2}}\right) \qquad ...(5.3.4)$$

14. In which $\text{erfc}(x) = 1 - \text{erf}(x)$ is the complementary error function defined as :

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty}\exp[-u^2]\,du \qquad ...(5.3.5)$$

15. Putting the value of $P(0/1)$ and $P(1/0)$ in eq. (5.3.2), we get

$$BER = \frac{1}{4}\left[\text{erfc}\left(\frac{i_D - \mu_0}{\sigma_0\sqrt{2}}\right) + \text{erfc}\left(\frac{\mu_1 - i_D}{\sigma_1\sqrt{2}}\right)\right]$$

Que 5.4. **Explain the term receiver sensitivity in reference to digital receiver performance.**

Answer

1. To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photodetector. The value of this minimum power level is called the receiver sensitivity.
2. A common method of defining the receiver sensitivity is as an average optical power (P_{avg}) in dBm incident on the photodetector.
3. Alternatively it may be defined as an optical modulation amplitude (OMA) given in terms of a peak to peak current at the photodetector output. The receiver sensitivity gives a measure of the minimum average power of OMA needed to maintain a maximum (worst case) BER at a specific data rate.
4. The receiver sensitivity factor Q in terms of signal currents from 1 and 0 pulses (I_1 and I_0, respectively) and their corresponding noise current variations (σ_1 and σ_0, respectively), and assuming there is no optical power in a zero pulse, yields.
$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \approx \frac{I_1}{\sigma_1 + \sigma_0}$$
5. The receiver sensitivity $P_{\text{sensitivity}}$ is found from the average power contained in a bit period for the specified data rate as :
$$P_{\text{sensitivity}} = \frac{P_1}{2} = \frac{I_1}{(2RM)} = Q\frac{(\sigma_1 + \sigma_0)}{(2RM)} \quad ...(5.4.1)$$
where R is the unity gain responsivity and M is the gain of the photodiode.
6. If there is no optical amplifier in a fiber transmission link, then thermal noise and shot noise are the dominant noise effects in the receiver.
7. The thermal noise is independent of the incoming optical signal power, but the shot noise depends on the received power.
8. Assuming there is no optical power in a received zero pulse, the noise variances for 0 and 1 pulses, respectively, are
$$\sigma_0^2 = \sigma_T^2 \text{ and } \sigma_1^2 = \sigma_T^2 + \sigma_{\text{shot}}^2 .$$
9. The shot noise variance for a 1 pulse is
$$\sigma_{\text{shot}}^2 = 2q\,RP_1\,M^2\,F(M)B_e$$
$$= 4q\,R\,P_{\text{sensitivity}}\,M^2F(M)B/2$$
10. The thermal noise current variance is :
$$\sigma_T^2 = \frac{4k_BT}{R_L}F_n\frac{B}{2}$$
11. Substituting $\sigma_1 = (\sigma_{\text{shot}}^2 + \sigma_T^2)^{1/2}$

and $\sigma_0 = \sigma_1$ in eq. (5.4.1), we have

$$P_{sensitivity} = \left(\frac{1}{R}\right)\frac{Q}{M}\left[\frac{qMF(M)BQ}{2} + \sigma_T\right]$$

Que 5.5. **Write a short note on error control technique.**

Answer

1. To control errors and to improve the reliability of a communication line, first it is necessary to be able to detect the errors and then either to correct them or retransmit the information.
2. Error detection methods encode the information stream to have a specific pattern.
3. If segments in the received data stream violate this pattern, then errors have occurred.
4. The two basic schemes for error correction are automatic repeat request (ARQ) and forward error correction (FEC).

i. ARQ :

1. ARQ schemes have been used for many years in applications such as computer communication links that use telephone lines and for data transmission over the Internet.
2. As shown in Fig. 5.5.1, the ARQ technique uses a feedback channel between the receiver and the transmitter to request message retransmission in case errors are detected at the receiver.

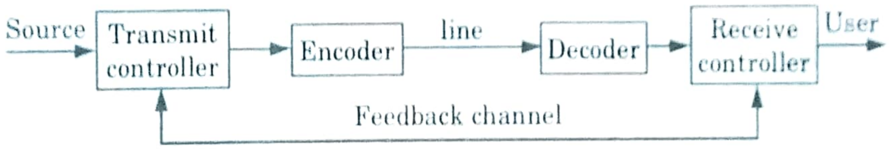

Fig. 5.5.1. Basic setup for an automatic-repeat-request (ARQ) error-correction scheme.

3. Since each such transmission adds at least one round-trip time of latency, ARQ may not be feasible for applications in which data must arrive within a certain time in order to be useful.

ii. Forward error correction :

1. Forward error correction avoids the shortcomings of ARQ for high bandwidth optical networks requiring low delays.
2. In FEC techniques, redundant information is transmitted along with the original information.
3. If some of the original data is lost or received in error, the redundant information is used to reconstruct it.

Que 5.6. **Draw eye diagram and explain eye pattern features.**

Answer

A. Eye diagram :

1. The eye diagram is powerful measurement tool for assessing the data handling ability of a digital transmission system.
2. This method has been used extensively for evaluating the performance of wire line systems and also applies to optical fiber data links.

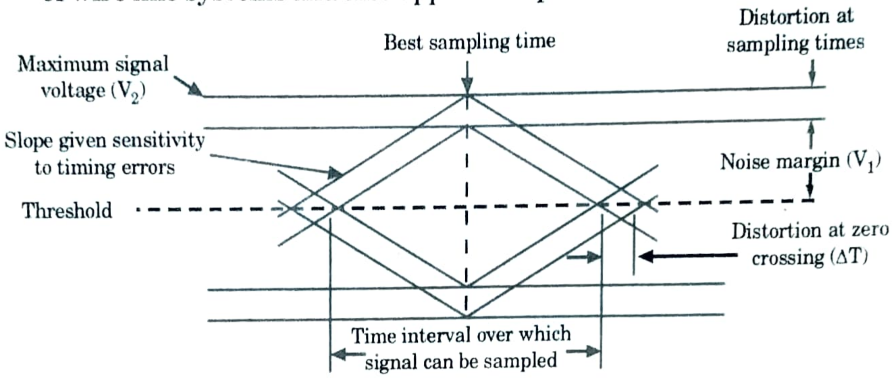

Fig. 5.6.1. Simplified eye diagram showing the key performance parameters.

B. Eye pattern features :

1. The eye pattern measurements are made in the time domain and allow the effects of waveform distortion to be shown immediately on the display screen of standard BER test equipment.
2. Fig. 5.6.2 shows a typical display pattern, which is known as an eye pattern or an eye diagram. The basic upper and lower bounds are determined by the logic one and zero levels, shown by b_{on} and b_{off}, respectively.

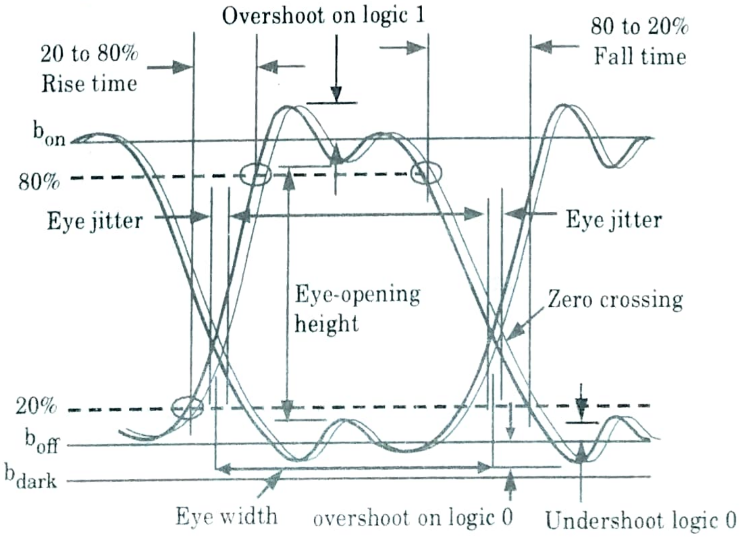

Fig. 5.6.2. General configuration of an eye diagram showing the definitions of fundamental measurement parameters.

3. The following information regarding the signal amplitude distortion, timing jitter, and system rise time can be derived :

i. The width of the eye opening defines the time interval over which the received signal can be sampled without error due to interference from adjacent pulses (known as intersymbol interference).

ii. The best time to sample the received waveform is when the height of the eye opening is largest. This height is reduced as a result of amplitude distortion in the data signal. The vertical distance between the top of the eye opening and the maximum signal level gives the degree of distortion. The more the eye closes, the more difficult it is to distinguish between ones and zeros in the signal.

iii. The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise. Noise margin is the percentage ratio of the peak signal voltage V_1 for an alternating bit sequence (defined by the height of the eye opening) to the maximum signal voltage V_2 as measured from the threshold level, as shown in Fig. 5.6.1. That is

$$\text{Noise margin (percent)} = \frac{V_1}{V_2} \times 100 \text{ percent}$$

iv. The rate at which the eye closes as the sampling time is varied (*i.e.*, the slope of the eye pattern sides) determines the sensitivity of the system to timing errors. The possibility of timing errors increases as the slope becomes more horizontal.

v. Timing jitter (also referred to as edge jitter or phase distortion) in an optical fiber system arises from noise in the receiver and pulse distortion in the optical fiber. The amount of distortion *DT* at the threshold level indicates the amount of jitter. Timing jitter is thus given by,

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

where T_b is one bit interval.

vi. The rise time is defined as the time interval between the points where the rising edge of the signal reaches 10 percent of its final amplitude to the time where it reaches 90 percent of its final amplitude. To convert from the 20 to 80 percent rise time to a 10 to 90 percent rise time, one can use the approximate relationship.

$$T_{10\text{-}90} = 1.25 \times T_{20\text{-}80}$$

A similar approach is used to determine the fall time.

vii. Any non-linear effects in the channel transfer characteristics will create an asymmetry in the eye pattern. If a purely random data stream is passed through a purely linear system, all the eye openings will be identical and symmetrical.

PART-2

Coherent Detection : Homodyne Detection and Heterodyne Detection, Digital Links : Point to Point Links, Power Penalties.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.7. **Draw a block diagram and explain the principle of coherent detection method in optical fiber.**

AKTU 2018-19, Marks 10

Answer

1. In coherent detection techniques the light is treated as a carrier medium which can be amplitude, frequency or phase modulated similar to the methods used in microwave radio systems.
2. The key principle of the coherent detection technique is to provide gain to the incoming optical signal by combining or mixing it with a locally generated continuous wave (CW) optical field.
3. The term mixing means that when two waves which have frequencies ω_1 and ω_2 are combined, the result will be other waves with frequencies equal to $2\omega_1$, $2\omega_2$ and $\omega_1 \pm \omega_2$.
4. For coherent light wave systems, all frequency components except $\omega_1 - \omega_2$ are filtered out at the receiver. The device used for creating the CW signal is a narrow linewidth laser called a local oscillator (*LO*).

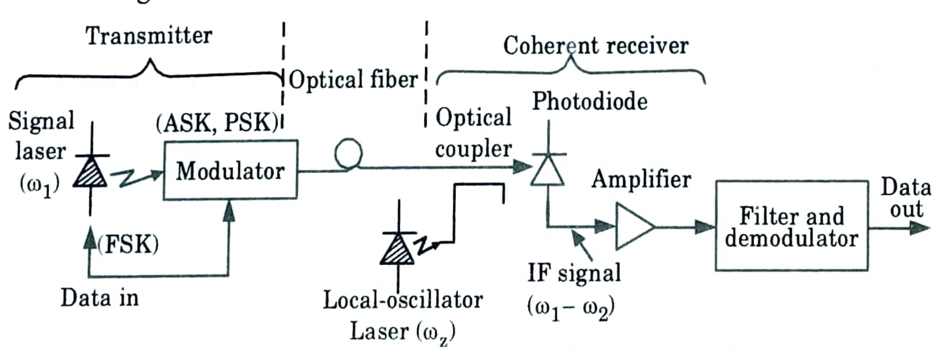

Fig. 5.7.1. Fundamental concept of coherent lightwave system. The three basic detection methods can have various modulation formats.

5. The electric field of the transmitted optical signal to be a plane wave having the form

$$E_s = A_s \cos [\omega_s t + \phi_s(t)]$$

where A_s is the amplitude of the optical signal field, ω_s is the optical signal carrier frequency, and $\phi_s(t)$ is the phase of the optical signal.

6. In a direct detection system the electrical signal coming into the transmitter amplitude modulates the optical power level of the light source. Thus output directly detected current is proportional to the intensity I_{DD} optical signal.

$$I_{DD} = E_s E_s^* = \frac{1}{2} A_s^2 \, [1 + \cos(2\omega_s t + 2\phi_s)]$$

$$I_{DD} = E_s E_s^* \frac{1}{2} A_s^2$$

7. At the receiving end in coherent lightwave systems, the receiver first adds a locally generated optical wave to the incoming information bearing signal and then detects the combination.
8. The mixing of the information bearing and local oscillator signals is done on the surface of the photodetector (before photodetection takes place). If the local oscillator (LO) field has the form

$$E_{LO} = A_{LO} \cos[\omega_{LO} t + \phi_{LO}(t)]$$

where A_{LO} is the amplitude of the local oscillator field, ω_{LO} and $\phi_{LO}(t)$ are the local oscillator frequency and phase, respectively, then the detected current is proportional to the square of the total electric field of the signal falling on the photodetector.

9. That is, the intensity $I_{coh}(t)$ is

$$I_{coh}(t) = (E_s + E_{LO})^2$$

$$= \frac{1}{2} A_s^2 + \frac{1}{2} A_{LO}^2 + A_s A_{LO} \cos[(\omega_s - \omega_{LO})\, t + \phi(t)] \cos\theta(t)$$

where $\phi(t) = \phi_s(t) - \phi_{LO}(t)$ is the relative phase difference between the incoming information bearing signal and the local oscillator signal, and

$$\cos\theta(t) = \frac{E_s . E_{LO}}{|E_s|\,|E_{LO}|}$$

represents the polarization misalignment between the signal wave and the local oscillator wave.

10. The optical power $P(t)$ is proportional to the intensity, at the photodetector we then have

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos[(\omega_s - \omega_{LO})\, t + \phi(t)] \cos\theta(t)$$

where P_s and P_{LO} are the signal and local oscillator optical powers, respectively, with $P_{LO} >> P_s$.

Que 5.8. **Write a short note on homodyne detection.**

AKTU 2017-18, Marks 10

OR

Explain the following :

i. Homodyne detection

ii. Heterodyne detection.

Answer

i. Homodyne detection :

1. When the signal carrier and local oscillator frequencies are equal, that is, when $\omega_{IF} = 0$, we have the special case of homodyne detection.

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos\phi(t) \cos\theta(t)$$

2. Thus one can use either OOK [varying the signal level P_s while keeping $\phi(t)$ constant] or PSK [varying the phase $\phi_s(t)$ of the signal and keeping P_s constant] modulation schemes to transmit information.
3. Since $P_{LO} >> P_s$ and P_{LO} is constant, the last term on the right hand side of contains the transmitted information.
4. Homodyne detection brings the signal directly to the baseband frequency, so that no further electrical demodulation is required.
5. Homodyne receivers yield the most sensitive coherent systems.
6. However, they are also the most difficult to build, since the local oscillator must be controlled by an optical phase locked loop.

ii. Heterodyne detection :

1. In heterodyne detection, the intermediate frequency ω_{IF} is non-zero and an optical phase locked loop is not needed.
2. Consequently heterodyne receivers are much easier to implement than homodyne receivers.
3. However, the price for this simplification is 3 dB degradation in sensitivity compared to homodyne detection.
4. Consider the output current at the receiver. Since $P_s << P_{LO}$ receiver output current then contains a DC term given by

$$i_{DC} = \frac{\eta q}{h\nu} P_{LO}$$

and a time varying IF, term given by

$$i_{IF}(t) = \frac{\eta q}{h\nu} \sqrt{P_s P_{LO}} \cos[\omega_{IF} + \phi(t)] \cos\theta(t)$$

5. The DC current is normally filtered out in the receiver, and the IF current gets amplified. One then recovers the information from the amplified current using conventional RF demodulation techniques.

Que 5.9. Derive an expression for the photo current in the case of a homodyne and heterodyne optical receiver systems.

AKTU 2016-17, Marks 10

Answer

1. A coherent field is generated locally at the receiver using a narrow-linewidth laser, called the local oscillator (LO).
2. It is combined with the incoming optical field using a beam splitter, typically a fiber coupler in practice.
3. Assuming the optical signal using complex notation as

$$E_s = A_s \exp[-i(\omega_0 t + \phi_s)], \qquad ...(5.9.1)$$

where ω_0 is the carrier frequency, A_s is the amplitude, and ϕ_s is the phase.

4. The optical field associated with the local oscillator is given by a similar expression,

$$E_{LO} = A_{LO} \exp[-i(\omega_{LO}t + \phi_{LO})], \quad ...(5.9.2)$$

where A_{LO}, ω_{LO}, and ϕ_{LO} represent the amplitude, frequency, and phase of the local oscillator, respectively.

5. The scalar notation is used for both E_s and E_{LO} after assuming that the two fields are identically polarized.
6. The optical power incident at the photodetector is given by

$$P = |E_s + E_{LO}|^2.$$

7. Using eq. (5.9.1) and eq. (5.9.2), then we get

$$P(t) = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos(\omega_{IF}t + \phi_s - \phi_{LO}) \quad ...(5.9.3)$$

where, $P(t) = A_s^2,\ P_{LO} = A_{LO}^2,\ \omega_{IF} = \omega_0 = \omega_{LO}$

8. The frequency $\upsilon_{IF} = \omega_{IF}/2\pi$ is known as the intermediate frequency (IF). When $\omega_0 \neq \omega_{LO}$, the optical signal is demoluated in two stages. Its carrier frequency is first converted to an intermediate frequency υ_{IF} (typically 0.1-5 GHz).
9. The resulting radio-frequency (RF) signal is then processed electronically to recover the bit stream. It is not always necessary to use an intermediate frequency.
10. In fact, there are two different coherent detection techniques to choose from, depending on whether or not ω_{IF} equals zero. They are known as homodyne and heterodyne detection techniques.

i. Homodyne detection :

1. In this coherent-detection technique, the local-oscillator frequency ω_{LO} is selected to coincide with the signal-carrier frequency ω_0 so that $\omega_{IF} = 0$.
2. From eq. (5.9.3), the photocurrent ($I = R_dP$, where R_d is the detector responsivity) is given by

$$I(t) = R_d(P_s + P_{LO}) + 2R_d\sqrt{P_s(t)P_{LO}} \cos(\phi_s - \phi_{LO}) \quad ...(5.9.4)$$

3. Typically, $P_{LO} >> P_s$, $+ P_{LO} \approx P_{LO}$. The last term in eq. (5.9.4) contains the information transmitted and is used by decision circuit.
4. Consider the case in which the local-oscillator phase is locked to the signal phase so that $\phi_s = \phi_{LO}$.
5. The homodyne signal is given by

$$I_p(t) = 2R_d\sqrt{P_s(t)P_{LO}} \quad ...(5.9.5)$$

ii. Heterodyne detection :

1. In the case of heterodyne detection the local-oscillator frequency ω_{LO} is chosen to differ from the signal-carrier frequency ω_0 such that the intermediate frequency ω_{IF} is in the microwave region ($\upsilon_{IF} \sim 1$ GHz).
2. Using eq. (3) together with $I = R_dP$, the photocurrent is now given by

$$I(t) = R_d(P_s + P_{LO}) + 2R_d\sqrt{P_s P_{LO}} \cos(\omega_{IF}t + \phi_s - \phi_{LO}) \quad ...(5.9.6)$$

3. Since $P_{LO} >> P_s$ in practice, the direct-current (DC) term is nearly constant and can be removed easily using bandpass filters.
4. The heterodyne signal is then given by the alternating-current (AC) term in eq. (5.9.6) or by

$$I_{ac}(t) = 2R_d\sqrt{P_s P_{LO}} \cos(\omega_{IF}t + \phi_s - \phi_{LO})$$

Que 5.10. **What is point-to-point link ? Enumerate the choice of components and their characteristics required for designing optical system.**

OR

With the help of a neat block diagram, explain the principle of working of point to point digital links. **AKTU 2019-20, Marks 10**

Answer

1. Point-to-point link is the simplest form of optical communication link that comprises of one transmitter and a receiver system.
2. For analyzing the performance of any link following important aspects are to be considered :

i. Distance of transmission. ii. Channel data rate.

iii. Bit-error rate.

3. To fulfill these requirements, the designer has a choice of the following components and their associated characteristics :

1. Multimode or single mode optical fiber :

a. Core size b. Core refractive index profile

c. Bandwidth or dispersion d. Attenuation

e. Numerical aperture or mode-field diameter

2. LED or Laser diode optical source :

a. Emission wavelength b. Spectral line width

c. Output power d. Effective radiating area

e. Emission pattern f. Number of emitting modes

3. Pin or avalanche photodiode (Optical detector) :

a. Responsivity b. Operating wavelength

c. Speed d. Sensitivity

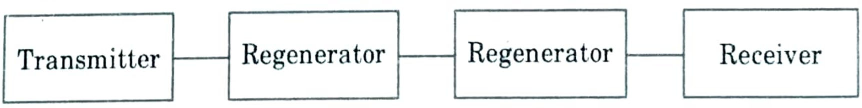

Fig. 5.10.1. Point to point fiber links.

4. When the link length extends between 20 to 100 km, losses associated with fiber cable increases.
5. In order to compensate the losses optical amplifier and regenerators are used over the span of fiber cable.
6. A regenerator is a receiver and transmitter pair which detects incoming optical signal, recovers the bit stream electrically and again convert back into optical form by modulating an optical source.

7. An optical amplifier amplifies the optical bit stream without converting it into electrical form.

Que 5.11. **Discuss the digital link design using the rise time budget.**

AKTU 2016-17, Marks 08

OR

Explain the analysis which carried out to measure overall performance of optical fiber. Explain link budget analysis.

AKTU 2017-18, Marks 10

Answer

Overall performance of optical fiber :

1. Two analyses usually are carried out to ensure that the desired system performance can be met : these are the link power budget and the system rise-time budget analyses.
2. In the link power budget analysis, one first determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified BER.
3. This margin can then be allocated to connector, splice and other components.

i. Link power budget :

1. An optical power loss model for a point-to-point link is shown in Fig. 5.11.1.

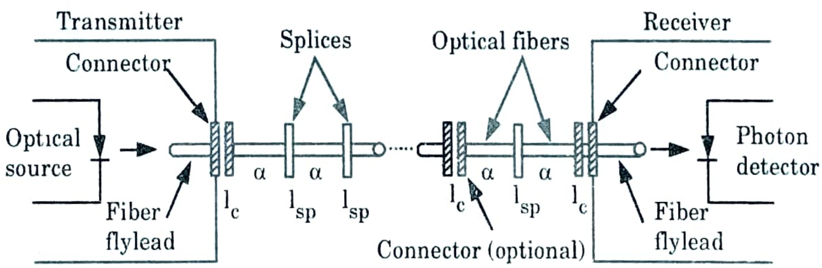

Fig. 5.11.1. Optical power loss model for a point-to-point link. The losses occur at connectors (l_c), at splices (l_{sp}), and in the fiber (α).

2. The optical power received at the photodetector depends on the amount of light coupled into the fiber and the losses occurring in the fiber and at the connectors and splices.
3. The link loss budget is derived from the sequential loss contributions of each element in the link. Each of these loss elements is expressed in decibels (dB) as

$$\text{loss} = 10 \log \frac{P_{out}}{P_{in}} \qquad ...(5.11.1)$$

where, P_{in} and P_{out} are the optical powers entering and leaving the loss element, respectively.

4. The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector, and allocates this loss to cable attenuation, connector loss, splice loss, and system margin.
5. Thus, if P_S is the optical power emerging from the end of a fiber flylead attached to the light source or from a source-coupled connector, and if P_R is the receiver sensitivity, then

$$P_T = P_S - P_R = 2l_c + \alpha L + \text{system margin} \quad ...(5.11.2)$$

6. Here, l_c is the connector loss, α is the fiber attenuation (dB/km), L is the transmission distance, and the system margin is nominally taken as 6 dB.

ii. Rise-time budget :

1. A rise-time budget analysis is a convenient method for determining the dispersion limitation of an optical fiber link. This particularly useful for digital systems.
2. In this approach, the total rise time t_{sys} of the link is the root sum square of the rise times from each contributor t_i to the pulse rise-time degradation :

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2\right)^{1/2}$$

3. The four basic elements that may significantly limit system speed are the transmitter rise time t_{tx}, the group-velocity dispersion (GVD) rise time t_{GVD} of the fiber, the modal dispersion rise time t_{mod} of the fiber, and the receiver rise time t_{rx}.
4. Single-mode fibers do not experience modal dispersion, so in these fibers the rise time is related only to GVD. The rise times of transmitters and receivers are generally known to the receiver.
5. To find the relation between the fiber rise time and the 3-dB bandwidth, we assume that the optical power emerging from the fiber has a Gaussian temporal response described by

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-t^2/2\sigma^2}$$

where, σ is the rms pulse width.

6. The 3-dB optical bandwidth $B_{3\,dB}$ is defined as the modulation frequency $f_{3\,dB}$ at which the received optical power has fallen to 0.5 of the zero frequency value.
7. Total system rise time is given as

$$t_{sys} = [t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2]^{1/2}$$

where, t_{mod} = Rise time resulting from modal dispersion

t_{tx} = Transmitter rise time

t_{GVD} = Rise time due to group-velocity-dispersion

t_{rx} = Receiver rise time

Que 5.12. **Write a short on OTDR and optical power meter.**

AKTU 2015-16, Marks 7.5

Answer

A. OTDR :

1. A measurement technique which is far more refined and which finds wide application in both the laboratory and the field is the use of optical time domain reflectometer (OTDR).
2. This technique is often called the backscatter measurement method.
3. It provides measurement of the attenuation on an optical link down its entire length giving information on the length dependence of the link loss.
4. A block schematic of the backscatter measurement method is shown in Fig. 5.12.1.
5. Here we observe that a light pulse is launched into the fiber in the forward direction from an injection laser using either a directional coupler or a system of external lenses with a beam splitter.

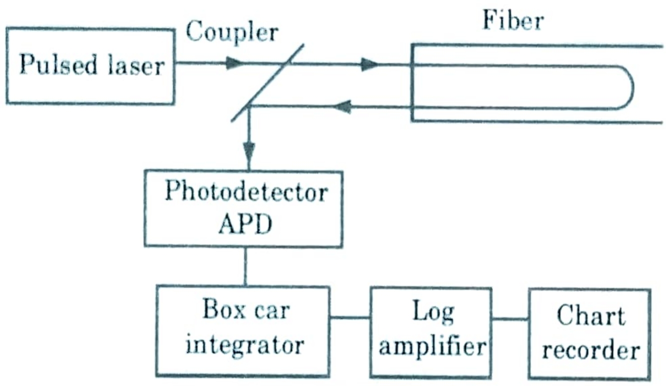

Fig. 5.12.1.

6. The backscattered light is detected using an avalanche photodiode receiver which drives an integrator in order to improve the received signal-to-noise ratio by giving an arithmetic average over a number of the measurements taken at one point within the fiber.
7. The signal from the integrator is fed through a logarithmic amplifier and averaged measurements for successive points within the fiber are plotted on a chart recorder.

B. Optical power meter :

1. The principle of operation of optical power meter is based on continuous optical emission conversion into electrical current using photodiodes.
2. Then the electrical current is amplified and an analog signal is converted into digital one for its processing and display of the power of two measured optical emission in dB and dBm.

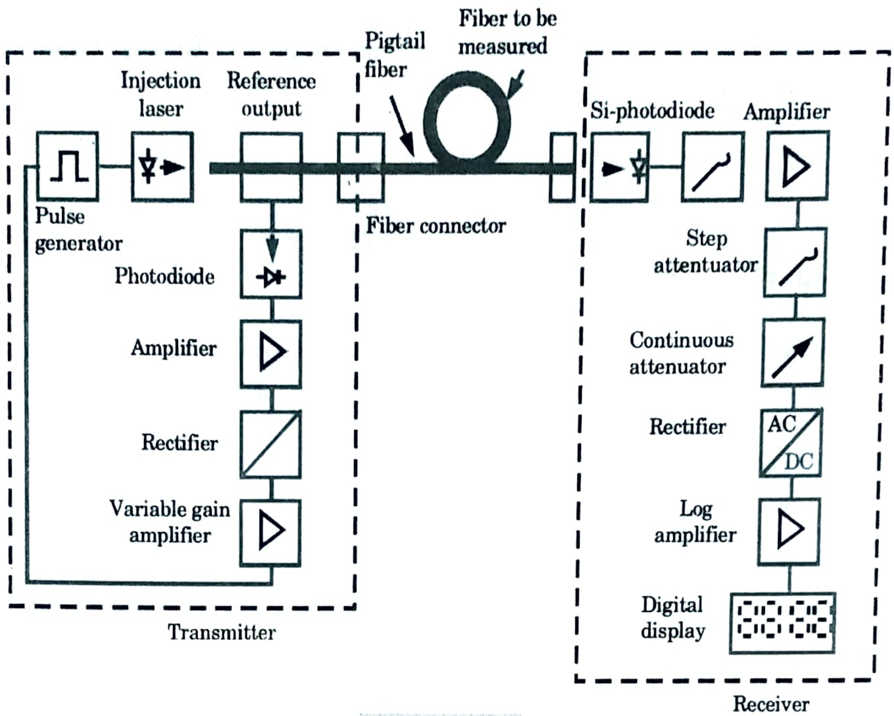

Fig. 5.12.2.

Que 5.13. **Discuss optical power penalties.**

Answer

1. Optical receiver sensitivity is affected due to several factors combinedly *e.g.* fiber dispersion, *SNR*.
2. Few major causes that degrade receiver sensitivity are modal noise, dispersive pulse broadening, mode partition noise, frequency chirping, reflection feedback noise.

i. **Modal Noise :**

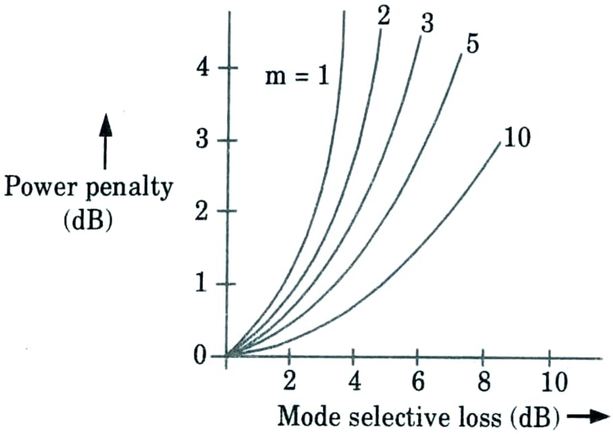

Fig. 5.13.1.

1. In multimode fibers, there is interference among various propagating modes which result in fluctuation in received power. These fluctuations are called modal noise.
2. Fig. 5.13.1 shows power penalty at

$$BER = 10^{-12}$$
$$\lambda = 1.3\ \mu m$$
$$B = 140\ \text{Mb/sec}$$

ii. Dispersive Pulse Broadening :

1. Receiver sensitivity is degraded by group velocity dispersion (*GVD*).It limits the bit rate distance product (*BL*) by broadening optical pulse.
2. Intersymbol interference exists due to spreading of pulse energy.

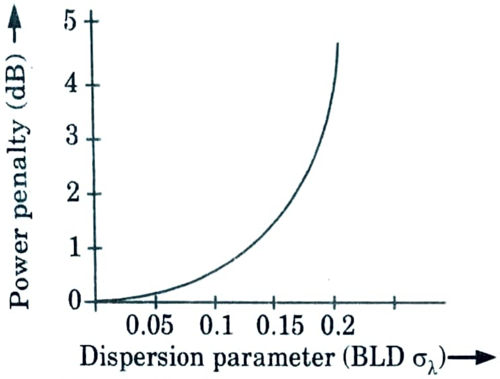

Fig. 5.13.2. Dispersion-induced power penalty.

3. In multimode fiber, various longitudinal modes fluctuate even though intensity remains constant. This creates mode partition noise (*MPN*).
4. A power penalty is said to improve *SNR* for achieving desired *BER*.
5. Fig. 5.13.3 shows power penalty at BER of 10^{-9} as a function of normalized dispersion parameter (BLD) for different value of mode partition coefficient (*K*).

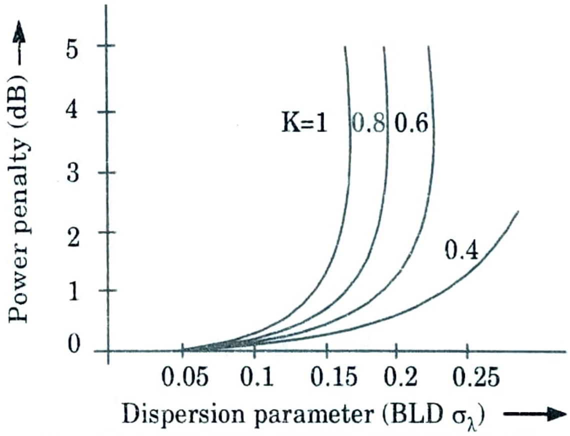

Fig. 5.13.3. MPN induced power penalty.

iii. Frequency Chirping :

1. The change in carrier frequency due to change in refractive index is called frequency chirping.

2. Because of frequency chirp the spectrum of optical pulse gets broaden and degrades system performance.

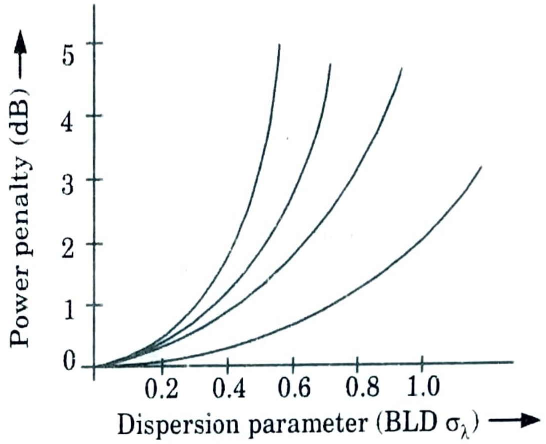

Fig. 5.13.4. Chirp induced power penalty.

3. Fig. 5.13.4 shows power penalty as a function of dispersion parameter BLD σ_λ for several values of bit period.

iv. Reflection feedback and noise :

1. The light which reflects due to refractive index discontinuities at splices and connectors are unintentional which may degrades receiver performance.
2. Reflection in fiber link originate at glass air interface, its reflectivity is given by

$$R_f = \frac{(n_f - 1)^2}{(n_f + 1)^2}$$

where, n_f is refractive index of fiber material

3. The noise that results from random intensity fluctuation is called relative intensity noise (*RIN*). *RIN* is measured in dB/Hz.

PART-3

Multichannel & Multiplexing Transmission Techniques, Basic Concept of Free Space Optics (FSO) Based Communication System.

Questions-Answers
Long Answer Type and Medium Answer Type Questions

Que 5.14. **What are the different multichannel transmission techniques used in optical communication ? Describe each in brief.**

AKTU 2015-16, Marks 7.5 **AKTU 2017-18, Marks 10**

Answer

The different multichannel transmission techniques are :

i. Multichannel Amplitude Modulation :

1. In some application the bit rate of each channel is relatively low but the numbers of channels are quite large. Typical example of such application is cable television (CATV).
2. Different channel information is amplitude modulated on different carrier frequency.
3. The composite FDM signal is used to modulate the intensity of semiconductor laser directly by adding it to the bias current.
4. At optical receiver, a bank of band pass filters separates the individual carriers.
5. Optical modulation index m is given by

$$m = \left(\sum_{i=1}^{N} m_i^2 \right)^{1/2}$$

where, N is number of channels and m_i is per channel modulation index.

ii. Multichannel Frequency Modulation :

1. The carrier to noise ratio requirement can be relaxed by changing the modulation format from AM to FM.
2. This results S/N ratio improvement over C/N ratio. S/N ratio at the output of FM detector is :

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{C}{N}\right)_{in} + 10 \log \left[\frac{3B}{2f_v} \left(\frac{\Delta f_{pp}}{f_v} \right)^2 \right] + w$$

where, B = Required bandwidth,
Δf_{pp} = Peak to peak frequency deviation of modulator,
f_v = Highest video frequency, and
w = Weighting factor.

iii. Sub-carrier multiplexing (SCM) :

1. Sub-carrier multiplexing (SCM) is employed in microwave engineering in which multiple microwave carriers for transmission of multiple channels are used.
2. If the microwave signal is transmitted optically by using optical fibers, the signal bandwidth can be exceeded upto 10 GHz for a single optical carrier. Such a technique is referred as SCM.
3. The input can be analog or digital base band signal. The input signals are modulated sub-carriers are then combined to give FDM signal.

4. The FDM signals are then combined in microwave combiner. The combined signal then modulates the intensity of semiconductor laser by adding it to bias current.
5. The received optical signal is then passed through low noise pin photo detector to convert it to original signal.

Que 5.15. **Discuss OTDM in brief.**

Answer

1. OTDM is a multiplexing technique that basically multiplexes a number of low bit rate optical channels in time domain. Several low-speed optical channels are multiplexed into a fixed electrical clock period, thus increasing the transmission speed.
2. Each signal is transmitted over a single communication channel by dividing the time frame into slots, one slot for each message signal.
3. Based on the time, each low-speed channel is allocated to a specific position, where it works in synchronized mode. The multiplexer and demultiplexer are timely synchronized and simultaneously switched to the next channel.
4. Usually, the optical pulse width is shortened in order to multiplex more channels within the fixed clock period. In addition, the shortened pulse width can reduce the crosstalk between channels because of more room left in bit rate.
5. However, short pulse width results in heavy dispersion as traveling distance increases. Therefore, transform-limited pulse and dispersion slope compensation technique need to be used to reduce the dispersion effect on OTDM.

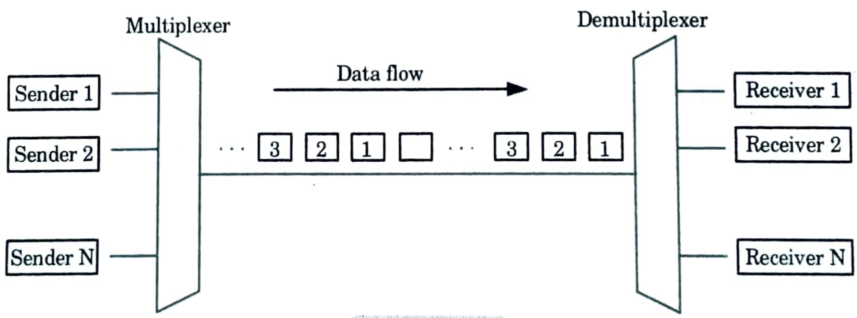

Fig. 5.15.1.

Que 5.16. **Write the methods of multiplexing techniques. Explain any one.**

OR

Write a short note on WDM and its components.

AKTU 2015-16, Marks 7.5

Answer

There are two methods of multiplexing techniques.

i. **OTDM :** Refer Q. 5.15, Page 5–22D, Unit-5.

ii. **WDM :**

1. Optical signals of different wavelength *i.e.*, (1300-1600 nm) can propagate without interfering with each other. The method of combining a number of wavelengths over a single fiber is called wavelength division multiplexing (WDM).
2. Fig. 5.16.1 shows a typical WDM link. At the transmitting end, there are several independently light sources, each emitting signal at a unique wavelength.

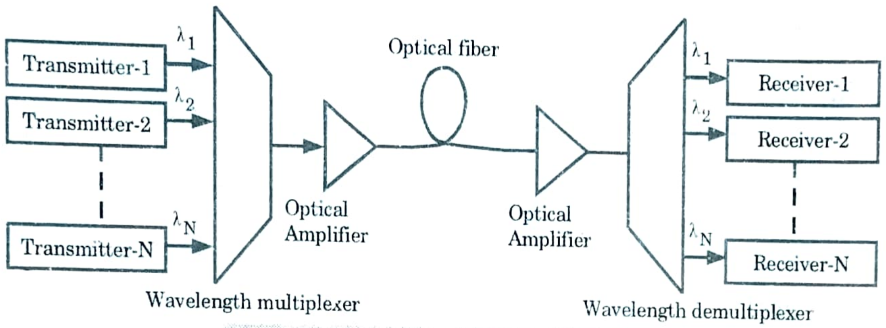

Fig. 5.16.1. Transfer characteristics.

3. Here a multiplexer is needed to combine these optical outputs into a serial spectrum of closely spaced wavelength signals and couple them onto a single fiber.
4. At the receiving end, a de-multiplexer is required to separate the optical signal into appropriate detection channels for signal processing.
5. To prevent spurious signals to enter into receiving channel, the de-multiplexer must have narrow spectral operation with sharp wavelength cut-offs.
6. The acceptable limit of crosstalk is – 30 dB.

Components :

1. For implementing WDM various active and passive components are required to combine, distribute, isolate and to amplify optical power at different wavelength.
2. Passive components are mainly used to split or combine optical signals. These types of components operate in optical domains.
3. These components don't need external control for their operation.
4. Commonly required passive components are :

i. $N \times N$ couplers

ii. Power splitters

iii. Power taps

iv. Star couplers

5. Most of the passive components are derived from basic star couplers. Star couplers can perform combining and splitting of optical power.

6. Therefore, star coupler is a multiple input and multiple output port device.

Que 5.17. **Explain the concept of free space optics (FSO) communication system.**

Answer

1. FSO communication systems are where free space acts as a communication channel between transceivers that are line-of-sight (LOS) for successful transmission of optical signals.
2. The channel can be atmosphere, space, or vacuum, whose characteristics determine the transmission and reception of optical signals for designing reliable and efficient communication systems.
3. Using FSO technology data is transmitted by propagation of light through atmospheric or space communication channels, allowing optical connectivity.
4. FSO communication offers a high data rate to meet the tremendous increasing demand of broadband traffic mostly driven by Internet access and HDTV broadcasting services.
5. Compared to fiber optics technology, FSO offers much more flexibility in designing optical network architectures at very high speeds, at tens and hundreds of Gbit/s rates.
6. However, FSO communication is affected by atmospheric effects, which limits sensitivity and achievable data rates with acceptable BER.
7. FSO communication is the most practical alternative to solve the bottleneck broadband connectivity problem. The data rates provided by FSO links continue to increase in both long and short-range applications.
8. FSO will be one of the most unique and powerful tools to address connectivity bottlenecks that have been created in high-speed networks during the past decade due to the tremendous success and continued acceptance of the Internet.