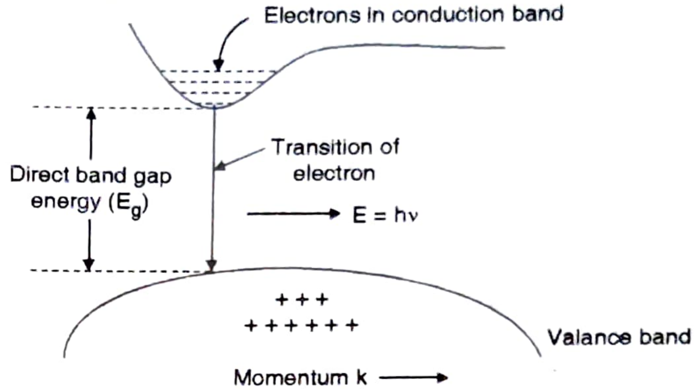
3.1 SEMICONDUCTOR PHYSICS BACKGROUND

- In this section, we will revise some topics from semiconductor physics, which are required to understand the principle of working of light sources.
- When even electron transition takes place between conduction band and valance band; energy as well as momentum are conserved.
- The momentum of photon is given by, $k = \frac{h\upsilon}{c}$.
- Here, h = plank's constant,

  c = speed of light and υ is the frequency.
- Depending on the shape of bandgap as a function of momentum; semiconductors are classified as direct bandgap or indirect bandgap materials.

3.1.1 Direct Bandgap Materials

- In a **direct band gap semiconductor**, the top of the valence band and the bottom of the conduction band occur at the same value of momentum.
- An electron from conduction band falls down and recombine with a hole in valance band. This falling electron emits energy of amount $h\upsilon$, that means it emits a photon.
- This phenomenon is shown in Fig. 3.1.1.



(1c1)**Fig. 3.1.1 : Direct Band Material**

- Here electrons and holes have same momentum value. There is a direct recombination of electron and hole.
- Such materials are called as direct bandgap materials and the direct bandgap semiconductor devices have higher internal quantum energy. These semiconducting materials are used for fabrication of LEDs and laser diodes.

3.1.2 Indirect Bandgap Materials

- In an **indirect band gap semiconductor**, the maximum energy of the valence band occurs at a different value of momentum to the minimum in the conduction band energy.
- The concept of indirect band material is shown in Fig. 3.1.2.

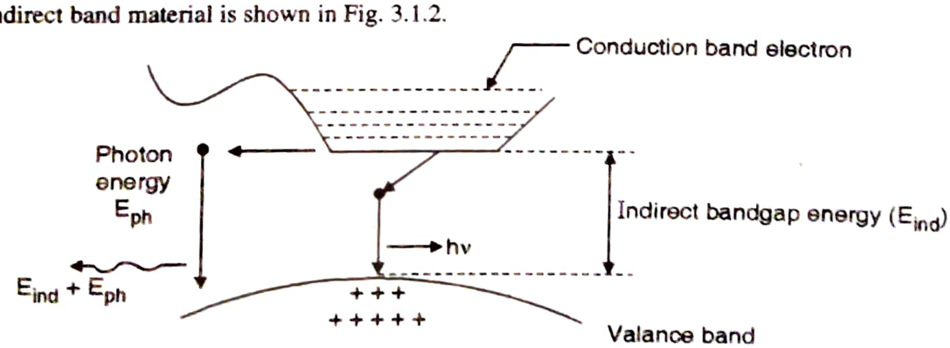


Fig. 3.1.2 : Indirect Band Material

- Here the conduction band minimum and valance band maximum energy levels occur at different values of momentum. An electron is not directly falling from conduction band to the valence band; but it falls in intermediate level before reaching to valance band. This combination process is relatively slow. Thus such materials have longer life time for charge carriers.
- By adding impurities, electron-hole recombination can be increased and the carrier lifetime can be effectively reduced.

3.2 LIGHT EMITTING DIODES (LEDS)

- LED as the name indicates is a Light Emitting Diode. A light-emitting diode (LED) is a semiconductor device that emits light when an electric current flows through it.
- Here the light output is obtained at different currents and by the application of a low voltage. This light source emits the light of different wavelengths right from ultraviolet region of electromagnetic spectrum to the far infrared region.
- But practically LEDs can give out the wavelength upto 500 nm.

  LEDs are divided into two groups :

  (a) Visible LED (b) Infrared LED
- Visible LEDs emits the light in the visible spectrum which generally ranges from 5600 A° to 7000 A°. While infrared LEDs emits the light in infrared region which generally ranges from 1.2 μm to 9000 A°.

Principle of operation

- LEDs work on the principle of Electroluminescence. On passing a current through the diode, minority charge carriers and majority charge carriers recombine at the junction.
- On recombination, energy is released in the form of photons. As the forward voltage increases, the intensity of the light increases and reaches a maximum. Here in case of LEDs, the supply of higher level electrons is provided by the battery connection.

Construction and Operation

- The symbol and the forward biased LED is as shown in Fig. 3.2.1.
- The lighting emitting diode is a p-n junction diode. It is a specially doped diode and made up of a special type of semiconductors with a suitable lens.
- The symbol of LED is shown in Fig. 3.2.1.

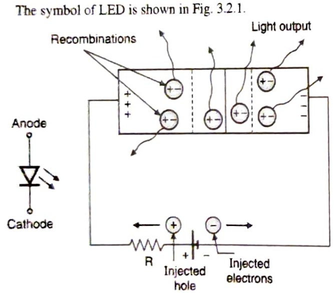


Fig. 3.2.1 : Construction of LED

- The length of anode terminal is made longer than that of cathode terminal. As shown in Fig. 3.2.1, the diode is made forward biased. Here the battery supplies the holes into 'p' region and electrons into 'n' region.
- These holes and electrons supplied by the battery are called as **injected charge carriers**. Now injected electrons, near the potential barrier gets recombined with the holes. That means the electrons are falling from higher **energy** level to lower energy level as shown in Fig. 3.2.2.

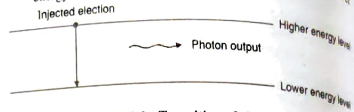


Fig. 3.2.2 : Transition of electron

- When this transition occurs then the energy is radiated out. When the diode is forward biased, then the electrons & holes are moving fast across the junction and they are combined constantly, removing one another out.
- Soon after the electrons are moving from the n-type to the p-type silicon, it combines with the holes, then it disappears. Hence it makes the complete atom & more stable and it gives the little burst of energy in the form of a tiny packet or photon of light.
- In case of ordinary diodes, the recombination is also taking place. But the photons are not radiated. Only the heat is developed because of this recombination. But in case of LEDs because of the use of material such as gallium arsenide the photons are radiated out.
- Generally two types of transition takes place.

  (a) Direct transition (b) Indirect transition

  This is shown in Fig. 3.2.3.

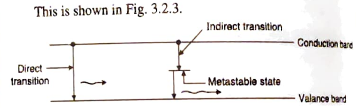


Fig. 3.2.3 : Direct and indirect transition

- In case of direct transition, the electron falls directly from higher energy level (conduction band) to the lower energy level (valance band).
- But in case of indirect transition, because of difference in the momenta of electron and holes, the electron when falling from conduction band stops at intermediate energy level (called as metastable state) for a certain time and then it will reach to the valance band. So definitely time required for indirect transition is more than that of direct transition.

3.3 MATERIAL USED FOR EMISSION OF LIGHT

- In case of LEDs different materials are used to get the radiation in infrared region and in the visible region. To get the radiation in infrared region GaAs material is used. It causes the **direct transition** and gives the wavelength nearly 885 nm. The energy output in this case 1.4 eV.

- Sometime the combination of GaAs with indium and aluminium is used.
- This gives the wavelength as follows :

  InGaAs → 8500 A°

  AlGaAs → 9000 A°
- To get the radiation in the visible region Gallium Phosphide (GaP) is used. This causes the indirect transition.
- If the nitrogen is dopped in GaP then it gives the visible radiation having the wavelength equals to 5650 A° . This gives green or yellow colours.
- Sometimes the combination of GaAs and P is used. If nitrogen is used as an dopent material in this case then GaAsP gives out the wavelength equals to 5900 A°. This is yellow coloured light.

Different materials emit different colors of light. Gallium

Material	Colour
Arsenide (GaAs)	infra-red.
Aluminium Gallium Arsenide Phosphide (AlGaAsP)	high-brightness red, orange-red, orange, and yellow
Gallium Arsenide Phosphide (GaAsP)	red to infra-red, orange
Gallium Phosphide (GaP)	red, yellow and green
Aluminium Gallium Phosphide (AlGaP)	green
Gallium Nitride (GaN)	green, emerald green
Gallium Indium Nitride (GaInN)	near ultraviolet, bluish-green and blue
Silicon Carbide (SiC)	blue as a substrate
Zinc Selenide (ZnSe)	blue
Aluminium Gallium Nitride (AlGaN)	ultraviolet

3.3.1 Difference between GaAs Infrared LED and GaAsP Visible LED

Sr. No.	Parameters	GaAs Infrared LED	GaAsP visible LED
1.	Type of Light	Radiates light in infrared region.	Radiates light in visible region.
2.	Type of Transistor	It possess direct transition.	For most of the wavelength transition is indirect.
3.	Incident Energy	Most of the incident energy is radiated.	Some of incident energy is converted into heat.
4.	Bandgap	Bandgap of GaAs = 1.4 eV.	Bandgap of GaAs P = 1.97 eV.
5.	WaveLength	Wavelength of light = 885 nm	Wavelength of light is 630 nm.

3.3.2 Characteristics and Figure of Merits of LED

- Before a light emitting diode can "emit" any form of light it needs a current to flow through it, as it is a current dependant device with their light output intensity being directly proportional to the forward current flowing through the LED.
- As the LED is to be connected in a forward bias condition across a power supply it should be *current limited* using a series resistor to protect it from excessive current flow. Never connect an LED directly to a battery or power supply as it will be destroyed almost instantly because too much current will pass through and burn it out.
- From the table above we can see that each LED has its own forward voltage drop across the PN junction and this parameter which is determined by the semiconductor material used, is the forward voltage drop for a specified amount of forward conduction current, typically for a forward current of 20mA.
- In most cases LEDs are operated from a low voltage DC supply, with a series resistor, RS used to limit the forward current to a safe value from say 5mA for a simple LED indicator to 30mA or more where a high brightness light output is needed.

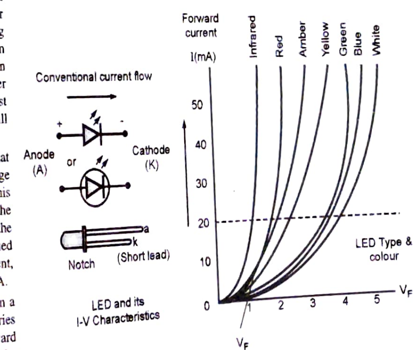


Fig. 3.3.1(a) : VI characteristics of LED

- The V – I characteristics of forward biased gallium arsenide LED is as shown in Fig. 3.3.1(b).
- The different electrical and optical parameters are as follows :
  (a) Reverse leakage current (I_R) = 50 nA.
  (b) Reverse voltage (V_R) = 30 V.
  (c) Forward current (I_F) = 10 to 80 mA.

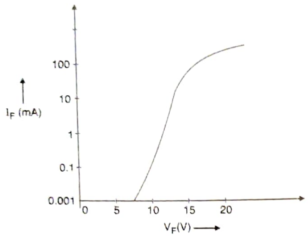


Fig. 3.3.1(b) : V – I characteristics of GaAs LED

  (d) Forward voltage (V_F) = 1.2 to 3.2 V
  (e) Power output (P_O) = 200 to 500 μW
  (f) Radiant intensity (I_O) = 2.4 mW/steradians
  (g) Peak wavelength (λ_p) = 900 nm.

3.3.3 Quantum Efficiency

(MU - May 2012)

- The quantum efficiency of an LED is defined as the ratio of number of photons emitted out to the number of electrons injected in.

$$\therefore \eta = \frac{\text{Number of photons emitted out}}{\text{Number of electrons injected in}}$$

Internal quantum efficiency of LED is given by,

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

Here τ = Total recombination lifetime

$$= \frac{\tau_r \cdot \tau_{nr}}{\tau_r + \tau_{nr}}$$

τ_r = Radiative recombination rise time

and τ_{nr} = Nonradiative recombination rise time

The external quantum efficiency is given by,

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

Here n = Refractive index of light source material

- Most of the LEDs are having quantum efficiency that is less than 1.
- The efficiency gets reduced because of the following factors.
  (a) Nature of material used.
  (b) Change in refractive index.
  (c) Angle made by emitted photons.
- Materials used for the manufacturing of LED may consist of the defects or flaws. So it may happen that the emitted photons gets trapped in these flaws and won't come out. This reduces the total number of output photons and in turn the quantum efficiency. The light rays (photons) coming out from the LED enters into the air medium which is having refractive index equals to 1.
- Because of change in refractive index, the bending of light rays takes place. This again reduces the quantum efficiency.
- Some of the light rays coming out from LED makes an angle of incidence greater than the critical angle. This light rays causes the internal reflections that means they will not come out from the LED structure.

3.3.4 Effect of Temperature

(1) As the temperature of LED goes on increasing, most of the electron – hole recombination causes the **nonradiative action**. That means photons are not emitted. So the power output from the LED gets reduced.

(2) Fig. 3.3.2(a) shows the variation of output power of LED with temperature. To provide the temperature compensation a simple circuit is used as shown in Fig. 3.3.2(b).

(3) The LED is having negative temperature coefficient, that means as the operating temperature goes on increasing the current through the LED starts reducing.

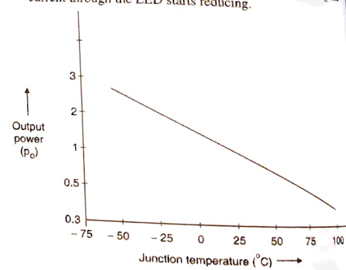


Fig. 3.3.2(a) : Variation of output power with temperature

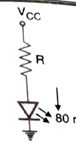


Fig. 3.3.2(b)

(4) But as shown in Fig. 3.3.3 this is compensated by using a transistor having a positive temperature coefficient.

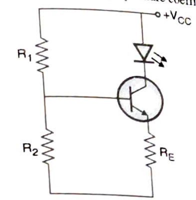


Fig. 3.3.3 : Temperature compensation

3.3.5 Protection Circuit for LED

- If the current passing through LED gets increased than the specified maximum current then the LED may burn. So to limit this current always a series resistance is used.
- Consider the diagram shown in Fig. 3.3.4. Let V_{CC} = 10 V and let the current passing through LED is 80 mA.

Then,

$$\text{Current limiting resistor (R)} = \frac{V_{CC} - V_{LED}}{I_{LED}} = \frac{10 - 2.4}{80 \text{ mA}}$$

$$\therefore R = 95\ \Omega$$

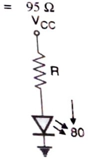


Fig. 3.3.4 : LED with current limiting resistor

Note :	Here V_{LED} = Voltage across LED = 2.4 V

3.3.6 Calculation of Irradiance at the Detector

- Consider a light from the LED is allowed to fall on the detector placed at a distance 'd' as shown in Fig. 3.3.5.
- Let 'A' is the area of the circular detector and θ is the divergence angle.

From Fig. 3.3.5 we have,

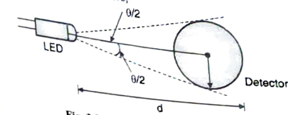


Fig. 3.3.5 : Irradiation at the detector

$$\tan\frac{\theta}{2} = \frac{r}{d}$$

$$\therefore r = d \tan\frac{\theta}{2}$$

- But θ is generally small,

$$\therefore r = d\frac{\theta}{2} \quad \ldots(3.3.1)$$

- We have, irradiance (H) at the detector,

$$H = \frac{\text{Output power}}{\text{Area}}$$

$$\therefore H = \frac{P_O}{\pi r^2} \quad \ldots(3.3.2)$$

- Now using Equation (3.3.1) we get,

$$H = \frac{P_O}{\pi \cdot \left(d \cdot \frac{\theta}{2}\right)^2}$$

$$\therefore H = \frac{4 P_O}{\pi d^2 \theta^2}$$

3.3.7 Advantages of LED

1. They are small in size.
2. Light in weight.
3. They are mechanically rugged.
4. They have lower operating temperature.
5. No complex driver circuitry is required.
6. Switch - on time is very small.
7. They have higher speed.
8. Available in different colours.
9. They have longer life compared to lamps.
10. Linearity is more.
11. Compatible with integrated circuits.
12. Cost is low.

3.3.8 Disadvantages

1. Output power gets affected by the temperature variation.
2. Quantum efficiency is low.
3. Gets damaged because of overvoltage and overcurrent.
4. LED light causes Blue pollution
5. LED fixtures are voltage Sensitive
6. LED fixtures donot allow spherical light Distribution

3.3.9 Applications

They are used in :

1. Various types of displays.
2. Source in optocouplers.
3. Infrared remote controls.
4. Indicator lamps.
5. In light batteries.
6. Indicators in measuring devices.
7. Picture Phones and Digital watches
8. Camera flashes and automotive heat lamps
9. Traffic signals and Burglar Alarms
10. Digital Computers and Calculators

3.4 LED STRUCTURES

The common LED structures used in fiber optic communication are as follows :

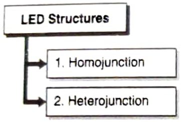


Fig. 3.4.1 : LED Structures

3.4.1 Homojunction

(1) If a p-n junction is made from two different mixtures of same types of atoms, then it is called as **homojunction**.

(2) That means homojunction is an interface between the layers of similar semiconducting material. But these layers of semiconducting material are having different dopings.

(3) Homojunction LED is also called as surface emitting LED.

(4) **Advantage :** An important advantage of homojunction LED is its low terminal impedance.

(5) **Disadvantage** : Emitted light is usually non-directional.

3.4.2 Heterojunction

- Heterojunction is an interface between dissimilar layers of semiconductors. These layers of semiconducting material are having different bandgaps.
- In case of heterojunction LED; the light is emitted from the edges; so such LED is also called as edge emitting LED.

Advantages

(i) Due to increased current density; a fine light spot is obtained.

(ii) The light emitting area is small, so it becomes easy to connect LED to the optical cable.

(iii) High speed data transmission is possible.

3.5 TYPES OF LED

MU - Dec. 2012, Dec. 2013, Dec. 2014, May 2016

The major types of LED are as follows :

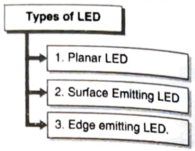


Fig. 3.5.1 : Types of LED

3.5.1 Planar LED

MU - May 2016

- The structure of planar LED is shown in Fig. 3.5.2.

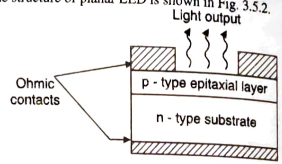


Fig. 3.5.2. structure of planar LED

- The p-type epitaxial layer is diffused on n-type of substrate and this fabrication is done using vapour phase epitaxial process.
- The internal reflection takes place in the structure; so low radiation is produced. That means limited amount of light is emitted out from such LEDs.
- Consider that the planner LED is fabricated 7from a material having refractive index n_1 then optical power emitted into lower refractive index n is,

$$P_{optical} = \frac{P_{int} F n^2}{4 n_1^2}$$

Here P_{int} = Internally generated power

and $P_{int} = \eta_{int} \frac{i}{q} h \frac{c}{\lambda}$

where η_{int} = Internal quantum efficiency

i = Forward bias current

q = Charge of electron

c = Speed of light

h = Planks constant

λ = Operating wavelength

Now, F = Transmission factor of semiconductor external interface

3.5.2 Surface Emitting LED

MU - Dec. 2011, May 2013, May 2017

- The technique pioneered by Burrus and Dawson with homostructure devices was to use an etched well in a GaAs substrate in order to prevent heavy absorption of the emitted radiation, and physically to accommodate the fiber.
- These structures have a low thermal impedance in the active region allowing high current densities and giving high-radiance emission into the optical fiber. As the name indicates; the light is emitted from the surface of LED structure.
- The plant of light emitting surface is placed in a perpendicular direction to the axis of optical fiber.

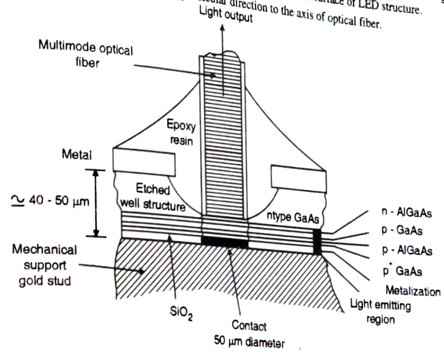


Fig. 3.5.3 : Double Heterodyne (DH) surface emitting LED

- Thus the light from LED can be directly coupled into the optical fiber. The structure of Double Heterodyne (DH) surface emitting LED is as shown in Fig. 3.5.3.
- The SiO_2 layer acts as insulator between p^+ GaAs and metal. The layer of p-AlGaAs is used to avoid recombinations and used to perform optical confinement. In this structure, a well is etched through the substrate of device and the optical fiber is cemented into it. A microlens is placed on the LED to improve coupling efficiency.
- The light emitted from the LED is directly coupled to the fiber. By using etching, the distance between active region and emitting surface is minimized.
- The different properties of surface emitter LED are :
  - (i) High radiance is obtained.
  - (ii) Low terminal impedance is obtained in the active region.
  - (iii) Due to Double Heterojunction (DH); the coupling efficiency (η) is increased.
  - (iv) Emission pattern is isotropic with 120° half power beam width.

This pattern is called as **Lambertian pattern**.

Advantages and disadvantages

Advantages

Following are the benefits or advantages of Surface Emitting LED:

1. Optical coupling coefficient of LED with external fiber system is relatively higher. Hence this LED offers high optical coupling efficiency.
2. Optical loss (due to internal absorption) is very low. This is because of carrier recombination near its top heterojunction.
3. InP/InGaAsP based LED is used for long wavelength applications.
4. It offers higher efficiency with low to high radiance.
5. The top n-GaAs contact layer ensures low thermal resistance and contact resistance. This allows high current densities and high radiation intensity.
6. The internal absorption in the device is very low due to larger bandgap confining layers. Moreover reflection coefficient at the back crystal face is high which gives good forward radiance.

Disadvantages

1. The surface emitting LED can transmit data rate less than 20 Mbps than edge emitting LED.
2. It contains short optical link with large NA (Numerical Aperture).
3. If the active layer temperature is increased then lifetime of LED is decreased.

3.5.3 Edge Emitting LED (ELED)

(MU - May 2011, Dec. 2011, May 2012, May 2014, May 2015)

- The Double Heterodyne (DH) AlGaAs edge emitting LED is shown in Fig. 3.5.4.

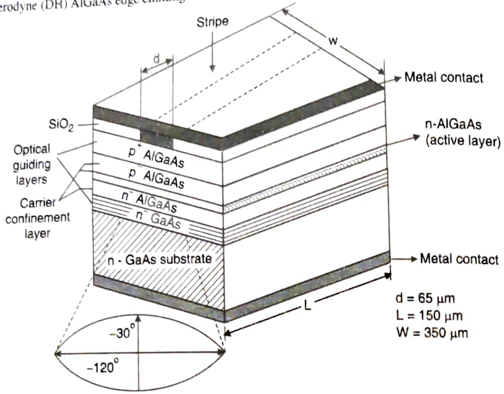


Fig. 3.5.4 : Edge emitting LED

- It is widely used in optical fiber communication system. Here collimated light from LED is required to be fed into the fiber with high coupling efficiency.
- Modern epitaxial growth techniques such as MBE, MOCVD etc. are used in order to design such complex LED structures.
- It consists of two optical guiding layers namely P^+ AlGaAs and n^- GaAs.
- Central active layer is made using InGaAs having narrow bandgap. It is bounded by wide bandgap layers such as p+ InGaAsP and n+ InP cladding layers.
- These two cladding layers help in confining injected electrons and holes into the middle layer. It also helps emitted photons to travel along LED axis as per optical properties. Both the guiding layers have refractive index lower than active region and higher than surrounding material.
- The strip geometry is similar to injection layer and it has transparent guiding layers with thin active layer. If the Numerical Aperture (NA) is low (less than 0.3) the edge emitting LED couples more optical power than surface emitting LED. The modulation bandwidth is in terms of hundreds of MHz.

Advantages and Disadvantages

Advantages

1. DH strip geometry has high radiance.
2. Strip geometry allows high carrier injection densities.
3. It has superior beam collimation property which offers greater coupling efficiency with fiber optic cable compare to surface emitting LED.
4. It offers higher efficiency with low to high radiance. It fulfills high brightness LED requirements of the lighting industry.
5. It radiates less power to the air compare to surface emitting LED due to reabsorption and interfacial recombination.
6. It offers better modulation bandwidth and more directional emission pattern.
7. It offers 5-6 times more coupled power into NA (Numerical Aperture) of step/graded index fibers. This is due to small beam divergence.
8. It offers high data rates (> 20 Mbps) than surface emitting LED.

Disadvantages

1. Its structure is complex.
2. It is difficult to design heat sink.
3. It is expensive compare to other LED types.
4. There are many issues to be handled during mechanical mounting and installation.

3.6 COMPARISON BETWEEN SURFACE EMITTING LED AND EDGE EMITTING LED

(MU - May 2017)

Sr. No.	Surface emitting LED	Edge emitting LED
1.	Light is emitted from the surface of the device.	Light is emitted from the edge of the device.
2.	Active layer is sandwiched between two layers.	It has transparent guiding layers with thin active layers.
3.	PAlGaAs performs optical confinement and avoids recombination process.	Light spreads into guiding layers reducing self absorption of active region.
4.	Less modulation bandwidth.	More modulation bandwidth.
5.	Couples more optical power for large NA.	Couples more optical power for low NA.
6.	Emission pattern is isotropic.	Wave guiding narrows the beam divergence.
7.	Easy to Fabricate	Difficult to Fabricate
8.	Easy to mount and Handle	Difficult to mount and Handle
9.	Require Less critical tolerance	Need Critical tolerance on fabrication
10.	Less Reliable	Highly Reliable
11.	Low System performance	High System performance
12.	Wide Spectral bandwidth	Narrow Spectral bandwidth
13.	Maximum quantum efficiency is upto 60%	Internal Qunatum efficiency is in the range of 60 to 80%

3.7 MODULATION OF LED

- In case of light sources; the response time (frequency response) is an important parameter.
- For LED, the response time gives the information about time required to change the light output with respect to input drive current. In another language; response time gives an idea of the delay in LED response.
- The response time is mainly dependant on following factors :
  (i) The doping level in active region.
  (ii) Injected carrier lifetime (τ_i) in the recombination region.
  (iii) Parasitic capacitance of LED.
- In case of LED, the property of light is modulated with the information signal.
- The property of light can be intensity, polarization or frequency.
- Consider that the drive current applied to LED input is modulated at a frequency 'ω' then the output optical power of LED is given by,

$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}}$$

Here, P_0 = Optical output power at zero modulation frequency

- The major source of delay in output is the parasitic capacitance but this delay can be reduced by applying a constant forward bias to the diode. Thus the modulation response of LED is dependant only on carrier recombination time.
- A typical frequency response of LED is shown in Fig. 3.7.1.

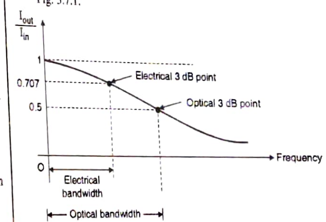


Fig. 3.7.1 : Frequency response of LED

- The modulation bandwidth of LED is expressed either in terms of electrical quantity or optical quantity.
- Electrical bandwidth is the value at which output electrical power is reduced to 3 dB down the input electrical power.
- The power is directly proportional to current; so electrical power ratio can be expressed as,

$$\text{Ratio} = 10 \log\left[\frac{P(\omega)}{P(0)}\right]$$

$$\therefore \text{Ratio} = 10 \log\left[\frac{I^2(\omega)}{I^2(0)}\right]$$

- Here I (0) and I (ω) represents the currents in transmitting and detecting circuits respectively.
- At the electrical bandwidth the current ratio is,

$$\frac{I(\omega)}{I(0)} = 0.707.$$

- Optical 3 dB point is at the frequency; where the current ratio is one half.

3.8 SOLVED PROBLEMS ON LED

Ex. 3.8.1 : What power is radiated by LED if its internal quantum efficiency η_{int} is 1.5 %, wavelength is 800 nm and forward current is 45 mA ?

☑ **Soln. :** Internal power is given by,

$$P_{int} = \eta_{int} \frac{i\,hc}{q\,\lambda}$$

Here
$\eta_{int} = 1.5\ \% = 0.015$
$i = 45\ mA = 45 \times 10^{-3}\ A$
q = Charge of electron
$= 1.602 \times 10^{-19}$
h = Plank's constant
$= 6.625 \times 10^{-34}$
c = Speed of light $= 3 \times 10^{8}$ m/sec
λ = Wavelength = 800 nm
$= 800 \times 10^{-9}$ m

$$\therefore P_{int} = \frac{0.015 \times 45 \times 10^{-3} \times 6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.602 \times 10^{-19} \times 800 \times 10^{-9}}$$

$$\therefore \mathbf{P_{int} = 1.0467\ mW}$$

UEx. 3.8.2 MU - May 2015, 7 Marks

The radiative and nonradiative recombination life times of the minority carriers in the active region of double heterojunction LED are 50 ns and 110 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 device current of 40 mA.

☑ **Soln. :**

Given, Radiative recombination lifetime $= \tau_r = 50$ ns

Non Radiative recombination lifetime $= \tau_{nr} = 110$ ns

Wavelength $= \lambda = 0.87\ \mu m$
$= 0.87 \times 10^{-6}$ m

Drive current $= i = 40$ mA
$= 40 \times 10^{-3}$ A

(i) The total recombination lifetime is,

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

$$\tau = \frac{50 \times 110}{50 + 110} = \mathbf{34.375\ ns}$$

Now internal quantum efficiency is,

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{34.375}{50}$$

$$= 0.6875 = \mathbf{68.75\ \%}$$

(ii) Internal power is given by,

$$P_{int} = \eta_{int} \frac{i\,hc}{q\,\lambda}$$

$$= \frac{0.6875 \times 40 \times 10^{-3} \times 6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.602 \times 10^{-19} \times 0.87 \times 10^{-6}}$$

$$\therefore \mathbf{P_{int} = 39.2155\ mW}$$

Ex. 3.8.3 : An optical transmitter uses DH structure InGaAsP LED operating at a wavelength of 1550 nm and $\tau_r = 25$ nsec, $\tau_{nr} = 90$ nsec.

If the LED is driven with a current of 35 mA.

(i) Find internal quantum efficiency and power generated internally

(ii) If n = 3.5 of the light source material, find the power emitted from the device.

☑ **Soln. :**

(i) The total recombination lifetime is,

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

$$\tau = \frac{25 \times 90}{25 + 90} = 19.56\ ns$$

Now internal quantum efficiency is,

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{19.56}{25}$$

$$\eta_{int} = 0.7824 = \mathbf{78.24\ \%}$$

(ii) Internal power is given by,

$$P_{int} = \eta_{int} \frac{hci}{q\lambda}$$

$$= \frac{0.7824 \times 6.626 \times 10^{-34} \times 3 \times 10^{8} \times 35 \times 10^{-3}}{1.602 \times 10^{-19} \times 1550 \times 10^{-9}}$$

$$\therefore \mathbf{P_{int} = 21.9217\ mW}$$

Now external quantum efficiency is,

$$\eta_{ext} = \frac{1}{n(n+1)^2} = \frac{1}{(3.5)(3.5+1)^2}$$

$$\mathbf{\eta_{ext} = 0.0141 = 1.41\ \%}$$

Optical power and internal power are related by,

$$\frac{P_{opt}}{P_{int}} = \eta_{ext}$$

$$\therefore P_{opt} = P_{int} \times \eta_{ext} = 21.9217 \times 10^{-3} \times 0.0141$$

$$\therefore \mathbf{P_{opt} = 0.0309\ mW}$$

UEx. 3.8.4 MU - May 2011, May 2014, 5 Marks

A typical LED emits light at a center wavelength of 920nm with Δλ = 20nm. Calculate the relative line width of this source in percent and Δf.

☑ **Soln. :**

Given, $\lambda = 920$ nm, $\Delta\lambda = 20$ nm

$$\text{Relative line width} = \frac{\Delta\lambda}{\lambda} = \frac{20}{920} = 0.021$$

Relative line with in percent $= \mathbf{2.1\%}$

UEx. 3.8.5 UQ - May 2013, 5 Marks

A typical LED emits light at a center wavelength of 820 nm with Δλ = 20 nm, Calculate the relative line width of this source in percent and Δf.

☑ **Soln. :**

LED emits light with λ = 820 nm centre wavelength Δλ = 20 nm

$$\text{Frequency spacing} \quad \Delta f = \frac{C}{2Ln} \qquad ...(1)$$

Where L = Length and
n = refractive index.

$$\text{Also wavelength spacing} \quad \Delta\lambda = \frac{\lambda^2}{2Ln} \qquad ...(2)$$

$$\therefore Ln = \frac{\lambda^2}{\Delta\lambda \times 2} = \frac{820 \times 820 \times 10^{-18}}{20 \times 10^{-9} \times 2}$$

$$= \frac{8.2 \times 8.2 \times 10^{-5}}{40}$$

Putting this value in Equation (1)

$$\Delta f = \frac{3 \times 10^{8} \times 40}{2 \times 8.2 \times 10^{-5}}$$

$$= \frac{12 \times 10^{9} \times 10^{5}}{134} = \frac{1200}{134} \times 10^{9} \times 10^{3}$$

$$= 8.9 \times 10^{12} \text{ frequency spacing}$$

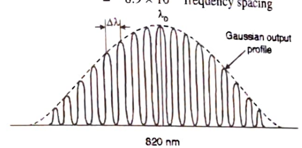


Fig. P. 3.8.5 : Typical spectrum from a gain guided GaAs laser diode

3.9 BASICS OF LASERS

UQ. Explain the basic working principle of lasers. **(MU – Q. 1(b), Dec. 16, 5 Marks)**

UQ. Explain working principle of LASER source used in optical fiber communication. **(MU – Q. 3(b), Dec. 17, 5 Marks)**

- The term **LASER** stands for light amplification by stimulated emission of radiation. Here the word **'light'** stands for the electromagnetic radiation which covers the range from ultraviolet region to the infrared region.
- The light has a dual nature. It consists of a wave nature and the energy. The energy contained by the light means, the number of photons contained by that light.
- The laser light is **'monochromatic'** in nature. That means this light is having a single colour or single wavelength (**mono** means one and **chroma** means colour).
- Similarly this light is **coherent** in the nature, that means all the wavelets contained in laser light are in the same phase. This is the major advantage of laser over ordinary light sources.
- The basic structure of any laser is based on an active medium (either a gas or semiconductor) contained between multiple reflectors. Shown in Fig. 3.9.1.

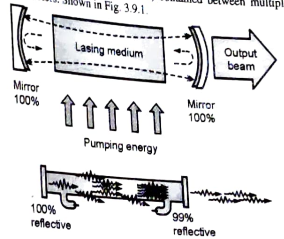


Fig. 3.9.1 : LASER

- A laser's reflectors contain light by oscillating it through a medium repeatedly allowing the energy to coherently build up with each pass using a process called stimulated emission.
- Laser radiation escapes due to a partially reflecting mirror in the assembly. This light can be used for a variety of applications including medical equipment, entertainment projectors, sensing for dynamic measurements, laser manufacturing, positioning, and machine vision.
- The first successful laser was designed by 'Maiman' in 1960. After that several improvements were done and now-a-days various types of laser are available. That are ruby lasers, Gaseous lasers, power lasers, semiconductor lasers etc.

Basic steps required to form laser beam are as follows :

There are generally three processes -

Basic steps of laser beam
- (i) Absorption
- (ii) Spontaneous emission
- (iii) Stimulated emission

Fig. 3.9.2 : Steps of Laser beam

(i) Absorption

- Under normal condition the tendency of electrons in case of the semiconducting material is to stay at the lower energy level. This lower energy level is called as ground state (E_1).

- If the photon of certain energy is incident on this electron then the electron absorbs this energy. So the total energy contained by that electron gets increased and now it is possible for that electron to shift towards the higher energy level (E_2).
- This process is shown in Fig. 3.9.3.

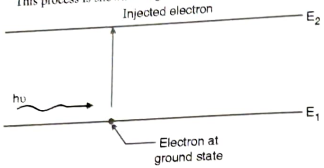


Fig. 3.9.3 : Absorption of photon

- Actually the number of electrons, absorbing the incident photons and travelling towards the higher energy level are more but for simplicity only one electron is shown. This transfer of electron is purely because of increase in its energy.
- Here the important consideration is that, the incident photon should provide sufficient energy to the electron to cause the motion of electron from E_1 to E_2. This sufficient energy in this case is the energy level difference between E_1 and E_2.
- That means the incident photon should provide atleast the energy $E_2 - E_1$. But if this much amount of energy is not provided by the incident photon, then the electron will absorb the energy, but it will not reach to the energy level E_2.
- In this case the electron gets shifted and occupies an intermediate energy level between E_1 and E_2. This intermediate energy level is called as metastable state. And after sometime the electron falls back to its original energy level that is ground state.

(ii) Spontaneous emission

- After the absorption process the electron or atoms are present at the higher energy level that means they possess the excited state. Now if no incident light (that means photons) are provided externally then these electrons stays at this stage for a short time. But after some time period, the electrons falls back to its original stage that is lower energy level.
- Consider one electron present at the higher energy level. When this electron falls back to the lower energy level, it will emit the energy which was absorbed by it during the absorption process. Thus it gives out the radiation.
- The energy emitted during this transition of electron from E_2 to E_1 is simply the energy level difference between these two energy levels. (that mean $E_2 - E_1$). This electrons falling back to ground state may directly comes to the ground state or it may follows 2 to 3 steps to reach to the ground state.
- The spontaneous emission process is shown in Fig. 3.9.4.

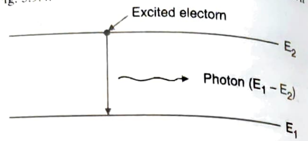


Fig. 3.9.4 : Spontaneous emission

(iii) Stimulated emission

- This is the key process of the formation of laser beam. Because in this process only the amplification of light takes place. Consider the electron or atom present in the excited state. We have discussed that after certain time period this atom falls due to spontaneous process and emits a photon.
- But before the occurrence of this spontaneous emission process, if the incident photon is allowed to strike to this excited atom then there is no chance for this atom to go to the further higher energy level.
- In this case once the external photon strikes to this excited atom, this atoms leaves its position from this higher energy level and it will emit the photon. Thus we are getting two photons at the output one which is striking on the excited atom and other coming out because of the excited atom leaving the higher energy level.
- So one input photon causes the emission of two photons and the light amplification takes place. This process is shown in Fig. 3.9.5.
- These two photons are in same phase and travelling in same direction.

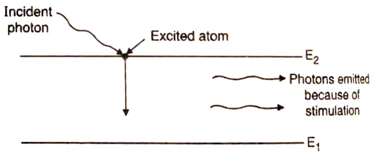


Fig. 3.9.5 : Stimulated emission

- Consider a box containing the excited atoms. Now if a photon that means a lightwave is applied to it as shown in Fig. 3.9.6, then the stimulated emission takes place, and the light wave gets amplified.
- Here the important thing is that, the input light wave should be applied to the excited atom before the occurrence of spontaneous emission process.

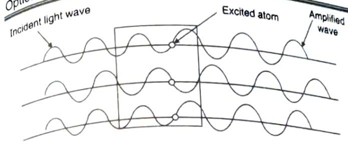


Fig. 3.9.6 : Amplification of light wave

- Otherwise no amplification of input wave will take place, rather in this case output wave will be having same amplitude as that of input wave.
- If instead of excited atoms, the atoms at the lower energy level are present in the box, then these atoms absorbs the energy from input wave and the amplitude of input wave gets reduced.
- So in this case to cause the amplification two conditions are necessary.
  (a) The input light wave (photons) should strike the excited atoms before the occurrence of spontaneous emission.
  (b) In the total structure the number of excited atoms should be more than that of atoms present at the ground level.
- The process in which the number of excited atoms made larger than that of the atoms present at ground state is called **"population inversion".**
- Similarly the time period for which the atoms present in this excited state should be made longer. This again makes easier to cause the stimulated emission.
- Thus in case of stimulated emission if number of atoms at the excited state are more, more number of photons are emitted. Thus causing amplification of light.
- All these photons are in same phase and are travelling in the same direction. Now this amplified light wave is called laser beam which is coherent and monochromatic in nature.

3.9.1 Comparison between Spontaneous and Stimulated Emission

Sr. No.	Spontaneous emission	Stimulated emission
1.	An excited electron; falls back to the lower energy level, giving out a photon. It represents spontaneous emission.	If external photon strikes an excited electron then this excited electron falls back to ground state, producing stimulated emission.
2.	Amplification action does not take place.	Amplification of photons take place.
3.	It does not depend on ambient electromagnetic field.	It depends on ambient electromagnetic field.
4.	This phenomenon takes place in light sources like LED, fluorescent tubes etc.	This is the basic phenomenon taking place in the formation of laser beam.
5.	There is no population inversion.	Population inversion is obtained by using various pumping techniques.

3.9.2 Advantages of Lasers over other Light Sources

Advantages

1. It has high information carrying capacity and hence is used in communication domain for transmission of information.
2. It is free from electro-magnetic interference. This phenomenon is used in optical wireless communication through free space for telecommunication as well as computer networking.
3. It has very minimum signal leakage.
4. Laser based fiber optic cables are very light in weight and hence are used in fiber optic communication system.
5. It is less damaging compare to X-rays and hence widely used in medical field for treatment of cancers. It is used to burn small tumors on eye surface and also on tissue surface.
6. High intensity and low divergence of laser is used for knocking down the enemy tank with accurate range determination. For this purpose neodymium and carbon dioxide laser types are used. Laser range finder is also used in several defence areas for medium range upto 10 Km.
7. Single laser beam can be focused in areas smaller than 1 micro diameter. One square micro area is needed to store 1 bit of data. This helps in storing 100 million data in one square cm. Due to this fact, laser is being used in laser CDs and DVDs for data storage in the form of audio, video, documents etc.

Disadvantages

1. It is expensive and hence more expenditure to the patients requiring laser based treatments.
2. It is costly to maintain and hence more cost to doctors and hospital management.
3. Increases complexity and duration of the treatment based on laser devices or equipment's.
4. Lasers cannot be used in many commonly performed dental procedures e.g. to fill cavities between teeth etc.
5. Laser beam is very delicate to handle in cutting process. The slight mistake in adjusting distance and temperature may lead to burning or discoloring of the metals. Moreover it requires higher power during the cutting process.
6. It is harmful to human beings and often burns them during contacts.

3.10 TYPES OF LASERS

According to the type of material used for the formation of laser beam, the lasers are classified as the :

- Solid state laser.
  - Ruby laser
  - Nd:YAG Laser
- Gaseous lasers,
  - He-Ne Laser
  - CO_2Laser
  - Excimer Laser
- Liquid lasers and
- Semiconductor lasers.

3.10.1 Solid State Lasers

The solid-state laser is a type of laser where the medium used is solid. The solid material used in these lasers is either glass or crystalline materials. Shown in Fig. 3.10.1.

(a) Working of Solid-State Laser

- Glass or crystalline materials used in a solid-state laser are used as impurities in the form of ions along with the host material. Doping is the term used for describing the process of addition of impurities to the substance.
- The dopants that are used in this type of laser are terbium (Tb), erbium (Eu), and cerium (Ce) which are rare earth elements. The host materials are ytterbium-doped glass, neodymium-doped yttrium aluminium garnet, neodymium-doped glass and sapphire. The most commonly used host material is neodymium-doped yttrium aluminium garnet.

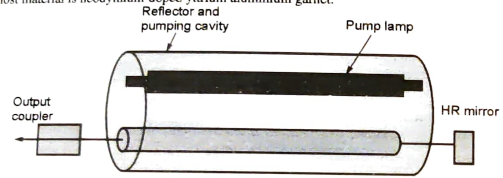


Fig. 3.10.1 : Solid State LASER

(b) Application of Solid-State Laser

1. The drilling of holes in the metals becomes easy with these lasers.
2. The push-type solid-state lasers are used for medical purposes such as for endoscopy.
3. They find application in the military and are used in the target destination system.

(c) Advantages of Solid-State Lasers

1. These lasers have casts that are economical.
2. The construction of a solid-state laser is simple.
3. The output can be both continuous and pulsed.
4. There is very less or zero chance of material in active medium going waste.
5. The efficiency of these lasers is high.

(d) Disadvantages of Solid-State Lasers

1. The output of solid-state lasers is not high.
2. The divergence of this laser is not constant and varies between 1 milliradian to 20 milliradians.
3. There is a power loss in the laser due to heating of the rod.

3.10.2 Types of Solid State LASER

(I) Ruby laser

This is a solid state laser which can be operated in a continuous mode or in a pulsed mode.

Principle of operation

Ruby rod contains a chromium atoms which are excited by the flash tube. The stimulated emission is done and the laser light of a particular wavelength is emitted.

Advantages

1. Both continuous and pulsed operations can be obtained.
2. Ruby rod being hard and robust material, it gives the ability of rough handling.
3. Life time of excited chromium atoms is considerably more, so it helps the easier stimulated emission process.
4. Higher power upto ten thousand million watts can be obtained from this laser.

Disadvantages

1. For a continuous operation cooling system should be provided.
2. Because of heating the length of ruby rod gets changed. So it will change the resonance wavelength of laser beam.
3. If the normal ruby laser is operated continuously then the ruby material may gets melt.
4. For a continuous operation a output power is only 1 watts.

Applications

Ruby lasers are used at several places such as welding operation, laser ranging system, earth rotational rate sensors etc.

(II) Nd : YAG Laser : (Neodynium Yattrium Aluminium Garnet Laser)

The Nd : YAG is a solid state material. It has good thermal and optical properties. So in many places instead of ruby laser Nd : Yag lasers are used.

Principle of operation

The photons from the flash tube excites the neodymium atoms to higher energy levels.

When they are stroked by another photons from the flash tube it causes the stimulated emission. Then by several reflections in optical cavity, the laser beam is formed.

Advantages

1. Nd : YAG material has good optical and thermal properties.
2. Large number of spikes of about 1 μsec can be obtained.

Disadvantages

1. Since the output spikes are not related to each other, coherence of laser beam is poor.
2. Power output is less (typically 2×10^4 watts.)
3. Power efficiency is less (0.1 %)

Applications

Since Nd : YAG is standard solid state material this laser can be used in place of ruby lasers, for example laser welding operation, soldering operation, continuous high power operations etc.

3.10.3 Gas Lasers

Gas lasers have an active medium made up of one or more gases or vapours. These lasers are classified as:

- Atomic gas lasers which is He-Ne laser
- Molecular gas lasers which is CO2 laser
- Ion gas lasers that are Argon laser

There are different types of gas lasers. These are :

(I) He - Ne (Helium - Neon) laser

He - Ne laser is a simple and inexpensive type of gas laser. It gives a very much narrow laser beam with a good quality.

Principle of operation

Initially the discharge in the plasma tube takes place. The filament produces continuous supply of electrons. The ionization of the He - Ne gas mixture takes place because of this stimulated emission the laser beam comes out from one of the ends.

Advantages

1. A continuous laser beam is formed.
2. This laser is having broad range of wavelength.
3. No need of a flash tube.
4. The laser light is very much sharp.
5. Low cost.

Disadvantages

1. The output power of laser beam is low.
2. For higher currents the laser action will not take place.

Applications

1. Used in interferometry.
2. Used as a source in holography.
3. It is used for semiconductor wafer inspection.

(II) Carbon dioxide (CO_2) laser

The CO_2 lasers are having the wavelength ranging from 9 μm to 11 μm. It works in both continuous and pulsed mode. In the continuous operation it produces the wattage upto 1 W and in the pulsed mode it produces the output upto 100 kilowatts. It has the higher output and higher efficiency.

The laser output for the this laser depends on the rotational or vibrational motions of the CO_2 molecules. The CO_2 molecule has three types of vibrational modes viz.

(a) Symmetric stretching mode.
(b) Bending or deformation mode.
(c) Asymmetric stretching mode.

Advantages of CO_2 lasers

1. Higher output power can be obtained.
2. Efficiency is high (around 40%)
3. CO_2 lasers are mechanically durable.

Disadvantages

1. For higher output powers, a single lined laser beam is not obtained.
2. Gas dynamic CO_2 lasers are bulky in nature and they produces noisy operation.
3. Higher output power CO_2 lasers requires a cooling system.
4. The cost of these lasers is high.

Applications

Because of higher power CO_2 lasers are used for several applications such as -

1. Cutting and welding of metals.
2. Spectroscopy.

3. Range finding systems.
4. Radar systems.
5. Heat treating operations.
6. Medical fields such as surgery.
7. Material scribing etc.

Note : Generally these lasers are used for higher power operations. If the output wattage requirement of laser beam is very high the pulsed operation of this laser is preferred instead of the continuous operation.

(iii) Excimer lasers

These are special types of lasers which emits the wavelength in the ultraviolet region. These lasers are related to the dia - atomic molecules. viz. H_{e2} and X_{e2}.

These atoms repels each other when they are present at the ground state. But when these atoms are excited. The state of atoms will be modified and now these atom produces a force of attraction between them. At this stage, these two atoms can be bound together to form as **excited state dimer,** which is called as excimer.

If these atoms are the atoms of inert gases, then they will reach at the more higher energy levels during population inversion process. Now when the stimulated emission is done at this stage, these atoms will emit the wavelength in the ultraviolet range of electromagnetic spectrum. Such a laser system is called as excimer laser.

Principle of operation

These lasers use a beam of electrons for the excitation of Excimer molecules. Then the population inversion is achieved by the atoms of this gas. During the stimulate emission these atoms falls to the ground stage and the molecule breaks. At this stage the laser beam having the wavelength in ultraviolet region is given out.

Advantages

1. They have high internal gain.
2. Range of wavelengths is available.
3. The divergence of laser beam is small.
4. There is no need to coat the output mirror's reflectivity.

Disadvantages

1. It has limited coherent length.
2. The degradation of gas takes place after some operations.
3. Upto certain extent the variation in the beam direction takes place.
4. A cooling system is required for this laser.
5. They are costly.

Applications

These lasers are used for several operations such as :

1. Material processing without causing vaporization.
2. For removal of polymer films from metal substrate.
3. In spectroscopy.
4. In photo chemistry.
5. For pattering of semiconductor integrated circuits.
6. In medical fields such as neurosurgery.
7. For atmospheric monitoring.
8. For the isotope separations.

3.10.4 Liquid Lasers

- Liquid lasers are also known as dye lasers. This is a type of laser in which liquids are used as an active medium.
- The active material used in the liquid laser is known as a dye and the commonly used dyes are sodium fluorescein, rhodamine B and rhodamine 6G.Shown in Fig. 3.10.2.

Working of Liquid Laser

- The active medium in this laser type is organic dye and the solvent used for dissolving the dye is either water, alcohol, or ethylene glycol.
- The dye is pumped to the capillary tube from the storage tank. This dye leaves the tubes with a flash lamp.
- The output beam then passes through a Brewster window to the output coupler which is a 50% reflective mirror.
- The output wavelength can vary to a wide range and the maxim output possible is 618 nm.

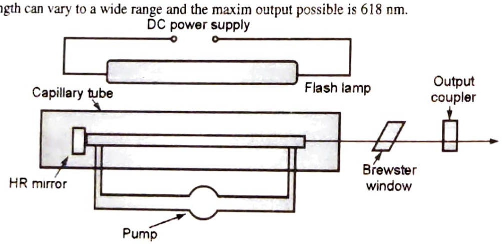


Fig. 3.10.2 : Liquid laser

Application of Liquid Laser

These lasers are commonly used for medical purposes as a research tool.

Advantages of Liquid Lasers

1. The efficiency is greater by 25%.
2. The wavelengths that are produced can be of varied ranges.
3. The diameter of the beam is less.
4. The beam divergence ranges between 0.8 milliradians and 2 milliradians, which is comparatively lesser than other lasers.

Disadvantages of Liquid Lasers

1. These lasers are expensive.
2. Tuning a laser to one frequency requires the use of a filter which makes it more expensive than other laser types.
3. It is difficult to determine which element is responsible for lases.

3.10.5 Semiconductor Lasers

- The semiconductor laser is a type of laser that is small in appearance and size.
- The operation of this laser is similar to LED but the characteristics of the output beam are of laser light.
- The manufacturing of semiconductor used in semiconductor diode is done uniquely. Shown on Fig. 3.10.3.

Working of Semiconductor Laser

- The active material used in a semiconductor laser is gallium arsenide and therefore, the laser is also known as Gallium Arsenide Laser.
- The working of a semiconductor laser is similar to the PN diode in forward biased condition. The PN material is connected to the DC power supply with the help of the metal contacts.
- The semiconductor laser is also known as the Injection Laser because the current is injected into the junction between P and N material.

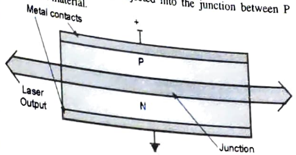


Fig. 3.10.3 : SemiConductor laser

Application of Semiconductor Lasers

- This laser is a transmitter of digital data naturally as the laser can be pulsed at different rates and pulse widths.
- These lasers find applications in optic cable communication.

Advantages of Semiconductor Lasers

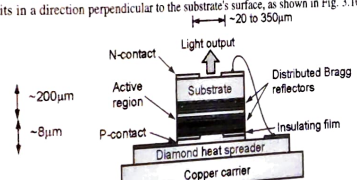
- They find many applications due to their small size and appearance.
- These lasers are economical.
- There is no use of mirrors.
- The power consumption is low.

Disadvantages of Semiconductor Lasers

- The divergence of the beam is more than 125 to 400 milliradians which is greater than other laser types.
- The output beam has an unusual shape as the medium used is short and rectangular.
- The working of this laser type is dependent on the temperature.

Vertical-Cavity Surface-Emitting Laser (VCEL or VCSEL)

- The Vertical-Cavity Surface-Emitting Laser (VCEL or VCSEL, or Vertical-Cavity Surface-Emitting Laser) is a semiconductor whose laser is emitted perpendicular to the top surface. It differs from an edge-fired laser, which emits the laser from the edge.
- VCSEL is a breakthrough light emitting device in optical communications, as well as a new form of optoelectronic technology with enormous development prospects.
- The edge emitting laser emits in a direction parallel to the substrate's surface and perpendicular to the cleavage surface, whereas the surface emitting laser emits in a direction perpendicular to the substrate's surface, as shown in Fig. 3.10.4



Schematic diagram of VCSEL

Fig. 3.10.4

- Its advantages over edge-emitting lasers include: easy two-dimensional planar and optoelectronic integration; circular beams are easy to achieve effective coupling with optical fibers; and circular beams are easy to achieve effective coupling with optical fibers.
- It is possible to create high-speed modulation, which can be used in long-distance, high-speed optical fiber communication systems. active
- The area size is extremely small, allowing for high packaging density and low threshold current; no cleavage is required after chip growth, allowing for on-chip tests;
- It operates in a single longitudinal mode over a large temperature and current range; and it is inexpensive.
- The most common emission wavelengths of VCSELs are in the range of 750–980 nm (often around 850 nm), as obtained with the GaAs/AlGaAs material system. However, longer wavelengths of e.g. 1.3 μm, 1.55 μm or even beyond 2 μm (as required for, e.g., gas sensing) can be obtained with dilute nitrides (GaInNAs quantum wells on GaAs) and from devices based on indium phosphide (InAlGaAsP on InP).

Characteristics of Vertical Cavity Surface Emitting Laser

- Since VCSELs emits a beam from the surface, i.e. top of the chip, it can be tested and analyzed on-wafer before it carves into any devices. This will reduce the fabrication cost.
- The mechanism and structure of Vertical-Cavity Surface-Emitting Laser make them able to use in two-dimensional arrays, unlike conventional edge-emitting lasers which can be used only in one dimensional.
- The light beam in a conventional edge-emitting laser has a high divergence angle and is difficult to couple into the optical fiber. Whereas VCSEL has a circular light beam, this is very easy for coupling into optical fibers, and it also has a lower divergence angle of the output beam. By regulating the thickness of the reflector layers, one can adjust the wavelength of the vertical cavity surface emitting laser.
- The surface-normal emission and almost identical geometry of the photodetector provide easy alignment and packaging.

VCSEL Basic Structure

- The structure of VCSEL is depicted in the graphic below. It is made up of distributed Bragg reflectors (DBR) that are developed alternately with high and low refractive index dielectric materials to form continuous growth of single or multiple quantum well active regions.
- In order to get the highest stimulated radiation efficiency and enter the oscillating field, 35 quantum wells are typically arranged towards the maximum of the standing wave field.
- The laser beam is output from the transparent window on the top, and a metal layer is coated on the bottom to improve the optical feedback of the DBR below.

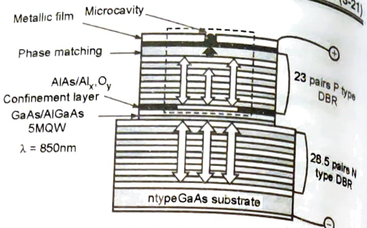


Fig. 3.10.5 : VCSEL Structure

- In fact, a powerful current converging structure must be utilized to complete the low-threshold current operation, similar to a general bar type semiconductor laser, and optical confinement and current intercepting confinement must be done at the same time.
- The semiconductor multilayer mode mirror DBR of the VCSEL is made of GaAs/AlAs, which is etched into an air-post (mesa) structure, as seen in the above image.
- The AlAs layer is oxidized in high-temperature water vapor to form an insulating AlxOy layer with a considerably lower refractive index, resulting in a structure that restricts light and carriers vertically.
- The high reflectivity, low loss DBR, and position of the active region in the cavity are all important factors in VCSEL design.

☞ Advantages of VCSEL

1. The outgoing beam is circular with a modest divergence angle, making it simple to couple with optical fibers and other optical components while also being very efficient.
2. It has the ability to perform high-speed modulation and can be used in long-distance, high-speed optical fiber communication systems.
3. Because the active area is tiny, single longitudinal mode and low threshold operation are simple to produce.
4. The electro-optical conversion efficiency could be larger than 50%, implying a longer gadget life. 5. It is simple to implement a two-dimensional array, apply it to a parallel optical logic processing system, achieve high-speed, large-capacity data processing, and use it in high-power devices.
5. The chip can be tested and the product screened before it is packaged, lowering the product's cost significantly.
6. It can be employed in laminated **optical integrated circuits** with micromechanical technology.

☞ Applications

VCSELs have many **applications**, the most important of which are briefly discussed in the following:

1. **Optical Communications** : Due to the short resonator round-trip time, VCSELs can be modulated with frequencies well in the gigahertz range.

This makes them useful as transmitters for **optical fiber communications** and for **free-space optical communications**. For short-range communications, 850-nm VCSELs are used in combination with **multimode fibers**. A data rate of e.g. 10 Gbit/s can be reached over a distance of a few hundred meters.

2. **Computer Mice** : An application area which was developed later, but has acquired a large market volume, is that of computer mice. A laser mouse with a VCSEL as light source can have a high tracking precision combined with a low electricity consumption, as is important for battery-powered devices.
3. **Gas Sensing** : Another prominent field of application is *gas sensing* with **wavelength-tunable** infrared VCSELs. Such devices are built e.g. as MEMS VCSELs, having a separate **output coupling mirror** the position of which can be tuned via thermal expansion, electrostatic forces, or a piezoelectric element. In this area, VCSELs partially compete with **distributed feedback lasers** (DFB lasers), but offer a smaller drive current, a wider tuning range and a higher modulation speed.
4. Optical oxygen sensors are of particular importance, because an **absorption** line at 760 nm is in reach of GaAs-based VCSELs, whereas longer-wavelength VCSELs which could be used for detecting water vapor, methane, or carbon dioxide need some further development before widespread use.
5. **Optical Clocks** : VCSELs can also be used in miniature **optical clocks**, where the laser beam probes an atomic transition in cesium vapor. Such clocks could become part of compact GPS devices.
6. **Laser Pumping** : Due to their high output powers, **VCSEL arrays** can often compete with diode bars (partially even with diode stacks), e.g. for pumping **solid-state lasers**.

⏭ 3.11 LASER DIODES-MODES AND THRESHOLD CONDITIONS

MU - May 2017

- Basically lasers are like oscillators operating at optical frequency.
- It consists of resonant cavity which provides a feedback and accordingly the oscillations takes place inside the cavity.

3.11.1 Fabry-Perot Resonator Cavity

MU - May 2013

- The Fabry Perot Resonator cavity consists of two flat partially reflecting mirrors facing towards each other. An optical feedback is established between the mirrors in longitudinal direction. Due to the optical feedback; the cavity acts like oscillator.
- The losses at certain resonant frequencies are compensated because, this cavity has a gain mechanism. The sides of cavity have rough edges, so that there is no unwanted light emission in that direction.
- The oscillations of light rays takes place inside the cavity; that means the light reflects back and forth inside the cavity.
- The wavelengths of light which are integer multiple of length of cavity gets added and comes out from the right mirror as shown in Fig. 3.11.1.
- The other wavelengths gets cancelled because they gets interfered destructively.

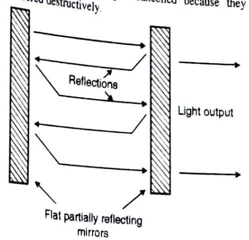


Fig. 3.11.1 : Fabry Perot Resonator cavity

- The resonant cavity provides selective feedback, so that it acts as oscillator. A typical dimensions of Fabry Perot Resonator are shown in Fig. 3.11.2.
- The longitudinal size is approximately 250 to 500 μm, later side is about 5 to 15 μm and transverse side is about 0.1 to 0.2 μm.

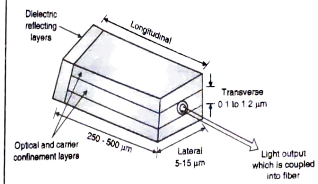


Fig. 3.11.2 : Fabry Perot Resonator

3.11.1(a) Modes of Cavity

MU - May 2012

- Because of optical radiations, electric and magnetic lines are developed in the cavity. These are called as modes of cavity.
- The major modes are Transverse Electric (TE) Mode and Transverse Magnetic (TM) mode. Along the major axes of cavity, half sinusoidal variations of electromagnetic fields are present. It produces following modes :

Modes of Cavity
- i. Longitudinal modes
- ii. Lateral modes
- iii. Transverse mode

Fig. 3.11.3 : Modes of Cavity

(i) Longitudinal modes

- These modes are related to the length of cavity (L). Since the length of cavity (L) is larger than lasing wavelength; longitudinal mode exist.
- The frequency spectrum of light emitted by laser diode is dependent on longitudinal modes.

(ii) Lateral modes

- Lateral modes are in the plane of p-n junction and these modes depend on the width of cavity.
- The lateral modes decide the shape of lateral profile of laser beam.

(iii) Transverse mode

- These modes are associated with the electromagnetic fields.
- The transverse modes are responsible for the radiation pattern and threshold current density of laser beam.

3.11.1(b) Threshold Conditions and Resonant Frequencies

MU - May 2012

- Consider that the axis of resonant cavity is along Z direction. Then the electromagnetic wave propagating along Z direction can be expressed as,

$$E(Z,t) = I(Z)\, e^{j(\omega t - \beta z)} \qquad \ldots(3.11.1)$$

Here $I(Z)$ = Optical field intensity

ω = Optical radian frequency

β = Phase shift

- When the number of electrons are made more in the conduction based; before starting the lasing action then it is called as population inversion.
- When the population inversion happens then the light amplification takes place in a laser. This is called as lasing condition.
- Optical radiant intensity varies exponentially with the distance 'Z' along the cavity and it is expressed as,

$$I(Z) = I(0)\, e^{\{\Gamma g(h\upsilon) - \bar{\alpha}(h\upsilon)\cdot Z\}} \qquad \ldots(3.11.2)$$

Here $I(0)$ = Initial radiant intensity

Γ = Optical field confinement factor and it represents fraction of optical power in the active layer.

$\bar{\alpha}$ = Absorption coefficient

g = Gain coefficient

$h\upsilon$ = Photon energy

Z = Distance travelled along the cavity

- If L is lateral length of cavity then one roundtrip in the cavity is Z = 2L
- The lasing condition takes place, when the gain of the guided modes exceed above optical loss, in one round trip (Z = 2L) through the cavity.
- Let r_1 and r_2 be the reflection coefficients of two mirrors in resonant cavity then the equation of lasing for Z = 2L can be expressed in terms of reflection coefficients as,

$$I(2L) = I(0)\, r_1 r_2\, e^{\{2L(\Gamma g(h\upsilon)) - \bar{\alpha}(h\upsilon)\}} \qquad \ldots(3.11.3)$$

- At the threshold conditions; steady state oscillations takes place inside the cavity. And under this conditions, the magnitude and phase of reflected wave is same as the transmitted wave.
- The threshold condition can be expressed as,

$$I(2L) = I(0) \qquad \ldots\text{for amplitude} \qquad \ldots(3.11.4)$$

$$\text{and} \quad e^{-2\beta L} = 1 \qquad \ldots\text{for phase} \qquad \ldots(3.11.5)$$

- Equation (3.11.5.) gives the resonant frequency of resonator cavity. The lasing condition takes place if the gain in cavity is greater than the threshold gain.

3.12 DIODE RATE EQUATIONS

- The diode rate equation gives relationship between optical output power and the diode drive current.
- For a p-n junction, the two diode rate equations are as follows :

(i) The rate of change of number of photons (ϕ) is,

$$\frac{d\phi}{dt} = C_n\phi + R_{spon} - \frac{\phi}{\tau_{ph}} \qquad \ldots(3.12.1)$$

(ii) The rate of change of number of electrons (n) is,

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{spon}} - C_n\phi \qquad \ldots(3.12.2)$$

Here C = Coefficient related to emission interaction and optical absorption

R_{spon} = Rate of spontaneous emission

τ_{ph} = Photon life time

J = Injection current density

q = Charge

d = Depth of carrier confinement region

- Under the steady state condition, $\frac{d\phi}{dt}$ and $\frac{dn}{dt}$ must be zero.
- Now for steady state condition, neglecting R_{spon} from Equation (3.12.1) we get,

$$C_n\phi - \frac{\phi}{\tau_{ph}} \geq 0$$

$$\therefore \quad C_n - \frac{1}{\tau_{ph}} \geq 0 \qquad \ldots(3.12.3)$$

- For steady state condition, $\frac{dn}{dt} = 0$. Denote threshold values of J and n by J_{th} and n_{th}. If the number of photons $\phi = 0$ then from Equation (3.12.2),

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{spon}}$$

$$\therefore \quad \frac{n_{th}}{\tau_{spon}} = \frac{J_{th}}{qd} \qquad \ldots(3.12.4)$$

- Equation (3.12.4) gives the condition for current required to sustain excess electron density under the spontaneous emission.
- At steady state $\frac{d\phi}{dt} = \frac{dn}{dt} = 0$ and n is denoted by n_{th}.

Thus Equations (3.12.1) and (3.12.2) becomes,

$$C_{nth}\phi_s + R_{spon} - \frac{\phi_s}{\tau_{ph}} = 0 \qquad \ldots(3.12.5)$$

$$\text{and} \quad \frac{J}{qd} - \frac{n_{th}}{\tau_{spon}} - C_{nth}\phi_s = 0 \qquad \ldots(3.12.6)$$

Here ϕ_s = Steady state photon density

Adding Equations (3.12.5) and (3.12.6) we get,

$$R_{spon} - \frac{\phi_s}{\tau_{ph}} + \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} = 0$$

$$\therefore \quad \frac{\phi_s}{\tau_{ph}} = R_{spon} + \frac{J}{qd} - \frac{n_{th}}{\tau_{sp}}$$

But from Equation (3.12.4),

$$\frac{n_{th}}{\tau_{spon}} = \frac{J_{th}}{qd}$$

$$\therefore \quad \frac{\phi_s}{\tau_{ph}} = R_{spon} + \frac{J}{qd} - \frac{J_{th}}{qd}$$

$$\therefore \quad \frac{\phi_s}{\tau_{ph}} = R_{spon} + \frac{(J - J_{th})}{qd}$$

$$\therefore \quad \phi_s = \tau_{ph} \cdot R_{spon} + \frac{\tau_{ph}(J - J_{th})}{qd} \qquad \ldots(3.12.7)$$

- The first term in Equation (3.12.7) indicates the number of photons from stimulated emission and second term indicates spontaneously generated photons.

3.13 STRUCTURES OF LASER DIODE

MU - May 2012

The different structures of laser diode are as follows :

Structures of Laser Diode
- 1. Gain guided laser
- 2. Index guided laser
- 3. Quantum well lasers
- 4. Quantum dot lasers

Fig. 3.13.1 : Structure of laser diode

3.13.1 Gain Guided Lasers

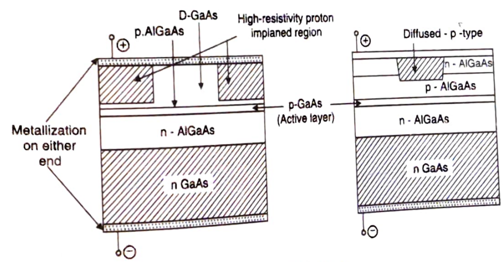


Fig. 3.13.2 : Gain Guided Laser

- Using strip geometry, it is possible to fabricate multimode injection laser with smaller number of lateral modes.

- Such laser is called as gain guided laser.
- This laser consists of active layer of GaAs sandwiched between two AlGaAs layers as shown in Fig. 3.13.2.
- The current is confined in the narrow strip by implanting highly resistive proton regions outside the active layer.
- For the shorter wavelength GaAs is used as active layer and to generate longer wavelength beam InGaAsP material is used as active layer.
- An important drawback of such laser is that the light output verses current characteristics is non-linear.
- The quantum efficiency (η) is low and it requires relatively high threshold currents.

3.13.2 Index Guided Lasers

- In order to overcome, the drawbacks of gain guided lasers, index guided lasers are used.
- In this case the thickness of active region is made variable.
- A ridge is produced above the active region. The edges of this ridge reflects the light.
- The reflected light is guided in the active layer and thus waveguide structure is formed.
- The structure of ridge waveguide injection laser is shown in Fig. 3.13.3.

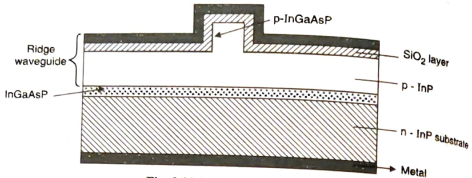


Fig. 3.13.3 : Index Guided Laser

- By varying the refractive index of different materials; the lateral modes of this laser are controlled.
- Depending on the refractive index variations; the ridge waveguide injection laser is divided into two types.
  (i) **Positive index waveguide :** In this case, the central region has higher refractive index and a single fundamental lateral mode is generated.
  (ii) **Negative index waveguide :** Here the central region has lower refractive index. The laser light beam contains some side lobes along with the mainbeam.

3.13.3 Quantum Well Laser

UQ. Write short note on Quantum Well Laser. **(MU - Q. 6(ii), Dec. 2019, 5 Marks)**

- A quantum well can be created by sandwiching a semiconductor, let's call it semiconductor A, between semiconductors B shown in Fig. 3.13.4.
- The left diagram in this picture shows the structure of quantum well laser where semiconductors A and B are stacked along z-direction. To create a quantum well along z-direction, semiconductor
- A must have a smaller band gap as compared to semiconductor, BEgap, A<Egap, B, shown if Fig. 3.13.4 on the right (be aware of where z-direction is) . The size of this well is normally at the order of 20 nm or less for quantum property to emerge. Consequently, the energy levels of electrons and holes in the well become quantized (discrete energy levels).

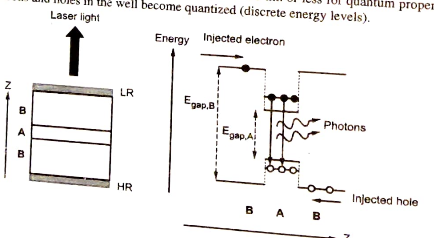


Fig. 3.13.4 : Quantum Well Laser

Working of Quantum Well laser

- When a current is applied to the quantum well, holes and electrons will be injected into the quantum well. This creates a **population inversion** of electrons and holes near the higher energy level and lower energy level, respectively. Subsequently, **electrons will spontaneously recombine with holes and emit photons**. These emitted photons will induce more recombination of electrons and holes (**stimulated emission**) which leads to more photons.
- Population inversion alone is not sufficient for lasing to occur, one needs an optical cavity as well. In QW laser, different types of **reflectors** (e.g. Bragg reflector) are used to achieve this. In the left diagram, these reflectors are represented by the grey layers. At the bottom, there is a **high reflective (HR) layer** while on top, there is a **low reflective (LR) layer**. With this optical cavity, spontaneously emitted photons will be bounced back and forth along the z-direction, triggering more stimulated emissions. *This will amplify the number of photons needed for lasing*. Since the top reflector has a lower reflectivity, photons (laser light) in the cavity will be emitted through this layer. A stable laser light will only be generated when the gain exceeds the round trip loss.
- In fact, adopting a quantum well structure improves the probability of electron-hole recombination which is one of the contributions to the low threshold current in QW laser. On top of that, if several single quantum well are arranged parallel to one another, a **multiple quantum well (MQW) laser** can be created. A MQW laser can give rise to a larger output power and a smaller threshold current in view of its improved optical confinement factor and increase in the density of states.

Advantages of Quantum Well Lasers

The advantages of quantum well lasers, compared to the conventional lasers are as follows :

1. Less forward current is required for the formation of laser beam.
2. High quantum gain and high output power is obtained.
3. It has low threshold current.
4. Under pulsed condition; frequency stability is obtained.
5. The line widths are narrower.
6. Higher modulation speeds are obtained.
7. Low noise is generated.
8. It is less temperature dependant.

3.13.4 Quantum Dot Laser

- A quantum dot laser is a semiconductor laser that uses quantum dots as the active laser material in its light emitting region. Due to the tight confinement of charge carriers in quantum dots, they exhibit an electronic structure similar to atoms.
- Lasers fabricated from such an active media exhibit device performance that is closer to gas lasers and avoid some of the negative aspects of device performance associated with traditional semiconductor lasers based on bulk active media.

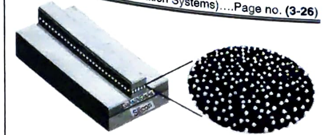


Fig. 3.13.5 : Quantum dot Laser

- By varying dot size and composition quantum dot lasers can operate at wavelengths previously not possible using semiconductor laser technology.
- Quantum dot lasers are finding commercial applications in medicine, display technologies, spectroscopy and tele-communications.
- Quantum dot lasers that are insensitive to temperature fluctuations are ideal for use in optical data communications and networks.

3.14 DISTRIBUTED FEEDBACK LASER (DFB)

(MU - May 2011, May 2014, Dec. 2014, May 2016)

- The periodic variation of refractive index is achieved in the multilayer structure along length of diode and it generates lasing action.
- Basically DFB lasers are used to generate single frequency operation. This is basically DH structure and the periodic variations in refractive index is obtained using Bragg diffraction grating.

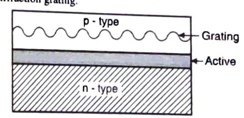


Fig. 3.14.1 : Distributed Feedback Laser(DFB)

- Near the Bragg wavelength; a single mode is reflected and the other modes having higher lasers are suppressed by oscillations. Here optical grating is applied over entire active region which is pumped as shown in Fig. 3.14.1.
- The DFB laser is less susceptible to the temperature variations. The higher modulation speed upto several gigabits / sec is obtained.
- The another variation in this laser is Distributed Bragg Refractor (DBR) in which grating is etched near cavity ends.

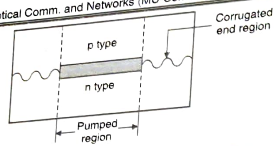


Fig. 3.14.2 : Distributed Bragg Refractor (DBR)

- In DBR the distributed feedback does not occur in the central active region as shown in Fig. 3.14.2.
- The DBR also provides single frequency operation but it is more susceptible to the temperature variations.

3.15 CHARACTERISTICS AND FIGURE OF MERIT

Important characteristics of laser diode are dynamic response, noise and reliability.

3.15.1 Dynamic Response

- The dynamic response indicates delayed behaviour of laser diode.

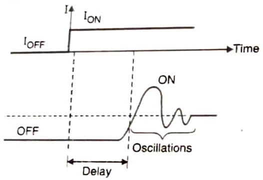


Fig. 3.15.1 : Dynamic Reponse

- If a step input current pulse is applied at the input of laser diode; then delayed light output is generated as shown in Fig. 3.15.1.
- Thus the dynamic response indicates the effect on switching ON and OFF of the laser.
- As shown in Fig. 3.15.1, the laser is not switched on instantly but there is ON delay about 0.5 nsec. Similarly there are oscillations after the delay. These oscillations last around 1 nsec. This effect produces deformity in the output pulse.

3.15.2 Noise

- In case of injection laser diode, the following factors introduce noise in the system :
  - (a) Frequency or phase noise
  - (b) Physical changes in the propagation conditions.
  - (c) Reflection of light in the backward direction.
  - (d) Mode partition noise.
- Due to the intensity fluctuations in the laser light output; the phase noise is produced. This noise is upto 1 MHz and it is represented by $\frac{1}{F}$ to $\frac{1}{F^2}$.
- Above 1 kHz, the noise spectrum is flat and it represents the quantum noise.
- The quantum noise produces into optical line width broadening. Due to the variations in operating temperature, the intensity of light output of the laser beam is fluctuated.
- This type of noise is called as Relative Intensity Noise (RIN) and it is related to the injection current and threshold current as,

$$RIN \propto \left(\frac{I_{threshold}}{I_{injection}}\right)^3$$

- Even though the power applied to laser is kept constant; the power distribution among various modes change with respect to time. It produces the noise.

3.15.3 Reliability

- The relationship between failure rate verses time is called as reliability curve. The degradation in the working of laser is called as failure rate.
- A typical curve of failure rate verses time for a laser is shown in Fig. 3.15.2. Due to its shape it is called as reliability bath tub curve.

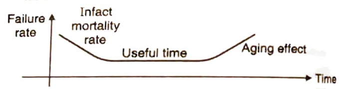


Fig. 3.15.2 : Reliability

- During the initial period, failure rate is more and it is called as infact mortality rate.
- The middle portion of curve is called as useful time, where failure rate is minimum and constant. In the later part also failure rate increases due to the aging effect. In order to maintain the lifetime; laser diodes must be operated within their specified ratings.

3.16 OPTICAL AMPLIFIER

There are also optical amplifiers which are very similar to VCSELs: they are basically VCSELs with reduced top mirror reflectivity.

❑ **Definition** : Optical amplifier is a device used in an optical communication system to directly amplify (boost) optical data signal without changing it into its electrical form.

By making use of Optical amplifiers in optical fiber communication, the optical integrity of the whole system is retained.

3.16.1 Need of Optical Amplifier

- During signal transmission, it is necessary to employ amplifiers within the network in order to have a distortionless data signal.
- When we talk about an optical communication system where data is transmitted in the form of light through fiber cable then the system also requires an amplification unit. This is so because when the signal is sent from an end to the other then various factors degrade the quality of the signal. Due to which it sometimes becomes impossible to regain the original information from that particular signal.
- If we use an electronic amplifier unit then it necessarily requires some additional units in order to convert the optical signal into electrical form and vice-versa. This process is somewhat time-consuming and makes the data transmission rate slower. However, the arrival of optical amplifiers has eliminated this problem. Thus, employing the optical amplifiers in an optical communication system allows us to have signal transmission to longer distance and at a faster rate without attenuation.

3.16.2 Working of a basic Optical Amplifier

- An optical communication system basically contains a transmitter, a receiver and a fiber cable that carries the information from an end to the other. However, an additional unit, optical amplifier in between the transmitter and receiver section is placed in order to boost the signal level. Shown in Fig. 3.16.1.

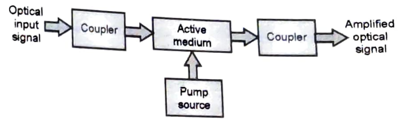


Fig. 3.16.1 : Operation of Optical Amplifier

- As it is true that a signal when transmitted through a fiber cable experiences least attenuation as compared to any other medium like a coaxial cable. However, signal amplification is also required during transmission through fiber cable in order to have long distance transmission.
- The Fig. 3.16.1 shows the amplification operation of an optical amplifier.
- The electrons present in the active medium gets energy from the pump source and gets excited to higher energy level. These electrons then triggered by the optical signal that causes them to return to a lower energy level.
- Thus stimulated emission occurs and several photons having same energy is emitted by the excited electrons while returning to ground state. Hence, an amplified optical signal is achieved.
- Optical amplifier utilizes stimulated emission and for its occurrence, population inversion must be created whose mechanism is the same as that used in laser diodes.
- As both the optical amplifier and laser diodes holds a similar structure but due to the absence of an optical feedback mechanism, only the applied input signal can be boosted. Thus, optical amplifiers do not have the ability to produce coherent output at its own.

3.16.3 Application of Optical Amplifier

Optical amplifiers can be employed in 3 ways between transmitter and receiver in order to achieve desired signal amplification.

1. **Booster / Power Amplifier**

- A booster or power amplifier is placed immediately after the transmission unit.
- It enhances the level of the signal before the signal is provided to the optical link for transmission.
- This is done in order to accomplish long-distance transmission. Shown in Fig.3.16.2.

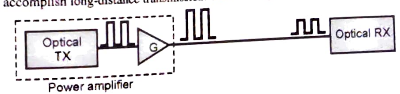


Fig. 3.16.2 : Power Amplifier

2. **Inline Amplifier**

- When we talk about inline amplifier unit then it is placed at some distances in the fiber link itself in order to restore the original message signal from the distorted one.

- As it offers medium gain then it becomes necessary to place multiple in-line amplifiers in case of long-distance transmission. Shown in Fig. 3.16.3.

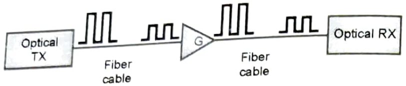


Fig. 3.16.3 : In-Line Amplifier

Pre-Amplifier

- A pre-amplifier is usually placed at the receiving end of the system. The transmitted signal must be of such level that it can be easily detected by the receiver.
- A signal that has transmitted a very long distance gets highly attenuated despite several amplifications during its journey. This causes difficulty for the receiver to detect the respective signal. Shown in Fig. 3.16.4.
- Thus, a preamplifier, having high gain is amplified by a preamplifier just before entering the receiver unit.

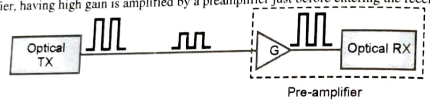


Fig. 3.16.4 : Pre-Amplifier

- It is to be noted here that the gain of an amplifier depends on the intensity and wavelength of the transmitted light signal.

3.16.4 Classification of Optical Amplifier

Optical amplifiers are basically classified into 3 categories namely :

1. Semiconductor optical amplifier
2. Doped fiber amplifier
3. Raman amplifier

1. **Semiconductor optical amplifier :** It is abbreviated SOA and its active medium is composed of alloys of the semiconductor from group III and V. They have the excellent capability to operate in both O-band along with C-band. They offer a rapid gain response of about 1 to 100 ps. Its gain varies with the variation in signal bit rate.
2. **Doped fiber amplifier :** It is abbreviated as DFA and the active medium is formed by lightly doping silica core with rare earth elements. Thus, also known as earth (erbium) doped fiber amplifier (EDFA). The working of DFA does not rely on the bitrate and format of the signal.
3. **Raman optical amplifier :** It is based on stimulated Raman scattering, thus named so. For signal amplification, it requires a standard transmission fiber cable. It is noteworthy in case of Raman amplifier that they do not require population inversion mechanism for amplification purpose.

3.17 SINGLE MODE LASERS

- The single mode lasers consists of only one longitudinal mode and one single traverse mode.
- Such lasers are surface emitting lasers and the light is emitted out from the chip surface and not from the side surface. Due to the single mode; the spectral width of emitted light is very narrow.
- In order to generate single mode laser beam; the length of lasing cavity L is adjusted in such as way that only a single mode falls in the bandwidth of device.

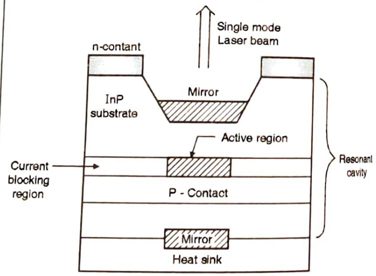


Fig. 3.17.1 : Single Mode Laser

- The most common single mode laser is a Vertical Cavity Surface Emitting Laser (VCSEL). In this laser diode; the laser beam is emitted in a perpendicular direction from the top surface of device.
- The basic architecture of VCSEL is shown in Fig. 3.17.1.

- Active region of this laser diode is small, thus threshold current is very low. It is around 100 μA. In order to produce the resonant beam, two mirrors are used. It consists of semiconducting material like Si or SiO_2 and oxide layer like Al_2O_3 layer.
- For the construction of VASEL usually GaAs – AlGaAs system is preferred because the lattice constant of this materials do not vary rapidly. Some configurations of VASEL makes use of built in frequency selective reflectors.

Advantages

Some common advantages of single mode lasers are as follows :

1. Since emission of laser beam is perpendicular to the surface, so multiple lasers can be formed onto a single chip in case of an array.
2. Due to small active region; threshold current is very small.
3. Modulation bandwidths are much larger.

3.18 MODULATION OF LASER DIODES

- Basically modulation is a process in which an information is put on the light wave.
- There are two types of modulation :

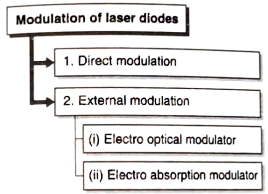


Fig. 3.18.1 : Modulation of laser diode

3.18.1 Direct Modulation

- This type of modulation is usually used when the data rate is less than 10 Gbits/sec.
- According to the input information, the laser drive current is varied and thus there is variation in optical output power.
- The modulation rate of laser diodes depend on following factors :
  (a) Spontaneous emission carrier lifetime (τ_{sp}) and it is function of semiconductor band structure and carrier concentration.
  (b) Stimulated carrier lifetime (τ) ; which depends on optical density in the lasing cavity.
  (c) Photon life time (τ_{ph}); and it is basically average time that the photon resides in the lasing cavity.

3.18.2 External Modulation

- In case of direct modulation; the laser is switched ON or OFF with an electrical drive current.
- For higher data rates, this phenomenon (called as chirp) is undesirable. So, for higher data rates; external modulation is used. Here, electrical driving signal changes the optical power level of external modulator and not the amplitude of laser light.
- The external modulator is integrated along with optical source in the same package.
- Usually, two types of external modulators are preferred.

(I) Electro optical modulator

- The light beam is splitted into two parts and these two light beams are sent through separate paths.
- High speed electrical signal changes the phase of light in one path.
- The two paths are recombined at the device output.
- If the recombination is constructive then it produces bright signal, representing '1'.
- If the recombination is distractive then the paths are cancelled and it represents '0'.

(II) Electro absorption modulator

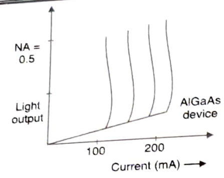
- Here an Indium Phosphide material (InP) is used and electrical signal changes the transmission properties of material.
- For a transparent material, it produces '1' and for opaque material, it produces '0'.

3.19 SPECTRAL WIDTH (FREQUENCY CHIRP)

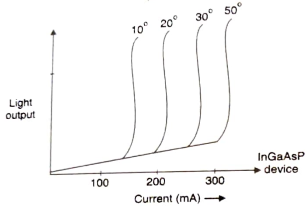
- Due to the dynamic behaviour; the delayed output response is obtained. That means when a direct modulation is used in laser; a wider laser time width is generated.
- This phenomenon is called as frequency chirp.
- In order to reduce the frequency chirp, following steps are used :
  (i) Bias the laser above threshold, so that the current does not drive the device below threshold level.
  (ii) Provide the damping for the oscillations produced after delay in the dynamic response of LED.

3.20 TEMPERATURE EFFECTS

- The gain injected lasers with strip geometry makes use of AlGaAs or InGaAsP.
- Figs. 3.20.1(a) and 3.20.1(b) shows the variation of threshold current with temperature.



(a)



(b)

Fig. 3.20.1 : Variation of threshold current with temperature

- The threshold current density (J_{th}) is expressed as,

$$J_{th} \propto e^{\frac{T}{T_0}}$$

Here T = Absolute temperature of the device

T_0 = Threshold temperature coefficient

- The value of 'T_0' depends on the material used. For AlGaAs it is 110 to 120°K and for InGaAsP it is 40 to 75° K.
- In order to minimize the effect of temperature, the temperature compensation circuitry can be added with laser diode.

⏭ 3.21 LIGHT SOURCE LINEARITY

- In optical analog signals, time varying analog signal s (t) is used to modulate optical source.
- Due to application of s (t), time varying optical output power P (t) is obtained and it is given by,

$$P(t) = P_t [1 + m\, s(t)] \qquad ...(3.21.1)$$

Here P_t = Optical power output when signal s (t) is not applied

m = Modulation index

- The modulation index is given by,

$$m = \frac{\Delta I}{I'_B} \qquad ...(3.21.2)$$

Here ΔI = Change in current about bias point, due to modulation

I'_B = I_B for LED

and I'_B = $I_B - I_{th}$ for laser diode

Here I_B = Bias current

and I_{th} = Threshold current

- To avoid the distortions in output signal; the value of modulation index must be in the range 0.25 to 0.50.
- That means the value of modulation index must be in the linear region of the graph of optical output of source verses drive current of source.
- If optical source is non-linear and the applied signal is simple cos wave that means x (t) = A cos ωt then the output of source is,

$$y(t) = A_0 + A_1 \cos \omega t + A_2 \cos 2\omega t + A_3 \cos 3\omega t \qquad ...(3.21.3)$$

- Thus the output consists of second harmonic distortion term 2ω, third harmonic distortion term 3ω etc.
- This type of distortion is called as harmonic distortion and n^{th} order harmonic distortion is given by,

$$n^{th} \text{ order harmonic distortion} = 20 \log \frac{A_n}{A_1} \qquad ...(3.21.4)$$

- Consider that the modulating signal of nonlinear source is

$$x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$$

Then the equation of output is,

$$y(t) = \sum_{m,n} B_{mn} \cos (m\omega_1 + n\omega_2) \qquad ...(3.21.5)$$

- Here the values of m and n are m and n = 0, ± 1, ± 2 ....
- The sum and difference of frequencies, that means the terms $\omega_2 - \omega_1, \omega_2 + \omega_1, \omega_2 - 2\omega_1, \omega_2 + 2\omega_1$,.... represents intermodulation distortion.

⏭ 3.22 COMPARISON BETWEEN LED AND LASER DIODE

UQ. Differentiate LED and LASER sources. **(MU - Q. 1(c), Dec. 15, May 17, May 18, Q. 1(a), Dec. 2019, 5 Marks)**

Sr. No.	Basis of Difference	LED	LASER
1.	**Full form**	LED stands for Light Emitting Diode.	LASER stands for Light Amplification by Stimulated Emission of Radiation.
2.	**Definition**	A semiconductor device which produces light when an electric current flows through it is called LED or Light Emitting Diode.	A device which emits light by the optical amplification using stimulated emission of electromagnetic radiation is called LASER.
3.	**Working principle**	The working of LED is based on the principle of electro-luminance.	The working of the LASER is based on the principle of stimulated emission.
4.	**Chromaticity**	LED is usually a polychromatic, i.e. it produces a broader band of wavelengths.	LASER is a monochromatic source of light as it generates the light of single wavelength.
5.	**Coherence**	LED is a non-coherent source of light, i.e. its photons are out of phase.	LASER is a coherent source of light, which means its photons are in phase.
6.	**Directionality**	LED generates a divergent beam of light. Thus, the light produced by the LED can travel in all directions randomly.	LASER produces a non-divergent beam of light which is highly directional.
7.	**Optical spectral width**	LED has a broader optical spectrum, usually ranging from 25 nm to 100 nm.	For LASER, the optical spectrum is much narrower, usually 0.01 nm to 5 nm.
8.	**Emission**	LED involves spontaneous emission.	LASER involves stimulated emission.
9.	**Optical power output**	LED has comparatively low optical output power.	LASER has high optical output power.
10.	**Temperature dependency**	The operation of LED is less dependent on the temperature.	The operation of LASER is quite temperature dependent.
11.	**Conversion efficiency**	LED has very low conversion efficiency, around 10% to 20%.	LASER has comparatively high conversion efficiency, around 30% to 70%.
12.	**Reliability**	LEDs are highly reliable devices.	The reliability of LASER is moderate.
13.	**Drive circuit**	LED has simple drive circuit.	The drive circuit of LASER is complex.
14.	**Impact on eyes**	LED is considered for human eyes.	LASER is not safe for naked human eyes. Therefore, there must be rendered eye safe while looking the LASER.
15.	**Feedback**	There is no need of feedback in LEDs.	A proper feedback is essential in LASER.
16.	**Power requirement**	LEDs require comparatively less power for operation.	LASER requires more power than LEDs.
17.	**Response**	LEDs have slow response.	LASER has comparatively faster response.
18.	**Cost**	The cost of LED is low.	The cost of LASER is more than LED.
19.	**Applications**	LEDs are used in several applications such as area illumination, communication over moderate distances at low data rate, automobile headlamps, display screens, etc.	LASER is used in optical communication, welding, metal cutting, medical surgery, etc.

3.23 BRIEF THEORY OF PHOTODETECTORS

MU - Dec. 2014

- Light sources emits the light that means they are converting electrical energy into the optical energy. They are used in the transmitter section of the communication system.
- Photodetectors are devices used for the detection of light – in most cases of its optical power. More specifically, photodetectors are usually understood as photon detectors, which in some way utilize the photo-excitation of electric carriers;
- Now at the receiver section, there should be a certain device which will convert the optical signal into the original electrical signal. This is achieved with the help of photodetectors.

Definition :

- An optical detector is a device that converts light signals into electrical signals, which can then be amplified and processed.
- It is an optoelectric device which absorbs an optical energy and converts it into the electrical energy.
- This process is called as photodetection process. In generally involves three steps,

1.	Absorption.
2.	Transportation of carriers.
3.	Generation of photocurrent.

1. **Absorption :** In the absorption process the optical energy falling on the photodector gets absorbed by it. It means a number of photons are absorbed by the photodetector. This will cause the generation of some charged carriers.
2. **Transportation of carriers :** In this process the newly generated carriers gets transported across the absorption region. In some photodetectors, a gain is provided to these charged carriers.
3. **Generation of photocurrent :** After the transportation of charged carriers; the collection of these carriers is done and the current flows through the external circuit. This current is mainly because of the photons falling on the photodetector, so this current is called as **photocurrent**.

3.23.1 Characteristics of Photodetectors

UQ. Derive an expression for responsivity of PIN photodiode. **(MU – Q. 3(c), Dec. 15, 5 Marks)**

UQ. Derive an expression for Responsivity of PIN photodiode. **(MU – Q. 4(b), May 17, 4 Marks)**

(i) Responsivity (R)

- This is the sensitivity of photodetector.
- Responsivity is defined as the ratio of detector output to the detector input.
- It is dependent on the wavelength of incoming light.
- So this is also called as the spectral responsivity.

$$\therefore\ R = \frac{I_{ph}}{P_{inc}} \quad ...(3.23.1)$$

where I_{ph} = photocurrent and

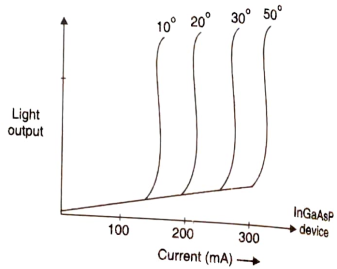
P_{inc} = incident optical energy

$$\therefore\ R = \frac{\eta\lambda\,(\mu m)}{1.24}\ (A/W) \quad ...(3.23.2)$$

where η = quantum efficiency of photodetector

It is also given by,

$$R = \frac{\eta q}{hf} = \frac{\eta\, q\, \lambda}{hc}$$



(ii) Quantum efficiency (η)

MU -May 2011, Dec. 2013, May 2014

- It is defined as the ratio of number of newly generated charge carriers to the number of incident photons

$$\therefore\ \eta = \frac{\text{Number of newly generated charge carriers}}{\text{Number of incident photons}}$$

$$\therefore\ \eta = \frac{I_{ph}/q}{P_{inc}/hf} \quad ...(3.23.3)$$

Here I_{ph} = Generated photocurrent

q = charge of electron

P_{in} = Total incident optical power and

hf = Energy contained by photons

$$\therefore\ \eta_{ext} = \frac{I_{ph} \cdot hf}{q\,P_{inc}} \quad ...(3.23.4)$$

- This is called as external quantum efficiency and denoted by η_{ext}.
- The internal **quantum efficiency** (η_i) is defined as the ratio of number of pairs created to the number of photons absorbed.

$$\therefore\ \eta_i = \frac{\text{Number of pairs generated}}{\text{Number of photons absorbed}}$$

- The value of internal quantum efficiency is high.

(iii) Noise Equivalent Power (NEP)

- Because of the incident light intensity, the charged carriers are generated.
- These charged carriers have the random motions.
- Thus the concentration of charged carriers get fluctuated.
- This will cause the fluctuation in the conductivity of the photoconductor. So the noise is generated in the photoconductors.
- The noise equivalent power is defined as incident optical power required to produce a signal to noise ratio (S/N) of unity in a bandwidth of 1 Hz.
- It is also defined as the ratio of noise current to the peak radiant sensitivity.

$$\therefore\ NEP = \frac{\text{Noise current}}{\text{Peak radiant sensitivity}}$$

(iv) Detectivity (D)

- The reciprocal of noise equivalent power is the detectivity (D)

$$\therefore\ D = \frac{1}{NEP}$$

$$\therefore\ D = \frac{\text{Peak radiant sensitivity}}{\text{Noise current}}$$

- When detectivity is multiplied by square root of the photoconductor area (A) then it is called as **specific detectivity** and denoted by D^*.

$$\therefore\ D^* = D \times A^{1/2}$$

(v) Dark current (I_D)

- When the light is not falling on the photodetector, then also some current is passing in the circuit.
- This current under the darkness condition is called as dark current.

(vi) Spectral response

- This is the ability of photodetector to give response to the incident light of different wavelength.
- It means that spectral response of detector should match to the spectral curve of the light source.

3.23.2 Expression of Responsivity in terms of Quantum Efficiency and Wavelength

MU - May 2012, May 2013, Dec. 2013, Dec. 2014, Dec. 2015

- The responsivity is basically ratio of output photocurrent to an incident optical power.

$$\therefore\ R = \frac{I_p}{P_{opt}} \quad ...(3.23.5)$$

- Now incident power of photodetector means output power of fiber optic cable.
- Energy contained in photons is E = hf; thus incident photon rate (r_p) can be expressed in terms of incident optical power as,

$$r_p = \frac{P_{opt}}{hf} \quad ...(3.23.6)$$

- Now quantum efficiency is the ratio of number of electrons collected (r_e) to the number of incident photons (r_p).

$$\therefore \eta = \frac{r_e}{r_p}$$

$$\therefore\ r_p = \frac{r_e}{\eta} \quad ...(3.23.7)$$

- Equating Equations (3.23.6) and (3.23.7) we get,

$$\frac{r_e}{\eta} = \frac{P_{opt}}{hf}$$

$$\therefore\ r_e = \frac{\eta\, P_{opt}}{hf} \quad ...(3.23.8)$$

- The output photocurrent is,

$$I_p = r_e \cdot q$$

where q is charge of an electron

$$\therefore\ I_p = \frac{\eta\, P_{opt}\, q}{hf} \quad ...(3.23.9)$$

- Putting Equation (3.23.9) in Equation (3.23.5) we get,

$$R = \frac{\eta q}{hf}$$

- But $f = \frac{c}{\lambda}$; where c = speed of light and λ = operating wavelength

$$\therefore\ R = \frac{\eta\, q\, \lambda}{hc} \quad ...(3.23.10)$$

- This is the expression of responsivity in terms of quantum efficiency and wavelength.
- Thus at a particular wavelength, responsivity is directly proportional to the quantum efficiency.

- The plot of responsivity against wavelength is shown in Fig. 3.23.1.

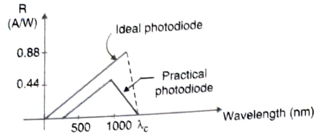


Fig. 3.23.1: Plot of responsivity against wavelength

3.24 CONVENTIONAL P-N JUNCTION PHOTODIODE

- A photodiode is a PN-junction diode that consumes light energy to produce an electric current.
- Sometimes it is also called a photo-detector, a light detector, and photo-sensor.
- These diodes are particularly designed to work in reverse bias conditions. This diode is very sensitive to light so when light falls on the diode it easily changes light into an electric current. Here photon current is flowing as if a reverse biased current is flowing in case of normal reverse biased diodes.

Principle of operation

- The incident light produces an electron hole pairs in the depletion region.
- Then the separation of electrons and holes takes place and the photocurrent flows through the circuit.

Construction

- The construction of P-N junction photodiode is as shown in Fig. 3.24.1.

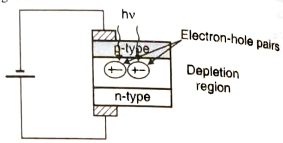


Fig. 3.24.1 : P-N junction photodiode

- It consists of a P-N junction. The reverse bias is provided as shown in Fig. 3.24.1.

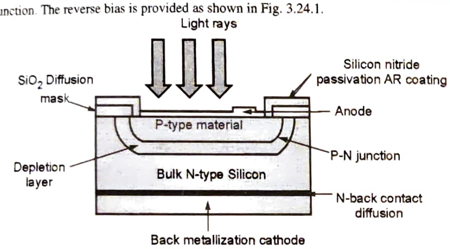


Fig. 3.24.2 : Cross Sectional of Photodiode

- The depletion region is formed between P and N region. The width of depletion region can be increased by increasing the reverse bias.
- The upper P layer is made thin so that maximum light rays can reach upto the depletion region.

Working

- When a light is made to illuminate the PN junction, covalent bonds are ionized. This generates hole and electron pairs.
- The depth at which photons can reach into the depletion region is dependent on the wavelength of incident light.
- Photocurrents are produced due to generation of electron-hole pairs. Electron hole pairs are formed when photons of energy more than 1.1eV hits the diode. When the photon enters the depletion region of diode, it hits the atom with high energy. This results in release of electron from atom structure. After the electron release, free electrons and hole are produced.
- In general, an electron will have a negative charge and holes will have a positive charge. The depletion energy will have built-in electric field.
- Due to that electric field, electron-hole pairs move away from the junction. Now these electrons and holes are attached towards the positive and negative terminals of battery respectively.
- The electron hole pairs formed outside the depletion region, gets diffused in the depletion region and also contributes and photocurrent. But the maximum probability is that they are getting recombined.

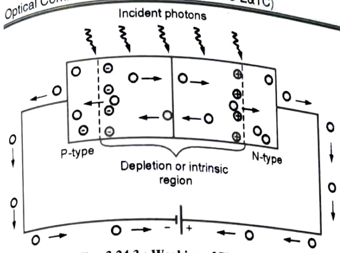


Fig. 3.24.3 : Working of Photodiode

- If the depletion region is made much wider, then the maximum number of photons can reach to the depletion region. But in this case the transit time i.e. the time required by the charged carriers to reach to the battery terminals, gets increased. Thus the response time of the photodiode will be made more. Thus always a compromise between these two conditions is done.
- The photon absorption intensity and photon energy are directly proportional to each other. When energy of photons is less, the absorption will be more. This entire process is known as Inner Photoelectric Effect.
- Intrinsic Excitations and Extrinsic Excitations are the two methods via which the photon excitation happens. The process of intrinsic excitation happens, when an electron in the valence band is excited by photon to conduction band.

V-I Characteristics

- The voltage vs. current characteristic of a photodiode is as shown in Fig. 3.24.4.
- The characteristics are shown in the negative region because the photodiode can be operated in reverse biased mode only.
- In the darkness condition i.e. when the light was not falling on photodiode, a very small amount of current was passing as shown in Fig. 3.24.4.
- When there is no light illumination, reverse current will be almost zero. The minimum amount of current present is called as Dark Current.
- Now as the light is incident on photodiode, the photocurrent is developed. As the incident light intensity is increased, a photocurrent also gets increased.

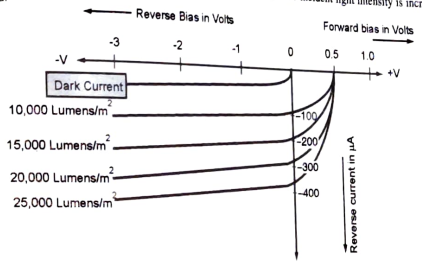


Fig. 3.24.4 : VI characteristics of photodiode

- The reverse saturation current in the photodiode is denoted by I0. It varies linearly with the intensity of photons striking the diode surface. The current under large reverse bias is the summation of reverse saturation current and short circuit current.

$$I = I_{sc} + I_0 (1 - eV/\eta V_t)$$

- Where I_{sc} is the short circuit current, V is positive for forward voltage and negative for reverse bias, Vt is volt equivalent for temperature, η is unity for germanium and 2 for silicon.

Advantages and Disadvantages of Photodiodes

Advantages of photodiode

1. It is highly sensitive to light. It shows a quick response when exposed to light.
2. It has a better frequency response and spectral response compared to LDR.
3. It is a linear circuit element. The photocurrent of the photodiode is extremely linear to the light level.
4. It can be manufactured from a variety of materials including, but not limited to, silicon, germanium, and indium gallium arsenide.
5. It can operate at high frequencies.
6. It has a lower noise level.
7. It is the fastest photodetector. The speed of the operation is extremely fast.

8. It has a low resistance but it can be used as a variable resistance. The intensity of the reverse light current varies with the intensity of the incident light energy for the fixed reverse bias voltage. Thus, the ratio of voltage to the current varies. So, there will be a variation in the resistance of the photodiode.
9. It has a low dark current.
10. It has a long lifetime. It can be used for years without any maintenance.
11. It has a compact size.
12. It requires no high voltage.
13. It is durable, reliable, and can withstand mechanical stress.
14. It is having a high quality/price performance.
15. It finds use in a wide range of applications because it can be made with a wide range of performance characteristics. Each application places different demands on its performance. Available in a wide range of packages including epoxy coated, transfer molded, cast, and hermetic packages as well as in chip form.
16. It is utilized in such diverse applications as spectroscopy, photography, analytical instrumentation, safety equipment, optical position sensors, beam alignment, surface characterization, laser range finders, optical communications, and medical imaging instruments.
17. It is usable with almost any visible or near-infrared light source such as LEDs; neon, fluorescent, incandescent bulbs; lasers; flame sources; sunlight; etc.
18. It can be designed and tested to meet the requirements of your application.

Disadvantages of photodiode

1. It has poor temperature stability. When the temperature increases, the dark current level also increases rapidly. Ambient temperature variations greatly affect its sensitivity and dark current.
2. It has a small active area.
3. There is a necessity for amplification at low irradiances.
4. It needs offset voltage.
5. Change in current is very small, hence may not be sufficient to drive the circuit.
6. Should not exceed the working temperature limit specified by the manufacturers.

Applications of Photodiode

1. Photodiodes are used in simple day-to-day applications. The reason for their prominent use is their linear response of photodiode to light illumination.
2. Photodiodes with the help of optocouplers provide electric isolation. When two isolated circuits are illuminated by light, optocouplers are used to couple the circuit optically. Optocouplers are faster compared to conventional devices.
3. Photodiodes are used in safety electronics such as fire and smoke detectors.
4. Photodiodes are used in numerous medical applications. They are used in instruments that analyze samples, detectors for computed tomography and also used in blood gas monitors.
5. Photodiodes are used in solar cell panels.
6. Photodiodes are used in logic circuits.
7. Photodiodes are used in the detection circuits.
8. Photodiodes are used in character recognition circuits.
9. Photodiodes are used for the exact measurement of the intensity of light in science and industry.
10. Photodiodes are faster and more complex than normal PN junction diodes and hence are frequently used for lighting regulation and optical communication.

3.25 PIN (P-I-N) PHOTODIODE

MU - Dec. 2013, Dec. 2014

- As the name indicates, this diode consists of an undopped intrinsic layer between the two highly dopped regions.
- It gives improved performance as compared to conventional photodiodes.

Construction

- The construction of PIN photodiode is as shown in Fig. 3.25.1.
- It consists of an undopped intrinsic i layer as shown in Fig. 3.25.1.

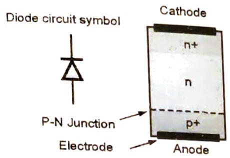


Fig. 3.25.1 : Construction details of PIN diode

- The width of this layer is more than that of dopped P^+ and N^+ layers.
- The resistivity of 'i' layer ranges from 10 ohms per centimetre to 100 KΩ per centimetre. While the resistivity of dopped P^+ and N^+ layers is less than 1 Ω. This diode has much larger depletion area. The changes in the properties of the diode are known from the intrinsic material. These diodes are made of silicon.
- The intrinsic region of the PIN diode acts like an inferior rectifier which is used in various devices such as attenuators, photodetectors, fast switches, high voltage power circuits, etc.

Working

- The PIN diode does not provide any gain. So the maximum internal quantum efficiency is 100 %.
- The working principle of the PIN diode exactly same as a normal diode. The main difference is that the depletion region, because that normally exists between both the P & N regions in a reverse biased or unbiased diode is larger.

- In any PN junction diode, the P region contains holes as it has been doped to make sure that it has a majority of holes. Likewise the N-region has been doped to hold excess electrons.
- The layer between the P & N regions includes no charge carriers as any electrons or holes merge As the depletion region of the diode has no charge carriers it works as an insulator.
- The depletion region exists within a PIN diode, but if the PIN diode is forward biased, then the carriers come into the depletion region and as the two carrier types get together, the flow of current will starts.
- When the PIN diode is connected in forward biased, the charge carriers are very much higher than the level of intrinsic carrier's attention.
- Due to this reason the electric field and the high level injection level extends deeply into the region.
- This electric field assists in speeding up of the moving of charge carriers from P to N region, which consequences in quicker operation of the PIN diode, making it an appropriate device for high frequency operations.

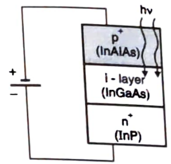


Fig. 3.25.2 : PIN photodiode

(a) Forward and Reverse characteristics of PIN Diode

Forward Biased PIN Diode

- When the diode is kept forward biased, the charges are continuously injected into the I-region from the P and N-region. This reduces the forward resistance of the diode, and it behaves like a variable resistance.
- The charge carrier which enters from P and N-region into the i-region are not immediately combined into the intrinsic region. The finite quantity of charge stored in the intrinsic region decreases their resistivity.
- Consider the Q be the quantity of charge stored in the depletion region. The τ be the time used for the recombination of the charges. The quantity of the charges stored in the intrinsic region depends on their recombination time. The forward current starts flowing into the I_F region.

$$Q = I_F \cdot \tau \qquad \text{...(1)}$$

Where, I_F – forward current

τ - recombination time

The resistance (R_s) of the current under forwarding biased is inversely proportional to the charge Q stored in the intrinsic region.

$$R_s = \frac{\omega}{(\mu_N + \mu_o)\cdot Q} \qquad \text{...(2)}$$

Where, w – width region

μ – electron mobility

μ_o – hole mobility

From equation (1) and (2), we get

$$R_s = \frac{\omega}{(\mu_N + \mu_o)\cdot I_F\,\tau}$$

The above equation shows that the resistance of the intrinsic region depends on the width of the region.

Reversed Biased PIN Diode

- When the reverse voltage is applied across the diode, the width of the depletion region increases. The thickness of the region increases until the entire mobile charge carrier of the I-region swept away from it. **The reverse voltage requires for removing the complete charge carrier from the I-region is known as the swept voltage.**
- In reverse bias, the diode behaves like a capacitor. The P and N region acts as the positive and negative plates of the capacitor, and the intrinsic region is the insulator between the plates.

$$C = \frac{\epsilon A}{w}$$

(b) Characteristics of PIN Diode

Low Capacitance

A PIN diode provides a lower value of capacitance because of the larger distance between the P and N sections. When just a low reverse potential is performed, the depletion section gets completely depleted. As the depletion process ends, the capacitance now do not provide modification with the applied potential because of the presence of a low amount of charge in the intrinsic section.

High Breakdown Voltage

Because of the presence of the intrinsic part, the PIN diode shows a higher value of breakdown voltage. This is because a greater voltage is needed in order to destroy the thick depletion section.

Sensitive to Photodetection

The depletion section is responsible for producing energy when radiation contacts its surface. The existence of an intrinsic section improves the area for radiation absorption. Therefore, these are broadly employed as photodetectors.

Storage of Carriers

This is the important feature of a PIN diode. The intrinsic section increases the area for carriers storage. The saved charge in the depletion section is responsible for the value of the current flowing across the circuit.

When the forward biasing condition is presented to the system, then, in this case, the instrument provides variable resistance features. The resistance changes with the supplied input voltage. Therefore, it does not generate distortion or rectification.

(c) Advantages and Disadvantages

Advantages

1. Less noise
2. Frequency response is good
3. High reverse voltages to be accepted
4. Less dark current
5. Linear
7. The depletion region is large
8. Used as a variable resistance device
9. The bias voltage is less
10. Junction capacitance is low
11. The response speed is high
12. Responsive to the light

Disadvantages

1. Less active area
2. Reverse recovery time is high because of power loss
3. Response time is not fast
4. Less sensitivity
5. There is no internal gain
6. Temperature-dependent
7. In dark current, it increases rapidly
8. Needs amplification at less illumination region

(d) Spectral response

The spectral response curve for PIN photodiode is as shown in Fig. 3.25.3.

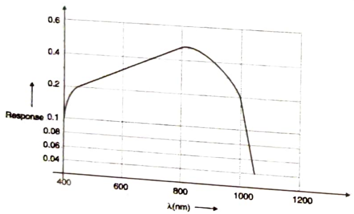


Fig. 3.25.3 : Spectral response of PIN photodiode

- At the ultraviolet side, the wavelength of incident light is less. It creates the electron hole pairs in the top p-layer. So these electron hole gets recombined before diffusing in the depletion region.
- While for the longer wavelength (IR range) the energy of photons is very low. $\left(E = h\,f = \frac{hc}{\lambda} \therefore E \alpha \frac{1}{\lambda} \right)$
- These photons doesn't provide any electron hole pair in the depletion region. But in the visible region electron hole pairs are created and the photocurrent is developed.

Current mode and voltage mode operation

- The current vs. voltage characteristic of PIN photodiode is as shown in Fig. 3.25.4. In a photoductive mode the photocurrent is slightly dependent on the reverse bias.

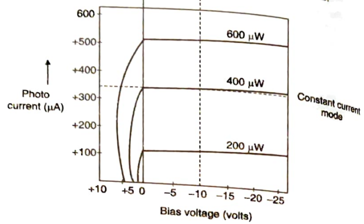


Fig. 3.25.4 : I-V characteristics of PIN photodiode

- For a constant reverse bias the current is linear. This is called as **current mode operation** of photodiode.
- In a photovoltic mode, when no reverse voltage is applied then for a constant current bias the output voltage is obtained which change with the change in incident radiation. This is called as **voltage mode operation** of photodiode.

Equivalent circuit

- The equivalent circuit of a PIN photodiode is as shown in Fig. 3.25.5.

Here, I_o = dark current
I_s = signal current
I_n = noise current
C_p = barrier capacitance
R_p = barrier resistance
R_s = series resistance
R_L = Load resistance.

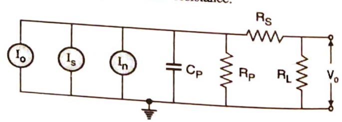


Fig. 3.25.5 : Equivalent circuit

- The output voltage is given by,

$$V_o = (I_o + I_s + I_n)\,R_L$$

- The dark current I_o is produced because of the reverse bias applied to the photodiode. It is also affected by the temperature.
- The signal current is the current developed because of incident radiation.
- The number of photons provided to the photodiode because of incident radiation is given by,

$$P = \frac{\lambda H}{h c} \quad ...(3.25.1)$$

Where λ = wavelength of incident light
h = Plank's constant
c = velocity of light
And H = incident radiation in watts / cm^2

- The photocurrent depends on following factors.
  (i) Number of photons falling on photodiode.
  (ii) Transmission and reflection property of a crystal.
  (iii) Active area of photodiode.
- Thus the photocurrent (I_{ph}) is given by,

$$I_{ph} = \eta F q A \quad ...(3.25.2)$$

Where η = quantum efficiency
F = fraction of incident photons transmitted by crystal
q = charge of electron
A = Active area of photodiode

- Now by using spectral response,

$$I_{ph} = \delta S_R H \quad ...(3.25.3)$$

Where, δ = relative response
S_R = peak spectral sensitivity
H = incident radiation.

- And in terms of active area 'A' this equation can be written as,

$$I_{ph} = H S_e A \quad ...(3.25.4)$$

Where,
S_e = Response of photodiode at the actual emission wavelength of the source

3.25.1 Noise Currents in PIN Photodiode

The different noise currents in PIN photodiodes are :

(a) Photon noise
(b) Shot noise
(c) Johnson noise
(d) Generation recombination noise.

(a) Photon noise

- The photons incident on the photodiode does not have the same arrival rate. There are random fluctuations in the arrival rate. This causes the random fluctuations in the input signal. This in turn creates the random fluctuations in the output signal.
- The noise current produced because of these fluctuations is called as **photon noise current.**

(b) Shot noise

- The ambient light where the photodiode is placed is called as **background radiation**. This causes some photocurrent to flow, because of thermal generation of electron hole pairs in the depletion region. This dark current gives the random fluctuations in the output current.
- The current produced because of shot noise is called shot noise **current** and is given by,

$$I_{shot} = \sqrt{2\,qB\,(I_D + I_P)}$$

Where, q = charge of electron = 1.602×10^{-19} coulomb
I_D = dark current
B = Bandwidth in Hz
I_P = photocurrent = $\frac{\eta P_0 q \lambda}{h c}$
Here P_0 = Incident optical power

(c) Johnson noise

- Under the thermal equilibrium, the charge carriers have the random motions.
- The noise current produced by these random motions is called as Johnson noise current and is given by,

$$I_{thermal} = \sqrt{\frac{4\,KTB}{R_T}}$$

K = Boltzman's constant
= 8.62×10^{-5} eV/K
= 1.38×10^{-23} Joule / K
T = temperature in Kelvin and 1K = 273 + °C
B = Bandwidth in Hz
R_T = Total resistance i.e. $R_{source} + R_{Load}$ is ohm.

(d) Generation recombination noise

- The fluctuations caused because of variations in the recombination rates of charged particles produces the generation recombination noise. This is generally very small.
- The total noise current is given by,

$$I_{total\ noise} = \left((I_{thermal})^2 + (I_{shot})^2 \right)^{1/2}$$

- The signal to noise ratio is given by,

$$\left(\frac{S}{N}\right) = \frac{I_{signal}}{I_{noise}} = \frac{I_P^2}{I_{thermal}^2 + \left(I_{total\ noise}^2 \times F_n\right)}$$

Where F_n = amplifier noise figure

Applications of PIN Diodes

The applications of PIN mainly include the following areas :

- The PIN diode is used as a high voltage rectifier. The intrinsic layer in the diode offers a partition between the both the layers, permitting higher reverse voltages to be tolerated

- The PIN diode is used as an ideal radio frequency switch. The intrinsic layer among the P & N layers increases the space between them. This also reduces the capacitance between both the regions, thus raising the level of isolation when the PIN diode is reverse biased.
- The PIN diode is used as a photo detector to convert the light into the current which takes place in the depletion layer of a photo diode, rising the depletion layer by inserting the intrinsic layer progresses the performance by increasing the volume in where light change occurs.
- This diode is an ideal element to give electronics switching in applications of electronics. It is mainly useful for RF design applications and also for providing the switching, or an attenuating element in RF attenuators and RF switches. The PIN diode is capable to give much higher levels of consistency than RF relays that are frequently the only other alternative.
- The main applications of the PIN diode are discussed in the above, although they can also be applied in some other areas

3.25.2 Solved Problems on PIN Photodiode

Ex. 3.25.1 : The load resistor of 1 MΩ is connected across a silicon p-i-n photodiode. The area of cell is 0.35 mm^2, $\epsilon = 10.5 \times 10^{-13}$ F/cm and electron saturation velocity is 10^7 m/sec. If the width of depletion region is 12 μm, calculate :

(a) transit time

(b) junction capacitance

(c) time constant of this photodiode.

☑ **Soln. :**

(a) The transit time is given by,

$$\text{transit time } (t_{tr}) = \frac{\text{Width of depletion region}}{\text{Saturation velocity of electrons}}$$

$$\therefore \quad t_{tr} = \frac{12 \times 10^{-6} \text{ (m)}}{10^7 \text{ (m/sec)}}$$

$$\therefore \quad \mathbf{t_{tr} = 1.2 \times 10^{-12} \text{ sec}}$$

(b) Junction capacitance is given by,

$$C_j = \frac{\epsilon A}{\text{Width}}$$

$$\text{Here } \epsilon = 10.5 \times 10^{-13} \times 10^2 \text{ F/m}$$

$$= \frac{10.5 \times 10^{-13} \times 10^2 \times 0.35 \times 10^{-6}}{12 \times 10^{-6}}$$

$$\therefore \quad \mathbf{C_j = 3.06 \times 10^{-12} \text{ farads}}$$

(c) Time constant is given by,

$$\tau = R_L \times C_j = 1\ M\Omega \times 3.06 \times 10^{-12}$$

$$\therefore \quad \tau = 3.06\ \mu\text{ sec}$$

Ex. 3.25.2 : A photodiode has a quantum efficiency of 65% when photons of energy 1.5×10^{-19} joules are incident upon it.

(i) At what wavelength is the photodiode operating.

(ii) Calculate the incident optical power required to obtain a photocurrent of 2.5 microamperes, when the photodiode is operating as above.

☑ **Soln. :**

(i) $$E = hf = \frac{hc}{\lambda} \quad \therefore \lambda = \frac{hc}{E} \quad \text{Here } E = 1.5 \times 10^{-19} \text{ J}$$

$$= \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{1.5 \times 10^{-19}}$$

$$= 1.325\ \mu\text{m}$$

∴ Photodiode is operating at 1.325 μm ...(1)

(ii)

$$\text{Responsivity } R = \frac{\eta q \lambda}{hc} = \frac{\eta q}{hc} = \frac{\eta q}{E}$$

$$= \frac{0.65 \times 1.602 \times 10^{-19}}{1.5 \times 10^{-19}}$$

$$= 0.694 \text{ A/W}$$

$$\text{also responsivity} = \frac{I_P}{P_{opt}}$$

$$\therefore \quad P_{opt} = \frac{I_P}{R}$$

$$\therefore \quad P_{opt} = \frac{2.5 \times 10^{-6}}{0.694}$$

$$= 3.6\ \mu W \quad ...(2)$$

The incident optical power is 3.6 μW.

Ex. 3.25.3 : An InGaAs pin photodiode has following parameters at wavelength of 1300 nm, I_D is 4 nA, η = 0.9 R_L = 1 kΩ, surface leakage carryout is negligible. Incident optical power is 300 nanowatts and receiver bandwidth is 20 MHz.

Find :

(i) Mean square quantum noise current.

(ii) Mean square thermal noise current at 25° C. Boltzman constant = 1.38×10^{-3} J/K.

☑ **Soln. :**

(i) Optical power = 300 nW

λ = 1300 nm

Dark current is 4 nA

η = 0.9

R_L = 1 kΩ

Bandwidth = 20 MHz

$$\text{Photocurrent } I_P = \frac{\eta P_0 q}{hf} = \frac{\eta P_0 q \lambda}{hc}$$

$$= \frac{0.9 \times 300 \times 10^{-9} \times 1.602 \times 10^{-19} \times 1300 \times 10^{-9}}{6.626 \times 10^{-34} \times 3 \times 10^8}$$

$$\therefore \quad I_P = 282.87 \text{ nA}$$

Total shot noise (quantum noise)

$$I_{shot} = \sqrt{2 q B (I_d + I_p)}$$

$$= \sqrt{2 \times 1.6 \times 10^{-19} \times 20 \times 10^6 \times [(282.87 + 4) \times 10^{-9}]}$$

$$\therefore \quad \mathbf{I_{shot} = 1.3558 \text{ nA}}$$

(ii) The thermal noise in the load resistor.

$$I_{thermal} = \sqrt{\frac{4 KTB}{R_T}}$$

$$= \sqrt{\frac{4 \times 1.38 \times 10^{-23} \times (273 + 25) \times 20 \times 10^6}{1 \times 10^3}}$$

$$\therefore \quad \mathbf{I_{thermal} = 18.138 \text{ nA}}$$

Ex. 3.25.4 : Consider a 870 nm receiver with a silicon p-i-n photodiode. Assume 20 MHz bandwidth, 65 % quantum efficiency, 1 nA dark current, 8 pF junction capacitance, and 3 dB amplifier noise figure. The receiver is illuminated with a 5 μW of optical power. Determine the RMS noise currents due to shot noise, thermal noise and amplifier noise. Also calculate the SNR.

☑ **Soln. :**

(i) Given : Bandwidth = 20 MHz

η = 65%, λ = 870 nm

Dark current = 1 nA ;

Junction capacitance = 8 pF

Noise figure = 3 dB

P_{opt} = 5 μW

$$\text{Responsivity} = \frac{\eta q \lambda}{hc}$$

$$= \frac{0.65 \times 1.602 \times 10^{-19} \times 870 \times 10^{-9}}{6.626 \times 10^{-34} \times 3 \times 10^8}$$

$$\therefore \quad R = 0.4557 \frac{A}{W}$$

Photo current is given by :

$$I_P = P_0 R = 5 \times 10^{-6} \times 0.4557 = 2.278\ \mu A$$

$$\text{Shot noise } I_{shot} = \sqrt{2 q B (I_P + I_d)}$$

$$= \sqrt{2 \times 1.602 \times 10^{-19} \times 20 \times 10^6 [(2.278 \times 10^{-6}) + 1 \times 10^{-9}]}$$

$$= 2 \times 1.602 \times 10^{-19} \times 20 \times 10^6 \times 2301 \times 10^{-9}$$

$$\therefore \quad \mathbf{I_{shot} = 3.822 \text{ nA}}$$

(ii) Assuming the load resistor to be 1 kΩ ,

$$\text{Thermal noise, } = \sqrt{\frac{4 KTB}{R_{Load}}}$$

$$= \sqrt{\frac{4 \times 1.38 \times 10^{-23} \times 298 \times 20 \times 10^6}{1 \times 10^3}}$$

Therefore RMS thermal noise current is,

$$I_{thermal} = 18.138 \text{ nA}$$

$$I_{total\ noise} = \sqrt{I_{thermal}^2 + I_{shot}^2}$$

$$\therefore \quad I_{total\ noise} = 18.536 \text{ nA}$$

(iii) The amplifier noise figure = 3 dB

$$\therefore \quad 3 \text{ dB} = 10 \log F_n$$

$$\therefore \quad F_n = 2$$

Signal to noise ratio is,

$$\frac{S}{N} = \frac{I_P^2}{I_{thermal}^2 + I_{total\ noise}^2 \times F_n}$$

$$= \frac{(2.278 \times 10^{-6})^2}{(3.435 \times 10^{-16}) + (3.4359 \times 10^{-16} \times 2)}$$

$$\therefore \quad \frac{S}{N} = 5034.81585$$

$$\therefore \quad \frac{S}{N} = 10 \log (5034.81585) \text{ dB}$$

$$\therefore \quad \mathbf{\frac{S}{N} = 37.019 \text{ dB}}$$

3.25.3 Amplification Action for PIN Photodiode

- The output current of photodiode is very small. So if such photodiodes are placed in the receiver circuits; it is always required to amplify output signal.
- The different amplification techniques are as follows

(a) Using op-amp and a fixed resistor

- This schematic diagram is as shown in Fig. 3.25.6.

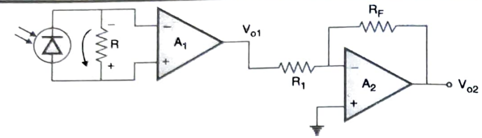


Fig. 3.25.6 : Simple amplification technique using op-amp

- The photodiode is connected across the op-amp terminals as shown in Fig. 3.25.6. This op-amp A_1 is having high input impedance and avoids the loading effects. This output V_{o1} is given to another op-amp or a voltmeter.
- Now as the light intensity falling on the photodiode starts increasing, the photocurrent also gets increased. This photocurrent produces the voltage drop across resistor R. The polarities as shown in Fig. 3.25.6. Thus the current gets converted into the corresponding voltage. One more opamp can be used to provide the amplification action.
- The gain of amplifier can be adjusted by changing the value of feedback resistor. In this circuit no battery is provided. So the voltage produced across 'R' provides the bias voltage to the photodiode. This bias voltage is not constant. It is changing with the change in incident radiation. But the error in this case will be minimum because the change in bias voltage of photodiode produces a very small change in the photocurrent.

(b) Photodiode with constant bias voltage

- This schematic diagram is as shown in Fig. 3.25.7.

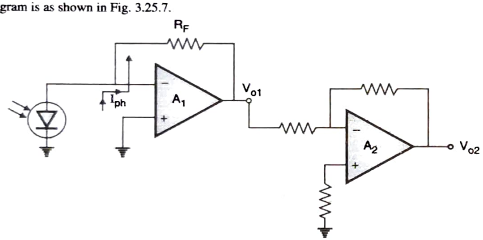


Fig. 3.25.7 : Photodiode with constant bias voltage

- Here the op-amp A_1 helps to provide the constant biasing voltage. As shown in Fig. 3.25.7, when the light is incident on photodiode a photocurrent starts flowing. Because of high input impedance of op-amp the photocurrent passes through feedback resistor R_F.
- The output voltage V_{o1} is given as,

$$V_{o1} = -I_{ph} \cdot R_F \quad ...(3.25.5)$$

- Now if the battery (E) is connected at positive input terminal of op-amp A_1 then

$$V_{o1} = (I_{ph} \cdot R_F + E) \quad ...(3.25.6)$$

Since this is inverted voltage one more op-amp A_2 is used. Here A_2 is a unity gain inverting amplifier.

3.26 AVALANCHE PHOTODIODE (APD)

UQ. Explain in detail working principle of RAPD. Why it is called reach through APD and compare its working with PIN diode? **(MU – Q. 4(b), Dec. 15, 8 Marks, Q. 3(b), Dec. 2019, 10 Marks)**

UQ. Explain principle of working of APD photo detector. **(MU – Q. 4(b), May 18, 5 Marks)**

UQ. Explain in detail working principle of Avalanche photodetector. Explain its merits and demerits. **(MU – Q. 4(a), Dec. 18, 10 Marks)**

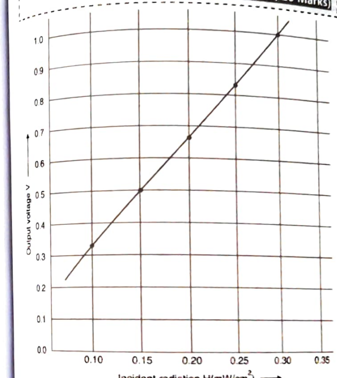


Fig. 3.26.1 : Graph of incident radiation Vs output voltage

- In case of conventional photodiodes and PIN photodiodes the output current is very small. This is because these photodiode are having a limited gain. Now in order to obtain the large gain i.e. large output, the avalanche photodiodes are used.
- The avalanche photodiode or APD was designed by a Japanese engineer namely "Jun-ichi Nishizawa" in the year 1952.
- An APD is a very responsive semiconductor detector that used the photoelectric effect to change light into electricity.
- In 2020, a graphene layer is added to this diode to avoid degradation eventually to maintain these diodes.
- In fiber-optic communication systems, the light is changed into electrical signals using a single component like avalanche photodiode or APD. In the avalanche process, charge carriers are produced through collisions.
- A light particle-like photon generates many electrons to produce an electric current.

Principle of operation

- In this case the reverse bias applied to the photodiode is near to the breakdown value.
- The incident light produces the electron hole pairs. Now these carriers travels with their saturation velocity. Now when they travel with the maximum velocity, they will colloid with the lattice. So new electron hole pairs are generated.
- These newly generated carriers travels along with initial carriers. Thus the multiplication of charge carriers takes place which increases the current. This process of generating more number of charged carriers is called as **impact ionization.**

Construction

- The construction of **reach through avalanche photodiode (RAPD)** is as shown in Fig. 3.26.2.
- If the silicon material is used, the efficiency about 90 % is obtained.

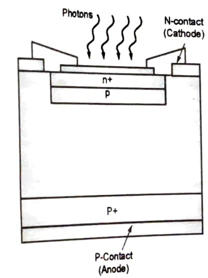


Fig. 3.26.2 : Constructional Details of APD

- It is a $p^+ \pi$-p-n^+ configuration as shown in Fig. 3.26.3.
- The construction of both the PIN photodiode and Avalanche photodiode is similar. This diode includes two heavily doped & two lightly doped regions. Here, heavily doped regions are P+ & N+ whereas lightly doped regions are I & P.

- In the intrinsic region, the depletion layer width is fairly thinner in this diode as compared to the PIN photodiode. Here, the p+ region works like the anode whereas the n+ region acts as the cathode. Here P layer is having high resistivity. So all the reverse bias is mostly applied across P N^+ region.
- When the applied reverse bias is increased, the width of the depletion region also gets increased.

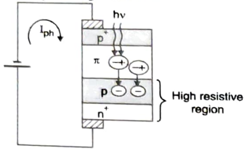


Fig. 3.26.3 : Construction of RAPD

Working

- The reverse bias is applied as shown in Fig. 3.26.2.
- When the light is incident on the top p^+ layer, the electron hole pairs are generated. More number of electron hole pairs are generated in the π layer.
- The charge carriers moves with their saturation velocity, because of the applied electric field.
- The lower $p - n^+$ region is a highly resistive region. Now the electrons will travel into the highly resistive region. Here the impact ionization takes place. That means a new charged carriers are generated in the high resistive region.
- The electric field required to do the impact ionization is from 10^4 V/cm to 10^5 V / cm. Thus the multiplication of charged carrier takes place. This increases the total photocurrent.
- Sometimes the gain upto 200 is obtained. Here the important factor is that the material should not have any defects. If such defects are present then the total photocurrent will gets reduced.

3.26.1 Electric Field Profile

MU -Dec. 2015

- An electric field profile of RAPD is shown in Fig. 3.26.4.

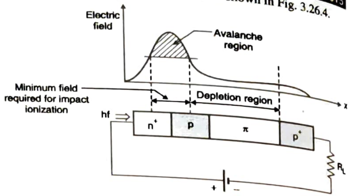


Fig. 3.26.4

- A depletion region is created due to small applied electric voltage. If the reverse voltage is increased; the depletion region widens across p region and it reaches π region.
- The π region is much wider than p region; the electric field in π region is much lower than $p - n^+$ region. This diode is normally operated in the fully depleted mode.
- The avalanche region is the gain region, which is created in the $n^+ - p$ region.

3.26.2 Parameters of APD

MU - May 2012

In case of avalanche photodiode to do the impact ionization, the required energy is more than the bandgap energy (E_g) of a material. The different parameters related to this process are as follows :

(i) Impact ionization coefficients

- To do the impact ionization process the coefficients related to electrons and holes are termed as αe and αh respectively.
- The electrons and holes have to travel a definite distance to create the new electron and hole pairs in the impact ionization process. This distance travelled by electrons and holes is in the direction of electric field.
- The reciprocal of the average distance is called as **ionization coefficient.** Thus impact ionization coefficient,

$$\alpha = \frac{1}{\text{Average distance travelled by electrons and holes generate new electron hole pairs in the direction of electric field}}$$

- The ionization coefficient is also defined as number of secondary electron – hole pairs per unit length.

$$\alpha = \frac{\text{Number of secondary electron hole pairs}}{\text{Unit length}}$$

(ii) Response time (τ)

- This is the total time period taken by a photodiode to generate the photocurrents.
- In case of APD, the gain provided by the impact ionization process is large. Here the bandwidth is reduced, because a definite time period is required by electrons and holes to do the impact ionization process. Thus the response time will be more.
- If the ratio $\frac{\alpha_e}{\alpha_h} = 1$, that means if ionization coefficient for both the electrons and holes is same, then both electrons and holes starts to do the impact ionization. So the time required will be more.
- That means bandwidth which is reciprocal of time period gets reduced. But if $\frac{\alpha_e}{\alpha_h}$ tends to as, then the time period is minimized.

(iii) Threshold ionization energy (E_i)

- The minimum amount of energy required to do the impact ionization is called as threshold ionization energy. This energy should be at least equal to the bandgap energy (E_g) of the material.
- The value of E_i affects the impact ionization coefficients.

(iv) Multiplication coefficient (M)

- In case of APD, after the impact ionization process the number of electrons and holes are increased.
- That mean a multiplication of charged carriers takes place. Thus the multiplication coefficient is defined as the ratio of output current to the input current. Here the current is related to the number of electrons and holes.
- The multiplication coefficients for electrons and holes are denoted by M_e and M_n respectively.

$$\therefore M_e = \frac{I_{eo}}{I_{ei}}$$

$$\text{and} \quad M_h = \frac{I_{no}}{I_{ni}}$$

- Where I_{eo} and I_{no} are the output currents of electrons and holes respectively and I_{ei} or I_{eo} are the input current related to electrons or holes respectively.

3.26.3 Noise Mechanism in APD

In case of avalanche photodiodes mainly there are three types of noise signals :

(i) Shot noise
(ii) Thermal noise
(iii) Avalanche noise

(i) Shot noise

- This noises is basically from the primary currents such as photo current, dark current and background current. Since these currents are primary currents they are not multiplied.
- So the value is small. Thus the value of shot noise is small.
- This current is given as

$$i_{shot} = \sqrt{2q\,(I_{ph} + I_B + I_D) \cdot G^2 \cdot F \cdot B}$$

where q = charge of electron
I_{ph} = photocurrent
I_B = Background current
I_D = Dark current
G = Gain of photodiode
F = Excess noise factor
B = Bandwidth

(ii) Thermal noise

- The thermal noise is created because of the change in the resistance values of an APD.
- This is given by,

$$i_{thermal} = \sqrt{\frac{4KT \cdot B}{R_{eq}}}$$

Here K = Boltzman's constant
T = The temperature of photodiode
B = Bandwidth
R_{eq} = Equivalent resistance

(iii) Avalanche noise

- This is the main source of noise. This noise is generated because of avalanche process taken place in case of APD.
- In case of avalanche process, the secondary carriers are generated because of the collisions created by electrons and holes. But the rate of generation of these secondary carriers is not fixed.
- There are variations in these rates. This will cause the variations in the number of secondary carriers generated. hus the noise current gets generated.
- These variations can be minimized by making the avalanche process asymmetric. A symmetric avalanche process means only one type of carriers that means either electrons or holes produces the secondary charge carriers.
- In other way if the ratio of electron ionization coefficient α_e to the hole ionization coefficient α_h is made maximum then it is possible that the avalanche process is asymmetric and the noise will be minimized.
- Thus to reduce the avalanche noise.

$$\frac{\alpha_e}{\alpha_h} = \infty$$

3.26.4 Advantages & Disadvantages

UQ. Explain its merits and demerits of Avalanche photodetector. **(MU - Q. 4(a), Dec. 18, 5 Marks)**

Advantages

1. The sensitivity range is high.
2. High performance.
3. Quick response time.
4. These diodes are applicable here the gain level is very important as the high voltage required, through lower reliability means that they are frequently less convenient to utilize.
5. It detects low-intensity light.
6. A single-photon generates a huge number of charge carrier pairs.

Disadvantages

1. The required operating voltage is high
2. The output of this diode is not linear
3. High range of noise
4. t is not used regularly because of the low reliability
5. It uses high reverse bias for its proper operation

3.26.5 Applications of APD

The **applications of avalanche photodiode include the following :**

1.	LASER scanner	2.	Analyzer bridge of antenna
3.	PET scanner	4.	Barcode reader
5.	Laser microscopy	6.	Laser Rangefinders
7.	Speed gun		

8. APDs are used in receivers of OFC (optical fiber communications), imaging, finding the range, laser microscopy, laser scanners & OTDR (optical-time domain reflectometers).
9. These are used in optical communications like receiving detectors. Their wide bandwidth & high sensitivity will make it very famous with designers. These diodes work through a reverse voltage beyond the junction that allows the formation of charge carrier pairs in reply to the radiation.

3.27 COMPARISON BETWEEN PIN PHOTODIODE AND APD

UQ. Differentiate PIN and RAPD photodiodes. **(MU – Q. 4(b), May 17, 4 Marks)**
UQ. Differentiate APD and PIN code. **(MU – Q. 1(b), Dec. 17, 5 Marks)**

Sr. No.	Parameters	PIN photodiodes	Avalanche photodiodes
1.	Layer	An undopped intrinsic layer (i) is placed between two highly dopped regions.	Here 'π' layer is placed between p and n regions.
2.	Gain	Gain is not provided.	More gain is provided.
3.	External Amplifier	Amplifier is required to connect externally.	No external amplifier required.
4.	Response Time	Response time is less.	More response time.
5.	Output Current	Output current is small.	More output current is obtained.
6.	Noise Current	Different noise currents are photon noise, shot noise, Johnson noise and generation recombination noise.	Different noise currents are shot noise, thermal noise and avalanche noise.
7.	Short Current	Shot current is, $I_{shot} = \sqrt{2qI_D B}$	Shot current is, $I_{shot} = \sqrt{2q\,(I_{ph} + I_B + I_D) \cdot G^2 \cdot F \cdot B}$
8.	Sensitivity	Sensitivity is less.	Higher sensitivity.
9.	Reverse bias	Low reverse bias is required.	High reverse bias is required.
10.	Temperature Stability	Good temperature stability.	Poor temperature stability.

3.28 SOLVED PROBLEMS ON APD

Ex. 3.28.1 : A given silicon avalanche photo diode has a quantum efficiency of 65% at a wavelength of 900 nm. Suppose 0.5 μW of optical power produces a multiplied photocurrent of 10 μA. Find the avalanche gain.

Soln. :

$$\text{Responsivity} \quad R = \frac{\eta q \lambda}{hc}$$

$$= \frac{0.65 \times 1.602 \times 10^{-19} \times 900 \times 10^{-9}}{6.626 \times 10^{-34} \times 3 \times 10^{8}}$$

Where q = Electron charge $= 1.602 \times 10^{-19}$ Coulomb

$$h = \text{Planck's constant} = 6.626 \times 10^{-34}\ \text{Js}$$

$$\therefore R = 0.4714\ \text{A/W}$$

$$\text{Now} \quad I_P = P_0 R = \text{optical power} \times \text{responsivity}$$

$$= 0.5\ \mu\text{W} \times 0.4714\ \text{A/W}$$

$$\therefore I_P = 235.73\ \text{nA}$$

Now multiplication factor is

$$M = \frac{\text{Multiplied photocurrent}}{I_P}$$

$$\therefore M = \frac{10 \times 10^{-6}}{235.73 \times 10^{-9}} = 42.42$$

Ex. 3.28.2 : An APD with a multiplication factor of 20 operates at a wavelength of 1.5 μm. Calculate the quantum efficiency and the output photocurrent from the device if its responsivity at this wavelength is 0.6 AW^{-1} and 10^{10} photons of wavelength 1.5 μmare incident upon it per second.

Soln. :

Given : APD with multiplication factor M = 20

$\lambda = 1.5\ \mu m$, $\quad R = 0.6\ AW^{-1}$

and 10^{10} photons of wavelength 1.5 μm are incident.

$$\text{Now, } R = \frac{\eta q \lambda}{hc}$$

$$\therefore \eta = \frac{Rhc}{q\lambda}$$

$$= \frac{0.6 \times 6.602 \times 10^{-34} \times 3 \times 10^{8}}{1.602 \times 10^{-19} \times 1.5 \times 10^{-6}}$$

$$= \frac{1.8 \times 6.602 \times 10^{-26}}{2.4 \times 10^{-25}}$$

$$= 4.95 \times 10^{-1} = 0.495 = 49.5\ \%$$

$$M = \frac{I}{I_P}$$

$$20 = \frac{I}{I_P}$$

$$\therefore I = 20 \times I_P$$

where I is the total output current at the operating voltage and I_P is the initial or primary photo current.

Assuming optical power to be 0.5 μW

$$\therefore I_P = P_0 R = 0.5 \times 10^{-6} \times 0.6$$

$$= 0.3 \times 10^{-6} = 0.3\ \mu A$$

$$\therefore I = 0.3 \times 10^{-6} \times 20 = 6 \times 10^{-6}$$

∴ Output current is 6 μA.

3.29 NOISE ANALYSIS IN DETECTORS

- Noise is basically on unwanted component mixed up with actual signal.
- In fiber optic cable, the noise is mainly created due to the spontaneous fluctuations of current of voltage applied to the source.
- The noise is classified as follows

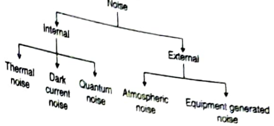


Fig. 3.29.1

- Optical detector is used to detect the optical pulse. The various noise sources in optical pulse detection are shown in Fig. 3.29.2.

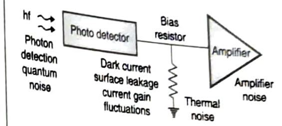


Fig. 3.29.2

3.29.1 Thermal Noise

- This is the noise taking place in the resistor present in the receiving device of optical cable.
- It is defined as the spontaneous fluctuations in the voltage and current, due to thermal interaction.
- This noise is present in the resistors at the room temperature and it is given by,

$$I_{thermal} = \sqrt{\frac{4\,KTB}{R}}$$

Here K = Boltzmann's constant
T = Absolute temperature
B = Bandwidth at the detector

3.29.2 Dark Current Noise

- The basic function of photodetectors is to accept incoming photons and then convert them into electric current. So, the output current of photodetector is directly proportional to incoming photons.
- If photodiode is used as a detector then a small reverse bias is applied across the diode. Now in the absence of incident light (photons); some current flow through the diode terminals. It is called as the dark current.
- Due to the dark current, there are random fluctuations in the output current of diode.
- This produces the shot noise and it is,

$$I_{shot} = I_{dark} = \sqrt{2q\,B\,I_d}$$

Here q = Charge of electron
B = Bandwidth
I_d = Dark current

3.29.3 Quantum Noise

- If amplitude modulation is used then quantum noise is same as the shot noise. But if energy contained by the photons that means hf is greater than KT; where K = Boltzman's constant and T is absolute temperature then quantum fluctuations are more than thermal fluctuations.
- The quantum noise is basically important to decide the quantum limit for digital transmission. This is because, the arrival of photon on the detector decides the output of the detector.
- The number of photons falling on the detector have Poisson's distribution and the probability of detecting 'M' photons in time period τ is given by,

$$P(M) = \frac{M_n^M e^{-(M_n)}}{M!}$$

Here M_n = Variance of probability distribution

- The rate of electrons generated due to incident photons is given by,

$$r_e = \frac{\eta_q P_{opt}}{hf}$$

Here η_q = quantum efficiency

and P_{opt} = optical incident power

- Ideally, the number of electrons generated in-time period 'τ' is same as average number of photons detected over this time period τ

$$\therefore M_n = r_e \cdot \tau \qquad \therefore M_n = \frac{\eta_q P_{opt} \tau}{hf}$$

3.30 COHERENT AND NONCOHERENT DETECTION

- One of the major aspects to any fiber optic transmitter is its power level. It is obvious that the fiber optic transmitter should have a sufficiently high level of light output for the light to be transmitted along the fiber optic cable to the far end.
- The type of light produced is also important. Light can be split into two categories, namely
  - o coherent and
  - o noncoherent light.
- Coherent optical communication and non-coherent optical communication basically use lasers without any essential difference in terms of light.
- Essentially, coherent light has a single frequency. Whereas incoherent light contains a wide variety of light packets all containing different frequencies, i.e. there is no single frequency present. This is in contrast to radio communication where term coherent refers to detection techniques in which the carrier is generated locally at the receiver for detection of signal.
- The function of optodetector is to accept incoming photons and converts it into electron-hole pair. This process requires high signal to noise ratio. To achieve this coherent detection technique is used.
- Often fiber optic systems will operate around a given wavelength, so we go for coherent optical communication.
- In optical fiber communication the term coherent refers to any technique which employs non linear mixing between two optical waves. To send the information signal it can be modulated either by amplitude, frequency or phase of the optical carrier. Therefore modulation techniques used are ASK, FSK, PSK.
- In the direct detection system the electrical signal coming into the transmitter, amplitude- modulates the optical power level of the light source. Thus the optical power is proportional to signal current level.
- At the receiver the incoming optical signal is converted directly into a demodulated electrical output. Thus the directly detected current is proportional to the intensity of the optical signal.

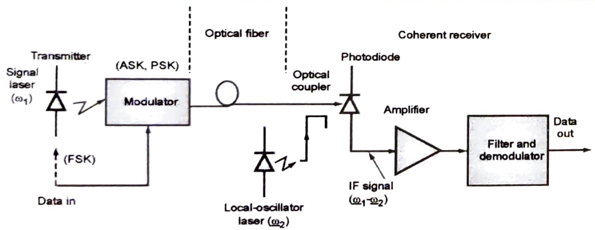


Fig. 3.30.1 : Coherent Optical Fiber System

- At the receiver in coherent optical systems, the receiver first adds a locally generated optical wave to the incoming signal and then detects the combination. There are four demodulation formats depending on how optical signal is mixed with local oscillator (which gives homodyne or heterodyne detection) and how electrical signal is detected (either synchronously or asynchronously). In coherent detection technique; a continuous wave laser beam acts as optical frequency oscillator.
- ASK, FSK or PSK of the optical carrier signal by the information signal is provided by external optical modulator And internal modulation of laser drive current is used to produce ASK, PSK or FSK.
- The detection is done using two types of techniques names
  - o homodyne detection and
  - o heterodyne detection.
- In case of homodyne detection; the local oscillator is generated from the same source as that of the signal. In case of heterodyne detection; the received signal is non-linearly mixed with the reference signal, to obtain the detection.
- Consider that, the electric field of received signal, is,

$$E_s \cos(\omega_s t + \phi)$$

and electric field of local oscillator is,

$$E_L \cos(\omega_L t) \qquad \text{...(3.30.1)}$$

- Now total field is the addition of two fields, given by Equations (3.30.1) and (3.30.2). ...(3.30.2)
- Now assume that, the output current of photodector is equal to the square of amplitude of total electric field.

$$\therefore I = [E_s \cos(\omega_s t + \phi) + E_L \cos(\omega_L t)]^2$$

$$\therefore I = E_s^2 \cos^2(\omega_s t + \phi) + 2 E_s \cos(\omega_s t + \phi) \cdot E_L \cos(\omega_L t) + E_L^2 \cos^2(\omega_L t) \qquad \text{...(3.30.3)}$$

- We have trigonometric identifies,

$$\cos^2\theta = \frac{1 + \cos 2\theta}{2}$$

and $\cos A \cos B = \frac{1}{2}[\cos(A+B) + \cos(A-B)]$

- Thus Equation (3.30.3) becomes,

$$I = \frac{E_s^2}{2}[1 + \cos(2\omega_s t + 2\phi)] + \frac{E_L^2}{2}[1 + \cos(2\omega_L t)] + E_s \cdot E_L \{\cos[(\omega_s + \omega_L)t + \phi] + \cos[(\omega_s - \omega_L)t] + \phi\}$$

$$\therefore I = \frac{E_s^2 + E_L^2}{2} + \frac{E_s^2}{2}\cos(2\omega_s t + 2\phi) + \frac{E_L^2}{2}\cos(2\omega_L t) + E_s E_L [\cos(\omega_s + \omega_L)t + \phi] + E_s E_L \cos[(\omega_s - \omega_L)t + \phi] \qquad \text{...(3.30.4)}$$

- The first term in Equation (3.30.4) is constant term. The second, third and fourth term represents high frequency components and the last term represents the intermediate frequency component. In case of heterodyne detection, the constant components and high frequency components are filtered. Thus output of heterodyne detection is intermediate frequency components.
- The amplitude of this component is directly proportional to incoming radiation. The coherent detection technique is as shown in Fig. 3.30.2.

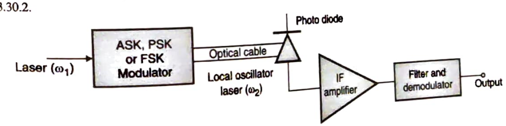


Fig. 3.30.2 : Coherent Detection Technique

- The transmitter laser has a frequency ω_1 and it is modulated using ASK, PSK or FSK.
- If ASK is used then the signal amplitude (A_s) has either '0' or '1' value and the phase ϕ_s remains constant. In FSK, the amplitude A_s remains constant the ϕ_s (t) represents either ω_1 or ω_2.

- In PSK, the phase is varied with the sine wave.

$$\therefore \phi_s(t) = m \sin \omega_m t$$

Where m = modulation index and ω_m = modulation frequency

- The transmitted optical signal is in the form,

$$E_s = A_s \cos[\omega_s t + \phi_s(t)]$$

Here A_s = Amplitude of signal $\quad \omega_s$ = carrier frequency $\quad \phi_s(t)$ = phase of signal

3.31 INTENSITY MODULATED DIRECT DETECTION

- Optical communication is an important part of modern communication techniques due to the excessive bandwidth of the light spectrum. Theoretically, optical communication has much higher system throughput than its radio frequency (RF) communication counterpart.
- Some typical optical communication scenarios include optical fiber communication, free-space optical communication, and visible light communication. In those communication scenarios, intensity modulation and direct detection (IM/DD) is a cost-effective communication scheme compared to coherent ones.
- In IM/DD, the intensity, or power, of the light beam from a laser or a light-emitting diode (LED) is modulated by the information bits and no phase information is needed. Due to this nature, no local oscillator is required for IM/DD communication, which greatly eases the cost of the hardware.
- In IM/DD, orthogonal frequency division multiplexing (OFDM), originally employed in radio frequency communication, is considered as a strong candidate solution to combat with channel distortions. Unlike RF-OFDM, IM/DD OFDM requires a real and positive baseband signal; there is no carrier frequency. This restriction to a real and positive signal fundamentally changes how we generate an optical OFDM signal.

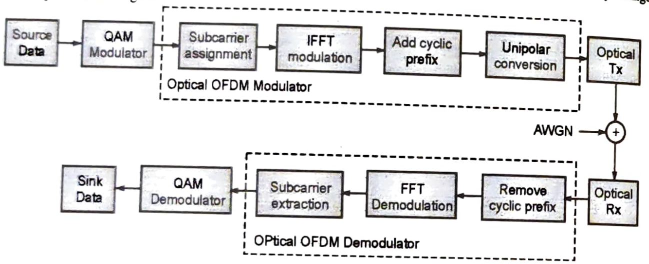


Fig. 3.31.1 : Block diagram of a typical IM/DD OFDM System

- In Fig. 3.31.1, a typical IM/DD OFDM system is shown. The OFDM box illustrates the steps required for optical OFDM. In OFDM, quadrature constellations are assigned to individual subcarriers in the frequency-domain. An inverse fast Fourier transform (IFFT) operation is then used to modulate these subcarriers, resulting in a time domain signal that can be transferred to an optical source.
- A cyclic prefix (CP) is usually added to prevent inter-carrier interference (ICI) prior to modulating the optical source. Both ACO-OFDM and DCO-OFDM impose a Hermitian symmetry to ensure a real, time-domain signal. However, ACO-OFDM modulates only odd subcarriers while DCO-OFDM modulates all subcarriers.
- Next, the signals must be converted to unipolar signals. For DCO-OFDM, the entire timedomain signal is DC-biased. After DC-biasing, any remaining negative values are clipped to zero. The optimal DC-bias to apply is proportional to the standard deviation of the electrical signal.
- For ACO-OFDM, due to the antisymmetry, all data that exist on the negative values of the time domain signal also exist on the positive values of the signal. Therefore, clipping the redundant negative values to zero is possible with no noise on the data carrying odd subcarriers. By imposing Hermitian symmetry on the subcarrier mapping, the maximum bandwidth of an OFDM signal is constrained to half the bandwidth of RF-OFDM, as half the subcarriers are carrying redundant data, the conjugate of the first half. Therefore, half the bandwidth of RF-OFDM is the maximum spectral efficiency possible for Hermitian symmetry based optical OFDM. Because DCO-OFDM modulates all available subcarriers, we will use it as a baseline modulation when comparing the spectral efficiency with other methods.

- On another note, polar OFDM, an optical OFDM not based on Hermitian symmetry, has the same maximum spectral efficiency as DCO-OFDM. Therefore, currently to the authors' knowledge, the maximum spectral efficiency of an IM/DD OFDM system is that of DCO-OFDM. The rate of DCO-OFDM is given below

$$R_{DCO} = \frac{N/2 - 1}{(N + N_{CP})} B \log_2 M \text{ bit/s}$$

- where B is the bandwidth, M is the quadrature amplitude modulation (QAM) modulation order, NCP is the number of samples used for the CP, and N is the length of the IFFT. ACO-OFDM, on the other hand, only uses the odd subcarriers of the available subcarriers. This makes ACOOFDM less spectrally efficient than DCO-OFDM by about half. The rate of ACO-OFDM is given

$$R_{ACO} = \frac{N/4}{(N + N_{CP})} B \log_2 M \text{ bit/s}$$

- For a fixed power allocation, for ACO-OFDM to have the same rate as DCO-OFDM, it requires a higher-order constellation and hence will have a higher bit error rate (BER) for the same signal-to-noise ratio (SNR).
- Therefore, for a fixed number of bits per a subcarrier, DCO-OFDM has a better spectral efficiency than ACO-OFDM. However, the DC-bias in DCO-OFDM will also increase the energy consumption of the system.
- Although DCO-OFDM has a better spectral efficiency given a fixed number of bits per subcarrier, the energy drawbacks of DCO-OFDM make DCO-OFDM less attractive than ACO-OFDM. DCO-OFDM requires an additional DC-bias on top of the DC-bias required for powering the optical source that significantly increases the required SNR for a given BER.
- ACO-OFDM was created to combat the high energy requirements of DCO-OFDM. As an energy-efficient technique, ACO-OFDM does not require an additional DC-bias. Instead, ACO-OFDM takes advantage of the antisymmetry in the time-domain signal created by only modulating the odd subcarriers. This redundancy in the negative values make it possible to simply clip to zero the negative values. While, ACO-OFDM is more energy efficient than DCO-OFDM, it has less spectral efficiency than DCO-OFDM. Additionally, ACO-OFDM like other OFDM signals has a high PAPR. The DC-bias in DCO-OFDM increases the average power and so decreases the PAPR for DCO-OFDM.

3.32 RECEIVER STRUCTURES

- Equivalent circuit of receiver, along which various noise sources is shown in Fig. 3.32.1.

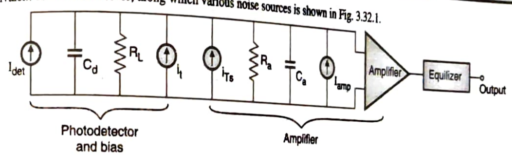


Fig. 3.32.1 : Receiver Structure

- Here optical detector is represented as a current source I_{det}.
- The receiver, basically consists of three main stages, namely photodetector, amplifier and an equalizer. Either a p-i-n photodiode or avalanche photodiode having gain M is used.
- The quantum efficiency of photodiode is η and its capacitance is C_d. The detector bias resistor generates a thermal noise current. The parallel combination of resistor 'R_a' and shunt capacitance 'C_a' represents input impedance of amplifier. The voltage appearing across this impedance, causes a current to flow in the amplifier output.
- All the noise sources are considered to be white noise. An equalizer is basically a linear frequency sharpening filter and it is used to compensate the effect of signal distortion and intersymbol interference. It basically transforms the output of amplifier in another form which is suitable for the following signal processing units.

3.33 BIT ERROR RATE OF OPTICAL RECEIVERS

- In case of fiber optic cable; due to the noise introduced at different stages, errors are produced. The rate at which errors occur is called as Bit Error Rate (BER).
- BER is defined at the ratio of number of errors to the total number of bits transmitted through the system. In case of optical cables; a bit rate of 1 error in 10^7 to 10^{10} is accepted. The minimum pulse energy, required to maintain a given BER, at the receiver is called as "Quantum limit".

- For data transmission over a longer distance, using optical cable; regenerative repeaters are used. In case of all repeaters (regenerators); attenuated and dispersed pulse train is received. The block schematic of regenerative repeater is shown in Fig. 3.33.1.
- The main function of regenerative circuit is to produce original pulse train at the output. But if too much dispersion is present then logic '1' can be considered as '0' and '0' can be considered as '1'. To minimize this type of error; a threshold level is considered. Above the threshold level, logic 1 is considered and below this level, logic 0 is considered.

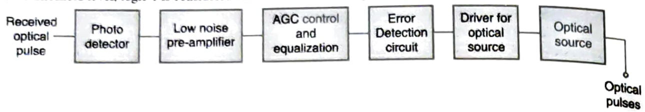


Fig. 3.33.1 : Block schematic of regenerative repeater

- Actually quantum noise in optical cable has poisson's distribution; but to maintain low BER (10^{-9}), the noise distribution is assumed to be Gaussian. Let P (0) represents the probability of transmitting zero and P (1) represents the probability of transmitting one. Due to error, when '0' is transmitted and '1' is received then this probability of false detection is P (1/0).
- Similarly, when '1' is transmitted and '0' is received then this probability of false detection is P (0/1). Since due to the presence of noise, errors occur at the received; we have to always consider Probability Density Function (PDF).
- The Gaussian PDF is defined as,

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(-x-m)^2/2\sigma^2}.$$

- This probability density function is shown in Fig. 3.33.2.

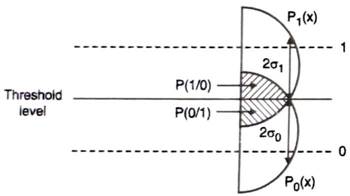


Fig. 3.33.2 : Probability density function

- Here 'm' is the mean value and 'σ' is the standard deviation of the distribution.
- P (x) describes the probability of detecting a noise current or voltage and σ represents rms value of this current or voltage.
- The shaded region of Fig. 3.33.2 represents the probability of false detection.
- If the probability of transmitting '1' and '0' is P (1) and P (0) respectively then the total probability of error is,

$$P(e) = P(1) \cdot P(0/1) + P(0) \cdot P(1/0)$$

- In terms of signal to noise ratio; the probability of error is,

$$P(e) = \frac{1}{2}\text{erfc}\left[\frac{\sqrt{S/N}}{2\sqrt{2}}\right]$$

3.34 RECEIVER PERFORMANCE

- The performance of digital receiver can be evaluated by measuring the probability of error and quantum limit.
- Let the number of errors be N_e and the total number of pulses in time 't' are N_t then according to the definition,

$$BER = \frac{N_e}{N_t} \qquad \therefore \quad BER = \frac{N_e}{B_t}$$

Where B_t is the bit rate or pulse transmission rate.

- BER depends on signal to noise ratio at the receiver and for optimal receiver performance it should be in the range 10^{-9} to 10^{-12}.
- The minimum amount of optical power required to obtain a specific receiver performance is called as sensitivity of the receiver. If the receiver has high sensitivity then such receiver can detect the smallest signals.
- The sensitivity of PIN photodiode and APD as a function of data (bit) rate is shown in Fig. 3.34.1.

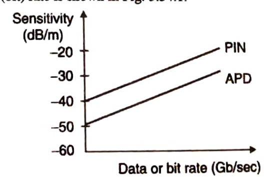


Fig. 3.34.1 : sensitivity of PIN photodiode and APD

- The quantum limit is the minimum optical pulse energy required to maintain a given BER that a practical receiver must satisfy. Using this concept it is possible to find the minimum received optical power required for a specific bit error rate performance.

3.35 Q FACTOR AND EYE DIAGRAM

- A *Q*-factor measurement occupies an intermediate position between the classical optical parameters (power, OSNR, and wavelength) and the digital end-to-end performance parameters based on BER(Bit Error Rate).
- A *Q*-factor is measured in the time domain by analyzing the statistics of the pulse shape of the optical signal.
- A *Q*-factor is a comprehensive measure for the signal quality of an optical channel taking into account the effects of noise, filtering, and linear/non-linear distortions on the pulse shape, which is not possible with simple optical parameters alone.

Definition 1

The Q-factor, a function of the OSNR, provides a qualitative description of the receiver performance. The Q-factor suggests the minimum signal-to-noise ratio (SNR) required to obtain a specific BER for a given signal. OSNR is measured in decibels. The higher the bit rate, the higher the OSNR ratio required. For OC-192 transmissions, the OSNR should be at least 27 to 31 dB compared to 18 to 21 dB for OC-48.

Definition 2

The Quality factor is a measure of how noisy a pulse is for diagnostic purposes. The eye pattern oscilloscope will typically generate a report that shows what the Q factor number is. The Q factor is defined as shown in the figure: the difference of the mean values of the two signal levels (level for a "1" bit and level for a "0" bit) divided by the sum of the noise standard deviations at the two signal levels. A larger number in the result means that the pulse is relatively free from noise.

Definition 3

Q is defined as follows: The ratio between the sums of the distance from the decision point within the eye (D) to each edge of the eye, and the sum of the RMS noise on each edge of the eye.

$$Q = \frac{|\mu_0 - D| + |\mu_0 - D|}{\sigma_1 + \sigma_0}$$

This definition can be derived from the following definition,

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)}$$

where $m_{1,0}$ are the mean positions of each rail of the eye, and $s_{1,0}$ are the S.D., or RMS noise, present on each of these rails.

For an illustration of where these values lie within the eye see the following Fig. 3.35.1.

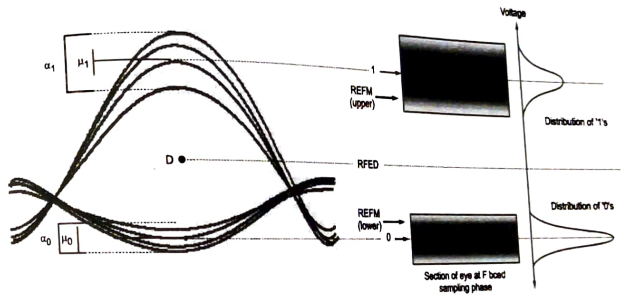


Fig. 3.35.1 : Eye Diagram

As Q is a ratio it is reported as a unit-less positive value greater than 1 (Q>!). A Q of 1 represents complete closure of the received optical eye. To give some idea of the associated raw BER a Q of 6 corresponds to a raw BER of 10-9.

Calculation of Q-Factor from OSNR

- The OSNR is the most important parameter that is associated with a given optical signal. It is a measurable (practical) quantity for a given network, and it can be calculated from the given system parameters.
- The following sections show you how to calculate OSNR. This section discusses the relationship of OSNR to the Q-factor.
- The logarithmic value of Q (in dB) is related to the OSNR by following Equation

$$Q_{dB} = 20 \log \sqrt{QSNR} \sqrt{\frac{B_0}{B_c}}$$

- In the equation, B_0 is the optical bandwidth of the end device (photodetector) and B_c is the electrical bandwidth of the receiver filter.
- Therefore, Q(dB) is shown in

$$Q_{dB} = OSNR + 10 \log \frac{B_0}{B_c}$$

- In other words, Q is somewhat proportional to the OSNR. Generally, noise calculations are performed by optical spectrum analyzers (OSAs) or sampling oscilloscopes, and these measurements are carried over a particular measuring range of B_m.
- Typically, B_m is approximately 0.1 nm or 12.5 GHz for a given OSA. From Equation showing Q in dB in terms of OSNR, it can be understood that if $B_0 < B_c$, then OSNR (dB)> Q (dB). For practical designs OSNR(dB) > Q(dB), by at least 1–2 dB.
- Typically, while designing a high-bit rate system, the margin at the receiver is approximately 2 dB, such that Q is about 2 dB smaller than OSNR (dB).
- The Q-Factor, is in fact a metric to identify the attenuation in the receiving signal and determine a potential LOS and it is an estimate of the Optical-Signal-to-Noise-Ratio (OSNR) at the optical receiver.
- As attenuation in the receiving signal increases, the dBQ value drops and vice-versa. Hence a drop in the dBQ value can mean that there is an increase in the Pre FEC BER, and a possible LOS could occur if the problem is not corrected in time.

3.36 POINT TO POINT LINK

MU - Dec. 2013

- Point-to-point links constitute the simplest kind of lightwave systems. Their role is to transport information, available in the form of a digital bit stream, from one place to another as accurately as possible.
- The link length can vary from less than a kilometer (short haul) to thousands of kilometers (long haul), depending on the specific application. For example, optical data links are used to connect computers and terminals within the same building or between two buildings with a relatively short transmission distance (<10 km).
- The simple fiber optic cable connecting the source and detector is as shown in Fig. 3.36.1. This is called as point to point link. Now the system requirements for this link are as follows :

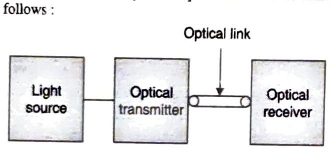


Fig. 3.36.1 : Point to point link

(i) The transmission distance required for the data to transfer from source to detector.
(ii) The bandwidth of channel.
(iii) The Bit Error Rate (BER).

Note : If we are sending 10^{-9} bits and if the error occurs in 1 bit then the bit error rate is 1 part in 10^{-9} bits.

The major requirements to transfer the data from source to detector is to select the following components :

(i) Light source.
(ii) Fiber optic cable.
(iii) Detector.

Now the selection of light source depends on the following factors :

(i) Wavelength of light emitted from source.
(ii) Number of operating modes.
(iii) Output power.
(iv) Area covered by output pulses coming from light source.

- Generally the Light Emitting Diodes (LED) or Laser Diode (LD) is used as light source.
- The cost of LED is less as compared to laser diode. But laser diodes gives the narrow output pulse as compared to LED.
- Ideally from the laser diode a single output pulse is obtained. This is coherent in nature.
- Thus it provides following advantages over LED :
  (i) High launching power.
  (ii) Large modulation bandwidths.
  (iii) Narrow spectral output.
  (iv) Higher bit rate.
  (v) Higher repeater spacing.
- Thus according to the type of application either LED or laser diode is selected as light source.
- The values of spectral width for LED is from 20 to 100 nm and for the laser diode it is 1 to 3 nm.
- The laser diode couplers 10 to 15 dB more optical power into the fiber optic cable as compared to LED light source. To transfer the data from source to detector either single mode or multimode optical fibers are used.
- The selection of particular optical fiber depends on following factors :
  (i) Refractive index profile.
  (ii) Losses in fiber that mean attenuation and dispersion.
  (iii) Acceptance angle.
  (iv) Numerical departure.
  (v) The size of core.
- Again if the silica glass fiber optic cable is used then it gives more accuracy as compared to plastic fiber optic cable.
- Now the selection of a particular detector depends on the following factors :
  (i) Responsitivity of detector. (ii) Quantum efficiency.
  (iii) Noise signals. (iv) Noise equivalent power.
  (v) Speed of detector.
- Generally PIN and APD detectors are used for the detection of optical signals. The advantages of PIN photodiode over the avalanche photodiode are as follows :
  (i) The cost is less.
  (ii) It is less sensitive to temperature
  (iii) Less reverse bias voltage is required.

- APD is mainly used in long distance links for high bit rate application. For the detection of low optical powers APD gives more sensitivity. Besides these components the splices and connectors are used in the system depending on the requirements.
- Connector is a demountable device. It is used to connect and disconnect the fibers. While the splices are used to connected the two optical fibers permanently.

3.37 SYSTEM CONSIDERATION

- An important parameter used in optical fiber system consideration is the bandwidth distance product or Band Width Distance Factor (BWDF).
- The BWDF is expressed in terms of MHz · km. Since the effect of dispersion always increases with the length of optical cable; manufacturers always specify BWDF in terms of MHz · km.
- While designing the communication system, using optical cable, the following points must be considered.
  (i) Select a proper combination of optical transmitter and receiver for a required data to be transmitted through the cable.
  (ii) Decide the operating power, required for transmission of data.
  (iii) Determine the proper specifications of system like impedance, bandwidth, fiber diameter, connectors etc.
  (iv) By considering all losses like fiber loss, loss due to splices, loss due to connectors etc; calculate the total optical loss of the system.
  (v) Prepare a power budget, keep a safety margin of 6 to 8 dB.
- Depending upon a distance to be transmitted; a type of low loss cable is selected. Similarly the choice of light source also depends on the distance.
- A selection of proper photodetector depends on the fiber type and transmitted power. A choice of particular modulation scheme is also dependent of the distance.
- To decide the performance of optical cable system; two types of analysis are used :
  (i) Link power budget (ii) Rise time budget
- Link power budget is basically related to the losses taking place throughout the optical system. To verify the system performance requirements like maximum bit rate, maximum transmission distance etc.; the rise time budget is used. Before selecting the components like source, detector etc; the operating wavelength is decided.
- The choice of operating wavelength depends on the distance and attenuation.
- For low attenuation and dispersion, the following wavelengths are preferred :
  (i) For short distance : 800 to 900 nm
  (ii) For longer distance : 1300 to 1550 nm.
- The selection of a particular fiber type, depends on following factors :
  (i) Numerical aperture (ii) Amount of attenuation
  (iii) Losses in connectors and splices.
  (iv) Environmental effects like temperature variations, radiation effects etc.
- There is a direct dependency of transmission distances and the data rates.
- Greater transmission distances are possible by using a combination of laser diode as a source and APD as detector. Higher data rate can be achieved if the transmission distance is small.
- If the data rate is kept low then it is possible to obtain the transmission for larger distances. By keeping the transmission distance minimum; it is possible to reduce the material dispersion and modal dispersion.

3.38 LINK POWER BUDGET

UQ. Write a short note on link power budget. **(MU – Q. 5(b), Dec. 15, 10 Marks)**

UQ. Write short note on : Link budget. **(MU – Q. 6(i), Dec. 16, 5 Marks)**

UQ. Derive an expression for Link Power Budget Analysis of optical fiber. **(MU – Q. 4(a), May 17, Dec. 17, 7 Marks)**

- The optical power budget in a fiber-optic communication link is the allocation of available optical power (launched into a given fiber by a given source) among various loss-producing mechanisms such as launch coupling loss, fiber attenuation, splice losses and connector losses, to ensure that adequate signal strength (optical power) is available at the receiver.
- When optical fiber link is used for communication purpose then the total loss in the system is the addition of losses taking place because of all components.
- The loss produced by every elements in the system is expressed in dB.
- It is given as,

$$\text{Loss (in dB)} = 10 \log \frac{P_{out}}{P_{in}}$$

Here, P_{out} = Output power from the element

P_{in} = Input power to the element

Optical power loss model is as shown in Fig. 3.38.1. In this particular model the connectors are used at the transmitter and receiver section.

- The splices are connected as shown in Fig. 3.38.1.

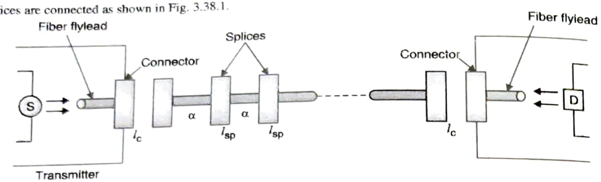


Fig. 3.38.1 : Optical power loss model

Here S = Light source
D = Detector
l_c = Losses taking place at connector
l_{sp} = Losses taking place at splices
α = Attenuation loss taking place in optical fiber.

- For the simplicity, other losses in optical fiber cable are neglected. Only the losses taking place because of attenuation are considered. Here to find out the total loss, the loss contributed by each element in the system is considered.
- Besides this the system margin is added. This is because, in future due to aging of components or due to temperature variations more losses may be added in the system. Similarly the portion of optical fiber connected to source and detector may adds some losses. This portion of optical fiber is called as fiber flylead.
- The loss contributed by fiber flylead is considered as 1 dB. The system margin is generally considered to be equals to 6-8 dB.
- Thus the total power loss in a point to point link is given as,

$$P_T = P_S - P_R \quad \text{...(3.38.1)}$$

Here P_S = Optical power coming from the end of flylead attached to light source
P_R = Sensitivity of receiver.

- Thus Equation (3.38.1) can also be written as,

$$P_T = (2\, l_c + \alpha\, L + \text{System margin}) \quad \text{...(3.38.2)}$$

Here, l_c = Losses taking place at the connector.
L = Length of optical fiber.
α = Attenuation taking place in optical fiber.

3.38.1 Procedure to Calculate Link Power Budget

- For the calculation of link power budget; a loss table is prepared.
- The following steps are used for the calculation of link power budget.

1. Calculate the amount of available light for the transmission. It is also called as allowed loss and it is obtained using the equation,

   Allowed loss = Source output – Receive sensitivity
2. Consider all loss factors in the system; like cable attenuation, connector losses, splice losses etc.
3. Subtract all these losses from the available loss.
4. The cable attenuation is usually specified by the manufacturer. This value is in the range 0.22 dB to 0.5 dB per kilometer. To calculate, total cable attenuation; multiply this value by the length of optical cable.
5. For longer distance transmission, splices are used. Ideally each splice produces a loss of 0.1 dB. Multiply this value by the number of splices used in system. It gives total splice loss.
6. Similarly for connectors; multiply the value of loss per connector by number of connectors. This gives total connector loss.
7. Consider a safety margin of 3 dB to 6 dB for overall system.
8. Subtract all these losses from the available power (allowed loss). If this value is positive then it indicates that a sufficient power margin is available.

3.38.2 Solved Problems on Link Power Budget

Ex. 3.38.1 : Components chosen for a digital optical fiber link of overall length 10 km and operating at a 20 Mbit/s using an RZ code are given below :

(i) LED capable of launching an average power of 0.1 mW at 0.85 μm [including connector loss into a 50 μm core diameter graded index fiber]
(ii) Fiber attenuation 2.5 dB/km and
(iii) Requires splicing every 2 km with a loss of 0.3 dB per splice. There is also a connector loss at the receiver of 1.5 dB.
(iv) The receiver requires mean incident optical power of – 46 dBm in order to give the necessary BER of 10– 10
(v) Predicted safety margin of 6 dB. Write down the optical power budget for the system and hence determine its viability.

Soln. : Given :

1. Fiber length 10 km 2. 20 Mbit using RZ code
   $\lambda = 0.85\ \mu m$
3. Fiber attenuation 2.5 dB/km [∴ total = 2.5 × 10 = 25 dB]
4. 4 splices (As length is 10 km and splice at every 2 km)
5. ∴ 4 × 0.3 = 1.2 dB
   Connector loss at receiver = 1.5 dB
6. Receiver – 46 dBm BER of 10^{-10}
7. Safety margin = 6 dB
8. The required receiver input signal is – 46 dBm.

[It must be noted that dBm is a unit that expresses the power level P as a logarithmic ratio of P referred to 1 mW i.e. power level in dBm = $10 \log_{10} \frac{P \text{ in mW}}{1 \text{ mW}}$ thus 0 dBm = 1 mW]

Thus positive values of dBm are greater than 1 mw and negative values of dBm are less than 1 W

Losses are measured in dBs whereas the absolute power in fiber communication is measured in dBm.

The required receiver input signal – 46 dBm and the LED can couple 0.1 mW or 100 μW that means $P_S = 10 \log \frac{0.1}{1} = -10$

We thus have

$$P_T = P_S - P_R = -10-(-46) = 36 \text{ dB}$$

Where P_S = Optical power engineering from LED
P_R = Receiver input signal

$$\text{Now Total loss} = \underbrace{25 \text{ dB}}_{\text{cable}} + \underbrace{1.2 + 1.5}_{\text{splices and connector}} + \underbrace{6 \text{ dB}}_{\text{margin}} = 33.7 \text{ dB}$$

The allowable loss is 36 dB and actual loss in 33.7 dB hence this budget is viable with 10 km link. Let us tabulate it now.

Table P. 3.38.1

Component parameter	Output / sensitivity / loss	Power margined dBs
LED output	– 10 dB	
Receiver sensitivity	– 46 dBm	
Allowed loss – 10 – (– 46)		36 dB
Fiber attenuation	25 dB	36 – 25 = 11 dB
Splices loss	1.2 dB	11 – 1.2 = 9.8 dB
Connector loss at receiver	1.5 dB	9.8 – 1.5 = 8.3 dB
Safety margin	6 dB	8.3 – 6 = 2.3 dB (Extra final margin)

Ex. 3.38.2 : A 1550 nm single mode digital fiber optic link needs to operate at 622 Mb/s over 80 km without amplifiers. A single mode In GaAsP laser launches an average optical power of 13 dBm into the fiber. The fiber has a loss of 0.35 dB/km. And there is a splice with a loss of 0.1 dB every kilometer. The coupling loss at the receiver is 0.5 dB and the receiver uses an InGaAs APD with a sensitivity of –39 dBm. Excess noise penalties are predicated to be 1.5 dB. Set up an optical power budget for this link and find the system margin. What is the system margin at 2.5 Gb/s with an APD sensitivity of –31dBm?

Soln. : The link loss budget considers the total optical power loss P_T that is allowed between the light source and the photo detector. It allocates this loss to cable attenuation, connector loss, splice loss and the system margin.

It P_S is the optical power and P_R is the receiver sensitivity then

$$P_T = P_S - P_R = 2\, l_c + \alpha L + \text{System margin where } l_c \text{ is connector loss}$$

α = Fiber attenuation in dB/km
L = Transmission distance

System margin is generally taken as 6 dB.

A convenient procedure for calculating the power budget is to use a spreadsheet or the losses in a tabular form.

Table P. 3.38.2

Component / loss parameter	Output / sensitivity / loss	Power margin dB
InGaAs laser output	13 dBm	
APD sensitivity at 2.5 Gbps	– 31 dBm	
Allowed loss [13 – (– 31)] = 44 dB		44 dB
Splice loss [79 km × 0.1 dB] for 79 splices	7.9 dB	44 – 7.9 = 36.1 dB
Fiber loss [80 km × 0.35]	28 dB	36.1 – 28 = 8.1 dB
Coupling loss at receiver	0.5 dB	8.1 – 0.5 = 7.6 dB
noise	1.5 dB	7.6 – 1.5 = 6.1 dB Final margin

The Table P. 3.38.2 gives the components in column 1, associated optical output, sensitivity, losses in column 2. Column 3 gives the power margin available after subtracting the losses. The final power margin is 6.1 dB.

Ex. 3.38.3 : Components are chosen for a digital optical fiber link of overall length 7 km and operating at a 20 Mbit/s using an RZ code. It is decided that an LED emitting at 0.85 μm with graded index fiber to a p-i-n photodiode is a suitable choice for the system components, giving no dispersion -equalization penalty. An LED which is capable of launching an average of 100μW of optical power [including connector loss into a 50μm core diameter graded index fiber is chosen]. The proposed fiber cable has an attenuation of 2.6 dB/km and requires splicing every km with a loss of 0.5 dB per splice. There is also a connector loss at the receiver of 1.5 dB. The receiver requires mean incident optical power of – 41 dBm in order to give the necessary BER of 10^{-10}, and it is predicted that a safety margin of 6 dB will be required. Write down the optical power budget for the system and hence determine its viability.

☑ **Soln. :** **Given :**

1. Fiber length 7 km
2. 20 M bits/s using RZ code
3. $\lambda = 0.85\ \mu m$
4. Fiber attenuation 2.6 dB / km [$\therefore$ total = 18.2 dB]
5. 6 splices with 0.5 dB each [$\therefore$ total = 3 dB loss]
6. Connector loss at receiver = 1.5 dB
7. Receiver – 41 dBm BER of 10^{-10}
8. Safety margin = 6 dB

The link loss budget considers the total optical power loss P_T that is allowed between the source and receiver and allocated this loss to cable attenuation, splice and connector loss and system margin.

The required receiver input signal is – 41 dBm (42 dB below 1 mW). The LED can coupled 100 μW (– 10 dB). We thus have 31 (41 – 10) dB allowable power loss.

Let us calculate all the losses

We have $P_T = P_S - P_R = 31$ dBs

where P_S = Optical power engineering form LED

P_R = Receiver input signal

$$\text{Now, Total loss} = \underbrace{2.6\text{ dB / km} \times 7}_{\text{cable}} + \underbrace{3}_{\text{connector}} + \underbrace{1.5}_{\text{margin}} + \underbrace{6}_{\text{and splices loss}}$$

$$= 18.2 + 3 + 1.5 + 6 = 28.7 \text{ dB}$$

Thus safety margin = 31 – 28.7=2.3 dB

Thus this budget is viable with 7 km link. Let us tabulate it now

Component parameter	Output / sensitivity / loss	Power margined dB
LED output	– 10 dBm	
Receiver sensitivity	– 41 dBm	
Allowed loss (– 10 – (41)) = 31 dB		31 dB
Fiber attenuation	18.2 dB	12.8 dB
Splices loss	3 dB	9.8 dB
Connector loss at receiver	1.5 dB	8.3 dB
Safety margin	6 dB	2.3 dB (extra final margin)

UEx 3.38.4 : (MU - Q. 4(b), Dec. 2019, 10 Marks)

An analog optical fiber system employs and LED which emits 3 dB mean optical power into air. However, a coupling loss of 17.5 is encountered when launching into a fiber cable. The fiber cable which extends for 6 km without repeaters exhibits a loss of 5 db km^{-1}. It is spliced every 1.5 km with an average loss of 1.1 dB per splice. In addition there is a connector loss at the receiver of 0.8 dB. The PIN-FET receiver has a sensitivity of –54 dBm at the operating bandwidth of the system. Assuming there is no dispersion-equalization penalty, perform an optical power budget for the system and establish a safety margin.

☑ **Soln. : Given :**

1. 3 dBm optical power
2. coupling loss = 17.5 dB
3. fiber loss = 6 km × 5 dB / km = 30 dB
4. 3 splicing joints (1.5 km distance) × 1.1 dB = 3.3 dB loss
5. connector loss = 0.8 dB
6. receiver sensitivity = – 54 dBm

Speared sheet for calculating optical link power budget :

Component / loss parameter	Output / sensitivity / loss	Power margin (dB)
LED output	3 dBm	
PIN FET sensitivity	– 54 dBm	
Allowed loss (3 – (– 54))		57 dB
Coupling loss	17.5 dB	57 – 17.5 = 39.5 dB
Fiber loss	30 dB	39.5 – 30 = 9.5 dB
Splicing loss	3.3 dB	9.5 – 3.3 = 6.2 dB
Connector loss	0.8 dB	6.2 – 0.8 = 5.4 dB (final safety margin)

Ex. 3.38.5 : An analog optical fiber link of length 2 km employs an LED which launches mean optical power of –10 dBm into a multimode optical fiber. The fiber cable exhibits a loss of 3.5 $dBkm^{-1}$ with splice losses 1.4 dB. In addition there is a connector loss at the receiver of 1.6 dB. The pin photodiode receiver has a sensitivity of –25 dBm for an SNR of 50 dB and with a modulation index of 0.5. It is estimated that a safety margin of 4 dB is required. Assuming here is no dispersion equalization penalty.

(i) Perform an optical power budget for the system operating under the above conditions and ascertain its viability

(ii) Estimate any possible increase in link length which may be achieved using an injection laser source which launches mean optical power of 0 dBM into the fiber cable. In this case the safety margin must be increased to 7 dB.

☑ ***Soln. : Given :***

(i) Fiber length = 2 km

(ii) Optical power source = – 10 dBm

(iii) Fiber loss = 3.5 dB/km × 2 km = 7 dB

(iv) Connector loss = 1.6 dB, splices loss = 1.4 dB

(v) Pin receiver sensitivity = – 25 dBm for SNR of 50 dB with modulation index 0.5

(vi) Safety margin = 4 dB

We have $P_T = P_S - P_R$

source receiver

$\therefore$ [– 10 dBm – (– 25 dBm)]=15 dB available

Total loss = 7 + 1.6 + 4 + 1.4 = 12.6 + 1.4

= 14 dB and 15 dB is available

Thus this budget is viable.

Let us tabulate the power link budget

Component /Loss parameter	Output/Sensitivity/loss	Power margin
LED output	– 10 dBm	
Pin receiver sensitivity	– 25 dBm	
Allowed loss	[– 10 dBm – (– 25 dBm)]	15 dB
Fiber loss	7 dB	15 – 7 = 8 dB
Splice loss	1.4 dB	8 – 1.4 = 6.6 dB
Connector loss	1.6 dB	6.6 – 1.6 = 5 dB
Safety margin	4 dB	5 – 4 = 1 dB extra margin available

If laser source launches optical power of 0 dBm then available allowed loss would be

$$0 - (-25) = 25 \text{ dBs}$$

$$25 = 3.5 \times (\text{length}) + \underbrace{3 \text{ dB}}_{\text{Connector Margin}} + \underbrace{7 \text{ dB}}_{\text{splice}}$$

$$25 - 10 = 3.5 \times \text{Fiber length}$$

$$\therefore \frac{15}{3.5} = \text{length of fiber} = 4.28 \text{ km}$$

The existing length is 2 km. The possible increase in link length is 2.28 km.

Ex. 3.38.6 : An edge-emitting LED operating at the wavelength of 1.3 μm launches22dBm of optical power into *a* single-mode fiber pigtail. The pigtail is connected to a single-mode fiber link which exhibits an attenuation of 0.4 $dBkm^{-1}$ at this wavelength. In addition, the splice losses on the link provide an average loss of 0.05 $dBkm^{-1}$. The transmission rate of the system is 280$Mbits^{-1}$ so that the sensitivity of the p-i-n photodiode receiver is –35 dBm. Penalties on the link require an allowance of 1.5 dB and a safety margin of 6dB is also specified. If the connector losses at the LED transmitter and p-i-n photodiode receiver are each 1 dB, calculate the unrepeated distance over which the link will operate.

☑ **Soln. :**

Given :

1. Optical power source = 22 dBm
2. Fiber attenuation = 0.4 dB/km
3. Slice losses = 0.05 dB/km
4. Penalties = 1.5 dB
5. Safety margin = 6 dB
6. Connector losses = 2 dB (one at receiver, one at source)
7. PIN receiver sensitivity = – 35 dBm

Total allowed loss = 22 – (– 35) = 57 dB

Total loss = $0.4 \times L + 0.05 \times L + 1.5 + 6 + 2$

= $(0.45)\, L + 1.5 + 6 + 2$

$\therefore$ $57 - 1.5 - 6 - 2 = 0.45 \times L$

$\frac{47.5}{0.45} = L$

$\therefore L = 105.55$ km

Ex. 3.38.7 : An engineer has the following components available :

(i) GaAlAS laser diode operating at 850 nm and capable of coupling 1 mW into a fiber.

(ii) 10 sections of cable each of which is 500 m long, has a 4 dB/km attenuation, and has connectors on both ends.

(iii) Connector loss of 2 dB/connector.

(iv) A pin photodiode receiver (– 45 dBm sensitivity)

(v) An avalanche photodiode receiver (– 56 dBm sensitivity)

Using these components, the engineer wishes to construct a 5 km link operating at 20 Mb/s. Perform optical budget and state which receiver should be used it a 6 dB system operating margin is required ?

☑ **Soln. :** λ = 850 nm ; 1mW power

Mean optical power launched into the fiber from the transmitter	= 1 mW =	0 dBm
APD receiver sensitivity at 20 Mb/s	=	– 56 dBm
$\therefore$ Total system margin	=	56 dB
1. Cabled fiber loss (5 km × 4dB/km)	20 dB	
2. Connector loss (2 × 2 dB) (at ends)	4 dB	
3. 10 sections (9 × 2 dB) (Connectors)	18 dB	
4. Safety margin	6 dB	
	48 dB	

$\therefore$ 56 dB – 48 dB = 8 dB extra power margin if APD receiver is used.

Now let us see what happens if PIN photo diode with – 45 dBm sensitivity is used.

From the transmitter 1 mW	0 dBm
PIN receiver sensitivity	– 45 dBm
	45 dB
$\therefore$ Total system margin	20 dB

1. Cabled fiber loss (5 km × 4dB/km)

2.	End connectors loss (2 × 2 dB)	4 dB
3.	Section connectors loss (9 connectors for 10 sections)	18 dB
4.	Safety margin	6 dB
		48 dB

This shows safety margin falls short and only 3 dB safely margin can be kept. Therefore the engineer must use APD receiver with – 56 dBm sensitivity.

3.39 RISE TIME BUDGET

(MU - May 2012, Dec. 2016)

- The purpose of the rise-time budget is to ensure that the system is able to operate properly at the intended bit rate. Even if the bandwidth of the individual system components exceeds the bit rate, it is still possible that the total system may not be able to operate at that bit rate.
- The concept of rise time is used to allocate the bandwidth among various components. The rise time T_r of a linear system is defined as the time during which the response increases from 10 to 90% of its final output value when the input is changed abruptly. Fig. 3.39.2 shown the concept graphically.

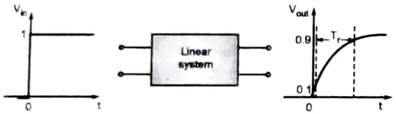


Fig. 3.39.1 : Rise Time Tr associated bandwidth-Limited System

- The rise time budget is used to determine the dispersion limitation of an optical link. The total rise time of a link is denoted by t_{sys} and it is given by,

$$t_{sys} = \sqrt{\sum_{i=1}^{N} t_i^2} \quad \ldots(3.39.1)$$

Here 't_i' is the rise time contributed by each element of a link.

- There are four basic elements which limit the speed of a system. These elements are in follows :

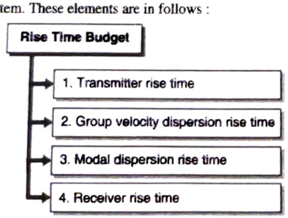


Fig. 3.39.1 : Rise time budget

1. Transmitter rise time (t_{tx})

This type of rise time is contributed by the light source and its driving circuitry. This value is generally known to the designer.

2. Group velocity dispersion rise time (t_{mat})

- The total optical link is formed from several sub-sections of optical fiber. Each fiber produces its own dispersion. So it becomes difficult to calculate the group delay dispersion rise time of entire fiber cable.
- For length 'L' of optical cable; this rise time is approximately given by,

$$t_{mat} = DL\sigma_\lambda \quad \ldots(3.39.2)$$

Here D = Dispersion of optical link

L = Length of optical link

σ_λ = Half power spectral width of light source.

3. Modal dispersion rise time (t_{mod})

- The modal dispersion rise time is given by,

$$t_{mod} = \frac{440}{B_M} \quad \ldots(3.39.3)$$

- Here B_M is the bandwidth of optical link of length L. Using empirical relation, it can be expressed as,

$$B_M = \frac{B_0}{L^q} \quad \ldots(3.39.4)$$

Here B_0 = Bandwidth of 1 km length of cable.

q = parameter ranging between 0.5 and 1.

- If q = 0.5 then it indicates that Q steady state modal equilibrium has been reached. And if q = 1 then it indicates a little mode mixing.
- Putting Equation (3. 39.4) in Equation (3.39.3) we get,

$$t_{mod} = \frac{440L^q}{B_0} \quad \ldots(3.39.5)$$

- If t_{mod} is expressed in nanoseconds and bandwidth is given in MHz then Equation (3.39.5) can be written as,

$$t_{mod} = \frac{440L^q}{B_0} \quad \ldots(3.39.6)$$

4. Receiver rise time (t_{rx})

- It results from the photodetector response and 3-dB electrical bandwidth of receiver front end.
- If 3-dB electrical bandwidth (B_{rx}) of receiver is expressed is MHz then t_{rx} is given by,

$$t_{rx} = \frac{350}{B_{rx}} \quad \ldots(3.39.7)$$

Now, according to Equation (3.39.1), the total rise time of system is,

$$t_{sys} = \sqrt{t_{tx}^2 + t_{mod}^2 + t_{mat}^2 + t_{rx}^2}$$

$$\therefore t_{sys} = \left[t_{tx}^2 + \left(\frac{440\,L^q}{B_0}\right)^2 + D^2\sigma_\lambda^2 L^2\left(\frac{350}{B_{rx}}\right)^2\right]^{1/2}$$

- In case of RZ (Return to Zero) format, the bandwidth and total system rise time are related by

$$\text{Bandwidth} = B_{Tmax} = \frac{0.35}{T_{sys.}}$$

- In case of NRZ (Non Return to Zero) format; bandwidth and total system rise time are related by,

$$B_{Tmax} = \frac{0.70}{T_{sys.}}$$

3.39.1 Solved Problems on Rise Time Budget

Ex. 3.39.1 : An optical fiber system is to be designed to operate an 8 km length without repeaters.

The rise times of the chosen components are

Source (LED) : 8 ns

Fiber cable : Intermodal : 5 ns/km

Intramodal : 1 ns/km

Detector (p-i-n) : 6 ns

Estimate maximum bit rate that may be achieved on the linked when using NRZ and RZ format.

Soln. :

Given : 8 km length without repeaters

Rise times = 8 ns = LED = 5 ns / km fiber cable (intra)

= 1 ns / km (inter)

PIN detector 6 ns

$$t_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2\right)^{1/2}$$

$$= [(8\text{ ns})^2 + [5\text{ ns / km} \times 8]^2 + [1\text{ ns / km} \times 8]^2 + [6\text{ ns}]^2]^{1/2}$$

$$= [(8\text{ ns})^2 + (40\text{ ns})^2 + (8\text{ ns})^2 + (6\text{ ns})^2]^{1/2}$$

$$\therefore t_{sys} = 42\text{ ns}$$

$$\text{Now } t_{sys} = \frac{0.70}{\text{Bit rate of NRZ}}$$

$$\therefore \text{Bit rate of NRZ} = \frac{0.70}{42\text{ ns}} = 0.0166 \times 10^9 = 16.6\text{ Mbit / s}$$

$$\text{Bit rate of RZ} = \frac{0.35}{42\text{ ns}} = 0.33 \times 10^{-3} \times 10^9 = 0.83 \times 10^7$$

$$= 8.3 \times 10^6\text{ b/s}$$

Thus, Maximum bit rate for NRZ = 16.6 Mbit / s

Maximum bit rate for RZ = 8.3 Mbit / s

Ex. 3.39.2 : The 10 to 90% rise times for possible components to be used in D-IM analog optical fiber link are specified as.

LED source : 10 nsec.

Fiber cable : Intermodal : 9 ns/km.

: Intramodal : 2 ns/km

APD Detector : 3 nsec.

The desired link length without repeaters is 5 km and the required BW is 6 MHz. Determine the above combination of components give an adequate response.

Soln. : **Given :** LED rise time : 10 ns

Fiber cable : 9 ns / km (intermodal) , 2 ns / km (intramodal)

APD detector = 3 ns, Link length = 5 km, B.W. = 6 MHz

$$t_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2\right)^{1/2}$$

$$t_{sys} = [(10\text{ ns})^2 + [9\text{ ns/km} \times 5\text{ km}]^2 + [2\text{ ns/km} \times 5]^2 + [3\text{ ns}]^2]^{1/2}$$

$$= [100 + (45\text{ ns})^2 + (10\text{ ns})^2 + (3\text{ ns})^2]^{1/2}$$

$$= [100 + 2025 + 100 + 9]^{1/2}$$

$$= [2234]^{1/2} = 47.26\text{ ns}$$

The total transition time degradation of a digital link should not exceed 70 % of an NRZ bit period or 35% of RZ bit period.

$$B_{T(max)} = \frac{0.70}{T_{sys}} = \frac{0.70}{47.26\text{ ns}} = 14.81\text{ Mbits/sec}$$

The rise time calculations indicate that this will support a maximum bit rate of 14.81 Mbits/s which for an NZR format is equivalent to a 3 dB optical bandwidth of 7.4 MHz (i.e. that NRZ format has two bit intervals per wavelength)

The desired required bandwidth is 6 MHz which will be supported.

Ex. 3.39.3 : A lab setup of optical fiber demo-system is to be tested over an 8 km length. The rise times of the chosen components are :

LED : 10 ns

p-i-n photodiode : 6 ns

Intermodal pulse broadening : 10 ns/km

Intermodal pulse broadening : 5 ns/km

From system rise time considerations, estimate the maximum bit rate achievable on the link when using an NRZ format.

Soln. :

Given : LED rise time : 10 ns, Detector : 6 ns

Intermodal : 10 ns/km

$$= 10\text{ ns} \times 8\text{ km} = 80\text{ ns}$$

$$\text{Intermodal} = 5\text{ ns/km} = 5 \times 8\text{ km} = 40\text{ ns}$$

$$t_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{yx}^2\right)^{1/2}$$

$$= [(10\text{ns})^2 + (80\text{ns})^2 + (40\text{ns})^2 + (6\text{ns})^2]^{1/2}$$

$$= 90.1997\text{ ns}$$

The total transition time degradation of digital link should not exceed 70% of NRZ bit period.

$$\therefore B_{Tmax} = \frac{0.70}{T_{sys}} = \frac{0.70}{90.1997 \times 10^{-9}}$$

$$= 7.76\text{ Mbits/sec}$$

Ex. 3.39.4 : An optical fiber system is to be designed to operate over an 8 km. length without repeaters. The rise times of the chosen components are :

Source (LED) : 8 ns

Fiber : Intermodal : 5 ns km^{-1}

(Pulse broadening) Intra modal : 1 ns km^{-1}

Detector (P-I-N photodiode) : 6 ns

From system rise time considerations, estimate the maximum bit rate that may be achieved on the link when using an NRZ format.

☑ **Soln. :**

$$T_{sys} = \left(t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2\right)^{1/2}$$

The total transition time degradation of a digital link should not exceed 70% of NRZ bit period.

$$\therefore T_{sys} = \left[8^2 + (8 \times 5)^2 + (8 \times 1)^2 + (6)^2\right]^{1/2}$$

$$= [64 + 1600 + 64 + 36]^{1/2}$$

$$T_{sys} = 42 \text{ ns}$$

Maximum bit rate using NRZ format

$$B_{T\,max} = \frac{0.70}{T_{sys}} = \frac{0.7}{42 \times 10^{-9}} = 16.67 \text{ Mbits/sec.}$$

3.40 BER (BIT ERROR RATE) CALCULATIONS

- In case of fiber optic cable; due to the noise introduced at different stages, errors are produced.
- The rate at which errors occur is called as Bit Error Rate (BER).
- BER is defined at the ratio of number of errors to the total number of bits transmitted through the system.
- In case of optical cables; a bit rate of 1 error in 10^7 to 10^{10} is accepted.
- The minimum pulse energy, required to maintain a given BER, at the receiver is called as "Quantum limit". For data transmission over a longer distance, using optical cable; regenerative repeaters are used. In case of all repeaters (regenerators); attenuated and dispersed pulse train is received.
- The block schematic of regenerative repeater is shown in Fig. 3.40.1.
- The main function of regenerative circuit is to produce original pulse train at the output. But if too much dispersion is present then logic '1' can be considered as '0' and '0' can be considered as '1'.

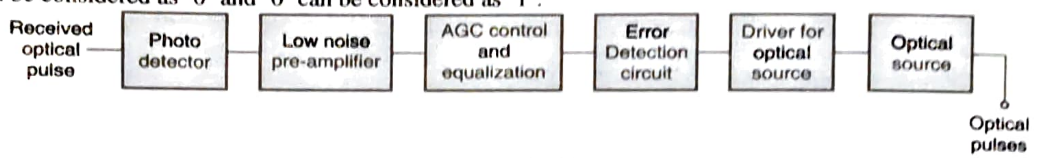


Fig. 3.40.1

- To minimize this type of error; a threshold level is considered. Above the threshold level, logic 1 is considered and below this level, logic 0 is considered.
- Actually quantum noise in optical cable has poisson's distribution; but to maintain low BER (10^{-9}), the noise distribution is assumed to be Gaussian.
- Let P (0) represents the probability of transmitting zero and P (1) represents the probability of transmitting one.
- Due to error, when '0' is transmitted and '1' is received then this probability of false detection is P (1/0).
- Similarly, when '1' is transmitted and '0' is received then this probability of false detection is P (0/1). Since due to the presence of noise, errors occur at the received; we have to always consider Probability Density Function (PDF).

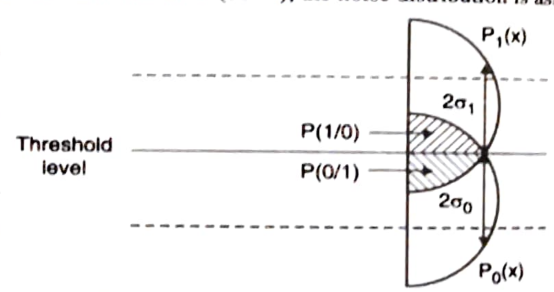


Fig. 3.40.2 : Probability density function

- The Gaussian PDF is defined as,

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(-x-m)^2/2\sigma^2}.$$

- This probability density function is shown in Fig. 3.40.2.
- Here 'm' is the mean value and 'σ' is the standard deviation of the distribution.
- P (x) describes the probability of detecting a noise current or voltage and σ represents rms value of this current or voltage.
- The shaded region of Fig. 3.40.2 represents the probability of false detection.
- If the probability of transmitting '1' and '0' is P (1) and P (0) respectively then the total probability of error is,

$$P(e) = P(1) \cdot P(0/1) + P(0) \cdot P(1/0)$$

- In terms of signal to noise ratio; the probability of error is,

$$P(e) = \frac{1}{2} \text{erfc}\left[\frac{\sqrt{S/N}}{2\sqrt{2}}\right]$$

Chapter Ends...