Optical Sources

Optical transmitter coverts 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).

Light Emitting Diodes(LEDs)

p-n Junction

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

layer = 10 µm. As the carriers are not confined to the immediate vicinity 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 confinement occurs due to bandgap discontinuity of the junction. Such a junction is call **heterojunction** and the device is called double **heterostructure.**
- In any optical communication system when the requirements is –

1. Bit rate f 100-2—Mb/sec.
2. Optical power in tens of micro watts.LEDs are best suitable optical source.

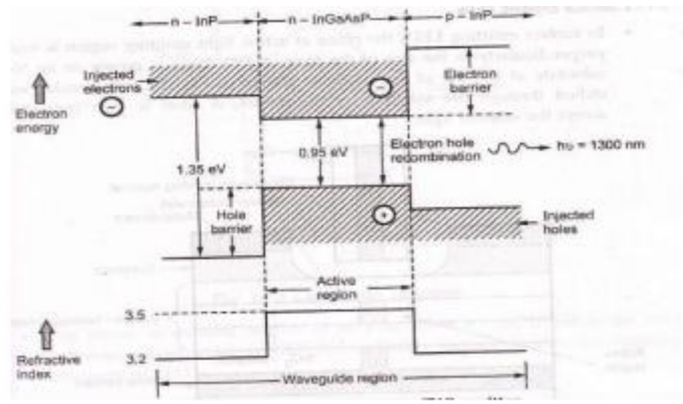
LED Structures

Heterojuncitons

- A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap.
- Heterojuctions 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 structure. A heterojunciton 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.



- The crosshatched regions represent the energy levels of freecharge. 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 heterjuction (DH) structure will confine both hole 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. Antoer advantage 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 –

  Surface emitting LED.
  Edge emitting LED.

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

 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

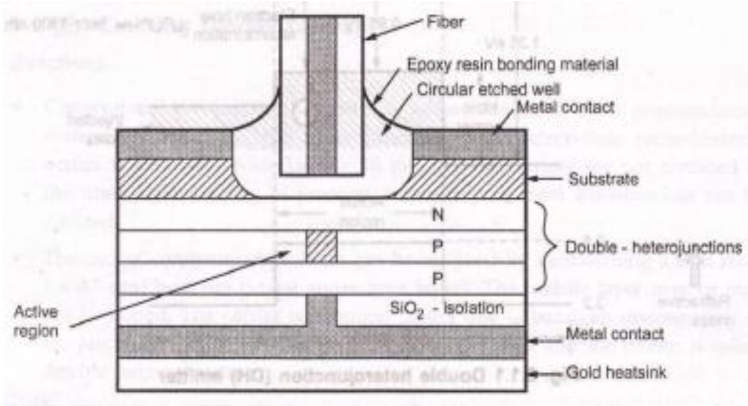


Fig. 3.1.2 Cross-section through a typical surface emitting LED

At the back of 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^o 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.

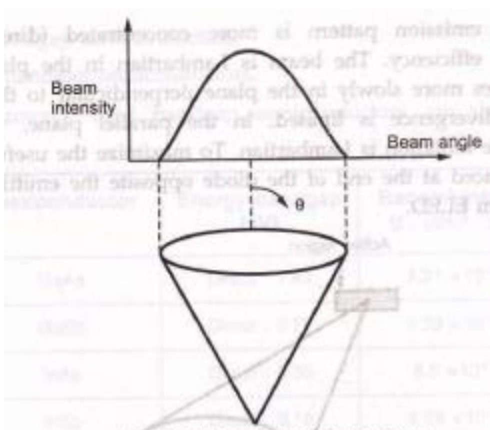


Fig. 3.1.3 Lambartian radiation

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

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 LED

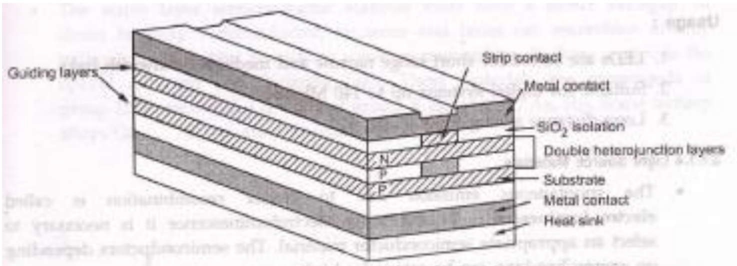


Fig. 3.1.4 Structure of edge emitting, DH, strip contact LED

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.

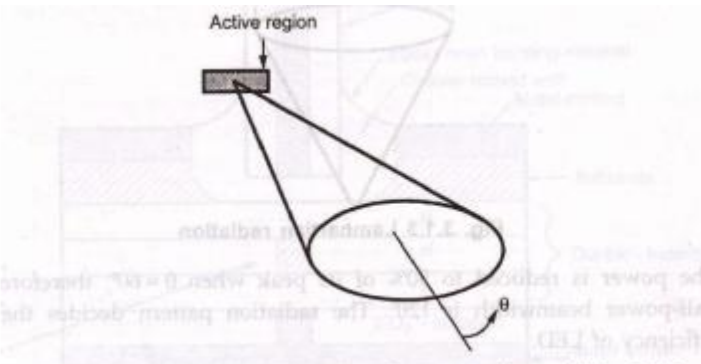


Fig. 3.1.5 Unsymmetric radiation from an edge emitting LED

Features of ELED:

- Linear relationship between optical output and current.
- Spectral width is 25 to 400 nm for $\lambda = 0.8 - 0.9$ µm.
- Modulation bandwidth is much large.

- Not affected by catastrophic gradation mechanisms hence are more reliable.
- ELEDs have better coupling efficiency than surface emitter.
- ELEDs are 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

Light Source Materials

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

Direct bandgap semiconductors
Indirect bandgap semiconductors.

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} and 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 elements (Al, Ga, In) and group V element (P, As, Sb). Some tertiary allos $Ga_{1-x}Al_xAs$ are also used.

Emission spectrum of $Ga_{1-x}Al_xAs$ LED is shown in Fig. 3.1.6.

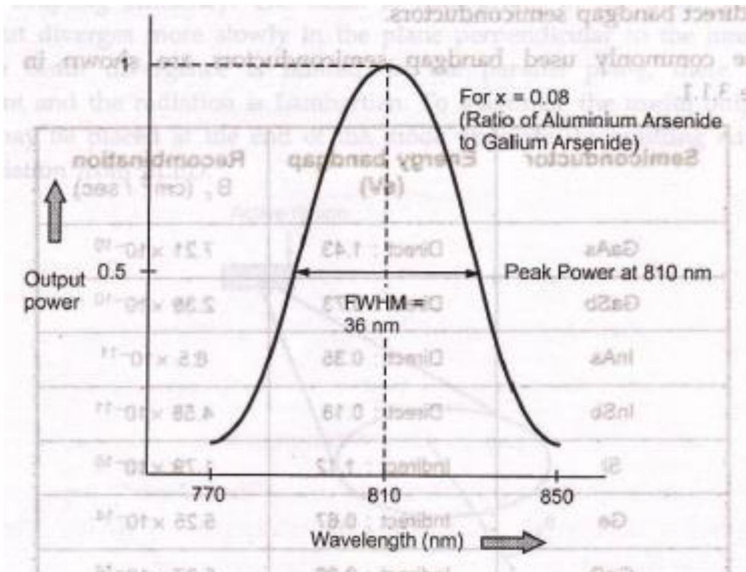


Fig. 3.1.6 Emission spectrum of $Ga_{1-x}Al_xAs$ LED

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 –

$$E = hv$$

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

$$\Rightarrow \qquad \lambda = \frac{hc}{E}$$

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.

$$\boxed{\lambda(\mu m) = \frac{1.24}{E_g(eV)}}$$

Different materials and alloys have different band gap energies

The bandgap energy (Eg) can be controlled by two compositional parameters x and y, within direct bandgap region. The quartenary alloy $In_{1-x} Ga_x As_y P_{1-y}$ is the principal material sued in such LEDs. Two expression relating Eg and x,y are –

$$E_g = 1.424 + 1.266\, x + 0266\, x^2 \quad \text{... 3.1.3}$$

$$E_g = 1.35 - 0.72\, y + 0.12\, y^2 \quad \text{... 3.1.4}$$

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

Solution : x = 0.07

$$E_g = 1.424 + 1.266\, x + 0266\, x^2$$

$$E_g = 1.424 + (1.266 \times 0.07) + 0266 \times (0.07)^2$$

Eg = 1.513 eV

Now

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

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

$$\lambda = 0.819\ \mu m$$

...**Ans.**

$$\lambda = \mathbf{0.82\ \mu m}$$

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

Solution : Comparing the alloy with the quartenary alloy composition.

$In_{1-x} Ga_x As P_{1-y}$ it is found that

x = 0.26 and y = 0.57

$$Eg = 1.35 - 0.72\, y + 0.12\, y^2$$

Using

Eg = 1.35-(0.72 x 0.57) + 0.12 x 0.57^2 Eg = 0.978 eV

Now

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

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

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

$$\lambda = \mathbf{1.27\ \mu m}$$ … **Ans.**

Quantum Efficiency and Power

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

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \quad \text{… 3.1.5}$$

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, $\tau_r = \frac{n}{R_{nr}}$

The internal quantum efficiency is given

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

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}} \quad \text{… 3.1.7}$$

Therefore internal quantum efficiency is given as –

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

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

From equation 3.1.5

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

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

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

- Optical power generated internally in LED is given as –

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

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

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

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

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

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

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

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

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

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 si 870 nm and the drive currect is 40 mA.

Solutions : Given : λ = 870 nm 0.87 x 10^{-6}m

τ_r = 60 nsec.

τ_{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:

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

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

$$P_{int} = \left(\frac{30}{60}\right)\left[\frac{(6.625 \times 10^{-34})(3 \times 10^{8}) \times 0.04}{(1.602 \times 10^{-19})(0.87 \times 10^{-6})}\right]$$

$$P_{int} = 34.22 \text{ mW}$$

Example 3.1.4 : A double heterjunciton 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 –

- Bulk recombination life time.
- Internal quantum efficiency.
- Internal power level.

Solution : λ = 1310 nm = (1.31 x 10^{-6}m)

τ_r = 30 ns

τ_{nr} = 100 ns

I = 40 MA – 0.04 Amp.

- **Bulk Recombination Life time (τ) :**

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

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

… **Ans.**

∴ τ = 23.07 **nsec.**

Internal euqntum efficienty (ηint)

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

$$\eta_{int} = 0.769$$

…

Ans. iii) Internal pwer level (Pint) :

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

Advantages and Disadvantages of LED

Advantages of LED

- Simple design.
- Ease of manufacture.
- Simple system integration.
- Low cost.
- High reliability.

Disadvantages of LED

- Refraction of light at semiconductor/air interface.
- The average life time of a radiative recombination is only a few nanoseconds, therefore nodulation BW is limited to only few hundred megahertz.
- Low coupling efficiency.
- Large chromatic dispersion.

Comparison of Surface and Edge Emitting LED

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

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 than emitting. Three different fundamental process occurs between the two energy states of an atom.

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 E1 is the lower state energy level.
E2 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 E1 is lower state energy level.
and E2 is higher state energy level. $E = (E2 - E1) = h.f.$

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 (E2 – E1) is incident on the atom it will be excited into the higher energy state E2 through the absorption of the photon

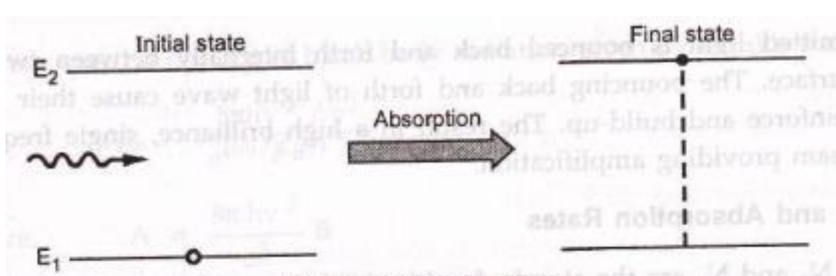


Fig. 3.1.7 Absorption

- When the atom is initially in the higher energy state E2, it can make a transition to the lower energy state E1 providing the emission of a photon at a frequency corresponding to E = h.f. The emission process can occur in two ways.

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

By stimulated emission when a photon having equal energy to the difference between the two states (E2 – E1) interacts with the atom causing it to the lower state with the creation of the second photon

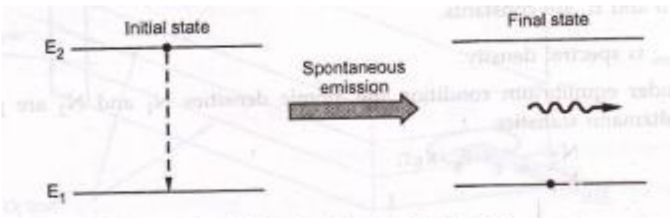


Fig. 3.1.8 Spontaneous emission

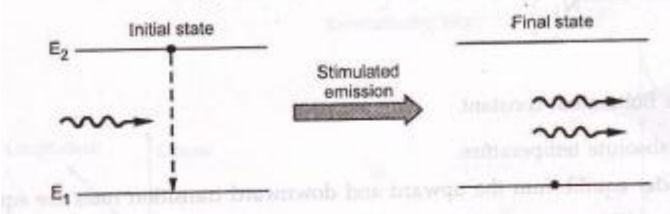


Fig. 3.1.9 Stimulated emission

- 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.