Unit-3

Optical Sources and Detectors

3.1 Optical Sources

- Optical transmitter converts electrical input signal into corresponding optical signal. The optical signal is then launched into the fiber. Optical source is the major component in an optical transmitter.
- Popularly used optical transmitters are Light Emitting Diode (LED) and semiconductor Laser Diodes (LD).

Characteristics of Light Source for Communication

- To be useful in an optical link, a light source needs the following characteristics :

i) It must be possible to operate the device continuously at a variety of temperatures for many years.

ii) It must be possible to modulate the light output over a wide range of modulating frequencies.

iii) For fiber links, the wavelength of the output should coincide with one of transmission windows for the fiber type used.

iv) To couple large amount of power into an optical fiber, the emitting area should be small.

v) To reduce material dispersion in an optical fiber link, the output spectrum should be narrow.

vi) The power requirement for its operation must be low.

vii) The light source must be compatible with the modern solid state devices.

viii) The optical output power must be directly modulated by varying the input current to the device.

ix) Better linearity to prevent harmonics and intermodulation distortion.

x) High coupling efficiency.

xi) High optical output power.

xii) High reliability.

xiii) Low weight and low cost.

Two types of light sources used in fiber optics are light emitting diodes (LEDs) and laser diodes (LDs).

3.1.1 Light Emitting Diodes (LEDs)

p-n Junctions

- Conventional p-n junction is called as **homojunction** as same semiconductor material is used on both sides junction. The electron-hole recombination occurs in relatively wide layer ≈ 10 μm. As the carriers are not confined to the immediate vacinity of junction, hence high current densities can not be realized.
- The carrier confinement problem can be resolved by sandwiching a thin layer (≈ 0.1 μm) between p-type and n-type layers. The middle layer may or may not be doped. The carrier confinment occurs due to bandgap discontinuity of the junction. Such a junction is called **heterojunction** and the device is called **double heterostructure.**
- In any optical communication system when the requirement is -

  i) Bit rate of 100-200 Mb/sec.

  ii) Optical power in tens of micro watts.
  LEDs are best suitable optical source.

3.1.1.1 LED Structures

Heterojunctions

- A **heterojunction** is an interface between two adjoining single crystal semiconductors with different bandgap.
- Heterojunctions are of two types, Isotype (n-n or p-p) or Antisotype (p-n).

Double Heterojunctions (DH)

In order to achieve efficient confinement of emitted radiation **double heterojunctions** are used in LED structures. A heterojunction is a junction formed by dissimilar semiconductors. Double heterojunction (DH) is formed by two different semiconductors on each side of active region. Fig. 3.1.1 shows double heterojunction (DH) light emitter.

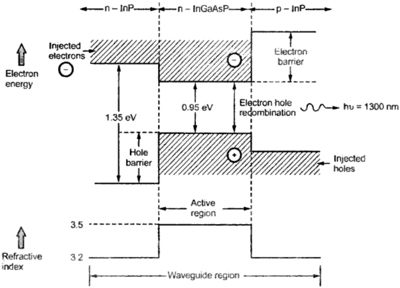

Fig. 3.1.1 Double heterojunction (DH) emitter

- The crosshatched regions represent the energy levels of free charge. Recombination occurs only in active InGaAsP layer. The two materials have different bandgap energies and different refractive indices. The changes in bandgap energies create potential barrier for both holes and electrons. The free charges can recombine only in narrow, well defined active layer side.
- A double heterojunction (DH) structure will confine both holes and electrons to a narrow active layer. Under forward bias, there will be a large number of carriers injected into active region where they are efficiently confined. Carrier recombination occurs in small active region so leading to an efficient device. Another advantage of DH structure is that the active region has a higher refractive index than the materials on either side, hence light emission occurs in an optical waveguide, which serves to narrow the output beam.

LED configurations

- At present there are two main types of LED used in optical fiber links -

1. Surface emitting LED.
2. Edge emitting LED.

Both devices uses a DH structure to constrain the carriers and the light to an active layer.

3.1.2 Surface Emitting LEDs

- In surface emitting LEDs the plane of active light emitting region is oriented perpendicularly to the axis of the fiber. A DH diode is grown on an N-type substrate at the top of the diode as shown in Fig. 3.1.2. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted light.

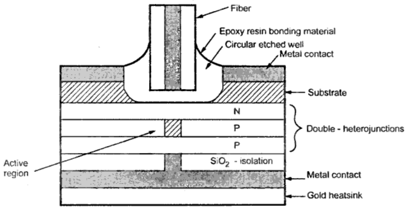

Fig. 3.1.2 Cross-section through a typical surface emitting LED

- At the back of the device is a gold heat sink. The current flows through the p-type material and forms the small circular active region resulting in the intense beam of light.

Diameter of circular active area = 50 μm

Thickness of circular active area = 2.5 μm

Current density = 2000 A/cm^2 half-power

Emission pattern = Isotropic, 120° beamwidth.

- The isotropic emission pattern from surface emitting LED is of Lambartian pattern. In Lambartian pattern, the emitting surface is uniformly bright, but its projected area diminishes as cos θ, where θ is the angle between the viewing direction and the normal to the surface as shown in Fig. 3.1.3. The beam intensity is maximum along the normal.

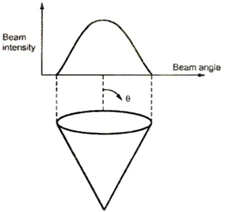

Fig. 3.1.3 Lambartian radiation

- The power is reduced to 50% of its peak when $\theta = 60°$, therefore the total half-power beamwidth is 120°. The radiation pattern decides the coupling efficiency of LED.

3.1.1.3 Edge Emitting LEDs (ELEDs)

- In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as **edge emitting** LED or ELED.
- It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber. Fig. 3.1.4 shows structure of ELED.

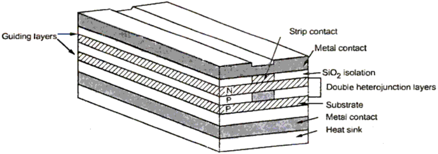

Fig. 3.1.4 Structure of edge emitting, DH, strip contact LED

Edge emitter's emission pattern is more concentrated (directional) providing improved coupling efficiency. The beam is Lambartian in the plane parallel to the junction but diverges more slowly in the plane perpendicular to the junction. In this plane, the beam divergence is limited. In the parallel plane, there is no beam confinement and the radiation is Lambartian. To maximize the useful output power, a reflector may be placed at the end of the diode opposite the emitting edge. Fig. 3.1.5 shows radiation from ELED.

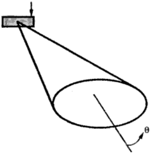

Fig. 3.1.5 Unsymmetric radiation from an edge emitting LED

Features of ELED :

1. Linear relationship between optical output and current.
2. Spectral width is 25 to 40 nm for $\lambda = 0.8 - 0.9$ µm.
3. Modulation bandwidth is much large.
4. Not affected by catastrophic gradation mechanisms hence are more reliable.
5. ELEDs have better coupling efficiency than surface emitter.
6. ELEDs are less temperature sensitive.

Usage :

1. LEDs are suited for short range narrow and medium bandwidth links.
2. Suitable for digital systems up to 140 Mb/sec.
3. Long distance analog links.

3.1.1.4 Light Source Materials

- The spontaneous emission due to carrier recombination is called **electro luminescence.** To encourage electroluminescence it is necessary to select an appropriate semiconductor material. The semiconductors depending on energy bandgap can be categorized into,

1. Direct bandgap semiconductors.
2. Indirect bandgap semiconductors.

- Some commonly used bandgap semiconductors are shown in following table 3.1.1.

Semiconductor	Energy bandgap (eV)	Recombination B_r (cm^3 / sec)
GaAs	Direct : 1.43	7.21×10^{-10}
GaSb	Direct : 0.73	2.39×10^{-10}
InAs	Direct : 0.35	8.5×10^{-11}
InSb	Direct : 0.18	4.58×10^{-11}
Si	Indirect : 1.12	1.79×10^{-15}
Ge	Indirect : 0.67	5.25×10^{-14}
GaP	Indirect : 2.26	5.37×10^{-14}

Table 3.1.1 Semiconductor materials for optical sources

- Direct bandgap semiconductors are most useful for this purpose. In direct bandgap semiconductors the electrons and holes on either side of bandgap have same value of crystal momentum. Hence direct recombination is possible. The recombination occurs within 10^{-8} to 10^{-10} sec.
- In indirect bandgap semiconductors, the maximum and minimum energies occur at different values of crystal momentum. The recombination in these semiconductors is quite slow i.e. 10^{-2} to 10^{-3} sec.
- The active layer semiconductor material must have a **direct bandgap**. In direct bandgap semiconductor, electrons and holes can recombine directly without need of third particle to conserve momentum. In these materials the optical radiation is sufficiently high. These materials are compounds of group III element (Al, Ga, In) and group V element (P, As, Sb). Some tertiary alloys Ga_{1-x} Al_x As are also used.

- Emission spectrum of $G_{a1-x}\ Al_xAs$ LED is shown in Fig. 3.1.6.

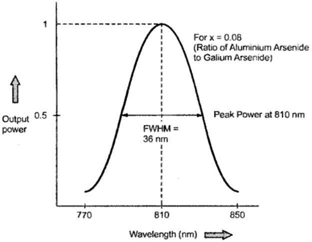

Fig. 3.1.6 Emission spectrum of $Ga_{1-x}\ Al_xAs$ LED

- The peak output power is obtained at 810 nm. The width of emission spectrum at half power (0.5) is referred as full width half maximum (FWHM) spectral width. For the given LED FWHM is 36 nm.
- The fundamental quantum mechanical relationship between gap energy E and frequency v is given as -

$$E = h\nu$$

$$E = h\frac{c}{\lambda}$$

$$\Rightarrow \qquad \lambda = \frac{hc}{E} \qquad \text{... 3.1.2}$$

where, energy (E) is in joules and wavelength (λ) is in meters. Expressing the gap energy (E_g) in electron volts and wavelength (λ) in micrometers for this application.

$$\boxed{\lambda(\mu m) = \frac{1.24}{E_g\,(eV)}} \qquad \text{... 3.1.2}$$

Different materials and alloys have different bandgap energies.

- The bandgap energy (E_g) can be controlled by two compositional parameters x and y, within direct bandgap region. The quarternary alloy

$In_{1-x}\,Ga_x\,As_y\,P_{1-y}$ is the principal material used in such LEDs. Two expressions relating E_g and x, y are -

$$\boxed{\begin{aligned} E_g &= 1.424 + 1.266\,x + 0.266\,x^2 \\ E_g &= 1.35 - 0.72\,y + 0.12\,y^2 \end{aligned}}$$

... 3.1.3

... 3.1.4

Example 3.1.1 : *Compute the emitted wavelength from an optical source having* $x = 0.07$.

Solution :

$$x = 0.07$$

$$\boxed{E_g = 1.424 + 1.266\,x + 0.266\,x^2}$$

$$E_g = 1.424 + (1.266 \times 0.07) + 0.266 \times (0.07)^2$$

$$E_g = 1.513 \text{ eV}$$

Now

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

$$\lambda = \frac{1.24}{1.513}$$

$$\lambda = 0.819\ \mu\text{m}$$

$$\lambda \approx \mathbf{0.82}\ \mu\text{m}$$

... Ans.

Example 3.1.2 : *For an alloy* $In_{0.74}\,Ga_{0.26}\,As_{0.57}\,P_{0.43}$ *to be used in LED. Find the wavelength emitted by this source.*

Solution : Comparing the alloy with the quartenary alloy composition.

$In_{1-x}\,Ga_x\,As_y\,P_{1-y}$ it is found that

$$x = 0.26 \text{ and}$$

$$y = 0.57$$

Using

$$\boxed{E_g = 1.35 - 0.72\,y + 0.12\,y^2}$$

$$E_g = 1.35 - (0.72 \times 0.57) + 0.12 \times 0.57^2$$

$$E_g = 0.978 \text{ eV}$$

Now

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

$$\therefore \quad \lambda = \frac{1.24}{0.978}$$

$$\lambda = 1.2671\ \mu m$$

$$\lambda \approx \mathbf{1.27\ \mu m} \qquad \text{... Ans.}$$

3.1.1.5 Quantum Efficiency and Power

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

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \qquad \text{... 3.1.5}$$

Where,

R_r is radiative recombination rate.

R_{nr} is non-radiative recombination rate.

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

non-radiative life time, $\tau_{nr} = \frac{n}{R_{nr}}$.

- The internal quantum efficiency is given as -

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

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}} \qquad \text{... 3.1.6}$$

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

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} \qquad \text{... 3.1.7}$$

Therefore internal quantum efficiency is given as -

$$\boxed{\eta_{int} = \frac{\tau}{\tau_r}} \qquad \text{... 3.1.8}$$

- If the current injected into the LED is I and q is electron charge then total number of recombinations per second is -

$$R_r + R_{nr} = \frac{I}{q}$$ From equation 3.1.5

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

$$\therefore \quad R_r = \eta_{int} \times \frac{I}{q} \qquad \text{... 3.1.9}$$

- Optical power generated internally in LED is given as -

$$P_{int} = R_r \cdot h\nu$$

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

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

$$\therefore \quad \boxed{P_{int} = \eta_{int} \cdot \frac{hc\,I}{q\lambda}} \qquad \text{... 3.1.10}$$

- Not all internally generated photons will available from output of device. The external quantum efficiency is used to calculate the emitted power. The external quantum efficiency is defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation

$$\eta_{ext} = \frac{1}{n(n+1)^2} \qquad \text{... 3.1.11}$$

- The optical output power emitted from LED is given as -

$$P = \eta_{ext} \cdot P_{int}$$

$$\boxed{P = \frac{1}{n\,(n+1)^2} \cdot P_{int}} \qquad \text{... 3.1.12}$$

Example 3.1.3 : *The radiative and non radiative recombination life times of minority carriers in the active region of a double heterojunction LED are 60 nsec and 90 nsec respectively. Determine the total carrier recombination life time and optical power generated internally if the peak emission wavelength is 870 nm and the drive current is 40 mA.* **[July/Aug.-2006, 6 Marks]**

Solution : Given : $\lambda = 870 \text{ nm} = 0.87 \times 10^{-6}$ m

$\tau_r = 60$ nsec.

$\tau_{nr} = 90$ nsec.

$I = 40$ mA $= 0.04$ Amp.

i) Total carrier recombination life time :

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

$$\frac{1}{\tau} = \frac{1}{60} + \frac{1}{90}$$

$$\frac{1}{\tau} = \frac{150}{5400}$$

$\therefore$ τ = **36 nsec.** ... **Ans.**

ii) Internal optical power :

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

$$P_{int} = \left(\frac{\tau}{\tau_r}\right)\left(\frac{hc\,I}{q\,\lambda}\right)$$

$$P_{int} = \left(\frac{36}{60}\right)\left[\frac{\left(6.625\times10^{-34}\right)\left(3\times10^{8}\right)\times0.04}{\left(1.602\times10^{-19}\right)\left(0.87\times10^{-6}\right)}\right]$$

P_{int} = **34.22 mW** ... **Ans.**

Example 3.1.4 : *A double heterojunction InGaAsP LED operating at 1310 nm has radiative and non-radiative recombination times of 30 and 100 ns respectively. The current injected is 40 mA. Calculate -*
i) Bulk recombination life time.
ii) Internal quantum efficiency.
iii) Internal power level.

Solution :

$$\lambda = 1310 \text{ nm} = \left(1.31\times10^{-6} \text{ m}\right)$$

$$\tau_r = 30 \text{ ns}$$

$$\tau_{nr} = 100 \text{ ns}$$

$$I = 40 \text{ mA} = 0.04 \text{ Amp.}$$

i) Bulk recombination life time (τ) .

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

$$\frac{1}{\tau} = \frac{1}{30} + \frac{1}{100}$$

$\therefore$ $\tau = \mathbf{23.07}$ **nsec.** ... **Ans.**

ii) Internal quantum efficiency (η_{int}) :

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

$$\eta_{int} = \frac{23.07}{30}$$

$\eta_{int} = \mathbf{0.769}$ ... **Ans.**

iii) Internal power level (P_{int}) :

$$\boxed{P_{int} = \eta_{int} \frac{hc\,1}{q\lambda}}$$

$$P_{int} = 0.769 \times \frac{\left(6.625 \times 10^{-34}\right)\left(3 \times 10^{8}\right)(0.04)}{\left(1.602 \times 10^{-19}\right)\left(1.31 \times 10^{-6}\right)}$$

$P_{int} = \mathbf{2.913}$ **mW** ... **Ans.**

3.1.1.6 Advantages and Disadvantages of LED

Advantages of LED

1. Simple design.
2. Ease of manufacture.
3. Simple system integration.
4. Low cost.
5. High reliability.

Disadvantages of LED

1. Refraction of light at semiconductor/air interface.
2. The average life time of a radiative recombination is only a few nonoseconds, therefore modulation BW is limited to only few hundred megahertz.
3. Low coupling efficiency.
4. Large chromatic dispersion.

3.1.1.7 Comparison of Surface and Edge Emitting LED

LED type	Maximum modulation frequency (MHz)	Output power (mW)	Fiber coupled power (mW)
Surface emitting	60	< 4	< 0.2
Edge emitting	200	< 7	< 1.0

3.1.2 Injection Laser Diode (ILD)

- The laser is a device which amplifies the light, hence the LASER is an acronym for light amplification by stimulated emission of radiation.
  The operation of the device may be described by the formation of an electromagnetic standing wave within a cavity (optical resonator) which provides an output of monochromatic highly coherent radiation.

Principle :

- Material absorb light rather than emitting. Three different fundamental process occurs between the two energy states of an atom.
  1) Absorption 2) Spontaneous emission 3) Stimulated emission.
- Laser action is the result of three process absorption of energy packets (photons) spontaneous emission, and stimulated emission. (These processes are represented by the simple two-energy-level diagrams).
  Where, E_1 is the lower state energy level.
  E_2 is the higher state energy level.
- Quantum theory states that any atom exists only in certain discrete energy state, absorption or emission of light causes them to make a transition from one state to another. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the two states.
  If E_1 is lower state energy level.
  and E_2 is higher state energy level.
  $E = (E_2 - E_1) = h.f.$
  where, $h = 6.626 \times 10^{-34}$ J/s (Plank's constant).
- An atom is initially in the lower energy state, when the photon with energy $(E_2 - E_1)$ is incident on the atom it will be excited into the higher energy state E_2 through the absorption of the photon.

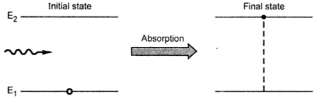

Fig. 3.1.7 Absorption

- When the atom is initially in the higher energy state E_2, it can make a **transition** to the lower energy state E_1 providing the emission of a photon at a frequency corresponding to E = h.f. The emission process can occur in two ways.

A) By **spontaneous emission** in which the atom returns to the lower energy state in random manner.

B) By **stimulated emission** when a photon having equal energy to the difference between the two states ($E_2 - E_1$) interacts with the atom causing it to the lower state with the creation of the second photon.

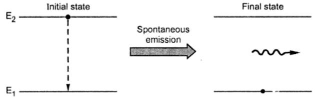

Fig. 3.1.8 Spontaneous emission

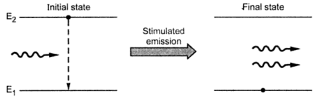

Fig. 3.1.9 Stimulated emission

- Spontaneous emission gives incoherent radiation while stimulated emission gives coherent radiation. Hence the light associated with emitted photon is of same frequency of incident photon, and in same phase with same polarization.
- It means that when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in constructive manner. The

emitted light is bounced back and forth internally between two reflecting surface. The bouncing back and forth of light wave cause their intensity to reinforce and build-up. The result in a high brilliance, single frequency light beam providing amplification.

Emission and Absorption Rates

- If N_1 and N_2 are the atomic densities in the ground and excited states.

Rate of spontaneous emission

$$R_{spon} = AN_2 \quad \text{... 3.1.13}$$

Rate of stimulated emission

$$R_{stim} = BN_2 \rho_{em} \quad \text{... 3.1.14}$$

Rate of absorption

$$R_{abs} = B' N_1 \rho_{em} \quad \text{... 3.1.15}$$

where,

A, B and B′ are constants.

ρ_{em} is spectral density.

- Under equilibrium condition the atomic densities N_1 and N_2 are given by Boltzmann statistics.

$$\frac{N_2}{N_1} = e^{(-E_g/K_BT)} \quad \text{... 3.1.16}$$

$$\frac{N_2}{N_1} = e^{(-h_v/K_BT)} \quad \text{... 3.1.17}$$

where,

K_B is Boltzmann constant.

T is absolute temperature.

- Under equilibrium the upward and downward transition rates are equal.

$$AN_2 + BN_2 \rho_{em} = B' N_1 \rho_{em} \quad \text{... 3.1.18}$$

Spectral density ρ_{em}

$$\rho_{em} = \frac{A/B}{(B'/B)[h^{hv/K_BT} - 1]} \quad \text{... 3.1.19}$$

Comparing spectral density of black body radiation given by Plank's formula,

$$\rho_{em} = \frac{8\pi h v^3 / c^3}{e^{(hv/K_B T)} - 1} \qquad \ldots 3.1.20$$

Therefore,

$$A = \frac{8\pi h v^3}{c^3} B \qquad \ldots 3.1.21$$

$$B' = B \qquad \ldots 3.1..22$$

- A and B are called **Einstein's coefficient.**

3.1.2.1 Fabry - Perot Resonator

- Lasers are oscillators operating at optical frequency. The oscillator is formed by a resonant cavity providing a selective feedback. The cavity is normally a Fabry-Perot resonator i.e. two parallel plane mirrors separated by distance L,

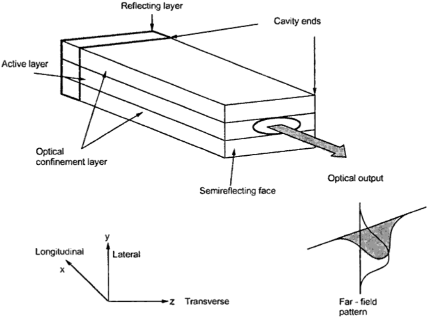

Fig. 3.1.10 Fabry-Perot resonator for laser diode

light propagating along the axis of the interferometer is reflected by the mirrors back to the amplifying medium providing optical gain. The dimensions of cavity are 25-500 μm longitudinal 5-15 μm lateral and 0.1-0.2 μm transverse. Fig. 3.1.10 shows Fabry-Perot resonator cavity for a laser diode.

- The two heterojunctions provide carrier and optical confinement in a direction normal to the junction. The current at which lasing starts is the threshold current. Above this current the output power increases sharply.

3.1.2.2 Distributed Feedback (DFB) Laser

- In DFB laser the lasing action is obtained by periodic variations of refractive index along the longitudinal dimension of the diode. Fig. 3.1.11 shows the structure of DFB laser diode.

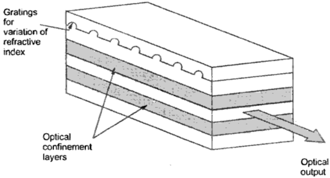

Fig. 3.1.11 DFB laser diode

Lasing Conditions and Resonant Frequencies

- The electromagnetic wave propagating in longitudinal direction is expressed as -

$$E(z, t) = I(z)\ e^{j(\omega t - \beta z)} \quad \text{... 3.1.23}$$

where,

I(z) is optical field intensity.

ω is optical radian frequency.

β is propagation constant.

- The fundamental expression for lasing in Fabry-Perot cavity is -

$$I(z) = I(0)\ e^{\left[\left\{\Gamma g(h\nu) - \bar{\alpha}(h\nu)\right\} z\right]} \quad \text{... 3.1.24}$$

where,

Γ is optical field confinement factor or the fraction of optical power in the active layer.

$\bar{\alpha}$ is effective absorption coefficient of material.

g is gain coefficient.

hv is photon energy.

z is distance traverses along the lasing cavity.

- Lasing (light amplification) occurs when gain of modes exceeds above optical loss during one round trip through the cavity i.e. z = 2L. If R_1 and R_2 are the mirror reflectivities of the two ends of laser diode. Now the expression for lasing expressing is modified as,

$$I(2L) = I(0) R_1 R_2 e^{[2L\{\Gamma g(h\nu) - \bar{\alpha}(h\nu)\}]} \quad \text{... 3.1.25}$$

The condition of lasing threshold is given as -

i) For amplitude : $I(2L) = I(0)$

ii) For phase : $e^{-j2\beta L} = 1$

iii) Optical gain at threshold = Total loss in the cavity.

i.e. $\Gamma g_{th} = \alpha_t$

- Now the lasing expression is reduced to -

$$\boxed{\Gamma g_{th} = a_t = \bar{\alpha} + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right)} \quad \text{... 3.1.26}$$

$$\Gamma g_{th} = \alpha_t = \bar{\alpha} + \alpha_{end} \quad \text{... 3.1.27}$$

where,

α_{end} is mirror loss in lasing cavity.

- An important condition for lasing to occur is that gain, $g \geq g_{th}$ i.e. threshold gain.

Example 3.1.5 : *Find the optical gain at threshold of a laser diode having following parametric values - $R_1 = R_2 = 0.32$, $\bar{\alpha} = 10\ cm^{-1}$ and $L = 500\ \mu m$.*

Solution : Optical gain in laser diode is given by -

$$\boxed{\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right)}$$

$$\Gamma g_{th} = 10 + \frac{1}{2 \times \left(500 \times 10^{-4}\right)} ln \left(\frac{1}{0.32 \times 0.32}\right)$$

$$\Gamma g_{th} = \mathbf{33.7\ cm^{-1}}$$ **... Ans.**

3.1.2.3 Power Current Characteristics

- The output optic power versus forward input current characteristics is plotted in Fig. 3.1.12 for a typical laser diode. Below the threshold current (I_{th}) only spontaneous emission is emitted hence there is small increase in optic power with drive current. At threshold when lasing conditions are satisfied. The optical power increases sharply after the lasing threshold because of stimulated emission.
- The lasing threshold optical gain (g_{th}) is related by threshold current density (J_{th}) for stimulated emission by expression -

$$g_{th} = \beta J_{th} \qquad \text{... 3.1.28}$$

where, β is constant for device structure.

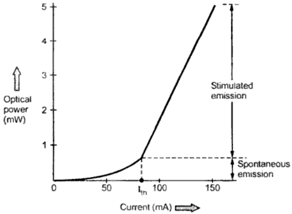

Fig. 3.1.12 Power current characteristics

3.1.2.4 External Quantum Efficiency

- The external quantum efficiency is defined as the number of photons emitted per electron hole pair recombination above threshold point. The external quantum efficiency η_{ext} is given by -

$$\eta_{ext} = \frac{\eta_i (g_{th} - \bar{\alpha})}{g_{th}} \qquad \text{... 3.1.29}$$

where,

η_i = Internal quantum efficiency (0.6-0.7).

g_{th} = Threshold gain.

$\bar{\alpha}$ = Absorption coefficient.

- Typical value of η_{ext} for standard semiconductor laser is ranging between 15-20 %.

3.1.2.5 Resonant Frequencies

- At threshold lasing

$$2\beta L = 2\pi m$$

where, $\beta = \frac{2\pi n}{\lambda}$ (propagation constant)

m is an integer.

$$\therefore \quad m = 2L \cdot \frac{n}{\lambda} \quad \text{... 3.1.30}$$

Since $c = v\lambda$

$$\therefore \quad \lambda = \frac{c}{v}$$

Substituting λ in 3.1.30

$$m = 2L \frac{nv}{c} \quad \text{... 3.1.31}$$

- Gain in any laser is a function of frequency. For a Gaussian output the gain and frequency are related by expression -

$$g(\lambda) = g(0)\, e^{\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]} \quad \text{... 3.1.32}$$

where,

g(0) is maximum gain.

λ_0 is center wavelength in spectrum.

σ is spectral width of the gain.

- The frequency spacing between the two successive modes is -

$$\boxed{\Delta \nu = \frac{c}{2 L n}} \quad \text{... 3.1.33}$$

The wavelength spacing is given as -

$$\boxed{\Delta \lambda = \frac{\lambda^2}{2 L n}} \quad \text{... 3.1.34}$$

Example 3.1.6 : *A GaAs laser operating at 850 nm and has length of 500 μm, refractive index n = 3.7. Calculate frequency and wavelength spacings.*

Solution : $\lambda = 950$ nm

$L = 500\ \mu m$

$n = 3.7$

Frequency spacing

$$\boxed{\Delta \nu = \frac{c}{2 L n}}$$

$$= \frac{3 \times 10^8}{2 \times \left(500 \times 10^{-6}\right) \times 3.7}$$

$$= 8.10 \times 10^{10} \text{ Hz}$$

$$= 81 \text{ GHz} \quad \text{... Ans.}$$

Wavelength spacing

$$\boxed{\Delta \lambda = \frac{\lambda^2}{2 L n}}$$

$$\Delta \lambda = \frac{\left(850 \times 10^{-9}\right)^2}{2 \times \left(500 \times 10^{-6}\right) \times 3.7}$$

$$\Delta \lambda = 0.19 \text{ nm} \quad \text{... Ans.}$$

3.1.2.6 Optical Characteristics of LED and Laser

- The output of laser diode depends on the drive current passing through it. At low drive current, the laser operates as an inefficient LED, when drive current crosses threshold value, lasing action begins. Fig. 3.1.13 illustrates graph comparing optical powers of LED operation (due to spontaneous emission) and laser operation (due to stimulated emission).

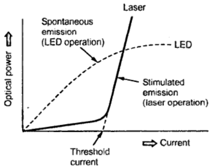

Fig. 3.1.13 Optical characteristics of an LED and laser compared

3.1.2.7 Spectral and Spatial Distribution of LED and Laser

- At low current laser diode acts like normal LED above threshold current, stimulated emission i.e. narrowing of light ray to a few spectral lines instead of broad spectral distribution, exist. This enables the laser to easily couple to single mode fiber and reduces the amount of uncoupled light (i.e. spatial radiation distribution). Fig. 3.1.14 shows spectral and spatial distribution difference between two diodes.

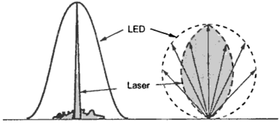

Fig. 3.1.14 Comparing (a) spectral and (b) spatial distribution of laser diodes

3.1.2.8 Advantages and Disadvantages of Laser Diode

Advantages of Laser Diode

1. Simple economic dsesign.
2. High optical power.
3. Production of light can be precisely controlled.
4. Can be used at high temperatures.
5. Better modulation capability.
6. High coupling efficiency.

7. Low spectral width (3.5 nm).
8. Ability to transmit optical output powers between 5 and 10 mW.
9. Ability to maintain the intrinsic layer characteristics over long periods.

Disadvantages of Laser Diode

1. At the end of fiber, a speckle pattern appears as two coherent light beams add or subtract their electric field depending upon their relative phases.
2. Laser diode is extremely sensitive to overload currents and at high transmission rates, when laser is required to operate continuously the use of large drive current produces unfavourable thermal characteristics and necessitates the use of cooling and power stabilization.

3.1.2.9 Comparison of LED and Laser Diode

Sr. No.	Parameter	LED	LD (Laser Diode)
1.	Principle of operation	Spontaneous emission.	Stimulated emission.
2.	Output beam	Non - coherent.	Coherent.
3.	Spectral width	Broad spectrum (20 nm - 100 nm).	Much narrower (1-5 nm).
4.	Data rate	Low.	Very high.
5.	Transmission distance	Smaller.	Greater.
6.	Temperature sensitivity	Less sensitive.	More temperature sensitive.
7.	Coupling efficiency	Very low.	High.
8.	Compatible fibers	Multimode step index multimode GRIN.	Single mode SI Multimode GRIN.
9.	Circuit complexity	Simple.	Complex.
10.	Life time	10^5 hours.	10^4 hours.
11.	Cost	Low.	High.
12.	Output power	Linearly proportional to drive current.	Proportional to current above threshold.
13.	Current required	Drive current 50 to 100 mA peak.	Threshold current 5 to 40 mA.
14.	Wavelengths available	0.66 to 1.65 μm.	0.78 to 1.65 μm.
15.	Applications	Moderate distance low data rate.	Long distance high data rates.

3.1.2.10 Important Formulae for LED and Laser

LED

1. $$\lambda = \frac{1.24}{E_g}$$

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

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

4. $$P_{int} = \eta_{int} \times \frac{hc\,I}{q\lambda}$$

LASER

1. $$\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$$

2. $$\Delta \nu = \frac{c}{2\,L\,n}$$

3. $$\Delta \lambda = \frac{\lambda^2}{2\,L\,n}$$

3.2 Optical Detectors

3.2.1 Principles of Optical Detectors

- The photodetector works on the principle of optical absorption. The main requirement of light detector or photodetector is its fast response. For fiber optic communication purpose most suited photodetectors are PIN (p-type- Intrinsic-n-type) diodes and APD (Avalanche photodiodes)
- The performance parameters of a photodetector are responsivity, quantum efficiency, response time and dark current.

3.2.1.1 Cut-off Wavelength (λ_c)

- Any particular semiconductor can absorb photon over a limited wavelength range. The highest wavelength is known as **cut-off wavelength** (λ_c). The cut-off wavelength is determined by bandgap energy E_g of material.

$$\boxed{\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g}} \qquad \text{... 3.2.1}$$

where,

E_g in electron volts (eV) and

λ_c cut-off wavelength is in μm.

Typical value of λ_c for silicon is 1.06 μm and for germanium it is 1.6 μm.

3.2.1.2 Quantum Efficiency (η)

- The quantum efficiency is defined as the number of electron-hole carrier pair generated per incident photon of energy $h\nu$ and is given as -

$$\eta = \frac{\text{Number of electron hole pairs generated}}{\text{Number of incident photons}}$$

$$\eta = \frac{I_p / q}{P_{in} / h\nu} \qquad \text{... 3.2.2}$$

where, I_p is average photocurrent.

P_{in} is average optical power incident on photodetector.

- Absorption coefficient of material determines the quantum efficiency. Quantum efficiency $\eta < 1$ as all the photons incident will not generate e-h pairs. It is normally expressed in percentage.

3.2.1.3 Detector Responsivity ($\Re$)

- The responsivity of a photodetector is the ratio of the current output in amperes to the incident optical power in watts. Responsivity is denoted by $\Re$.

$$\Re = \frac{I_p}{P_{in}} \qquad \text{... 3.2.3}$$

But

$$\eta = \frac{I_p / q}{P_{in} / h\nu} = \frac{I_p}{q}\frac{h\nu}{P_{in}}$$

$\therefore$

$$\frac{I_p}{P_{in}} = \frac{\eta q}{h\nu} \qquad \text{... 3.2.4}$$

Therefore

$$\boxed{\Re = \frac{\eta q}{h\nu} = \frac{\eta q \lambda}{hc}} \qquad \because \nu = \frac{c}{\lambda} \qquad \text{... 3.2.5}$$

- Responsivity gives transfer characteristics of detector i.e. photo current per unit incident optical power.
- Typical responsivities of pin photodiodes are -
  Silicon pin photodiode at 900 nm → 0.65 A/W.
  Germanium pin photodiode at 1.3 μm → 0.45 A/W.
  In GaAs pin photodiode at 1.3 μm → 0.9 A/W.

Example 3.2.1 : *Compute the cut-off wavelength for silicon and germanium PIN diodes. Their bandgap energies are 1.1 eV and 0.67 eV respectively.*

Solution : For silicon :

Cut-off wavelength is given as

$$\boxed{\lambda_c = \frac{1.24}{E_g}}$$

$$\lambda_c = \frac{1.24}{1.1}$$

$$\lambda_c = \mathbf{1.12\ \mu m} \qquad \textbf{... Ans.}$$

For germanium :

$$\lambda_c = \frac{1.24}{0.67}$$

$$\lambda_c = \mathbf{1.85\ \mu m} \qquad \textbf{... Ans.}$$

Example 3.2.2 : *A PIN photodiode is fabricated by GaAs which has bandgap energy of 1.43 eV at 300 °K. Find its upper cut-off wavelength.*

Solution : $E_g = 1.43$ eV

$$\boxed{\lambda_c = \frac{1.24}{E_g}}$$

$$\lambda_c = \frac{1.24}{1.43}$$

$$\lambda_c = 0.867\ \mu m$$

$$\lambda_c = \mathbf{867\ nm} \qquad \textbf{... Ans.}$$

Example 3.2.3 : *On an In GaAs photodetector a pulse of 85 ns emits 6×10^6 photons at 1300 nm wavelength. Average e-h pairs generated are 5.4×10^6. Calculate quantum efficiency of detector.*

Solution : Number of photons emitted = 6×10^6

Average e-h pair generated = 5.4×10^6

The quantum efficiency is given by -

$$\boxed{\eta = \frac{\text{Number of e - h pair generated}}{\text{Number of incident photons}}}$$

$$\eta = \frac{5.4 \times 10^6}{6 \times 10^6}$$

$$\eta = 0.9 = \mathbf{90\ \%}$$ ... **Ans.**

Example 3.2.4 : *Photons having energy 1.53 $\times 10^{-19}$ Joules are incident on a photodiode having responsivity of 0.65 A/W. If output power is 10 μW. Find the generated photocurrent.*

Solution :

$$\Re = 0.65 \ \text{A/W}$$

$$P_0 = 10 \ \mu\text{W}$$

Responsivity is given as -

$$\Re = \frac{I_P}{P_0}$$

$$\boxed{I_P = \Re \, P_0}$$

$$I_P = 0.65 \times 10$$

$$I_P = \mathbf{6.5\ \mu A}$$ ... **Ans.**

3.2.1.4 Working of Photodiodes

- In order to convert the modulated light back into an electrical signal, photodiodes or photodetectors are used. As the intensity of optical signal at the receiver is very low, the detector has to meet high performance specifications.
  - The conversion efficiency must be high at the operating wavelength.
  - The speed of response must be high enough to ensure that signal distortion does not occur.
  - The detection process introduce the minimum amount of noise.
  - It must be possible to operate continuously over a wide range of temperatures for many years.
  - The detector size must be compatible with the fiber dimensions.

- At present, these requirements are met by reverse biased p-n photodiodes. In these devices, the semiconductor material absorbs a photon of light, which excites an electron from the valence band to the conduction band (opposite of photon emission). The photo generated electron leaves behind it a hole, and so each photon generates two charge carriers. This increases the material conductivity so called **photoconductivity** resulting in an increase in the diode current. The diode equation is modified as -

$$I_{diode} = (I_d + I_s)(e^{Vq/\eta kT} - 1) \quad \text{... 3.2.6}$$

where,

I_d is dark current i.e. current that flows when no signal is present.

I_s is photo generated current due to incident optical signal.

Fig. 3.2.1 shows a plot of this equation for varying amounts of incident optical power.

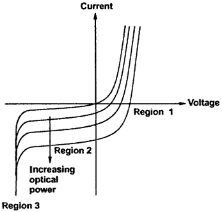

Fig. 3.2.1 V-I characteristics of photodiode

- Three regions can be seen forward bias, reverse bias and avalanche breakdown.

i) Forward bias, region 1 : A change in incident power causes a change in terminal voltage, it is called as **photovoltaic mode.** If the diode is operated in this mode, the frequency response of the diode is poor and so photovoltaic operation is rarely used in optical links.

ii) Reverse bias, region 2 : A change in optical power produces a proportional change in diode current, it is called as **photoconductive mode** of operation which most detectors use. Under these condition, the exponential term in equation 3.2.6 becomes insignificant and the **reverse bias current** is given by -

$$I_{diode} = (I_d + I_s)$$

- **Responsivity** of photodiode is defined as the change in reverse bias current per unit change in optical power, and so efficient detectors need large responsivities.

iii) Avalanche breakdown, region 3 : When biased in this region, a photo generated electron-hole pair causes avalanche breakdown, resulting in large diode for a single incident photon. Avalance photodiodes (APDs) operate in this region. APDs exhibit carrier multiplication. They are usually very sensitive detectors. Unfortunately V-I characteristic is very steep in this region and so the bias voltage must be tightly controlled to prevent spontaneous breakdown.

3.2.2 PIN Photodiode

- PIN diode consists of an intrinsic semiconductor sandwiched between two heavily doped p-type and n-type semiconductors as shown in Fig. 3.2.2.

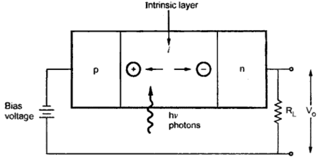

Fig. 3.2.2 PIN photodiode

- Sufficient reverse voltage is applied so as to keep intrinsic region free from carriers, so its resistance is high, most of diode voltage appears across it, and the electrical forces are strong within it. The incident photons give up their energy and excite an electron from valance to conduction band. Thus a free electron hole pair is generated, these are called as **photocarriers.** These carriers are collected across the reverse biased junction resulting in rise in current in external circuit called **photocurrent.**
- In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current.

- PIN detectors can be operated in two modes : **Photovoltaic** and **photoconductive**. In photovoltaic mode, no bias is applied to the detector. In this case the detector works very slow, and output is approximately logarithmic to the input light level. Real world fiber optic receivers never use the photovoltaic mode.
- In photoconductive mode, the detector is reverse biased. The output in this case is a current that is very linear with the input light power.
- The intrinsic region some what improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allows the selection of material capable of responding to the desired operating wavelength.

Characteristics of common PIN photodiodes

Sr. No.	Parameters	Symbol	Unit	Si	Ge	InGaAs
1.	Wavelength	λ	μ m	0.4 - 1.1	0.8 - 1.8	1.0 - 1.7
2.	Reponsivity	$\Re$	A/W	0.4 - 0.6	0.5 - 0.7	0.6 - 0.9
3.	Quantum efficiency	η	%	75 - 90	50 - 55	60 - 70
4.	Dark current	I_d	nA	1 - 10	50 - 500	1 - 20
5.	Rise time	T_r	nS	0.5 - 1	0.1 - 0.5	0.02 - 0.5
6.	Bandwidth	B	GHz	0.3 - 0.6	0.5 - 3	1 - 10
7.	Bias voltage	V_b	V	50 - 100	5 - 10	5 - 6

3.2.2.1 Depletion Layer Photocurrent

- Consider a reverse biased PIN photodiode.

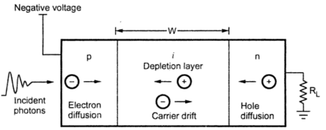

Fig. 3.2.3 Reverse biased PIN diode

- The total current density through depletion layer is -

$$J_{tot} = J_{dr} + J_{diff} \quad \text{... 3.2.7}$$

where,

J_{dr} is drift current density due to carriers generated in depletion region.

J_{diff} is diffusion current density due to carriers generated outside depletion region.

- The drift current density is expressed as -

$$J_{dr} = \frac{I_P}{A}$$

$$J_{dr} = q\,\phi_0\,(1 - e^{-\alpha_s w}) \quad \text{... 3.2.8}$$

where,

A is photodiode area.

ϕ_0 is incident photon flux per unit area.

- The diffusion current density is expressed as -

$$J_{diff} = q\phi_0 \frac{\alpha_s L_P}{1 + \alpha_s L_P} e^{-\alpha_s w} + q\,P_{n0} \frac{D_P}{L_P} \quad \text{... 3.2.9}$$

where,

D_P is hole diffusion coefficient.

P_n is hole concentration in n-type material.

P_{n0} is equilibrium hole density.

Substituting in equation 3.2.7, total current density through reverse biased depletion layer is -

$$J_{tot} = q\,\phi_0 \left[1 - \frac{e^{-\alpha_s w}}{1 + \alpha_s L_P}\right] + q\,P_{n0} \frac{D_P}{L_P} \quad \text{... 3.2.10}$$

3.2.2.2 Response Time

- Factors that determine the response time of a photodiode are -

  i) Transit time of photocarriers within the depletion region.

  ii) Diffusion time of photocarriers outside the depletion region.

  iii) RC time constant of diode and external circuit.

- The transit time is given by -

$$t_d = \frac{w}{v_d} \quad \text{... 3.2.11}$$

- The diffusion process is slow and diffusion times are less than carrier drift time. By considering the photodiode response time the effect of diffusion can be calculated. Fig. 3.2.4 shows the response time of photodiode which is not fully depleted.

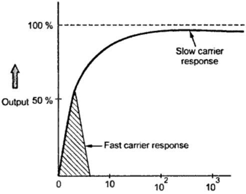

Fig. 3.2.4

- The detector behaves as a simple low pass RC filter having passband of

$$\boxed{B = \frac{1}{2\pi R_T C_T}} \qquad \dots 3.2.12$$

where,

R_T is combination input resistance of load and amplifier.

C_T is sum of photodiode and amplifier capacitance.

Example 3.2.5 : *Compute the bandwidth of a photodetector having parameters as -*
Photodiode capacitance = 3 pF
Amplifier capacitance = 4 pF
Load resistance = 50 Ω
Amplifier input resistance = 1 MΩ

Solution : Sum of photodiode and amplifier capacitance

$$C_T = 3 + 4 = 7 \text{ pF}$$

Combination of load resistance and amplifier and input resistance

$$R_T = 50\ \Omega \ ||\ 1\ \text{M}\Omega \approx 50\ \Omega$$

$$\boxed{\text{Bandwidth of photodetector } B = \frac{1}{2\pi R_T C_T}}$$

$$B = \frac{1}{2\pi\, 50 \times 7 \times 10^{-12}}$$

$$B = \mathbf{454.95\ MHz}$$ ... **Ans.**

3.2.3 Avalanche Photodiode (APD)

- When a p-n junction diode is applied with high reverse bias breakdown can occur by two separate mechanisms direct ionization of the lattice atoms, *zener breakdown* and high velocity carriers causing impact ionization of the lattice atoms called *avalanche breakdown*. APDs uses the avalanche breakdown phenomena for its operation. The APD has its internal gain which increases its responsivity.
- Fig. 3.2.5 shows the schematic structure of an APD. By virtue of the doping concentration and physical construction of the n^+ p junction, the electric field is high enough to cause impact ionization. Under normal operating bias, the I-layer (the p^- region) is completely depleted. This is known as **reach through** condition, hence APDs are also known as **reach through APD** or **RAPDs.**

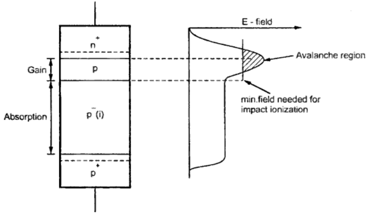

Fig. 3.2.5 APD schematic and variation of E-field across diode

- Similar to PIN photodiode, light absorption in APDs is most efficient in I-layer. In this region, the E-field separates the carriers and the electrons drift into the avalanche region where carrier multiplication occurs. If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APDs are usually biased just below breakdown, with the bias voltage being tightly controlled.

- The multiplication for all carriers generated in the photodiode is given as -

$$M = \frac{I_M}{I_P} \quad \text{... 3.2.13}$$

where,

I_M = Average value of total multiplied output current.

I_P = Primary unmultiplied photocurrent.

- Responsivity of APD is given by -

$$\boxed{\Re_{APD} = \frac{\eta q}{h\nu} M}$$

$$\Re_{APD} = \frac{\eta q \lambda}{hc} M \qquad \because \nu = \frac{c}{\lambda}$$

$$\Re_{APD} = \Re_0 M \quad \text{... 3.2.14}$$

where, $\Re_0$ = Unity gain responsivity.

Example 3.2.6 : *A given APD has a quantum efficiency of 65 % at wavelength of 900 nm. If 0.5 μwatt of optical power produces a multiplied photocurrent of 10 μA. Find the multiplication factor M.*

Solution : Given :

Quantum efficiency η = 65 % = 0.65

Wavelength λ = 900 nm = 900×10^{-9} m

Incident optical power P_{in} = 0.5 μwatt = 0.5×10^{-6} W

Multiplied output current I_M = 10 μA = 10×10^{-6} Amp.

Responsivity is given by,

$$\Re = \frac{\eta q \lambda}{hc}$$

$$\Re = \frac{0.65 \times (1.6 \times 10^{-19}) \times (900 \times 10^{-9})}{(6.63 \times 10^{-34}) \times (3 \times 10^{8})}$$

$$\Re = 0.4705 \quad AW^{-1}$$

Now, photocurrent $I_p = P_{in} \times \Re$

$$= (0.5 \times 10^{-6}) \times 0.4705$$

$$= 2.3529 \times 10^{-7} \text{ Amp.}$$

$$= 0.2352 \ \mu A$$

Multiplication factor $M = \dfrac{I_M}{I_P}$

$$= \frac{(10 \times 10^{-6})}{2.3529 \times 10^{-7}} = \mathbf{4.25} \qquad \text{... Ans.}$$

Characteristics of common APDs

Sr. No.	Parameters	Symbol	Unit	Si	Ge	InGaAs
1.	Wavelength	λ	µm	0.4 - 1.1	0.8 - 1.8	1.0 - 1.7
2.	Responsivity	$\Re_{APD}$	A/W	80 - 130	3 - 30	5 - 20
3.	APD gain	M	–	100 - 500	50 - 200	10 - 40
4.	k-factor	kA	–	0.02 - 0.05	0.7 - 1.0	0.5 - 0.7
5.	Dark current	I_d	nA	0.1 - 1	50 - 500	1 - 5
6.	Rise time	T_r	nS	0.1 - 2	0.5 - 0.8	0.1 - 0.5
7.	Bandwidth	B	GHz	0.02 - 1	0.4 - 0.7	1 - 10
8.	Bias voltage	V_b	V	200 - 250	20 - 40	20 - 30

3.2.4 Comparison of PIN and APD

Sr. No.	Parameters	PIN	APD
1.	Sensitivity	Less sensitive (0 - 12 dB).	More sensitive (5 to 15 dB).
2.	Biasing	Low reverse biased voltage (5 to 10 V).	High reverse biased voltage (20 - 400 volts).
3.	Wavelength region	300 - 1100 nm.	400-100 nm.
4.	Gain	No internal gain.	Internal gain.
5.	S/N ratio	Poor.	Better.
6.	Detector circuit	Simple.	More complex.
7.	Conversion efficiency	0.5 to 1.0 Amps/watt.	0.5 to 100 Amps/watt.
8.	Cost	Cheaper.	More expensive.
9.	Support circuitry required	None.	High voltage and temperature compensation.

3.2.5 MSM Photodetector

- Metal-semiconductor-metal (MSM) photodetector uses a sandwiched semiconductor between two metals. The middle semiconductor layer acts as optical absorbing layer. A Schottky barrier is formed at each metal semiconductor interface (junction), which prevents flow of electrons.
- When optical power is incident on it, the electron-hole pairs generated through photo absorption flow towards metal contacts and causes photocurrent.
- MSM photodetectors are manufactured using different combinations of semiconductors such as - GaAs, InGaAs, InP, InAlAs. Each MSM photodetectors has distinct features e.g. responsivity, quantum efficiency, bandwidth etc.
- With InAlAs based MSM photodetector, 92 % quantum efficiency can be obtained at 1.3 μm with low dark current. An inverted MSM photodetector shows high responsivity when illuminated from top.
- A GaAs based device with travelling wave structure gives a bandwidth beyond 500 GHz.

3.2.6 Important Formulae for PIN and APD

PIN photodiode

1. $$\lambda_c = \frac{1.24}{E_g}$$

2. $$\eta = \frac{I_p / q}{P_0 / h\nu}$$

3. $$\Re = \frac{\eta q}{h\nu} = \frac{I_p}{P_0}$$

APD

1. $$B = \frac{1}{2\pi R_T C_T}$$

Points to Remember

Optical Source

1. Performance parameters at light sources.

i) Peak wavelength : The wavelength at which the source emits the most power is called **peak wavelength**. It should be matched to the wavelengths that are transmitted with the least attenuation through the optical fiber. The most common peak wavelengths are 850 nm, 1310 nm, 1550 nm.

ii) **Spectral width** : Ideally all the light emitted from light source would be at the peak wavelength, but practically, the light is emitted in a range of wavelengths centered at the peak wavelength. This range is called the **spectral width** of the source.

iii) **Emission pattern** : The radiation of light is called the **emission pattern** of light source. Emission pattern affects the amount of light that can be coupled into optical fiber.

iv) **FWHM (Full Width Half Maximum)** : It is used to describe the width of a spectral emission at the 50 % amplitude points.

v) **Speed** : The rise or fall time of source power gives the speed. The source should turn on and off fast enough to meet the bandwidth limits of the system.

2. Light emitter converts electrical signal into corresponding light signal that can be injected into a fiber.
3. LED and laser diodes work on the principle of generation of photons due to electron-hole recombination. The wavelength of the emitted light depends on the semiconductor material, while the spectral width and modulation capabilities are determined by the device structure and the bias network.
4. **Radiance** is defined as optical power radiated into a solid angle per unit emitting surface area. Radiance is specified by watts/cm^2/steradian.

Optical Detector

1. Light detectors enable an optical signal to be converted back into electrical pulses that are used by the receiving end of the fiber optic data.
2. A photodiode may be simple PIN structure or an APD with internal gain.
3. The responsivity of a photodiode depends on the material.
4. Performance parameters of light detectors.

i) **Responsivity** : The responsivity of a photodetector is the ratio of the current output to the light input. The theoretical maximum responsivity is 1.05 A/W at a wavelength of 1310 nm.

ii) **Quantum efficiency** : Quantum efficiency is the ratio of primary electron hole pairs created by incident photons to number of photons incident on the diode.

iii) **Response time** : Response time represents the time needed for the photodiode to respond to optical inputs and produce an external current.

iv) **Dark current** : Dark current refers to the flow of current through a detector in the absence of light.

Review Questions

Optical Source

1. *List the characteristics of light sources required in optical communication.*
2. *Describe the construction and working of LED.*
3. *Explain the structure of surface emitting and edge emitting LEDs.*
4. *Compare the performance parameters of surface emitting LED and edge emitting LED.*
5. *Deduce the expression at internal quantum efficiency and internally generated optical power for LED. From this expression how external efficiency and power is calculated ?*
6. *Explain the principle of laser action. Explain also the spontaneous and stimulated emission process.*
7. *Give the necessary conditions for lasing threshold.*
8. *Explain the structure of -*
   i) Fabry-Perot resonator.
   ii) DFB laser diode.
9. *Derive expression for lasing condition and hence for optical gain.*
10. *Explain the power current characteristics of laser diode.*
11. *Give the expression for -*
    i) External quantum efficiency.
    ii) Frequency spacing.
    iii) Wavelength spacing.
    State the significance of each parameter in the expression.
12. *Compare the parameters of LED and LASER.*

Optical Detector

1. *With a proper sketch briefly explain the structure of PIN diode.*
2. *Explain the following term relating to PIN photodiode with proper expressions.*
   i) Cut-off wavelength.
   ii) Quantum efficiency.
   iii) Responsivity.
3. *Explain the structure and principle of working of APD.*
4. *Deduce the expression for total current density for APD.*
5. *How the response time of APD is estimated ?*
6. *Give expression for passband of APD detector.*
7. *Compare the performance parameters of PIN and APD.*

University Questions

Q.1 *Using rate equations for photons and carriers (electrons), show that laser is a threshold device.* **[July/Aug.-2006, 8 Marks]**

Ans. : Refer section 3.1.2.2.

Q.2 *With a neat diagram, explain the working of an edge emitting LED. Also mention its special features and usage.* **[July/Aug.-2006, 6 Marks]**

Ans. Refer section 3.1.1.3.

Q.3 *The radiative and non radiative recombination life times of minority carriers in the active region of a double heterojunction LED are 60 nsec and 90 nsec respectively. Determine the total carrier recombination life time and optical power generated internally if the peak emission wavelength is 870 nm and the drive current is 40 mA.* **[July/Aug.-2006, 6 Marks]**

Ans. : Refer example 3.1.3.

Q.4 *A double-hetero junction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 25 and 90 ns respectively. The drive current is 35 mA.*

i) Find the internal quantum efficiency and the internal power.

ii) If the refractive index of the light source material is n = 3.5. Find the power emitted from the device. **[Jan./Feb.-2007, 12 Marks]**

Ans. : Refer example 3.1.4.

Q.5 *A semiconductor laser is operating continuously at a certain current. Its output power changes slightly because of transient current fluctuations. Show that the laser power will attain its original value through an oscillatory approach. Obtain the frequency and the damping time of such oscillations.* **[Jan./Feb.-2007, 10 Marks]**

Ans. : Refer sections 3.1.2.3 and 3.1.2.5.

Q.6 *Derive the expression of power generated internally to the LED and is given by,*

$P_{int} = \eta_{int} \dfrac{hcI}{q\lambda}$ *where* η_{int} *= Internal quantum efficiency.* **[July/Aug.-2007, 8 Marks]**

Ans. : Refer section 3.1.1.5.

Q.7 *A double hetero junction In GaAs LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 30 ns and 100 ns respectively. The drive current is 40 mA. What is the internal quantum efficiency? What is the power generated internally to the LED ?* **[July/Aug.-2007, 6 Marks]**

Ans. : Refer similar example 3.1.4.

Q.8 *Explain the operation of DFB and DBR LASERS.* **[Jan./Feb.-2008, 8 Marks]**

Ans. : Refer section 3.1.2.2.

Q.9 *Explain the operation of an APD.* **[Jan./Feb.-2008, 6 Marks]**

Ans. : Refer section 3.2.3.

Q.10 *Draw the diagram of a typical GaAlAs double hetero-structure light emitter along with energy band diagram and refractive index profile and explain.* **[July/Aug.-2008, 10 Marks]**

Ans. : Refer section 3.1.1.1.

Q.11 *Sketch and explain the Fabry - Perot resonator cavity of laser.* **[July/Aug.-2008, 10 Marks; July/Aug.-2009, 6 Marks]**

Ans. : Refer section 3.1.2.1.

Q.12 *With a neat diagram of cross-section of typical GaAs as double-hetero structure LED, explain the structure and operation of the device.* **[Jan./Feb.-2009, 5 Marks]**

Ans. : Refer section 3.1.1.1.

Q.13 *Explain the principle of laser action. Briefly explain the structure of VCSEL single mode laser with a neat diagram.* **[Jan./Feb.-2009, 5 Marks]**

Ans. : Refer section 3.1.2.

Q.14 *A GaAs laser operating at 1300 nm has a 400 μm length and a refractive index n = 3.5. What are the frequency and wavelength spacings* **[Jan./Feb.-2009, 4 Marks]**

Ans. : Refer similar example 3.1.3.

Q.15 *Describe the emission patterns of different types of LED and laser diode.* **[Jan./Feb.-2009, 4 Marks]**

Ans. : Refer section 3.1.1.4.

Q.16 *Write short note on : Avalanche photodiode.* **[Jan./Feb.-2009, 5 Marks]**

Ans. : Refer section 3.2.3.

Q.17 *Draw the cross-section diagram of GaAl as double-hetero-structure LED and energy band diagram and explain.* **[July/Aug.-2009, 6 Marks]**

Ans. : Refer section 3.1.1.1.