29. Consider a semiconductor laser operating at 900 nm. If the spectral width over which the gain is available is 15 nm. What is the maximum cavity length for single longitudinal mode operation ? Assume the refractive index $n = 3.6$.

30. Determine the slope efficiency of a laser diode operating at $\lambda = 1300$ nm if its external quantum efficiency of $\eta_{ext} = 0.1$.

31. What are stimulated emission and spontaneous emission ? Explain the principle of laser action. **[UPTU 2003-04]**

32. What are the advantages of semiconductor lasers over light emitting diodes for communication ? **[UPTU 2003-04]**

33. Explain the working principle of a non-semiconductor LASER using suitable diagram. **[UPTU 2004-05]**

34. What is meant by optical and electrical confinement in a LASER ? How is it achieved ? Explain. **[UPTU 2004-05]**

35. What is population inversion ? Explain the mechanism of population inversion in a three level or four level system. **[UPTU 2007-08]**

36. Derive an expression for the threshold value of gain for laser oscillations. **[UPTU 2007-08]**

37. What is internal quantum efficiency, differential quantum efficiency and total efficiency of semiconductor laser ? **[UPTU 2007-08]**

38. Explain the necessity of carrier confinement and optical confinement in semiconductor laser. How these confinements are achieved ? Explain the structure of any one double heterojunction semiconductor laser. **[UPTU 2007-08]**

39. Explain semiconductor injection laser. Find its internal quantum efficiency and show how it is related to the differential external quantum efficiency. **[UPTU 2008-09]**

40. The threshold current of a particular laser diode doubles when its temperature is increased by 50°C. Determine the characteristic temperature of the laser.

41. Determine the threshold gain for a semiconductor laser with a length of 250 μm, $\alpha = 5\ mm^{-1}$ and end faces reflectives 90% and 80%. What is the corresponding photon lifetime ?

42. A GaAs injection laser with a cavity of length 500 μm has a loss coefficient of 20 cm^{-1}. The measured differential external quantum efficiency of the device is 45%. Calculate the internal quantum efficiency of the laser. The refractive index of GaAs is 3.6.

❑❑❑

Optical Sources 2: The Light Emitting Diode

7

INSIDE THIS CHAPTER

7.1. INTRODUCTION

Optical sources for fiber communication should satisfy some desirable properties in terms of :

- intensity
- radiation pattern
- emission wavelength
- spectral characteristics
- response time.

Semiconductor diode sources of the LED and LD types are a natural choice for fiber optic systems due to :

- high efficiency
- compact size
- low power consumption
- high reliability.

A light-emitting diode (LED) is a semiconductor diode that emits incoherent narrow spectrum light when electrically biased in the forward direction of the *p-n* junction. This effect is a form of **electroluminescence.**

An LED is usually a small area source, often with extra optics added to the chip that shapes its radiation pattern. The colour of the emitted light depends on the composition and condition of the semiconducting material used, and can be infrared, visible, or near ultraviolet.

Semiconductor materials can be classified as :

- Direct bandgap materials
- Indirect bandgap material

In **direct bandgap materials** charge carriers can make a transitions from the conduction to the valance band at the same K value *i.e.,* without a change in momentum. For this reason direct bandgap materials such as GaAs are the most appropriate and efficient materials for generation of light.

DO YOU KNOW

LEDs project all their light forwards whereas most common light sources emit light in all directions.

Indirect band materials (Ex. Si), if used will need photon assisted transitions to conserve the momentum.

There are several reasons because of which semiconductor light emitting diodes (LED) are preferred light sources and these are :

1. They give adequate power.
2. They give adequately low noise.
3. The dimensional characteristics of LED's are compatible with those of optical fiber, which means that coupling of fibers with light source will be easier.
4. The light from LED can be varied or modulated by varying the applied voltage or current through the device which is essentially the information to be transmitted.

7.2. HISTORY OF LED

- In the early 20th century, **Henry Round of Marconi Labs** first noted that a semiconductor junction could produce light. Russian Oleg Vladimirovich Losev independently created the first LED in the mid-1920s; his research, though distributed in Russian, German and British scientific journals, was ignored.
- Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955.
- Experimenters at Texas Instruments, Bob Biard and Gary Pittman, found in 1961 that gallium arsenide gave off infrared (invisible) light when electric current was applied.
- Biard and Pittman were able to establish the priority of their work and received the patent for the infrared light-emitting diode.
- Nick Holonyak Jr., then of the General Electric Company and later with the University of Illinois at Urbana-Champaign, developed the first practical visible-spectrum LED in 1962 and is seen as the **"father of the light-emitting diode".**
- Holonyak's former graduate student, M. George Craford, invented in 1972 the first yellow LED, brighter red and red-orange LED's.

Shuji Nakamura of Nichia of Japan demonstrated the first high-brightness blue LED based on InGaN, borrowing on critical developments in GaN nucleation on sapphire substrates and the demonstration of p-type doping of GaN which were developed by I. Akasaki and H. Amano in Nagoya. The existence of the blue LED led quickly to the first white LED, which employed a Y3A15O12:Ce, or "YAG", phosphor coating to mix yellow (down-converted) light with blue to produce light that appears white. Nakamura was awarded the 2006 Millennium Technology Prize for his invention.

7.3. LIGHT SOURCE MATERIALS

LEDs that emit light of different colour are made of different semiconductor materials. The semiconductor materials that are used for the active layer of an optical source must have a direct band gap. Various binary, ternary and quaternary semiconductors are used for optical sources. **Binary semiconductor** contains a single anion and single cation, that are used in LED includes : SiC, ZnSe, GaN, GaP, GaAs, InP, InAs, GaSb. The first three are wideband gap semiconductors and are used to generate blue light. But presently they are of very little use because they are very inefficient. More lightly nitrogen doped material is used for yellow emitter. When GaP is doped with both zinc and oxygen, it emits red light.

- **Ternary semiconductors** such as GaAsP, GaAlAs and InGaAs are used because they can adjust the energy gaps to a desired wavelength by choosing the appropriate composition.
- **Ternary** LEDs have the advantage that they can be tuned at a specific wavelength when energy gap varies with the composition. At a first level approximation, it varies linearly and is given by :

$$E_g(A_{1-x}B_xC) = E_g(AC) + [E_g(BC) - E_g(AC)]x \qquad ...(7.1)$$

But a more accurate representation is

$$E_g(A_{1-x}B_xC) = E_g(AC) + [E_g(BC) - E_g(AC)]x - b_{AB}x(1-x) \qquad ...(7.2)$$

where x = Fraction of component B

b_{AB} = bowing parameter (experimentally determined parameter *i.e.,* always positive)

The **direct semiconductors** are those in which electrons and holes on either side of the forbidden energy gap have the same value of crystal momentum and therefore direct recombination is possible. In direct bandgap semiconductors electroluminance is possible and this process is shown in Fig. 7.1.

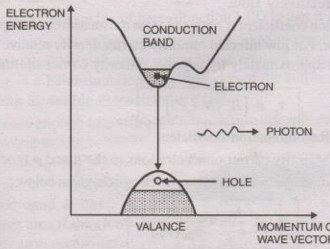


Fig. 7.1. Energy-momentum diagram of direct bandgap semiconductor.

The maximum energy of valence band occurs at the same value of electron crystal momentum as the minimum energy of the condition band. Thus when electron hole recombination take place, the electrons momentum remains virtually constant and bandgap energy E_g may be emitted as light. This direct transition of an electron across the energy gap provides an efficient mechanism for photon emission and average time before the recombination, the minority carrier remains in a free state is short *i.e.*, 10^{-8} to 10^{-10} sec.

> **DO YOU KNOW**
>
> LEDs have a life time of between 25,000-50,000 hours.

In **indirect bandgap semiconductors** the maximum and minimum energies occur at different values of crystal momentum, as shown in Fig. 7.2.

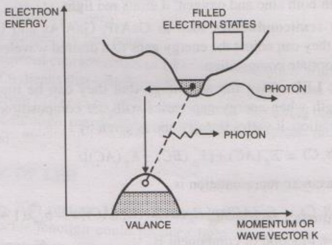


Fig. 7.2. Electron-momentum diagram of indirect bandgap semiconductor.

Electron hole recombination occur when electron loses momentum such that the value of momentum occurs corresponds to the maximum energy of valence band. The conversion of momentum requires the emission or absorption of a third particle known as **photon**. The three particle recombination process is for less probable than the two particle process. Thus the recombination in indirect bandgap semiconductors is relatively slow.

The recombination coefficient is obtained from the measured absorption coefficient of the semiconductor. For low infected minority carrier density relative to the majority carriers, it is related approximately to radiative minority carrier lifetime τ_r by

$$\tau_r = [B_r (N + P)]^{-1} \qquad ...(7.3)$$

where, B_r = Recombination coefficient

N and P = Majority carrier concentrations in the n and p type regions.

The formula relating electron energy to wavelength is given below :

$$\lambda = \frac{hc}{\varepsilon_{ph}} = \frac{1.24}{\varepsilon_{ph}(Ev)} \qquad ...(7.4)$$

where λ = Wavelength in microns

h = Plancks constant = $6.63 \times 10^{-34} = 4.14 \times 10^{-15}$ eV.s

c = Speed of light = 3×10^8 metres.sec

ε_{ph} = Photon energy in eV

This means that the materials of which the LED is made determine the wavelength of light emitted. The following table shows energies and wavelengths for commonly used materials in semiconductor LED's and lasers :

Table 7.1. Bandgap Energy and Possible Wavelength Ranges in Various Materials.

Material	Formula	Wavelength Range λ (μm)	Bandgap Energy W_g (eV)
Indium Phosphide	InP	0.92	1.35
Indium Arsenide	InAs	3.6	0.34
Gallium Phosphide	GaP	0.55	2.24
Gallium Arsenide	GaAs	0.87	1.42
Aluminium Arsenide	AlAs	0.59	2.09
Gallium Indium Phosphide	GaInP	0.64-0.68	1.82-194
Aluminium Gallium Arsenide	AlGaAs	0.8-0.9	1.4-1.55
Indium Gallium Arsenide	InGaAs	1.0-1.3	0.95-1.24
Indium Gallium Arsenide Phosphide	InGaAsP	0.8-1.7	0.73-135

7.4. HETEROJUNCTIONS

A **heterojunction** is a junction in which the p and n type materials are different semiconductors.

A heterojunction is not unlike an ordinary *p-n* junction. The difference in bandgap energies creates a one-way barrier. Charge carriers (electrons or holes) are attracted over the barrier from the material of higher bandgap energy to the one of lower bandgap energy.

The **two basic LED configurations being used for fiber optics are :**

(1) Surface emitters (also known as burrus or front emitters)

(2) Edge emitters

- One major advantage of heterojunction LED is that it can be an edge emitter.
- In GaAlAs heterojunction the LED's light is created in a central region sandwiched between two regions that contain more aluminium. Because there is a heterojunction on either side of the active region, this structure is known as **double hetrostructure *DH*.**
- It's easy enough to construct a *p-n* junction that will emit light of the required wavelength.

As illustrated in Fig. 7.3, *p-n* junctions are necessarily very thin, flat and need to cover a relatively large area if they have to produce any meaningful amount of light. Further, light is spontaneously emitted in all directions and since the

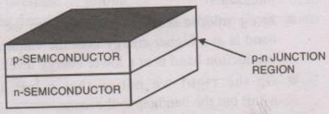


Fig. 7.3. Simple p-n Junction LED.

semiconductor material is transparent over the band of wavelengths produced, the light will disperse in all directions. It is very difficult to get any mean-ingful amount of light into a fiber from a regular *p-n* junction.

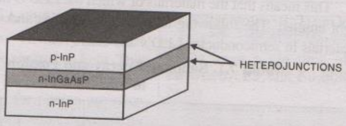


Fig. 7.4. Double Heterojunction LED.

What is needed is a way of producing light in a more localized area, with a greater intensity and with some way of confining the light produced such that we can get it (or a lot of it), into a fiber. The heterojunction is the answer to this problem.

Double Heterojunction : When a layer of material with a particular bandgap energy is sandwiched between layers of material with a higher energy bandgap a double heterojunction is formed. This is called a double heterojunction because there are two heterojunctions present—one on each side of the active material. The double heterojunction forms a barrier which restricts the region of electron-hole recombination to the lower bandgap material. This region is then called the **active region**. An energy diagram of a double heterojunction is shown in Fig. 7.5.

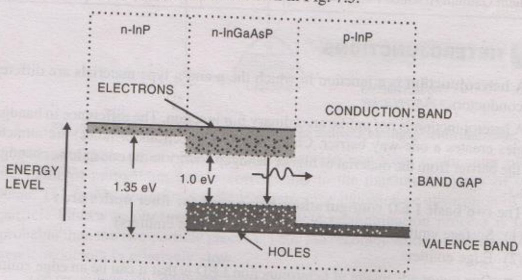


Fig. 7.5. Energy Bands in a Double Heterojunction.

The diagram shows the energy levels for the **three sections** of the double heterojunction.

- On the **left** is n-InP. The lower dotted line represents the energy level of the valence band in this material. The upper dotted line represents the lowest energy in the valence band for this material. Thus there is a bandgap difference of 1.35 eV.
- In the **middle section** of the diagram we see n-InGaAsP. Here the valence band is at a higher energy than the valence band of the adjacent n-InP. The conduction band is at a lower energy level.
- On the **right** we notice that p-InP has higher energy levels than n-InP but the bandgap is the same.

Electrons are attracted across the left-hand junction from the n-InP to the n-InGaAsP. Holes are attracted across the right-hand junction from the p-InP into the n-

InGaAsP. Recombination takes place in the n-InGaAsP and spontaneous emission (or lasing) occurs.

7.5. LED POWER AND EFFICIENCY

The internal quantum efficiency of the device is limited by the absense of optical amplification through stimulated emission in the LED. The power generated internally by an LED may be determined by the consideration of excess electrons and holes in the *p* and *n*-type material respectively, when it is forward biased and carrier injection takes place at the device contacts.

The excess density of electrons Δ_n and holes Δ_p is equal since the injected carriers are created and recombined in pairs such that charge neutrality is maintained within the structure.

In extrinsic materials one type of carrier will have much higher concentration than other type, example. In the *p*-type region the hole concentration will be much higher than the electron concentration.

Generally the **excess minority carrier density decays exponentially with time *t*** according to the relation

$$\Delta n = \Delta n(0) \exp\left(\frac{-t}{\tau}\right) \quad ...(7.5)$$

where, $\Delta n(0)$ = Initial injected excess electron density.

t = Total carrier recombination life time.

Δn = Small fraction of the majority carriers and comprises all of the minority carriers.

When there is a constant flow of current into the junction diode, an equilibrium condition is established. In this case the total rate at which carriers are generated will be the sum of the externally supplied and the thermal generation rates.

The **current density *J*** in amperes per square meter may be written as

J/ed in electrons per cubic meter per second.

where, e = Charge on an electron.

d = Thickness of the recombination region.

A **rate equation for carrier recombination** in the LED :

$$\frac{d(\Delta n)}{dt} = \frac{J}{ed} - \frac{\Delta n}{\tau} \,(\text{m}^{-3}\text{s}^{-1}) \quad ...(7.6)$$

The condition for equilibrium is obtained by setting the derivative in Eqn. (7.6) to zero. Hence the **steady state electron density** when a constant current is flowing into the junction region is :

$$\Delta n = \frac{J\tau}{ed} \,(\text{m}^{-3}) \quad ...(7.7)$$

In steady state the total number of carrier recombinations per second or the **recombination rate r_t :**

$$r_t = \frac{J}{ed} = r_r + r_{nr} \ (\text{m}^{-3}) \quad ...(7.8)$$

where r_r is the radiative recombination rate per unit volume and r_{nr} is the nonradiative recombination rate per unit volume.

From Eqn. (7.8) the **total number of recombinations per second R_t** :

$$R_t = \frac{i}{e} \quad ...(7.9)$$

Internal Quantum Efficiency : The LED **internal quantum efficiency** η_{int} (the ratio of the radiative recombination rate to the total recombination rate) :

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}} = \frac{R_r}{R_t} \quad ...(7.10)$$

where R_r is the total number of radiative recombinations per second. Rearranging Eqn. (7.10) and substituting from Eqn. (7.9) gives :

$$R_r = \eta_{int} \frac{i}{e} \quad ...(7.11)$$

The **optical power generated** internally by the LED, P_{int} is :

$$P_{int} = \eta_{int} \frac{i}{e} hf \quad ...(7.12)$$

or

$$P_{int} = \eta_{int} \frac{hci}{e\lambda} \quad ...(7.13)$$

For the exponential decay of excess carriers :

The **radiative minority carrier lifetime** is

$$\tau_r = \frac{\Delta n}{r_r}$$

The **nonradiative minority carrier lifetime** is

$$\tau_{nr} = \frac{\Delta n}{r_{nr}}.$$

Therefore from Eqn. (7.10) the **internal quantum efficiency** is :

$$\eta_{int} = \frac{1}{1 + \left(\frac{r_{nr}}{r_r}\right)} = \frac{1}{\left[1 + \left(\frac{\tau_r}{\tau_{nr}}\right)\right]} \quad ...(7.14)$$

The **total recombination lifetime** τ can be written as $\tau = \frac{\Delta n}{r_t}$ which, using Eqn. (7.8), gives

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad ...(7.15)$$

Hence

$$\eta_{int} = \frac{\tau}{\tau_r} \quad ...(7.16)$$

External Quantum Efficiency

To find the emitted power, one needs to consider the external quantum efficiency (η_{ep}). It is defined as the ratio of the optical power emitted externally P_e to the electrical power provided to the device P or

$$\eta_{ep} \cong \frac{P_e}{P} \times 100\%$$

Also the optical power emitted P_e into a medium of low refractive index n from the face of a planar LED fabricated from a material of refractive index n_x is given by

$$P_e = \frac{P_{int} F_n^2}{4n_x^2}$$

where P_{int} = Power generated internally

F = Transmission factor of the semiconductor-external interface

Coupling Efficiency

When coupling the light output into a fiber, a further loss is enountered. The consideration of this coupling efficiency is very complex, however it is possible to use an approximate simplified approach.

Let us assume that,

For step index fibers, all the light incident on the exposed end of the core within the acceptance angle θ_a is coupled then for a fiber in air :

$$\theta_a = \sin^{-1} (n_1^2 - n_2^2)^{1/2} \quad ...(7.17)$$

$$= \sin^{-1} (\text{NA}) \quad ...(7.18)$$

Also, incident light at angles greater than θ_a will not be coupled. For a Lambertion source, the radiant intensity at an angle θ, $I(\theta)$ is given by

$$I(\theta) = I_0 \cos\theta \quad ...(7.19)$$

where, I_0 = Radiant intensity along the line

$\theta = 0$

Considering a source which is smaller than, and in close proximity to, the fiber core. By assuming cylindrical symmetry, the coupling efficiency (η_c) is given by

$$\eta_c = \frac{\int_0^{\theta_a} I(\theta) . \sin\theta . d\theta}{\int_0^{\pi/2} I(\theta) . \sin\theta . d\theta} \quad ...(7.20)$$

From the above equation, we get

$$\eta_c = \frac{\int_0^{\theta_a} I_0 . \cos\theta . \sin\theta . d\theta}{\int_0^{\pi/2} I_0 . \cos\theta . \sin\theta . d\theta} = \frac{\int_0^{\theta_a} I_0 . \sin 2\theta . d\theta}{\int_0^{\pi/2} I_0 . \sin 2\theta . d\theta}$$

$$\eta_c = \frac{\left[-I_0 \cdot \frac{\cos 2\theta}{2}\right]_0^{\theta_a}}{\left[-I_0 \frac{\cos 2\theta}{2}\right]_0^{\pi/2}}$$

DO YOU KNOW

High power LEDs can be driven at currents from hundreds of mA to more than an ampere and can emit over thousand lumens.

$$\boxed{\eta_c = \sin^2 \theta_a} \quad \text{...(7.21)}$$

Therefore, from Eq. (7.21)

$$\boxed{\eta_c = (NA)^2} \quad \text{...(7.22)}$$

Above equation is for the coupling efficiency allows estimates for the percentage of optical power coupled into the step index fiber relative to the amount of optical power emitted from the LED.

7.6. LED STRUCTURES

Mainly there are five major types of LED structure but only two have been widely used in optical fiber communication. These are :

- Planar LED
- Dome LED
- Surface emitter LED
- Edge emitter LED
- Superluminescent LED.

7.6.1. Planar LED

It is the simplest of the structures that are available and is fabricated by either liquid or vapour phase epitaxial process over the whole surface of a GaAs substrate. This involves a *p*-type diffusion into the *n*-type substrate in order to create the junction as shown in Fig. 7.6.

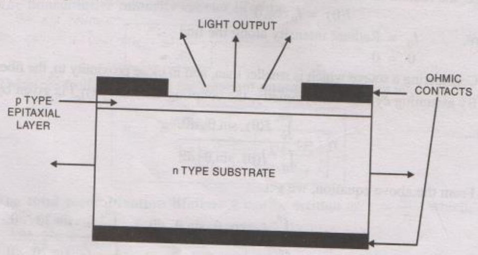


Fig. 7.6.

(*i*) Forward current flow through the junction gives **Lambertian spontaneous emission** and the device emits light from all surfaces.

(*ii*) Only a limited amount of light escapes the structure due to total internal reflection, and therefore the radiance is low.

7.6.2. Dome LED

The structure of a typical dome LED is shown in Fig. 7.7.

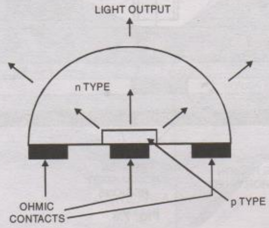


Fig. 7.7.

(*i*) A hemisphere of *n*-type GaAs is formed around *p*-region.

(*ii*) The diameter of the dome is chosen to maximize the amount of internal emission reaching the surface within the critical angle of the GaAs air interface.

(*iii*) The device has a **higher external power efficiency** than the planar LED.

(*iv*) However, the geometry of the structure is such that the dome must be far larger than the active recombination area, which gives a greater effective emission area and thus reduces the radiance.

7.6.3. Surface Emitter LED's

A method for obtaining high radiance is to restrict the emission to a small active region within the device. 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 radiation emission into the optical fiber.

The structure of a high radiance etched well *DH* surface emitter for the 0.8 to 0.9 μm wavelength band is shown in Fig. 7.8.

The power coupled into a multimode step index fibre :

$$\boxed{P_c = \pi(1-r) A R_D (NA)^2} \quad \text{...(7.23)}$$

where r = Fresnel reflection coefficient at the fibre surface.

A = Smaller of the fibre core cross section or the emission area of the source.

and R_D = Radiance of the source.

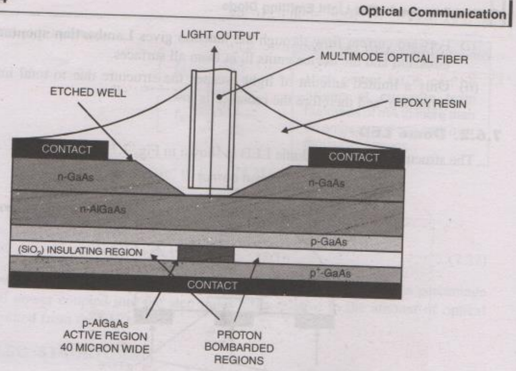


Fig. 7.8.

The **power coupled into the fiber is also dependent on many other factors** including;

- the distance
- alignment between the emission area and the fiber
- the SLED emission pattern
- the medium between the emitting area and fiber.

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

7.6.4. Edge Emitter LED's

Another basic high radiance structure currently used in optical communications is the stripe geometry. This device has a similar geometry to a conventional contact stripe injection laser as shown in Fig. 7.9.

(*i*) It takes advantage of transparent guiding layers with a very thin active layer (50 to 100 μm) in order to reduce self absorption in the active layer.

(*ii*) The consequent waveguiding narrows the beam divergence to a half power width of around 30° in the plane perpendicular to the junction.

(*iii*) However, the lack of waveguiding in the plane of the junction gives a Lambertian output with a half power width of around 120°.

The enhanced waveguiding of the edge emitter enables it in theory to couple 7.5 times more power into low NA fiber than a comparable surface emitter. Coupling efficiency may be achieved into low NA fiber with surface emitters by the use of a lens.

The stipe geometry of the edge emitter allows very high carrier injection densities for given drive currents. Thus it is possible to couple approaching a milliwatt of optical

power into low *NA* (0.14) multimode step index fiber with edge emitting LED's operating at high drive currents *i.e.*, 500 mA.

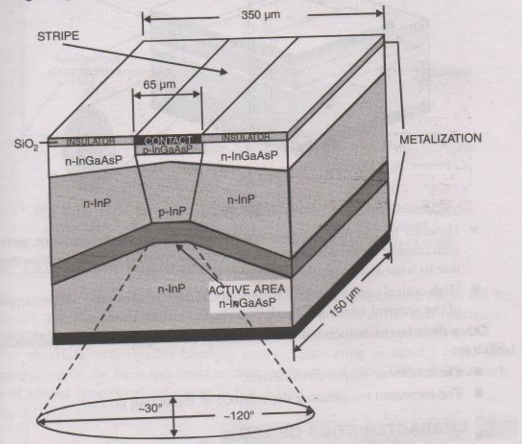


Fig. 7.9.

Edge emitters have also been found to have a substantially better modulation bandwidth of the order of hundreds of megahertz than comparable surface emitting structures with the same drive level.

7.6.5. Super Luminescent LED's

A third device geometry which is already providing significants benefits over both SLED's and ELED's for communication applications is the superluminescent diode or SLD. This device gives **several advantages :**

1. A high output power.
2. A directional output beam.
3. A narrow spectral linewidth.

All of the which prove useful for coupling significant optical power levels into optical fiber to single mode fiber. Figure 7.10 shows the structures of the SLD.

- For operation the injected current is increased until stimulated emission and hence amplification occurs, but because there is high loss at one end of the device, no optical feedback takes place.
- Although there is amplification of the spontaneous emission, no laser oscillations builds up.

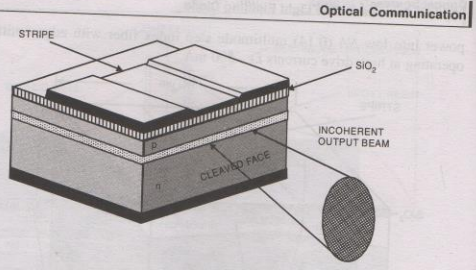


Fig. 7.10.

- However the operation in the current region for stimulated emission provides gain causing the device output to increase rapidly with increase in drive current due to what is effectively single pass amplification.
- High optical output power can therefore be obtained together with a narrowing of the spectral width which also results from stimulated emission.

Other **drawbacks associated with the SLD in comparison with conventional LED's** are :

- The nonlinear output characteristic
- The increased temperature dependence of the output power.

7.7. CHARACTERISTICS OF LED's

7.7.1. Optical Output Power–Current Characteristics

The ideal **light output power against current characteristic** for an LED is shown in Fig. 7.11.

It is linear corresponding to the linear part of the injection laser optical power output characteristic before lasing occurs. Basically LED is a very linear device in comparison with the majority of injection lasers and hence it is more suitable for **analog transmission.** Practically LED's exhibit nonlinear behaviour because it depends on configuration utilized.

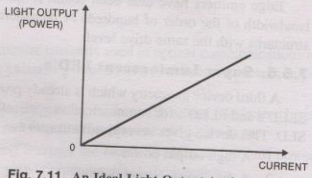


Fig. 7.11. An Ideal Light Output Against Current Characteristics an LED.

Therefore it is necessary to use same form of **linearizing circuit technique to get the linear performance of the device** to allow its use in high quality analog transmission systems Fig. 7.12 (*a*) and (*b*) shows the light output against current characteri-stics for good surface and edge emitters respectively.

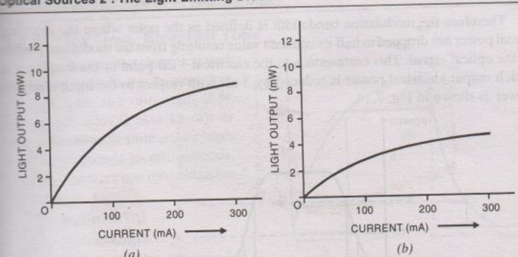
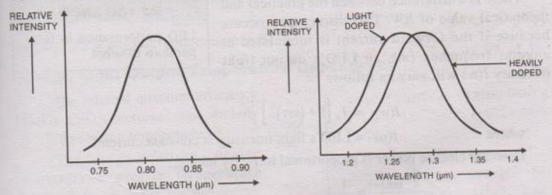


Fig. 7.12. Light Output Power Into Air Against d.c. Driven Current.
(*a*) An AlGaAs Surface Emitter with 50 μm Diameter Dot Contact.
(*b*) An AlGaAs Edge Emitter with a 65 μm Wide Stripe and 100 μm Length.

7.7.2. LED Output Spectrum

The spectral linewidth of an LED operating at room temperature in the 0.8 to 0.9 μm wavelength band is usually between 25 and 40 nm at the half maximum intensity points.

For materials with smaller bandgap energies operating in the 1.1 to 1.7 μm wavelength region the linewidth tends to increase to around 50 to 160 nm. **Two such types of output spectrums** are shown in Fig. 7.12.



(*a*) *Output spectra for an AlGaAs surface emitter with doped active region.*

(*b*) *Output spectra for an InGaAsP surface emitter showing both lightly doped and heavily doped cases.*

Fig. 7.13. LED Output Spectra.

Figure 7.13(*b*) shows the increase in linewidth due to increased doping levels. There is a shift to lower peak emission wavelength through reduction in doping and hence the active layer composition must be adjusted if the same centre wavelength is to be maintained.

7.7.3. Modulation Response

In optical communication the **modulation bandwidth** may be defined in either electrical or optical terms. Normally electrical terms are used because the bandwidth can be determined via electrical circuitry.

Therefore the modulation bandwidth is defined as the point where the electrical signal power has dropped to half its constant value resulting from the modulated portion of the optical signal. This corresponds to the electrical 3 dB point or the frequency at which output electrical power is reduced by 3 dB with respect to the input electrical power as shown in Fig. 7.14.

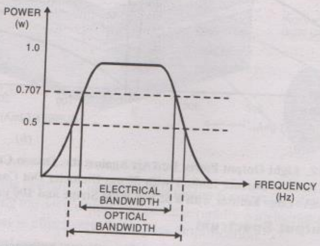


Fig. 7.14. Frequency response of the optical source.

The **relationship between bandwidth and rise time** is given as

$$BW = \frac{0.35}{t_r} \quad ...(7.24)$$

There is a difference between the practical and theoretical value of *BW*. This discrepancy occurs because if the forward current is modulated at angular frequency (*w*), an LED's output light intensity *I*(*w*) will vary as follows :

> **DO YOU KNOW**
>
> LED performance is temperature different.

$$I(w) = I_o\left[1+(\omega\tau)^2\right]^{-1/2} \quad ...(7.25)$$

where $I(o)$ = LED's light intensity at constant current.

Detected electric power is proportional to I^2. By taking,

$$\frac{I^2(\omega)}{I^2(o)} = \frac{1}{2} \quad ...(7.26)$$

which is a –3 dB decline. Hence bandwidth becomes,

$$BW = \Delta\omega = \frac{1}{\tau} \quad ...(7.27)$$

That is an LED modulation bandwidth is limited by the recombination lifetime of the charge carriers.

Another **important characteristics** of an LED is **power bandwidth product.** The product of LED's power output power and its modulation bandwidth is constant.

$$BW \times P = \text{Constant}$$

i.e., by increasing bandwidth, the output power will decrease and vice versa.

7.7.4. Life Time, Rise/Fall Time

Life time τ of the charge carriers is the time between the moment they excited and the moment they recombine. This is also known as **recombination life time** and it ranges from nanoseconds to milliseconds. Basically there are two recombination life times :

(*a*) Radiative (τ_r)

(*b*) Nanoradiative (τ_{nr}).

Thus **total carrier lifetime** is given as :

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad ...(7.28)$$

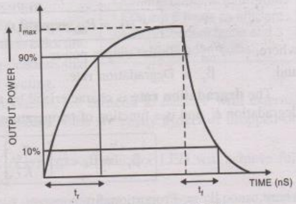


Fig. 7.15. Rise Time/Fall Time.

Rise/fall time (τ_r) is defined as 10 to 90% of the maximum value of the pulse as shown in Fig. 7.15.

Rise/fall time is determined by an LED's capacitance (*C*), input step current with amplitude (I_P) and total recombination life time (τ).

$$\tau_r = 2.2\left[\tau + \left(\frac{1.7\times10^{-4}\times T^o K \times C}{I_P}\right)\right] \quad ...(7.29)$$

where T = absolute temperature in K.

7.7.5. Light Output Temperature Dependence

The internal quantum efficiency of the LED's decreases exponentially with increasing temperature.

The edge-emitting device exhibits a greater temperature dependence than the surface emitter and the output of SLD is *strongly* dependent on the junction temperature.

Figure 7.16 shows the variation of optical output power with temperature for different LED's.

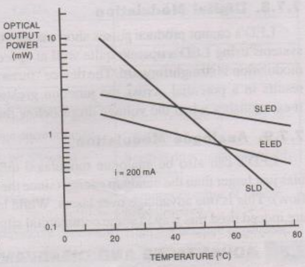


Fig. 7.16.

7.7.6. Reliability

LED's are generally not affected by the **catastrophic degradation.** They do **exhibit gradual gradation (defects).**

The optical output power $P_e(t)$ may be expressed as a function of the operating time t :

$$P_e(t) = P_{out} \exp(-\beta_r t) \quad ...(7.30)$$

where, P_{out} = Initial output power

and β_r = Degradation rate.

The **degradation rate** is characterized by the activation energy of homogeneous degradation E_a and is a function of temperature :

$$\beta_r = \beta_0 \exp\left[-\frac{E_a}{KT}\right] \quad ...(7.31)$$

where, β_0 = Proportionality constant,

K = Boltzmann's constant,

T = Absolute temperature of the emitting region.

7.7.7. Low Cost

LED's have been very low in cost compared to communication lasers. This is highly controversial. Communication LED's and lasers are not too different in their structures and are comparable in manufacturing cost. Connecting to single mode fiber (pigtailing) is significantly more costly than connecting to multimode fiber and since lasers are commonly used with single mode and LED's with multimode there is a cost difference here.

However whilst most LED's cant be used with single-mode fiber, lasers certainly can be used with multimode fiber. In early 1996, people began to use the lasers from CD-ROM players for short distance communications on MM fibre. These are about 1/10 the cost of standard communications LED's (simply because they are made in vast volume—several million per year).

7.7.8. Digital Modulation

LED's cannot produce pulses short enough to be used at gigabit speeds. However, systems using LED's operate quite well at speeds of up to around 300 Mbps. Digital modulation is straightforward. The device "turns on" when the forward voltage applied results in a potential across the junction greater than the bandgap energy required. It extinguishes when the voltage drops below that.

7.7.9. Analogue Modulation

LED's can also be analogue modulated quite simply by maintaining a forward bias just larger than the bandgap energy (since the device response is linear with current flow). This is one advantage over lasers. While lasers can be analogue modulated and are indeed used this way in some commercial situations, this is not an easy thing to do.

7.8. ADVANTAGES AND DISADVANTAGES OF USING LED'S

Advantages of Using LED's

- LED's produce more light per watt than do incandescent bulbs; this is useful in battery powered or energy saving devices.

- LED's can emit light of an intended color without the use of color filters that traditional lighting methods require.
- When used in applications where dimming is required, LED's do not change their color tint.
- LED's are ideal for use in applications that are subject to frequent on-off cycling.

DO YOU KNOW

Commercially available LEDs are 5 times as efficient as incandescent bulbs and 3 times to halogen bulbs.

- LED's, being solid state components, are difficult to damage with external shock. Fluorescent and incandescent bulbs are easily broken if dropped on the ground.
- LED's light up very quickly. A typical red indicator LED will achieve full brightness in microseconds.
- LED's used in communications devices can have even faster response times.
- LED's can be very small and are easily populated onto printed circuit boards.

Disadvantages of Using LED's

- LED's are currently more expensive, price per lumen, on an initial capital cost basis, than more conventional lighting technologies.
- LED performance largely depends on the ambient temperature of the operating environment. Driving an LED difficult in high ambient temperatures may result in overheating of the LED package, eventually leading to device failure.
- LED's must be supplied with the correct current. This can involve shunt resistors or regulated power supplies.
- LED's cannot be used in applications that need a sharply directive and collimated beam of light. LED's are not capable of providing directivity below a few degrees.

7.9. COMPARISON BETWEEN LED AND LASER DIODE

S. No.	Parameter	LED	Laser diode
1.	Cost	Its cost is cheap	It is costly.
2.	Lifetime	Small	Very large
3.	Coherence	Incoherent	Beam is coherent
4.	Power output	Low output	High output
5.	Linearity	It gives linear light output over large current range	Linearity range is smaller as compared to LED.
6.	Directionality	Beam is broader and spreading	Beam is directional and highly collimated
7.	Fabrication	Simple structure	Complex because of double hetrostructure
8.	Temperature dependance	Less temperature dependent	High temperature dependent
9.	Cooling system required	No	Yes
10.	Suitability for long distance	No	Yes, because of single frequency

S. No.	Parameter	LED	Laser diode
11.	Information capacity	Efficiently used upto 600 Mb/s	10 Gb/S to 1000 Gb/s
12.	Reliability	High but less than laser diode.	Very high MTBF (mean time between failure).
13.	Driving electronics	Simple circuitry	Slightly complex because of integration of various feedbacks from photodiodes etc.

Summary

Example 7.1. A double heterojunction InGaAsP LED operating at 1310 nm has radiative and non-radiative recombination times of 30 and 100 ns respectively. The injected current is 40 mA. Calculate :

(a) Bulk recombination life time.

(b) Internal quantum efficiency.

(c) Internal power level.

Solution. Given that,

$$\lambda = 1310 \text{ nm} = 1310 \times 10^{-9} \text{ m}$$
$$\tau_r = 30 \text{ n sec}$$
$$\tau_{nr} = 100 \text{ n sec}$$
$$i = 40 \text{ mA}$$

(a) Bulk recombination life time τ is given by

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$
$$= \frac{1}{30} + \frac{1}{100} = \frac{130}{3000}$$
$$\boxed{\tau = 23.07 \, n \text{ sec.}} \quad \textbf{Ans.}$$

(b) Internal quantum efficiency is given by

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.07}{30}$$
$$\boxed{\eta_{int} = 0.769} \quad \textbf{Ans.}$$

(c) Internal power level is given by

$$P_{int} = \eta_{int} \frac{hci}{e\lambda} = \frac{0.769 \times 6.62 \times 10^{-34} \times 3 \times 10^{8} \times 0.04}{1.6 \times 10^{-19} \times 1.31 \times 10^{-6}}$$
$$\boxed{P_{int} = 2.913 \text{ mW}} \quad \textbf{Ans.}$$

Example 7.2. Determine the power radiated by an LED if its quantum efficiency is 3% and the weak wavelength is 670 nm.

Solution. Given that,

$$\lambda = 670 \text{ nm} = 670 \times 10^{-9} \text{ m}$$
$$h = 6.62 \times 10^{-34}$$
$$C = 3 \times 10^{8}$$

Typically values of I for LED's are in the range of 50 to 150 mA. Hence taking $i =$ 50 mA

Radiated power is given by

$$P(\text{mW}) = [\eta_{int} \, E_P(eV)] \, I(mA)$$
$$= \left[\eta_{int} \cdot \frac{hc}{\lambda}\right] I$$
$$= \frac{3}{100} \times \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{670 \times 10^{-9}} \times 50 \times 10^{-3}$$
$$= \frac{1}{100} \times 1.86 \times 50 = 0.93 \times 10^{-3} \text{ W}$$
$$\boxed{P = 0.93 \text{ mW}} \quad \textbf{Ans.}$$

Example 7.3. A LED emits the light having a peak wavelength of 890 nm have radiative recombination time of 100 ns. If the bulk recombination life time is 130 ns and drive current is 14 mA. Determine the non-radiative recombination time.

Solution. Given that,

$$\lambda = 890 \text{ nm} = 890 \times 10^{-9} \text{ m}$$
$$\tau_r = 100 \text{ ns}$$
$$\tau = 130 \text{ ns}$$
$$i = 14 \text{ mA}$$

The bulk recombination life time τ is given by

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$
$$\frac{1}{130} = \frac{1}{100} - \frac{1}{\tau_{nr}}$$
$$\frac{1}{\tau_{nr}} = \frac{1}{100} - \frac{1}{130} = \frac{30}{13000}$$
$$\tau_{nr} = \frac{1300}{3}$$
$$\boxed{\tau_{nr} = 433 \text{ ns}} \quad \textbf{Ans.}$$

Example 7.4. Determine the power internally generated within the device when the peak emission wavelength is 0.87 μm at a drive current of 40 mA. The internal quantum efficiency of the device is 0.625.

Solution. Given that,

$$\lambda = 0.87 \text{ μm} = 0.87 \times 10^{-6} \text{ m}$$

$\eta_{int} = 0.625$
$i = 40$ mA

The internally generated power is given by

$$P_{int} = \eta_{int} \cdot \frac{hci}{e\lambda}$$

$$= \frac{0.625 \times 6.62 \times 10^{-34} \times 3 \times 10^{8} \times 40 \times 10^{-3}}{1.6 \times 10^{-19} \times 0.87 \times 10^{-6}}$$

$$= 35.6 \times 10^{-3} \text{ W}$$

$\boxed{P_{int} = 35.6 \text{ mW}}$ **Ans.**

Example 7.5. A planar LED is fabricated from GaAs which has a refractive index of 3.6. Calculate the optical power emitted into air as a % of the internal optical power for the device if the transmission factor at the crystal air interface is 0.68.

Solution. Given that,

$F = 0.68$
$n_x = 3.6$

Refractive index (n) for air = 1.

The optical power emitted is given by

$$P_e \simeq \frac{P_{int}\, Fn^2}{4Fn_x^2}$$

$$\simeq \frac{P_{int} \times 0.68 \times 1}{4 \times (3.6)^2} \cong 0.013\, P_{int.}$$

Thus emitted power is only 1.3% of the optical power generated internality.

Example 7.6. The light output from the GaAs is coupled into a step index fiber with a numerical aperture of 0.2, a core refractive index of 1.4 and a diameter larger than the diameter of the device. Determine :

(a) Coupling efficiency into the fiber.

(b) Optical loss relative to the power emitted from the LED.

Solution. Given that,

$NA = 0.2$
$n = 1.4$

(a) Coupling efficiency is given by

$$\eta_c = (NA)^2 = (0.2)^2 = 0.04$$

$\boxed{\eta_c = 0.04}$ **Ans.**

(b) The optical loss is determined by

$$\text{Loss} = -\log_{10} \frac{P_c}{P_e} = -\log_{10} (\eta_c) = -\log_{10} (0.04)$$

$\boxed{\text{Loss} = 14.0 \text{ dB}}$ **Ans.**

Example 7.7. A *DH* surface emitter has an emission area diameter of 50 µm and is but joined to an 80 µm core step index fiber with a numerical aperture of 0.15. The radiance of device is 30 W Sr^{-1} cm^{-2} at a operating drive current of 40 mA. Determine the optical power coupled into the fiber if the Fresenl reflection coefficient at the index matched fiber surface is 0.01.

Solution. Given that,

$r = 0.01$
$NA = 0.15$
$R_D = 30$ W sr^{-1} cm^{-2}
$i = 40$ mA

$$\text{Radius, } (R) = \frac{50}{2} \,\mu\text{m} = 25 \times 10^{-6} \text{ m} = 25 \times 10^{-4} \text{ cm.}$$

Optical power coupled into the fiber is given by

$$P_c = \pi(1 - r)A\, R_D\, (NA)^2$$

and the emission area (A) is calculated

$$A = \pi(25 \times 10^{-4})^2$$

$$A = 1.96 \times 10^{-5} \text{ cm}^2.$$

Therefore, $P_c = 3.14\,(1 - 0.01)\, 1.96 \times 10^{-5} \times 30 \times (0.15)^2$

$= 41.1 \times 10^{-6}$ W

$\boxed{P_c = 41.1 \,\mu\text{W}}$ **Ans.**

✓ **Example 7.8. A surface emitting LED launches 150 µM of optical power into a millimode step index fiber. Calculate the overall power conversion efficiency if the 25 mA forward current is flowing the device and the corresponding forward voltage across the diode is 2.5 V.**

Solution. Given that,

$P_c = 150 \,\mu\text{W} = 150 \times 10^{-6}$ W

Forward current = 25 mA

Forward Voltage drop = 2.5 V

The overall power conversion efficiency of may be given by

$$\eta_{pc} = \frac{P_c}{P}$$

and P = Forward current × Forward voltage drop

$= 25 \times 10^{-3} \times 2.5 = 6.25 \times 10^{-2}$ W

Therefore, $$\eta_{pc} = \frac{150 \times 10^{-6}}{6.25 \times 10^{-2}}$$

$$\eta_{pc} = 24 \times 10^{-4}$$

$\boxed{\eta_{pc} = 0.24\%}$ **Ans.**

Example 7.9. When a constant dc drive current is applied to the device, the optical output power is 300 μW. If the minority carrier recombination life time for an LED is 5 ns, calculate the optical output power when the device is modulated with an rms drive current corresponding to dc drive current at 20 MHz frequency.

Solution. Given that,

$$P_{dc} = 300\ \mu\text{W} = 300 \times 10^{-6}\ \text{W}$$
$$f = 20\ \text{MHz} = 20 \times 10^{6}\ \text{Hz}$$
$$\tau_i = 5\ \text{ns} = 5 \times 10^{-9}\ \text{s}$$

The optical output power $P_e(W)$ of the device is given by

$$P_e = P_{dc}\left[1 + (\omega\tau_i)^2\right]^{-1/2}$$
$$= 300\times10^{-6}\left[1+\left(2\pi\times 20\times10^{6}\times5\times10^{9}\right)^2\right]^{-1/2}$$
$$= 300\times10^{-6}\left[1+\left(2\times3.14\times10^{8}\times10^{-9}\right)^2\right]^{-1/2}$$
$$= 300\times10^{-6}\left[1.39\right]^{-1/2}$$
$$= 254.2\times10^{-6}\ \text{W}$$

$$\boxed{P_e = 254.2\ \mu\text{W}}\ \textbf{Ans.}$$

Example 7.10. A double hetrojunction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and non-radiative recombination times of 25 and 10 ns respectively. The drive current is 35 mA.

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

(ii) If the refractive index of the light source material is η = 3.5, find the power emitted from the device. **[UPTU 2005-06]**

Solution. Given that,

$$\tau_r = 25\ \text{ns}$$
$$\tau_{nr} = 90\ \text{ns}$$
$$\eta = 3.5$$
$$\lambda = 1310\ \text{nm} = 1.31 \times 10^{-6}\ \text{m}$$
$$i = 35\ \text{mA}$$

Bulk recombination life time is given by

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{25\times90}{25+90} = \frac{2250}{115} = 19.6\ \text{ns}$$

(i) Internal quantum efficiency

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{19.6}{25} = 0.784$$

$$\boxed{\eta_{int} = 0.784}\ \textbf{Ans.}$$

$$\text{Internal power level} = \eta_{int}\cdot\frac{hci}{q\lambda}$$
$$= 0.784\times\frac{(6.625\times10^{-34})\times(3\times10^{8})\times(0.035)}{(1.6\times10^{-19})\,(1.31\times10^{-6})}$$
$$= \frac{543.99\times10^{-29}}{2096\times10^{-28}}$$

$$\boxed{\eta_{power} = 2.60\ \text{mW}}\ \textbf{Ans.}$$

(ii) Power emitted from the device,

$$P = \frac{P_{int}}{n(n+1)^2}$$
$$= \eta_{ext}\, P_{int}$$
$$= \frac{0.026}{3.5(3.5+1)^2} = \frac{0.026}{70.875} = 0.000366\ \text{W}$$

$$\boxed{P \cong 0.366\ \text{mW}}\ \textbf{Ans.}$$

Example 7.11. The external power efficiency of an InGaAsP/InP planar LED is 0.75% when the internally generated optical power is 30 mW. Determine the transmission factor for the InP-air interface if the drive current is 37 mA and the potential difference across the device is 1.6 V. The refractive index of InP may be taken as 3.46.

Solution. Given that,

$$I = 37\ \text{mA}$$
$$V = 1.6\ \text{V}$$
$$\eta_{ep} = 0.75\%$$
$$P_{int} = 30\ \text{mW}$$
$$n_x = 3.46$$

The external power efficiency of planar LED is given by

$$\eta_{ep} = \frac{P_e}{P}\times100$$

where, $P = I \times V = 37 \times 1.6 \times 10^{-3} = 59.2 \times 10^{-3}$ W

$$\therefore\quad \eta_{ep} = \frac{P_e}{59.2\times10^{-3}}\times100$$
$$P_e = 0.75\times59.2\times10^{-3}\times100$$
$$P_e = 4.4\times10^{-4}\ \text{W}$$

Transmission factor is given by

$$F = \frac{P_e\,.4.n_x^2}{P_{int}\times n^2} = \frac{4.4\times10^{-4}\times4\times(3.46)^2}{30\times10^{-3}\times1}$$

$$\boxed{F = 0.7}\ \textbf{Ans.}$$

Example 7.12. A GaAs planar LED emitting at a wavelength of 0.85 μm has an internal quantum efficiency of 60% when passing a forward current of 20 mA s^{-1}. Estiamte the optical power emitted by the device into air and hence determine the external power efficiency if the potential difference across the device is 1 V. It may be assumed that the transmission factor at the GaAs air interface is 0.68 and the refractive index of GaAs is 3.6.

Solution. Given that,

$$\lambda = 0.85\ \mu m$$
$$\eta_{int} = 0.6$$
$$i = 20 \times 10^{-3}\ As^{-1}$$
$$v = 1$$
$$f = 0.68$$
$$n_x = 3.6$$

Internal power of an LED is given by

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

$$= \frac{0.6 \times 6.62 \times 10^{-34} \times 2.998 \times 10^{8} \times 20 \times 10^{-3}}{1.602 \times 10^{-19} \times 0.85 \times 10^{-6}}$$

$$= 17.5 \times 10^{-3}\ W = 17.5\ mW$$

Thus the optical power emitted by the device will be

$$P_e = \frac{P_{int}\ Fv}{4n_x^2}$$

$$= \frac{17.5 \times 10^{-3} \times 0.68 \times 1}{4 \times (3.6)^2} = 230 \times 10^{-6}\ W$$

$$\boxed{P_e = 230\ \mu W}$$ **Ans.**

External power efficiency is given by

$$\eta_{ep} = \frac{P_e}{P} \times 100 \qquad \text{where, } P = I \times V$$

$$= \frac{230 \times 10^{-6}}{1 \times 20 \times 10^{-3}} \times 100$$

$$\boxed{\eta_{ep} = 1.15\%}$$ **Ans.**

Summary

1. Light emitting diodes (LED's) are semiconductor *p-n* junction operating under proper forward biased conditions and are capable of emitting external spontaneous radiations in the visible range (370 nm to 770 nm).
2. LED's are special diodes that emits light when connected in a circuit. They are frequently used as "pilot" light in electronic appliances.
3. In a regular diode the electron hole recombinations release energy in the thermal rather than the variable portion of the spectrum.

4. The internal quantum efficiency is given by
$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$
5. The bulk recombination life time t is given by
$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$
6. LED's that emits different colours are made of different semiconductor materials. The semiconductor materials that are used for the active layer of an optical source must have a direct bandgap.
7. A heterojunction is a junction in which the *p* and *n*-type materials are different semiconductors.
8. Basically two LED's configurations are used for fiber optics
   - Surface emitters.
   - Edge emitters.
9. A single heterostructure (SH) is sometimes used for for window for surface emitters.
10. In double heterostructure (ΔH) the upper and lower confinement layers are so designed because they have a lower index of refraction and thus confine the light by reflection at the interface.
11. The two different types of LED emission pattern are
    - Surface emitting LED.
    - Edge emitting LED.
12. The light power coupled into a step index fiber having a numerical operture (NA) can be given by
$$P_{in} = P_o(NA)^2$$
$$P_{in} = P_o \sin^2 QA$$
13. The rise/fall time of an LED is given by
$$t_r = 2.2\left[\tau + \left(\frac{1.7 \times 10^{-4} \times T^{o}K \times C}{I_P}\right)\right]$$
14. In electronics the general relationship between bandwidth and rise time is given by
$$BW = \frac{0.35}{t_r}$$
15. The external power efficiency of an LED is given by
$$\eta_{ep} = \frac{P_e}{P} \times 100\%$$
16. There are five major types of LED structure :
    - Surface emitter LED
    - Edge emitter LED
    - Superluminescent LED
    - Planar LED
    - Dome LED
17. The power coupled P_c into a multimode step index fiber may be given by
$$P_c = \pi(1 - r)\, A\, R_D\, (NA)^2$$
18. Rapid degradation in LED's is similar to that in a injection lasers because of growth of dislocations and precipitate type defects in the active region.
19. The optical output power $P_e(t)$ may be expressed as a function of operating *t* and is given by