OPTICAL COMMUNICATION (EEC-701) –UNIT-III

Optical sources- LEDs, Structures, Materials, Quantum efficiency, Power, Modulation, Power bandwidth product.
Laser Diodes- Basic concepts, Classifications, Semiconductor injection Laser: Modes, Threshold conditions, External quantum efficiency, Laser diode rate equations, resonant frequencies, reliability of LED & ILD

Optical sources

The function of an optical transmitter is to convert incoming electrical signals into outgoing optical signals. The major component of the transmitter is the optical source, which either a semiconductor light-emitting diode (LED) or laser diode. Semiconductor diode devices have the advantages over other light sources of small size, high efficiency, high reliability, suitable wavelength ranges, small emission areas matching fiber cores, and the ability to be directly current modulated.

1. LED sources

Light-emitting diodes are simply forward-biased p-n junctions, which emit light by spontaneousemission. Spontaneous emission (or electroluminescence) is caused by radiative recombination ofelectron-hole pairs in the depletion region. LED's are temporally and spatially incoherent sourcesthat emit over a broad spectral bandwidth (20-150 nm) and large angular bandwidth.

Advantages of LED:

1.*Simpler fabrication*. There are no mirror facets and in some structures no stripedgeometry.
2. *Cost*. The simpler construction of the LED leads to much reduced cost which isalways likely to be maintained.
3. *Reliability*. The LED does not exhibit catastrophic degradation and has proved farless sensitive to gradual degradation than the injection laser. It is also immune toself-pulsation and modal noise problems.
4. *Generally less temperature dependence*. The light output against currentcharacteristic is less affected by temperature than the corresponding characteristicfor the injection laser. Furthermore, the LED is not a threshold device and thereforeraising the temperature does not increase the threshold current above theoperating point and hence halt operation.
5. *Simpler drive circuitry*. This is due to the generally lower drive currents and reducedtemperature dependence which makes temperature compensation circuits unnecessary.
6. *Linearity*. Ideally, the LED has a linear light output against current characteristic
This can prove advantageous whereanalog modulation is concerned.

Drawbacks:
(a) Generally lower optical power coupled into a fiber (microwatts);
(b) Usually lower modulation bandwidth;
(c) Harmonic distortion.

1.1 LED power and efficiency

The power generated internally by an LED may be determined by consideration of theexcess 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 Δn and holes Δp is equal since theinjected carriers are created and recombined in pairs such that charge neutrality is maintainedwithin the structure. In extrinsic materials one carrier type will have a muchhigher concentration than the other and hence in the *p*-type region, for example, the holeconcentration will be much greater than the electron concentration. Generally, the excessminority carrier density decays exponentially with time *t* according to the relation:

$$\Delta n = \Delta n(0)\exp(-t/\tau) \qquad \text{..... (1)}$$

where $\Delta n(0)$ is the initial injected excess electron density and τ represents the total carrier recombination lifetime.

When there is a constant current flow into the junction diode, an equilibrium conditionis 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. Hence a rateequation for carrier recombination in the LED can be expressed in the form

$$\frac{d(\Delta n)}{dt} = \frac{J}{ed} - \frac{\Delta n}{\tau} \quad (\mathrm{m^{-3}\,s^{-1}}) \qquad \text{.......(2)}$$

The condition for equilibrium is obtained by setting the derivative in Eq. (2) to zero. Hence:

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

Equation (3) therefore gives the steady-state electron density when a constant current isflowing into the junction region.

It is also apparent from Eq. (2) that in the steady state the total number of carrierrecombi-nations per second or the recombination rate r_t will be:

$$r_t = \frac{J}{ed} \quad (\mathrm{m^{-3}})$$

$$= r_r + r_{nr} \quad (\mathrm{m^{-3}}) \qquad (5)$$

wherer_r is the radiative recombination rate per unit volume and r_{nr} is the non-radiativerecombination rate per unit volume. Moreover, when the forward-biased current into thedevice is *i*, then from Eq. (7.4) the total number of recombinations per second R_t becomes:

$$R_t = \frac{i}{e} \qquad (6)$$

The LED internal quantum efficiency* η_{int}, which can be defined as the ratio of theradiative recombination rate to the total recombination rate,

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}}$$

$$= \frac{R_r}{R_t} \qquad (8)$$

whereR_r is the total number of *radiative* recombination per second. Rearranging Eq. (8)and substituting from Eq. (6) gives:

$$R_r = \eta_{int} \frac{i}{e} \quad (9)$$

Since *R*r is also equivalent to the total number of photons generated per second each photon has an energy equal to *hf*joules, then the optical power generatedinternally by the LED, *P*int, is:

$$P_{int} = \eta_{int} \frac{i}{e} hf \quad \text{(W)}$$

he internally generated power in terms of wavelength ratherthan frequency gives:

$$P_{int} = \eta_{int} \frac{hci}{e\lambda} \quad \text{(W)}$$

For the exponential decay of excess carriers depicted by Eq. (1) the radiative minoritycarrier lifetime is τr = Δ*n*/*r*r and the non-radiative minority carrier lifetime is τnr = Δ*n*/rnr.Therefore, from Eq. (7.7) the internal quantum efficiency is:

$$\eta_{int} = \frac{1}{1 + (r_{nr}/r_r)} = \frac{1}{1 + (\tau_r/\tau_{nr})}$$

Furthermore, the total recombination lifetime τ can be written as τ = Δ*n*/*r*tgives:

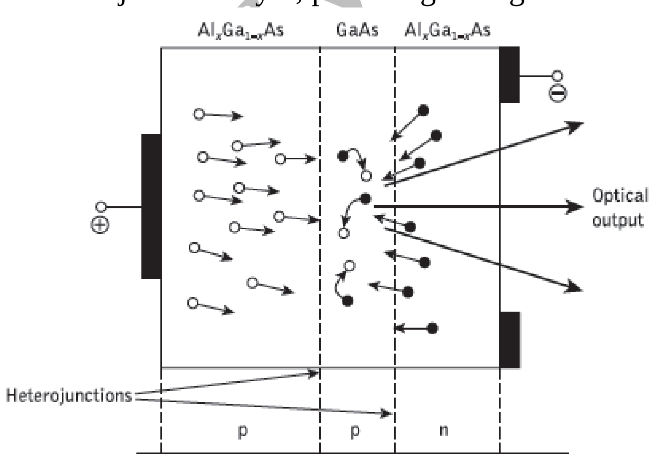
$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

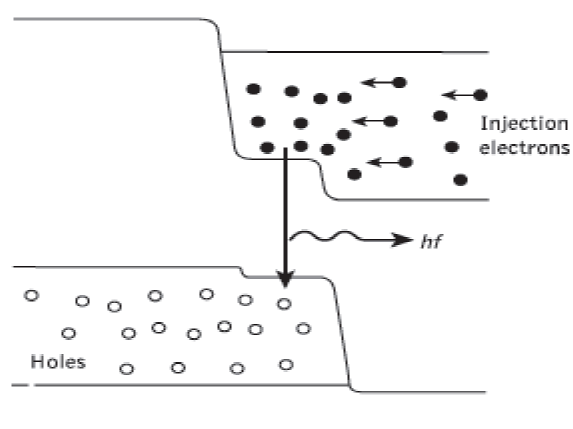
Hence,

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

1.2 The double-heterojunction LED

The principle of operation of the DH LED is illustrated in Figure. The device shown consists of a *p*-type GaAs layer sandwiched between a *p*-type AlGaAs and an *n*-typebAlGaAs layer. When a forward bias is applied electrons from the *n*-type layer are injected through the *p*–*n* junction into the *p*-type GaAs layer where they become minority carriers. These minority carriers diffuse away from the junction recombining with majority carriers (holes) as they do so. Photons are therefore produced with energy corresponding to the band gap energy of the *p*-type GaAs layer. The injected electrons are inhibited from diffusing into the *p*-type AlGaAs layer because of the potential barrier presented by the p–p heterojunction, Hence, electroluminescence only occurs in the GaAs junction layer, providing both good internal quantum efficiency and high-radiance emission.





The DH structure is therefore used to provide the most efficient incoherent sources for application within optical fiber communications. Nevertheless, these devices generally exhibit the previously discussed constraints in relation to coupling efficiency to optical fibers.

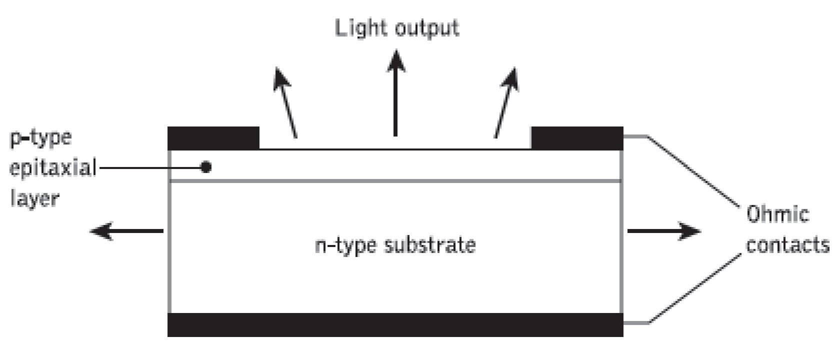
1.3 LED structures

Types of LED

a. Planar LED
b. Dome LED
c. Surface Emitter LED
d. Edge-Emitter LED
e. Super luminescent LEDs

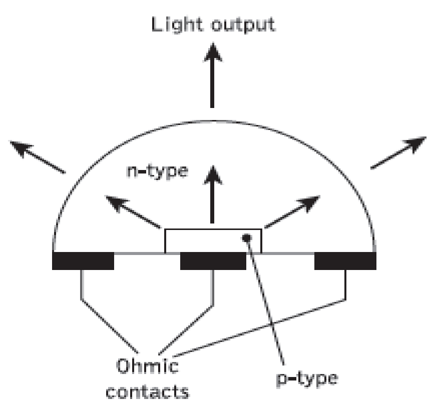
1.3.1 Planar LED

The planar LED is the simplest of the structures that are available and is fabricated by either liquid- or vapor-phase epitaxial processes over the whole surface of a GaAs substrate. This involves p-type diffusion into the *n*-type substrate in order to create the junction. Forward current flow through the junction gives Lambertianspontaneous emission and the device emits light from all surfaces. However, only a limited amount of light escapes the structure due to total internal reflection and therefore the radiance is low.

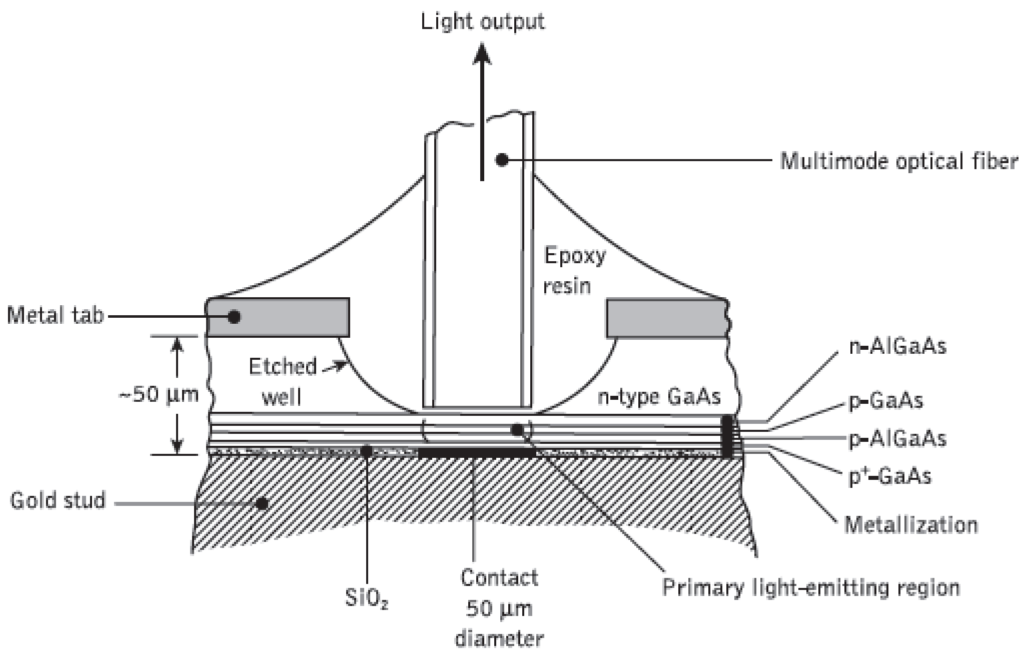


1.3.2 DOME LED

The structure of a typical dome LED is shown in Figure. A hemisphere of *n*-type GaAs is formed around a diffused *p*-type region. 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. Hence this device has higher external power efficiency than the planar LED. 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.



1.3.3 Surface Emitter LED



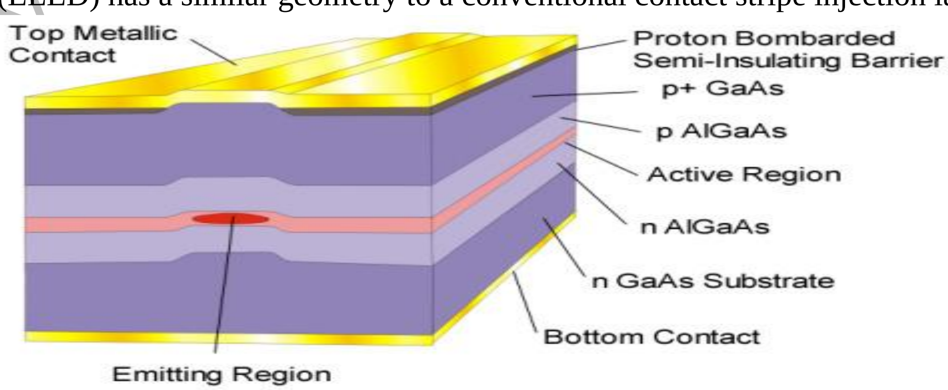
Surface emitter LED (SLED) has been widely employed within optical fiber communications in which A method for obtaining high radiance is to restrict the emission to a small active region within the device. These structures have low thermal impedance in the active region allowing high current densities and giving high-radiance 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 Figure. The internal absorption in this device is very low due to the larger band-gap-confining layers, and the reflection coefficient at the back crystal face is high giving good forward radiance. The emission from the active layer is essentially isotropic, although the external emission distribution may be considered Lambertian with a beam width of 120° due to refraction from a high to a low refractive index at the GaAs–fiber interface. The power coupled Pc into a multimode step index fiber may be estimated from the relationship:

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

Where r is the Fresnel reflection coefficient at the fiber surface, A is the smaller of the fiber core cross-section or the emission area of the source and R_D is the radiance of the source.

1.3.4 Edge emitter LED

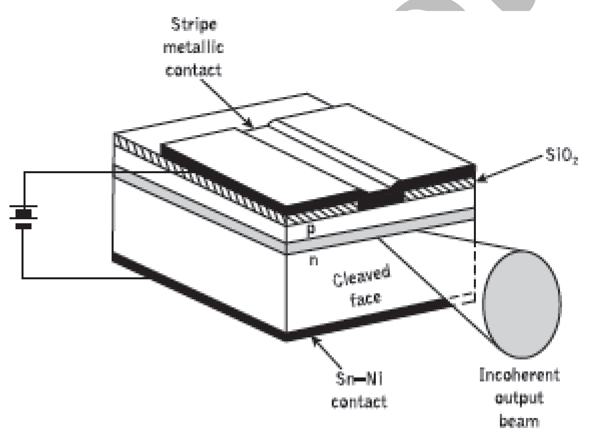
Edge emitter LED (ELED) has a similar geometry to a conventional contact stripe injection laser

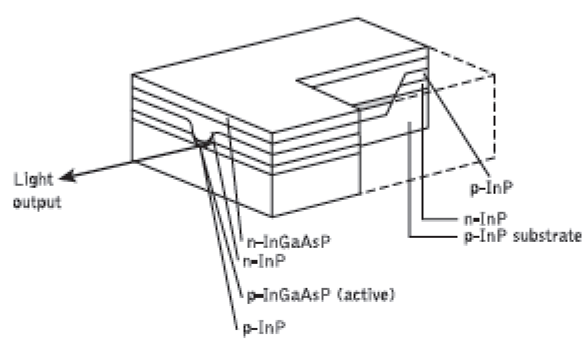


It takes advantage of transparent guiding layers with a very thin active layer (50 to 100 μm) in order that the light produced in the active layer spreads into the transparent guiding layers, reducing self-absorption in the active layer. The consequent wave guiding narrows the beam divergence to a half-power width of around 30° in the plane perpendicular to the junction. However, the lack of wave guiding in the plane of the junction gives a Lambertian output with a half-power width of around 120°.The ELED active layer was heavily doped with Zn to reduce the minority carrier lifetime and thus improve the device modulation bandwidth. In this way a 3 dB modulation bandwidth of 600 MHz was obtained. Very high coupled optical power levels into single-mode fiber in excess of 100 μW have been obtained with In GaAsP ELEDs at drive currents as low as 50 mA.

1.3.5 Super luminescent LED

Another device geometry which is providing significant benefits over both SLEDs and ELEDs for communication applications is the Super luminescent diode or SLD. This device offers advantages of:
(a) A high output power;
(b) A directional output beam; and
(c) A narrow spectral line width.
All of which prove useful for coupling significant optical power levels into optical fiber. The super radiant emission process within the SLD tends to increase the device modulation bandwidth over that of more conventional LEDs.



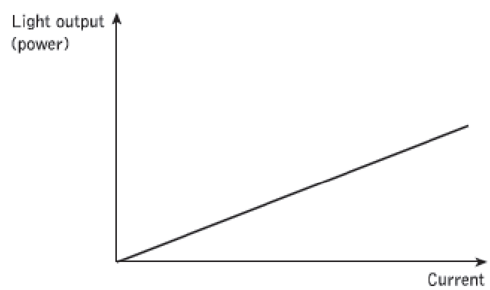


A Super luminescent light emitting diode is, similar to a laser diode, based on an electrically driven pn-junction that, when biased in forward direction becomes optically active and generates amplified spontaneous emission over a wide range of wavelengths. The peak wavelength and the intensity of the SLED depend on the active material composition and on the injection current level. SLEDs are designed to have high single pass amplification for the spontaneous emission generated along the waveguide but, unlike laser diodes, insufficient feedback to achieve lasing action. This is obtained very successfully through the joint action of a tilted waveguide and anti-reflection coated (ARC) facets.

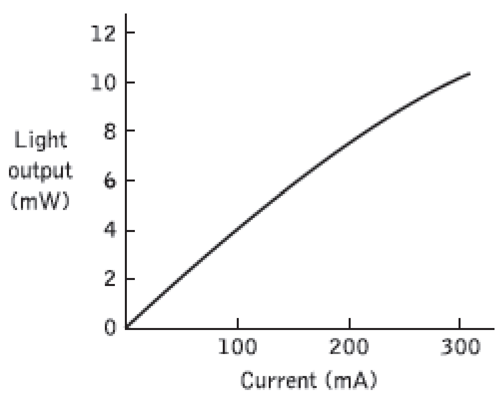
1.4 LED Characteristics

Optical output power

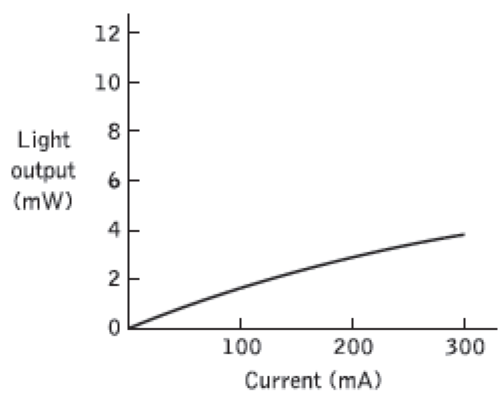
LED is a very linear device in comparison with the majority of injection lasers and hence it tends to be more suitable for analog transmission where severe constraints are put on the linearity of the optical source. However, in practice LEDs do exhibit significant nonlinearities which depend upon the configuration utilized. It is therefore often necessary to use some form of linear circuit technique in order to ensure the linear performance of the device to allow its use in high-quality analog transmission systems.



(a) Ideal LED characteristics

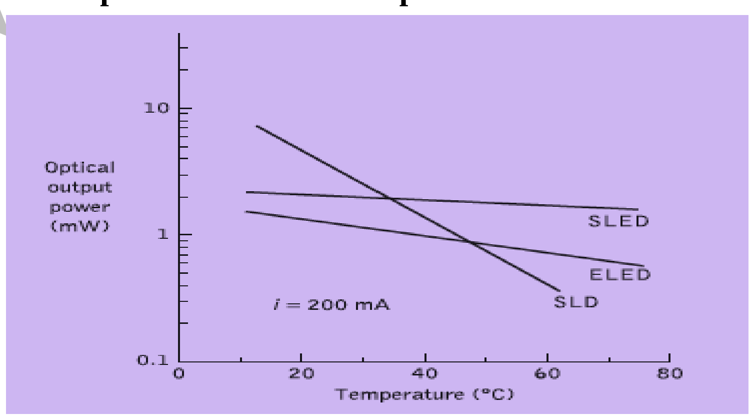


(b) Surface emitter with a 50 µm diameter dot Contact



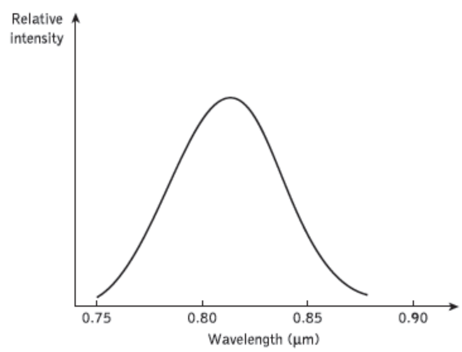
(c) Edge emitter with a 65 µm wide stripe and 100 µm length

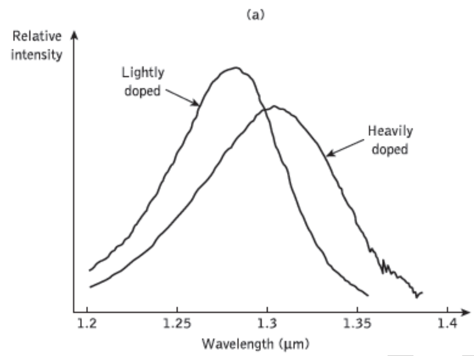
Light output temperature dependence for three important LED structures emitting at a wavelength of 1.3 µm



1.4.2 Output spectrum

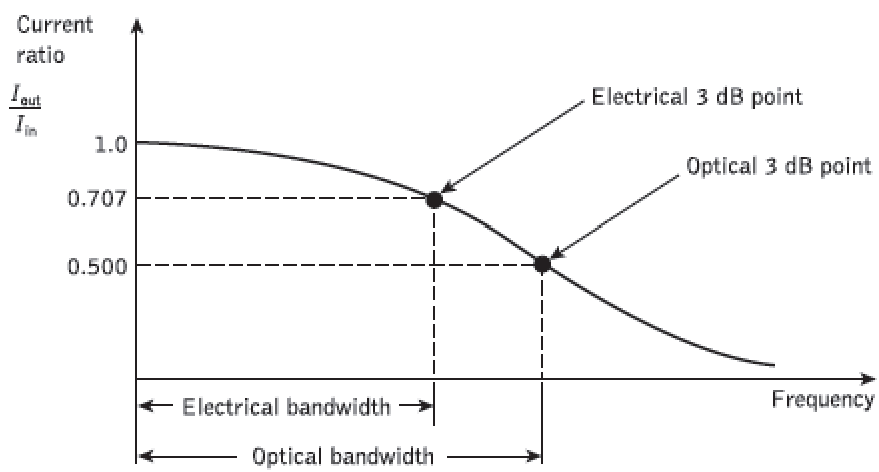
The spectral line width of an LED operating at room temperature in the 0.8 to 0.9 μm wavelength band is usually between 25 and 40 nm at the half maximum intensity points. For materials with smaller band gap energies operating in the 1.1 to 1.7 μm wavelength region the line width tend to increase to around50 to 160 nm. Examples of these two output spectra are shown in Figure. The increases in line width are due to increased doping levels and the formation of band tail states. This becomes apparent in the differences in the output spectra between surface- and edge-emitting LEDs where the devices have generally heavily doped and lightly doped.





1.5 Modulation bandwidth

The modulation bandwidth in optical communications may be defined in either electrical or optical terms. When the associated electrical circuitry in an optical fiber communication system to use the electrical definition where the electrical signal power has dropped to half its constant value due to the modulated portion of the optical signal. This corresponds to the electrical 3 dB point or the frequency at which the output electric power is reduced by 3 dB with respect to the input electric power. Alternatively, if the 3 dB bandwidth of the modulated optical carrier (optical bandwidth)is considered, we obtain an increased value for the modulation bandwidth.



OPTICAL SOURCE: LASER

In optical Communication three main types of optical light source are available. These are:
(a) Wideband 'continuous spectra' sources (incandescent lamps);
(b) Monochromatic incoherent sources (light-emitting diodes, LEDs);
(c) Monochromatic coherent sources (lasers).

The major requirements for an optical fiber emitter which are outlined below:

1. A size and configuration compatible with launching light into an optical fiber. Ideally, the light output should be highly directional.

2. Must accurately track the electrical input signal to minimize distortion and noise. Ideally, the source should be linear.

3. Should emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient.

4. Preferably capable of simple signal modulation over a wide bandwidth extending from audio frequencies to beyond the gigahertz range.

5. Must couple sufficient optical power to overcome attenuation in the fiber plus additional connector losses and leave adequate power to drive the detector.

6. Should have a very narrow spectral bandwidth in order to minimize dispersion in the fiber.

7. Must be capable of maintaining a stable optical output which is largely unaffected by changes in ambient conditions (e.g. temperature).

8. It is essential that the source is comparatively cheap and highly reliable in order to compete with conventional transmission techniques.

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**”. A laser differs from other sources of light because it emits light *coherently*. Lasers have many important applications. They are used in common consumer devices such as optical disk drives, laser printers, and barcode scanners. Lasers are used for both fiber-optic and free-space optical communication.

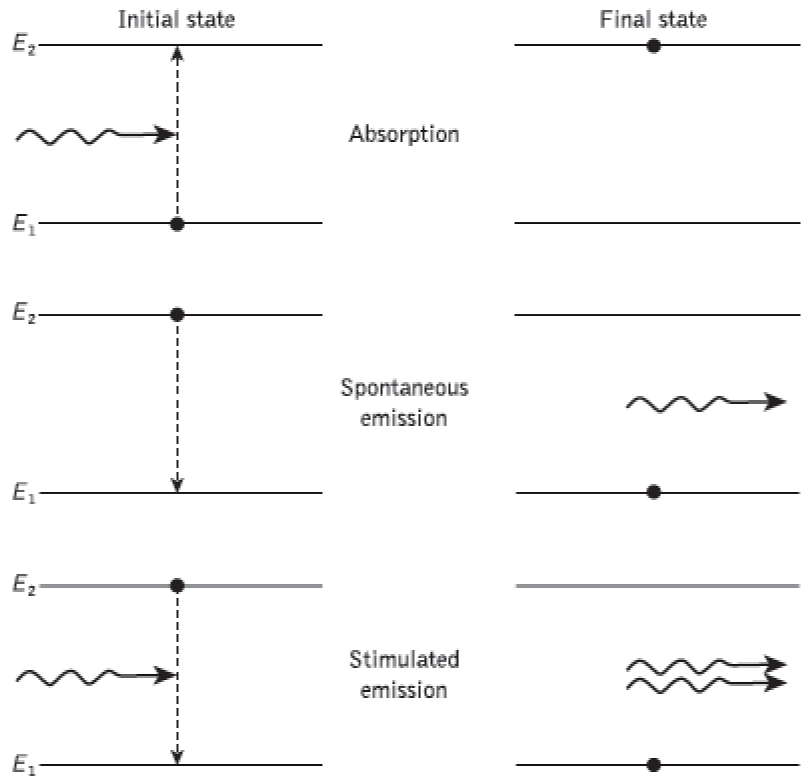
2.1 Basic Concepts

2.1.1 Absorption and emission of radiation

The interaction of light with matter takes place in discrete packets of energy or quanta, called photons. Furthermore, the quantum theory suggests that atoms exist only in certain discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy state to another. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the higher energy state $E2$ and the lower energy state $E1$ by the expression:

$$E = E2 - E1 = hf$$

Where $h = 6.626 \times 10^{-34}$ J s is Planck’s constant. These discrete energy states for the atom may be considered to correspond to electrons occurring in particular energy levels relative to the nucleus. Hence, different energy states for the atom correspond to different electron configurations, and a single electron transition between two energy levels within the atom will provide a change in energy suitable for the absorption or emission of a photon.



This emission process can occur in two ways:

(a) By spontaneous emission in which the atom returns to the lower energy state in an entirely random manner;
(b) By stimulated emission when a photon having an energy equal to the energy difference between the two states ($E2 - E1$) interacts with the atom in the upper energy state causing it to return to the lower state with the creation of a second photon.

It is the stimulated emission process which gives the laser its special properties as an optical source. The photon produced by stimulated emission is generally of an identical energy to the one which caused it and hence the light associated with them is of the same frequency. The light associated with the stimulating and stimulated photon is in phase and has the same polarization. Therefore, in contrast to spontaneous emission, coherent radiation is obtained.

2.1.2 The Einstein relations

In 1917 Einstein demonstrated that the rates of the three transition processes of absorption, spontaneous emission and stimulated emission were related mathematically. He achieved this by considering the atomic system to be in thermal equilibrium such that the rate of the upward transitions must equal the rate of the downward transitions. The population of the two energy levels of such a system is described by Boltzmann statistics which give:

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

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

Where $N1$ and $N2$ represent the density of atoms in energy levels $E1$ and $E2$, respectively, with $g1$ and $g2$ being the corresponding degeneracy of the levels, K is Boltzmann's constant and T is the absolute temperature.

As the density of atoms in the lower or ground energy state $E1$ is $N1$, the rate of upward transition or absorption is proportional to both $N1$ and the spectral density ρf of the radiation energy at the transition frequency f. Hence, the upward transition rate $R12$ may be written as:

$$R12 = N1\rho f\, B12$$

where the constant of proportionality $B12$ is known as the Einstein coefficient of absorption.

For spontaneous emission the average time that an electron exists in the excited state before a transition occurs is known as the spontaneous lifetime $\tau 21$. If the density of atoms within the system with energy $E2$ is $N2$, then the spontaneous emission rate is given by the product of $N2$ and $1/\tau 2$. This may be written as $N2A21$ where $A21$, the Einstein coefficient of spontaneous emission, is equal to the reciprocal of the spontaneous lifetime.

The rate of stimulated downward transition of an electron from level 2 to level 1 may be obtained in a similar manner to the rate of stimulated upward transition. Hence the rate of stimulated emission is given by

$$R21 = N2A21 + N2\rho f\, B21$$

For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore $R12 = R21$, or:

$$N1\rho f\, B12 = N2A21 + N2\rho f B21$$

It follows that:

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

and:

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

Substituting values from equations

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

Planck showed thatthe radiation spectral density for a black body radiating within a frequency range f to f + d$f$is given by

$$\rho_f = \frac{8\pi h f^3}{c^3}\left[\frac{1}{\exp(hf/KT) - 1}\right]$$

After comparing equations,

$$B_{12} = \left(\frac{g_2}{g_1}\right) B_{21}$$

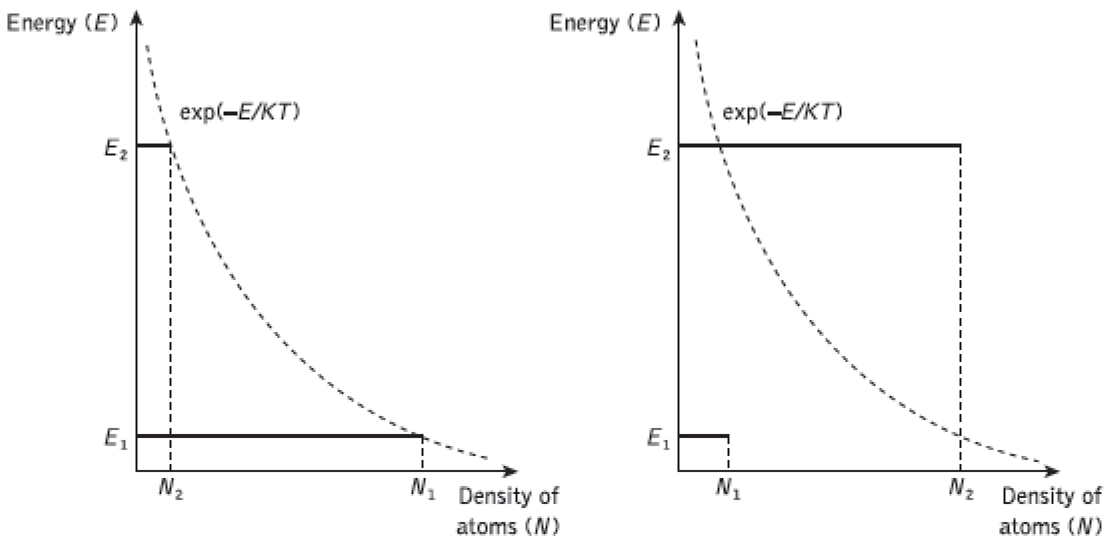
&

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}$$

The ratio of the stimulated emission rate to the spontaneous emission rate is given by:

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf/KT) - 1}$$

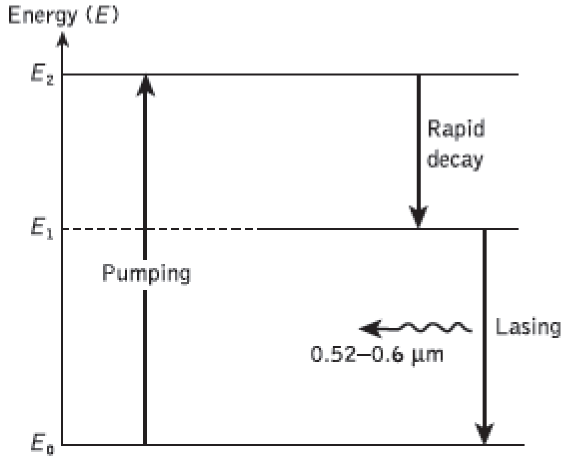
2.1.3 Population inversion

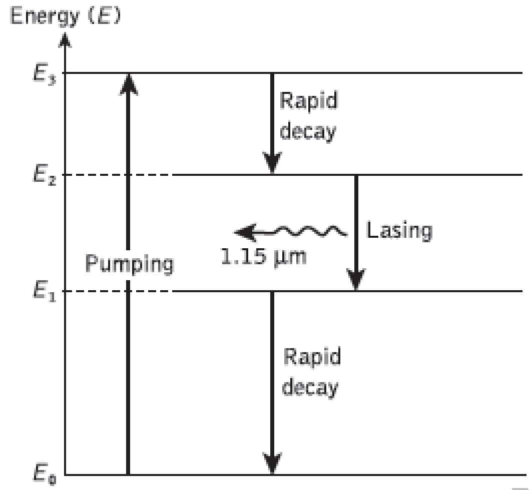


Under the conditions of thermal equilibrium given by the Boltzmann distribution, the lower energy level $E1$ of the two-level atomic system contains more atoms than the upper energy level$E2$, which is normal for structures at room temperature. However, to achieve optical amplification it is necessary to create a non-equilibrium distribution of atoms such that the population of the upper energy level is greater than that of the lower energy level (i.e. $N2 > N1$). This condition is known as population inversion.

In order to achieve population inversion it is necessary to excite atoms into the upper energy level $E2$ and hence obtain a non-equilibrium distribution. This process is achieved using an external energy source and is referred to as 'pumping'. When the two levels are equally degenerate (or not degenerate), then $B12 = B21$. Thus the probabilities of absorption and stimulated emission are equal, providing at best equal populations in the two levels.

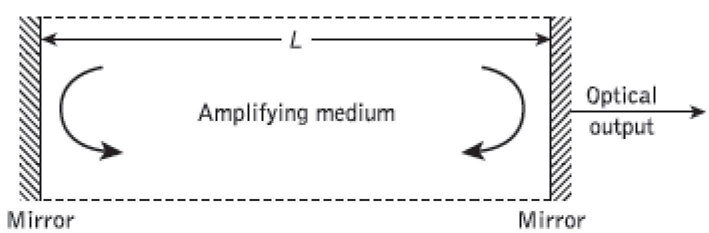
Population inversion may be obtained in systems with three or four energy levels. To achieve population inversion both systems display a central metastable state in which the atoms spend an unusually long time. It is from this metastable level that the stimulated emission or lasing takes place.





2.1.4 Optical feedback and laser oscillation

Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more. Continuation of this process effectively creates avalanche multiplication, and when the electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained. To achieve this laser action it is necessary to contain photons within the laser medium and maintain the conditions for coherence. This is accomplished by placing or forming mirrors (plane or curved) at either end of the amplifying medium. The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity. Hence the optical signal is fed back many times while receiving amplification as it passes through the medium.



Since the structure forms a resonant cavity, when sufficient population inversion exists in the amplifying medium the radiation builds up and becomes established as standing waves between the mirrors. Thus when the optical spacing between the mirrors is *L*, the resonance condition along the axis of the cavity is given by:

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

where λ is the emission wavelength, *n* is the refractive index of the amplifying medium and*q* is an integer. Alternatively, discrete emission frequencies *f* is defined by:

$$f = \frac{qc}{2nL}$$

The different frequencies of oscillation within the laser cavity are determined by the various integer values of *q* and each constitutes a resonance or mode. These modes are separated by a frequency interval δf where:

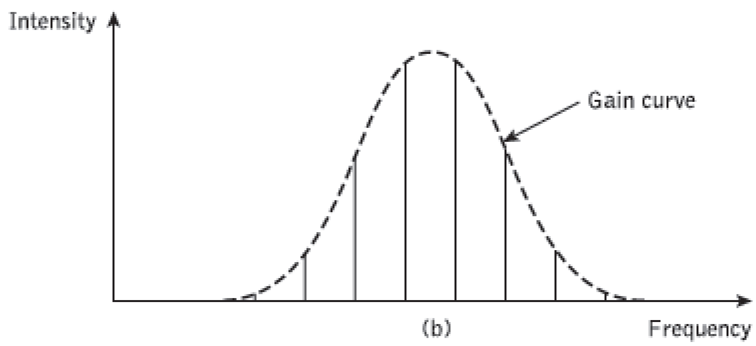
$$\delta f = \frac{c}{2nL}$$

The mode separation in terms of the free space wavelength, assuming δf_ f and as$f = c/\lambda$, is given by:

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

Hence,

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



2.1.4 Threshold condition for laser oscillation

The steady-state conditions for laser oscillation are achieved when the gain in the amplifying medium exactly balances the total losses. Hence, although population inversion between the energy levels providing the laser transition is necessary for oscillation to be established, it is not alone sufficient for lasing to occur. We assume the amplifying medium occupies a length L completely filling the region between the two mirrors which have reflectivity's $r1$ and $r2$. On each round trip the beam passes through the medium twice. Hence the fractional loss incurred by the light beam is:

$$\text{Fractional loss} = r_1 r_2 \exp(-2AL)$$

It is found that the increase in beam intensity resulting from stimulated emission is exponential

Therefore if the gain coefficient per unit length produced by stimulated emission is C cm−1, the fractional round trip gain is given by:

$$\text{Fractional gain} = \exp(2CL)$$

Hence:

$$\exp(2CL) \times r_1 r_2 \exp(-2AL) = 1$$

And

$$r_1 r_2 \exp[2(C - A)L] = 1$$

The threshold gain per unit length may be obtained by rearranging the above expression to give:

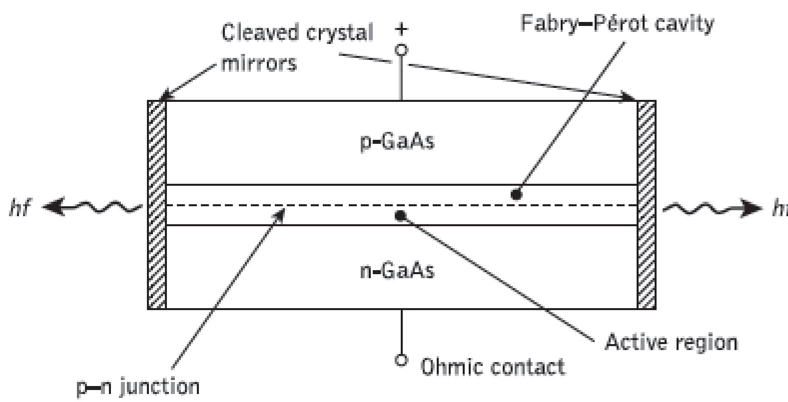
$$\bar{g}_{th} = \bar{\alpha} + \frac{1}{2L} \ln \frac{1}{r_1 r_2}$$

The second term on the right hand side represents the transmission loss through the mirrors.

2.2 The Semiconductor Injection Laser

Stimulated emission by the recombination of the injected carriers is encouraged in the semiconductor injection laser (also called the injection laser diode (ILD) or simply the injection laser) by the provision of an optical cavity in the crystal structure in order to provide the feedback of photons. This gives the injection laser several major advantages over other semiconductor sources (e.g. LEDs) that may be used for optical communications. These are as follows:

1. High radiance due to the amplifying effect of stimulated emission. Injection lasers will generally supply mill watts of optical output power.
2. Narrow line width on the order of 1 nm (10 Å) or less which is useful in minimizing the effects of material dispersion.
3. Modulation capabilities which at present extend up into the gigahertz range and will undoubtedly be improved upon.
4. Relative temporal coherence which is considered essential to allow heterodyne (coherent) detection in high-capacity systems, but at present is primarily of use in single-mode systems.
5. Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than the dispersed unfocused emission.



Schematic diagram of a GaAs homojunction injection laser with a Fabry–Pérot cavity

The DH injection laser fabricated from lattice-matched III–V alloys provided both carrier and optical confinement on both sides of the *p*–*n* junction, giving the injection laser a greatly enhanced performance. This enabled these devices with the appropriate heat sinking to be operated in a CW mode at 300 K with obvious advantages for optical communications

2.2.1 Efficiency

It is the differential external quantum efficiency which is the ratio of the increase in photon output rate for a given increase in the number of injected electrons. If *P*e is the optical power emitted from the device, *I* is the current, *e* is the charge on an electron and *hf*is the photon energy, then:

$$\eta_D = \frac{dP_e/hf}{dI/e} \simeq \frac{dP_e}{dI(E_g)}$$

Where *E*g is the band gap energy expressed in eV. It may be noted that efficiency gives a measure of the rate of change of the optical output power with current and hence defines the slope of the output characteristic. The internal quantum efficiency of the semiconductor laser η_i,

$$\eta_i = \frac{\text{number of photons produced in the laser cavity}}{\text{number of injected electrons}}$$

It is related to the differential external quantum efficiency by the expression

$$\eta_D = \eta_i \left[\frac{1}{1 + (2\bar{\alpha}L / \ln(1/r_1 r_2))} \right]$$

Where A is the loss coefficient of the laser cavity, L is the length of the laser cavity and $r1$,$r2$ is the cleaved mirror reflectivity.

Another parameter is the total efficiency (external quantum efficiency) η_T which is efficiency defined as:

$$\eta_T = \frac{\text{total number of output photons}}{\text{total number of injected electrons}}$$

$$= \frac{P_e/hf}{I/e} \simeq \frac{P_e}{IE_g}$$

As the power emitted P_e changes linearly when the injection current I is greater than the threshold current Ith, then:

$$\eta_T \simeq \eta_D \left(1 - \frac{I_{th}}{I}\right)$$

For high injection current (e.g. $I = 5I$th) then $\eta_T \approx \eta_D$, whereas for lower currents ($I \approx 2I$th) the total efficiency is lower and around 15 to 25%.

The external power efficiency of the device (or device efficiency) η_{ep} in converting electrical input to optical output is given by:

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

For the total efficiency we find:

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

2.2.2 Stripe geometry

The DH laser structure provides optical confinement in the vertical direction through the refractive index step at the heterojunction interfaces, but lasing takes place across the whole width of the device.

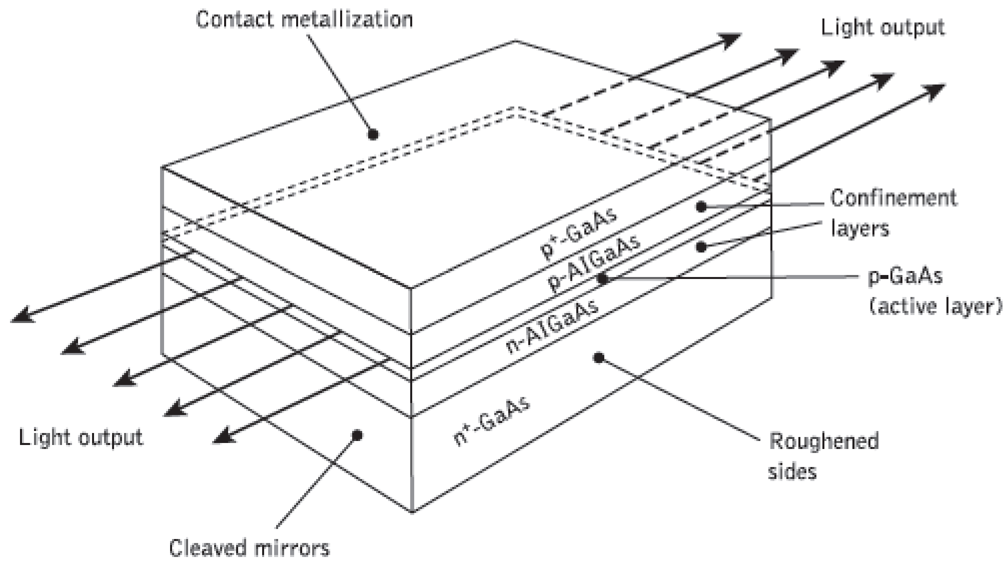
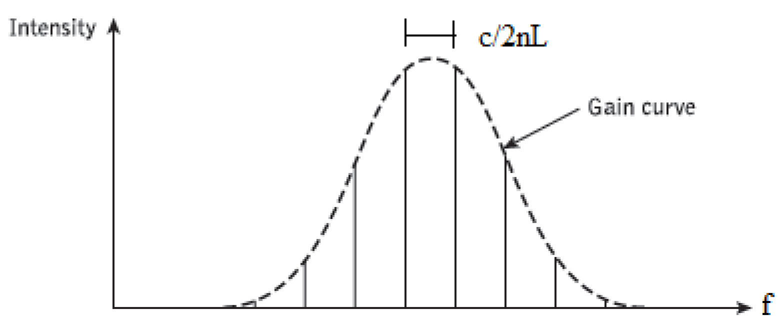


Figure shows the broad-area DH laser where the sides of the cavity are simply formed by roughening the edges of the device in order to reduce unwanted emission in these directions and limit the number of horizontal transverse modes. However, the broad emission area creates several problems including difficult heat sinking, lasing from multiple filaments in the relatively wide active area and unsuitable light output geometry for efficient coupling to the cylindrical fibers.

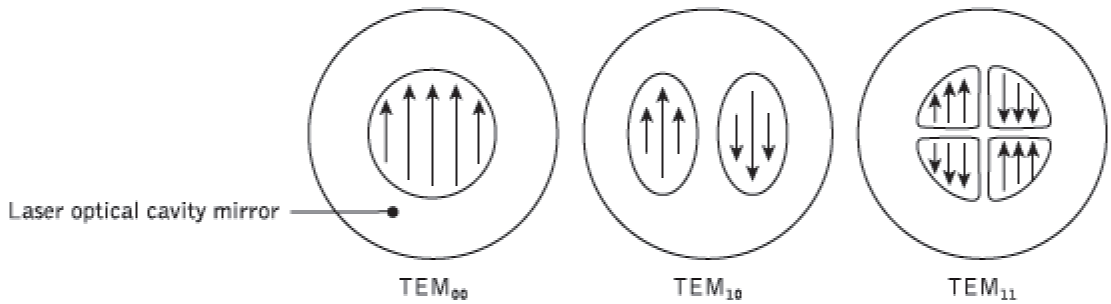
To overcome these problems while also reducing the required threshold current, laser structures in which the active region does not extend to the edges of the device were developed. A common technique involved the introduction of stripe geometry to the structure to provide optical containment in the horizontal plane.

2.2.3 Laser modes

LASER contains a large number of modes which are generated within the laser cavity. Hence the laser emission will only include the longitudinal modes contained within the spectral width of the gain curve as shown in figure.



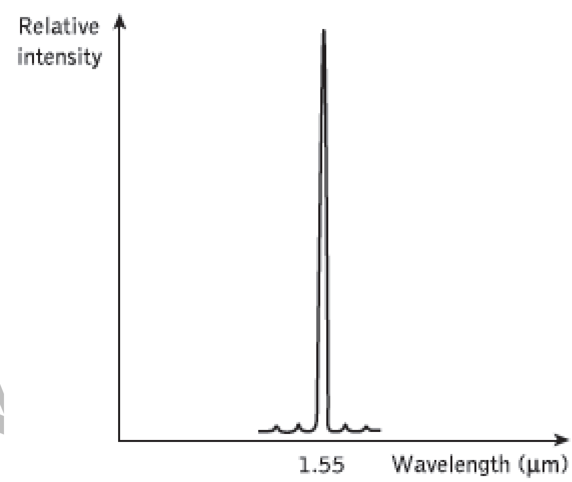
This gives rise to resonant modes which are transverse to the direction of propagation. These transverse electromagnetic modes are designated in a similar manner to transverse modes in waveguides by $TEM_{lm}$where the integers *l* and *m* indicates the number of transverse modes. In the case of the TEM_{00} mode all parts of the propagating wave front are in phase. This is not so, however, with higher order modes (TEM10, TEM11, etc.) where phase reversals produce the various mode patterns. Thus the greatest degree of coherence, together with the highest level of spectral purity, may be obtained from a laser which operates in only theTEM_{00} mode. Higher order transverse modes only occur when the width of the cavity is sufficient for them to oscillate.



The correct stripe geometry inhibits the occurrence of the higher order lateral modes by limiting the width of the optical cavity, leaving only a single lateral mode which gives the output spectrum.

2.2.4 Single-mode operation

For single-mode operation, the optical output from a laser must contain only a single longitudinal and single transverse mode. Hence the spectral width of the emission from the single-mode device is far smaller than the broadened transition line width. Single transverse mode operation, however, may be obtained by reducing the aperture of the resonant cavity such that only the TEM00 mode is supported. To obtain single-mode operation it is then necessary to eliminate all but one of the longitudinal modes. One method of achieving single longitudinal mode operation is to reduce the length of the cavity until the frequency separation of the adjacent modes given by $\delta f = c/2nL$ is larger than the laser transition line width or gain curve. Then only the single mode which falls within the transition line width can oscillate within the laser cavity.



2.2.5 External quantum efficiency g_{th}

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

Experimentally, $\eta_{ext}$is calculated from the straight-line portion of the curve for the emitted optical power P versus drive current I, which gives

$$\eta_{ext} == 0.806\ \lambda$$

2.3 Laser Diode Rate Equation

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

=Cnφ+Rsp-...(1)

= stimulated emission+ spontaneous emission+ photon loss; which governs the number of photons φ and

=--Cnφ .....(2)

= injection+ spontaneous recombination+ stimulated emission; which governs the number of electrons n

Where; C= coefficient describing the strength of the optical absorption

Rsp=rate of spontaneous emission into lasing mode

τ_{ph}= photon life time

τ_s= spontaneous recombination lifetime

on solving equation 1 and 2 for a steady state condition will yield an expression for the output power.

In first equation assuming R_{sp} is negligible and nothing that dφ/dt must be positive is small, we have;

$$Cn-1/\tau_{ph} \geq 0$$

This shows that n must exceed a threshold value nth in order for φ to increase. So from eq 1, this threshold value can be expressed in terms of the threshold current J_{th} needed to maintain an inversion level $n=n_{th}$ in steady state when no. Of photons φ=0

=

This expression defines the current requirement to sustain an excess electron density in the laser when spontaneous emission is the only decay mechanism,

Now consider the photon and electron rate equations in the steady state condition at the lasing threshold

$$0=Cn_{th}\varphi_s+R_{sp}-\varphi_s/\tau_{ph}\text{......}(4)$$

$$0=--Cn_{th}\varphi_s\text{........}(5)$$

After adding these two equations, the no of photons per unit volume

$$\boldsymbol{\varphi_{s=}(J-J_{th})+\tau_{ph}R_{sp}}$$