Optical Sources 1: The Laser

6

INSIDE THIS CHAPTER

6.1. INTRODUCTION

The word LASER is an acronym for **light amplification by stimulated emission of radiation.** It is a device that produces optical radiation by the process of **stimulated emission.**

Laser light is different from the ordinary light source in following ways :

- Laser beam produces coherent light *i.e.,* in same phase and of same frequency while ordinary light source such as incadescent lamp sources produces incoherent light.
- Laser beam is highly monochromatic while ordinary light sources spread over a wavelength range of 100 Å to 1000 Å.
- Laser beam is extremely intense while the intensity of ordinary light source decreases rapidly with distance.
- Laser beam does not diverge while ordinary light source are highly divergent *i.e.,* the light travels long distances with spreading.

Many types of materials including gas, liquid and semiconductors can form the lasing medium. For optical fibre systems, the exclusively used laser sources are semiconductor laser diodes.

Semiconductor laser diodes were developed in the 1970s and they have found vast commercial applications in compact disc (CD) players. Semiconductor lasers are similar to other lasers, such as conventional solid state and gas lasers, in that the emitted radiation has spatial and temporal coherence. This means that laser radiation is highly monochromatic and it produces highly directional beams of light. There are many reasons those **differentiate semiconductor lasers from other lasers :**

- In semiconductor lasers the quantum transitions are associated with the band properties of materials while in conventional lasers transitions occur between discrete energy levels.
- The semiconductor laser is very compact in size *i.e.,* 0.1 mm long.
- The divergence of laser beam is considerably larger than in a conventional laser because of its very narrow active region.
- The spatial and spectral characteristics of a semiconductor laser are strongly influenced by the properties of junction medium *i.e.,* doping and band tailing.

DO YOU KNOW

Laser light is coherent or in-phase light.

6.2. BASIC CONCEPTS

To understand the light generating mechanism within the major optical sources used in optical fiber communications, we have to consider both the fundamental atomic concepts and the device structure. In this section, we elaborate the basic principles which govern the operation of both these optical sources.

6.2.1. Absorption of Radiation

The light interaction with matter takes place in discrete packets of energy or quanta known as **photons**. The quantum theory suggests that atom exist only in certain discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy to another.

If an atom is initially in a lower state 1, it can rise to a higher state 2 by absorbing a quantum of radiation (photon) of frequency f is given by

$$\boxed{E = E_2 - E_1} \qquad \text{...(6.1)}$$

$$hf = E_2 - E_1$$

$$\boxed{f = \frac{E_2 - E_1}{h}} \qquad \text{...(6.2)}$$

where, $h = 6.626 \times 10^{-34}$ Js (Planck's Constant)

Figure 6.1 shows a two energy state or level atomic system where an atom is initially in the lower energy state E_1.

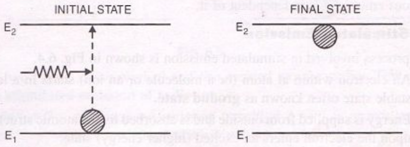


Fig. 6.1. Absorption.

This process is known as absorption of radiation.

6.2.2. Spontaneous Emission

If we take a material confine in some space and then bombard it with energy in a form that the material will absorb and then spontaneous emission of light occur. Materials capable of stimulated emission or distinguished by the fact that they have a high energy state *i.e.*, meta stable because it can hold its high energy state for some time before decaying spontaneously. Figure 6.2 shows a material treated in this way.

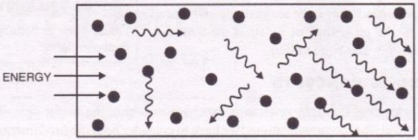


Fig. 6.2. Spontaneous Emission in Material.

Excited atoms decay and emits photons randomly in all directions. Let us now consider an atom initially in higher (excited) state 2. Excited state with higher energy is inherently unstable and hence atom is excited state does not stay for longer time and it jumps to the lower energy state 1 emitting a photon of frequency f. This is known as **spontaneous emission of radiation** and is shown in Fig. 6.3.

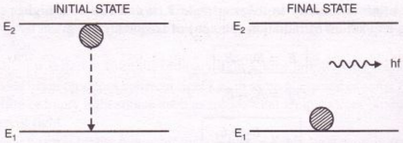


Fig. 6.3.

The probability of spontaneous emission of $2 \rightarrow 1$ is determined only by the properties of states 2 and 1. This is denoted by A_{21}, which is known as **Einstein's coefficient of spontaneous emission of radiation.** In this case, the probability of spontaneous emissions is independent of it.

6.2.3. Stimulated Emission

The process involved in stimulated emission is shown in Fig. 6.4.

1. An electron within at atom (or a molecule or an ion) starts in a low energy stable state often known as **ground state.**
2. Energy is supplied from outside and is absorbed by the atomic structure where upon the electron enters an excited (higher energy) state.
3. A photon arrives with an energy close to the same amount of energy as the electron needs to give up to reach a stable state.

4. The arrriving photon triggers a resonance with the excited atom. Thus the excited electron leaves its excited state and transitions to a more stable state giving up the energy difference in the form of a photon.

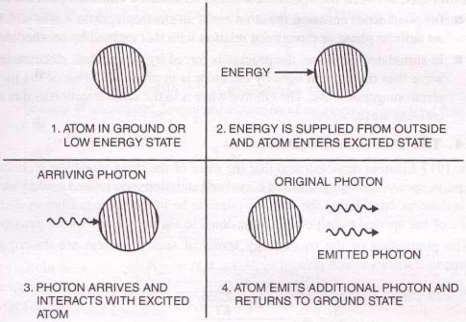


Fig. 6.4. Stimulated Emission.

Here the important characteristic is that when a new photon is emitted it has identical wavelength, phase and direction characteristics as the existing photon.

According to the Einstein, an atom in an excited energy state may under the influence of the electromagnetic field of a photon of frequency f incident upon it jumps to a lower energy state, emitting an additional photon of same frequency (f) as shown in Fig. 6.5.

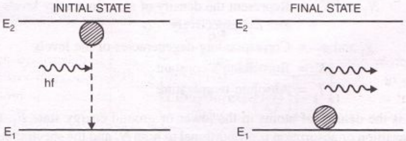


Fig. 6.5.

Thus two photons, one original and one emitted move together. This process is known as **stimulated emission of radiation.**

The probability of stimulated emission transition $2 \rightarrow 1$ is proportional to the energy density ρ_f of the stimulating radiation and is given by

$$\boxed{B_{21}\,\rho_f}$$

where, B_{21} = **Einstein's coefficient of stimulated emission of radiation**

The total probability for an atom in state 2 to drop to the lower state 1 is therefore,

$$\boxed{P_{21} = A_{21} + B_{21}\rho_f}$$

Difference between the spontaneous and stimulated emission processes :

- In spontaneous emission the atom emits an electromagnetic waves which has no definite phase or directional relation with that emitted by another atom.
- In stimulated emission, the process is forced by the incident electromagnetic wave thus the emitted light by the atom is in phase with that of the incident electromagnetic wave. The emitted wave is in the same direction as that of the incident wave.

6.2.4. The Einstein Relations

In 1917 Einstein demonstrated that the rates of the three transition processes of absorption, spontaneous emission and stimulated emission were related mathematcially. This is done by considering the atomic system to be in thermal equilibrium such that the rate of the upward transitions must be equal to the rate of downward transitions.

The population of the two energy levels of such a system are described by Botlzmann statistics which give :

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

$$= \frac{g_1}{g_2}\exp\left(\frac{E_2 - E_1}{KT}\right) \qquad \text{...(6.3)}$$

$$\boxed{\frac{N_1}{N_2} = \frac{g_1}{g_2}\exp\left(\frac{hf}{KT}\right)} \qquad \text{...(6.4)}$$

where, N_1 and N_2 = Represent the density of atom in energy levels E_1 and E_2 respectively.

g_1 and g_2 = Corresponding degeneracies of the levels.

K = Boltzmann's constant

T = Absolute temperature

If N_1 is the density of atoms in the lower or ground energy state E_1, the rate of upward transition or absorption is proportional to both N_1 and the spectral density ρ_f of the radiation energy at the transition frequency f. Hence the upward transition rate R_{12} (electron transition from level 1 to level 2) may be written as

$$\boxed{R_{12} = N_1 \rho_f B_{12}} \qquad \text{...(6.5)}$$

where, B_{12} = Einstein coefficient of absorption

Similarly atoms in the higher or excited energy state can undergo electron transitions from level 2 to level 1 either spontaneously or through simulation by the radiation field. For spontaneous emission the average time an electron exists in the excited state before transition occurs is known as the **spontaneous lifetime τ_{21}.**

If N_2 is the density of atoms within the system with energy E^2 then the spontaneous emission rate is given by the product of N_2 and $\frac{1}{\tau_2}$. This may be written as

$$\boxed{N_2 A_{21}}$$

where, A_{21} = Einstein coefficient of spontaneous emission.

The rate of stimulated downward transition of an electron from level 2 to level 1 is given by

$$\boxed{N_2 \rho_f B_{21}}$$

where, B_{21} = Einstein coefficient of stimulated emission.

The **total transition rates** from level 2 to level 1, R_{21} is the sum of spontaneous and stimulated contributions. Hence,

$$\boxed{R_{21} = N_2 A_{21} + N_2 \rho_f B_{21}} \qquad \text{...(6.6)}$$

For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore,

$$R_{12} = R_{12}$$

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

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

and

$$\rho_f = \frac{A_{21}/B_{21}}{\left(\frac{N_1 B_{12}}{N_2 B_{21}} - 1\right)} \qquad \text{...(6.7)}$$

Subtituting the value of $\frac{N_1}{N_2}$ in above equation, we get

$$\boxed{\rho_f = \frac{A_{21}/B_{21}}{\left[\left(\frac{g_1 B_{12}}{g_2 B_{21}}\right)\exp\left(\frac{hf}{KT}\right)\right] - 1}} \qquad \text{...(6.8)}$$

Since we have assumed that atomic system is in thermal equilibrium, it produces a radiation density which is identical to black body radiation. **According to Planks** the radiation spectral density for a black body radiating within a frequency range f to $f + d$ is given by

$$\boxed{\rho_f = \frac{8\pi h f^3}{C^3}\frac{1}{\left[\exp\left(\frac{hf}{KT}\right) - 1\right]}} \qquad \text{...(6.9)}$$

Comparing Eqs. (6.8) and (6.9) we get the **Einstein relation**

$$B_{12} = \left(\frac{g_2}{g_1}\right) B_{21} \qquad \text{...(6.10)}$$

and

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{C^3}} \qquad \text{...(6.11)}$$

From Eq. (6.10) it is observed that when the degeneracies of two levels are equal ($g_1 = g_2$), then the probabilities of absorption and stimulated emission are equal. Therefore the ratio of the stimulated emission rate to the spontaneous emission rate is given by

$$\boxed{\frac{\text{Stimulated Emission Rate}}{\text{Spontaneous Emission Rate}} = \frac{B_{21}\,\rho_f}{A_{21}} = \frac{1}{\exp\left(\frac{hf}{KT}\right) - 1}} \qquad \text{...(6.12)}$$

6.2.5. Population Inversion

The condition of thermal equilibrium given by Boltzmann distribution defines that, the lower energy level E_1 of the two level atomic system contains more atoms than the upper energy level E_2. This situation is normal for structures at room temperature is shown in Fig. 6.6.

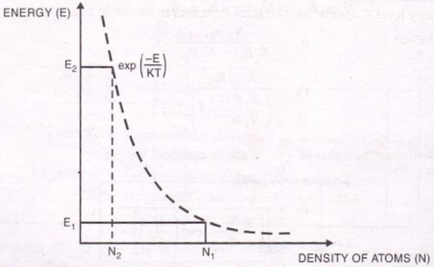


Fig. 6.6. Population in two energy level Boltzmann distribution.

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 lower energy level (*i.e.*, $N_2 > N_1$). This condition is known as **population inversion** and is shown in Fig. 6.7.

To achieve population inversion it is necessary to excite atoms into the upper energy level E_2 and hence a non-equilibrium distribution is obtained. This process is achieved by using an external energy source and is known as **pumping**.

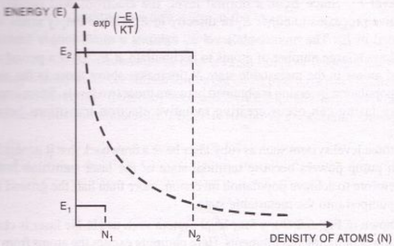


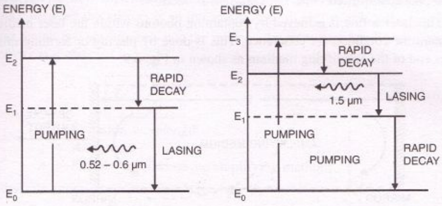
Fig. 6.7. Non-equilibrium Distribution Showing Population Inversion.

A common method used for pumping involves the application of intense radiation. In previous case atoms are excited into the higher energy state through stimulated absorption. When the two levels are equally degenerated (or not degenerated). Then

$$B_{12} = B_{21}$$

i.e., the two level system does not lend itself. Thus the probabilities of absorption and stimulated emission are not equal, providing at best equal population in the two levels.

Population inversion may be obtained in systems with three or four energy levels. The energy level diagrams for two such systems are shown in Fig. 6.8.



(a) Three level system—ruby (crystal) laser.

(b) Four level system—He-Ne (g as) laser.

Fig. 6.8. Energy level diagram showing population inversion and lasing for two semiconductors laser.

For population inversion both systems display a central metastable state in which the atoms spend an unusally long time and from this metastable level stimulated emission or lasing takes place. The three level system consists of a ground level E_0, a metastable level E_1 and a third level above the metastable level E_2.

Initially the atomic distribution will follow Boltzmann's law. With suitable pumping the electrons in some of the atoms may be excited from the ground state into the higher level E_2. Since E_2 is a normal level, the electrons will rapidly decay by nonradiative processes to either E_1 or directly to E_0. Hence empty states will always be provided in E_2. The metastable level E_1 exhibits a much longer lifetime than E_2 which allows a large number of atoms to accumulate at E_1. Over a period of time the density of atoms in the metastable state N_1 increases above those in the ground state N_0 and a population inversion is obtained between these two levels. Stimulated emission and hence lasing can occur creating radiative electron transitions between level E_1 and E_0.

The three level system such as ruby laser have a drawback that it generally requires very high pump powers because terminal state of the laser transition is the ground state. Therefore to achieve population inversion, more than half the ground state atoms must be pumped into the metastable state.

As shown in Fig. 6.8 (*b*), a four level system such as He-Ne laser is characterized by much lower pumping requirements. Here pumping excites the atoms from the ground state into energy level E_3 and decay rapidly to the meta stable level E_2. Since the populations of E_3 and E_1 remain essentially unchanged, a small increase in the number of atoms in energy level E_2 creates population inversion and lasing takes place between this level and level E_1.

6.2.6. Optical Feedback and Laser Oscillation

In the laser light amplification occurs when a photon collids with an atom in the excited energy state, it causes the stimulated emission of a second photon and then both these photon releases two more. Because of this continuous process **avalanche multiplication** occurs. When electromagnetic waves corresponding to these photons are in phase, **amplified coherent emission** is obtained.

This laser action is achieved by containing photons within the laser medium and maintain the condition for coherence. This is done by placing or forming mirrors at either end of the amplifying medium as shown in Fig. 6.9.

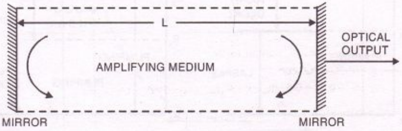


Fig. 6.9. Basic Laser Structure Incorporating Plane Mirrors.

The optical cavity formed is more analogous to an oscillator than an amplifier because it provides positive feedback of the photons by reflection at the mirrors at either end of the cavity. Therefore the optical signal is fedback many times while receiving amplification is passes through the medium. Hence this structure acts as a **Fabry-Perot resonator**. Although the amplification of signal from a single pass through the medium is quite small, the net gain can be large after multiple passes. The losses in the amplifying medium result from factors such as :

- Absorption and scattering in the amplifying medium

- Absorption, scattering and diffraction at the mirrors
- Nonuseful transmission through the mirrors.

In the laser cavity oscillations occur over a small range of frequencies, hence the device is not a perfectly monochromatic source but emits over a narrow spectral spectral band. In this band the central frequency is obtained by the mean energy level difference of the stimulated emission transitions. Figure 6.10 shows the spectral emission from the device.

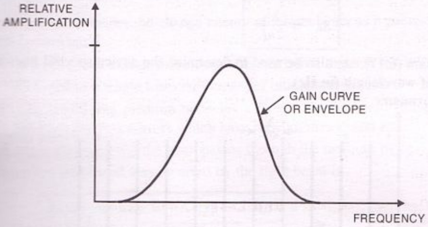


Fig. 6.10. Relative amplification in the laser showing gain curve.

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. These standing waves exist only at frequencies for which the distance between the mirrors is an integral number of half wavelengths.

If L is the optical spacing between the mirrors, the resonance condition along the axis of cavity is given by

$$\boxed{L = \frac{\lambda q}{2n}} \qquad \text{...(6.13)}$$

where,
λ = Emission wavelength.
q = An integer
n = Refractive index of the amplifying medium

and the discrete emission frequencies f are given by

$$\boxed{f = \frac{qc}{2nL}} \qquad \text{...(6.14)}$$

where, c = Velocity of light

The different frequencies of oscillation with in the laser cavity are determined by various integer value q and each constitutes a resonance or mode. These modes are separated by a frequency interval δf, where

$$\boxed{\delta f = \frac{c}{2nL}} \qquad \text{...(6.15)}$$

Mode separation in terms of free space wavelength is given by

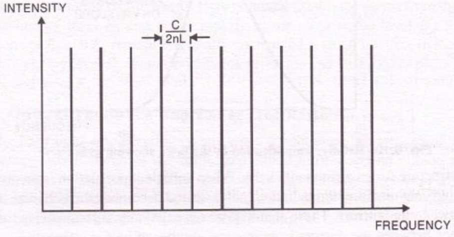
$$\delta\lambda = \frac{\lambda.\delta f}{f} \qquad \left[\begin{array}{l}\text{assuming, } \delta f << f \\ \text{and } 'f = \frac{c}{f}\end{array}\right]$$

$$= \frac{\lambda^2}{c}.\delta f \qquad ...(6.16)$$

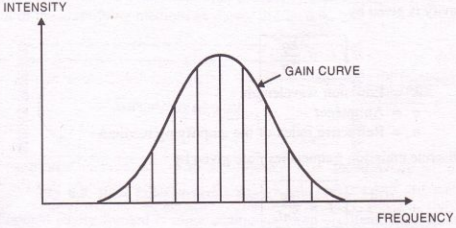
Substituting the value of δf from Eq. (6.16) we get

$$\boxed{\delta\lambda = \frac{\lambda^2}{2nL}} \qquad ...(6.17)$$

Equation (6.17) can also be used to determine the device spectral linewidth as a function of wavelength (in Hz).



(a) Modes in the laser cavity.



(b) The longitudinal modes in the laser output.

Fig. 6.11.

When large number of modes are generated within the laser cavity, the spectral output from the device is defined by the **gain curve**. Thus laser emission will only include longitudinal modes contained within the spectral width of gain curve. Figure 6.11 shows the condition where several modes are prevent in laser output. Such type of device is known as **multimode.**

6.2.7. Threshold Condition for Laser Oscillation

The steady state conditions for laser oscillation are achieved when the gain in the amplyfying medium exactly balances the total losses. Thus population inversion between the energy levels providing the laser transition is necessary for oscillation to be exstablished, but it is not only sufficient to produce lasing.

In addition a minimum or threshold gain within the amplyfying medium must be attained such that laser oscillations are initiated and sustained.

Calculation of Threshold Gain

Here we will consider the change energy of a light beam as it passes through the amplifying medium :

- All the losses except those due to transmission through the mirrors may be included in a single loss coefficient per unit length $\overline{\alpha}$ cm^{-1}.
- The amplifying medium occupies a length L completely filling the region between the two mirrors which have reflectivities r_1 and r_2.
- On each round trip the team passes through the medium twice.

Hence the **fractional loss** incurred by the light beam is

$$\boxed{\text{Fractional loss } = r_1 r_2 \exp(-2\,\overline{\alpha}L)} \qquad ...(6.18)$$

The increase in beam intensity resulting from stimulated emission is exponential in nature.

Therefore, if the gain coefficient per unit length produced by stimulated emission in $\overline{g}$ cm^{-1}, the **fractional round trip gain** is given by

$$\boxed{\text{Fractional gain } = \exp(2\overline{g}L)} \qquad ...(6.19)$$

Hence, $\exp(2gL) \times r_1 r_2 \exp(-2\overline{\alpha}L) = 1$

and : $r_1 r_2 \exp(2\overline{g} - \overline{\alpha})L = 1$ ...(6.20)

By rearranging the above equations, we may get the threshold gain per unit length.

$$\boxed{\overline{g}_{th} = \overline{\alpha} + \frac{1}{2L}\ln\frac{1}{r_1 r_2}} \qquad ...(6.21)$$

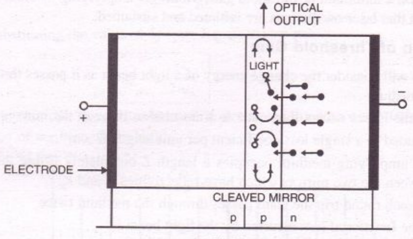
In the above equation, the **second term** on the right hand side represents the transmission loss through the mirrors. It is important to note that the parameters displayed in above equation are totally dependent on the laser type.

6.3. HETEROJUNCTIONS

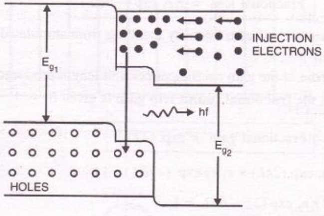
A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap energies. Devices which are fabricated with heterojunctions are known as **heterostructure.** Heterojunctions are classified as

(*a*) Isotype (*n-n* or *p-p*)
(*b*) Anisotype (*p-n*)

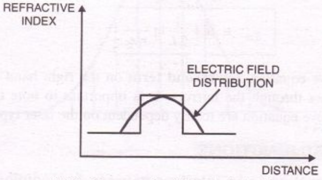
The **isotype heterojunction** provides a potential barrier within the structure which is used for the confinement of minority carriers to a small active region. It reduces the carrier diffusion length, therefore volume within the structure where radiative combination may occur. Generally this technique in used for the fabrication of injection lasers and high radiance LEDs.



(a) The Layer Structure



(b) Energy Band Diagram



(c) The Corresponding Refractive Index Diagram

Fig. 6.12. The double heterojunction infection laser.

Anisotype heterojunctions with sufficiently large bandgap differences improve the injection efficiency of either electrons or holes. Because of the different refractive indices at either side of the junction, both types of heterojunction provide a dielectric step. This is used to provide radiation confinement to active region. The efficiency of containtment depends upon the magnitude of the step.

Usually the heterojunctions are used to provide potential barriers in injection lasers. In double heterojunction (DH) structure the carrier and optical confinement reduces the threshold currents required for lasing by a factor of ≃ 100. Figure 6.12 shows the layer structure and energy band diagram of DH injection laser.

For laser oscillation, a heterojunction is shown either side of the active layer.

If a voltage same as bandgap energy of the active layer is applied, a large number of electrons (or holes) are injected into the active layer and laser oscillations start. These carriers are confined to the active layer by the energy barriers provided by the heterojunctions which are placed within the diffusion length of the injected carrier. Figure 6.12 shows that a refractive index step at the heterojunction provides radiation containtment to the active layer.

Careful fabrication of heterojunctions is very important to reduce defects at the interfaces such as misfit dislocations or inclusions which causes non-Radiative recombination and therefore reduces the internal quantum efficiency.

Semiconductor Materials

The semiconductor materials used for optical sources should fulfill the following criteria.

***(a) p-n* Junction Formation :** To the formation of *p-n* junctions, the materials must lend themselves with suitable characteristics for carrier injections.

***(b)* Efficient Electroluminescence :** The fabricated devices must have a high probability of radiative transitions and therefore a high internal quantum efficiency. Thus the materials used must be either direct bandgap semiconductors or indirect bandgap semiconductors with appropriate impurity centres.

***(c)* Useful Emission Wavelength :** The materials should emit light at a suitable wavelength to be utilized with current optical fibers and detectors (0.8 to 1.7 μm). Ideally bandgap variation should be allowed with appropriate doping and fabrication.

Table 6.1 shows some common materials used in the fabrication of sources for optical fiber communications.

Table 6.1

Material Systems Used	Useful Wavelength Range (μm)	Substrate
$GaAs/Al_x\,Ga_{1-x}\,As$	0.8 – 0.9	GaAs
$GaAs/In_x\,Ga_{1-x}\,P$	0.9	GaAs
$Al_y\,Ga_{1-y}\,As/Al_x\,Ga_{1-x}\,As$	0.65 – 0.9	GaAs
$In_{1-x}\,Ga_x\,As_y\,P_{1-y}/InP$	0.92 – 1.7	InP
$Ga_{1-y}\,Al_y\,As_{1-x}\,Sb_x/GaSb$	1.0 – 1.7	GaSb

6.4. THE SEMICONDUCTOR INJECTION LASER

In this section the electroluminescent properties of forward biased *p-n* junction diode have been cansidered. In the semiconductor injection laser, stimulated emission by the recombination of the injected carriers is encouraged. Thus injection laser has **several advantages** over other semiconductor sources. These are as follows :

(*a*) High radiance due to the amplifying effect of stimulated emission. Generally injection lasers supply milliwatts of optical power output.

(*b*) Narrow bandwidth of the order of ≤ 1 nm which is used to minimize the effects of materials dispersion.

(*c*) Modulation capabilities can be extended to gigahertz range.

(*d*) Relative temporal coherence allows heterodyne (coherent) detection in high capacity systems but presently used in single mode systems.

(*e*) Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than the dispersed infocused emission. This provides efficient coupling of optical output power into the fiber.

These advantages together with the compatibility of injection laser with optical fibers led to the early developments of the device in 1960s. Early injection lasers had the form of a **Fabry Perot cavity.** Often it is fabricated in gallium arsenide which was the major III-V compound semiconductor with electroluminescent properties at the appropriate wavelength for first generation systems.

Fabry-Perot Lasers

The Fabry-Perot laser is conceptually like an LED with a pair of end mirrors. The mirrors are required to create the right conditions for lasing to occur but practically it is somewhat more complex. The Fabry-Perot laser gets its name from the fact that its cavity acts as a Fabry-Perot resonator.

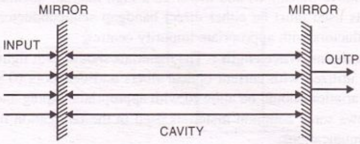
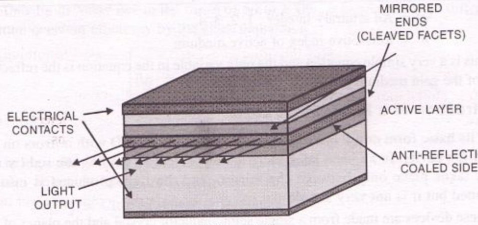


Fig. 6.13. Fabry-Perot filter.

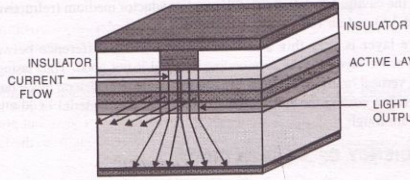
Light enters the cavity through a partially silvered mirror on the left and leaves it through a partially silvered mirror on the right. Only wavelengths that resonate within the cavity are able to pass through while other wavelengths are strongly attenuated.

The **principle of the Fabry-Perot filter** is illustrated in Fig. 6.13. When we put two mirrors opposite to each another they form a resonant cavity. Light will bounce between the two mirrors. When the distance between the mirrors is an integral multiple of half wavelengths, the light will reinforce itself. Those wavelengths which are not resonant undergo destructive interference and are reflected away.

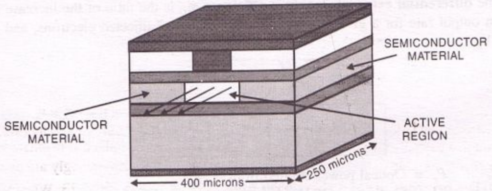
In this principle the light is emitted within the cavity itself rather than arriving from outside. In some sense every laser cavity is a Fabry-Perot cavity. But when the cavity is very long compared to the wavelength involved we get a very large number of resonant wavelengths all of which are very close together. Thus the important filtering characteristics of the Fabry-Perot cavity are lost.



(*a*) Unguided



(*b*) Gain Guided



(*c*) Index Guided

Fig. 6.14. Directing the light in a Fabry-Perot laser.

Wavelengths produced are related to the distance between the mirrors by the following formula :

$$\boxed{C_l = \frac{\lambda q}{2n}} \qquad ...(6.22)$$

where λ = Wavelength

C_l = Length of the cavity

q = An arbitrary integer : 1, 2, 3, 4...
n = Refractive index of active medium

This is a very simple equation and the only variable in the equation is the refractive index of the gain medium (dielectric) in the cavity.

Construction of a Fabry-Perot Laser

In its basic form an FP laser is like an edge-emitting LED with mirrors on the ends of the cavity. In an ideal laser there is no problem of guiding the light at all. Lasing takes place only between the mirrors and the light produced is exactly positioned but it is not very simple.

These devices are made from a single semiconductor crystal and the planes of the crystal are exactly parallel. When the device is constructed it is not cut up but rather cleaved (cracked) along the planes of the crystal. This results in exactly parallel mirrors at each end of the cavity. The interface of the semiconductor medium (refractive index usually around 3.5) and air (RI around 1.1) forms a mirror.

The active layer is very thin and the refractive index difference between the material of the active layer and the surrounding material is not good. Thus lasing is not obtained in the vertical (transverse) mode. We can get lasing in the lateral mode but this is minimized by either coating the sides with an anti-reflection material or just making sure the sides are rough.

6.5. EFFICIENCY OF A LASER DIODE

A number of ways are there to define the operational efficiency of the semiconductor laser.

The **differential external quantum efficiency** η_D is the ratio of the increase in photon output rate for a given increase in the number of injected electrons, and is given by

$$\eta_D = \frac{dP_e/hf}{dI/e}$$

$$\boxed{\eta_D \simeq \frac{dP_e}{dI(E_g)}} \qquad \text{...(6.23)}$$

where, P_e = Optical power emitted from device
I = Current
e = Charge on an electron
hf = Photon energy
E_g = Energy bandgap in eV.

η_D gives a measure of the rate of change of optical power output with current and hence defines the slope of the output characteristics in the lasing region for a particular device, sometimes η_D is known as **slope quantum efficiency**. For a CW semiconductor laser, its value lies in the range of 40-60%.

Internal quantum effeciency (η_i) of the semiconductor laser is given by

$$\eta_i = \frac{\text{No. of photons produced in the laser cavity}}{\text{No. of injected electrons}} \qquad \text{...(6.24)}$$

Usually its value lies in the range of 50 to 100%. It is related to the differential external quantum efficiency by the given expression :

$$\boxed{\eta_D = \eta_i \left[\frac{1}{1 + \left\{ \dfrac{2\,\overline{\alpha}\,L}{\ln\left(\dfrac{1}{r_1 r_2}\right)} \right\}} \right]} \qquad \text{...(6.25)}$$

where, $\overline{\alpha}$ = Loss coefficient of the laser cavity
L = Length of laser cavity
r_1, r_2 = Cleaved mirror reflectivities.

Total efficiency (external quantum efficiency) η_T is defined as

$$\eta_T = \frac{\text{Total number of output photons}}{\text{Total number of injected electrons}} = \frac{P_e/hf}{I/e}$$

$$\boxed{\eta_T \simeq \frac{P_e}{IE_g}} \qquad \text{...(6.26)}$$

P_e changes linearly when the injection current I is greater threshold current Ith then :

$$\boxed{\eta_T \equiv \eta_D \left(1 - \frac{I_{th}}{I}\right)} \qquad \text{...(6.27)}$$

The **external power efficiency** of the device η_{ep} is converting electrical input to optical output is given by

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

$$\boxed{\eta_{ep} = \frac{P_e}{IV} \times 100\%} \qquad \text{...(6.28)}$$

where, $P = IV$ = d.c. electrical input power

Using eqn. (6.28), for total efficiency, we get

$$\boxed{\eta_{ep} = \eta_T \left(\frac{E_g}{V}\right) \times 100\%} \qquad \text{...(6.29)}$$

6.6. STRIPE GEOMETRY

The *DH* laser structure provides optical confinement in the vertical direction through the refractive index step at the hetero function interfaces but lasing takes place across the whole width of the device. Figure 6.17 shows the broad area *DH* laser where the sides of the cavity are simply formed by roughing the edges of the device to reduce unwanted emission in there directions and limit the number of horizontal transverse modes.

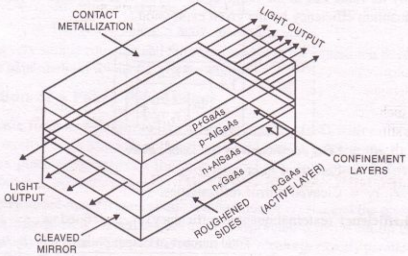


Fig. 6.15. A Broad Area GaAs/AlGaAs DH Injection Laser.

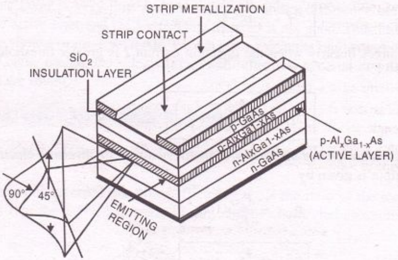


Fig. 6.16. Schematic Representation of an Oxide Stripe AlGaAs DH Injection Laser.

But **broad emission area creates several problems** like :

- difficult heat sinking.
- lasing from multiple filaments in the relatively wide active area.
- unsuitable light output geometry for efficient coupling to the cylinderical fibers.

To **overcome these problems,** threshold current is reduced therefore the laser structures in which the active region does not extend to the edges of the device were developed. A common technique used in **stripe geometry** to provides optical containtment in the horizontal plane. Figure 6.18 shows the structure of a DH stripe contact laser.

- Here the active region is within the stripe because major current flow through the device.
- The stripe is formed by the creation of high resistance area on either side by proton bombardment or oxide isolation techniques.
- Therefore the stripe acts as a guiding mechanism which overcomes the major problems of broad area device.

- The stripe contact device also gives single transverse (in direction parallel to junction plane) mode operation while broad area device tends to allow multimode operation in this horizontal plane.
- Typically the output beam divergence is 45° perpendicular to the plane of the junction and 9° parallel to it.
- In such types of structures active regions are planar and continuous. Therefore the stimulated emission characteristics of these injection lasers are determined by the carrier distribution along the function plane.

6.7. INJECTION LASER STRUCTURES

6.7.1. Gain Guided Lasers

DO YOU KNOW

For optical fiber communication systems requiring bandwidths > 200 MHz, semiconductor injection laser diode is preferred over the LED.

By the use of stripe geometry, fabrication of multimode injection lasers with a single or small number of lateral modes is achieved. These devices are known as **gain guided lasers**. The constraint of the current flow to the stripe is realized by two ways :

(1) by implanting the regions outside the stripe with protons to make them highly senstive.

(2) by oxide or *p-n* junction isolation.

There is an active layer of gallium arsenide bounded on both sides by aluminium gallium arsenide region in stripe DH laser. This technique is widely used for multimode laser structures, applied in the shorter wavelength region. The current is confined by etching a narrow stripe in a silicon dioxide film.

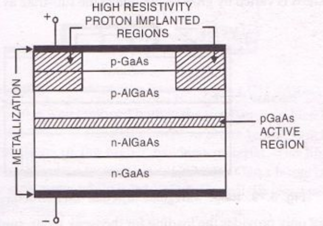


Fig. 6.17. Proton isolated stripe GaAs/AlGaAs laser.

Basically there are two technique used for the fabrication of gain guided laser structures.

(*a*) Proton isolated stripe structure.

(*b*) *p-n* junction isolated stripe structure.

Figure 6.17 shows the proton isolated stripe laser, in which the resistive region formed by the proton bombardment gives better current confinement than the simple oxide stripe and has superior thermal properties due to the absence of the silicon dioxide layer.

Figure 6.18 shows the *p-n* junction isolated which involves a selective diffusion through the *n*-type surface region in order to reach the *p*-type layers.

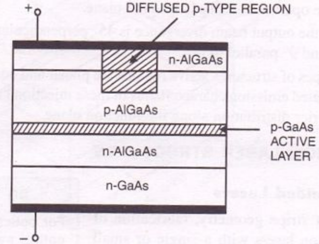


Fig. 6.18. *p-n* **Junction isolated GaAs/AlGaAs laser.**

But none of these regions are able to confines all the radiation and current to the stripe region, thus spreading occurs on both sides of the stripe. Planer stripe lasers provide **high efficient coupling** into multimode fibers with stripe widths of 10 μm or less but significantly lower coupling efficiency is achieved into small core diameter single mode fibers.

6.7.2. Index Guided Lasers

With the development of index guided injection lasers drawback of gain guided laser structures were overcome. In some of the index guided lasers, the active region waveguide thickness is varied by growing a ridge in the substrate as shown in Fig. 6.19.

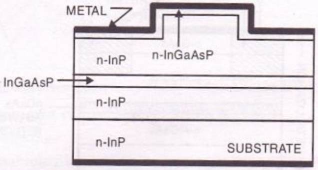


Fig. 6.19. Ridge waveguide injection laser structure.

The ridge not only provides the loading for the weak index guiding but also acts as a narrow current confining stripe. These devices have been fabricated to operate at various wavelengths with a single lateral mode and with **output powers** of 25 mW, the **threshold current** for CW at room temperature is as low as 18 mA. Typically the threshold currents for such weak guided structures are in the range of 40 to 60 mA. Figure 6.20 shows the variation of light output with current.

Alternatively, the variations in the confinement layer thickness or the refractive index can be achieved in **planar active waveguide**. The inverted rib waveguide device is also known as plano convex waveguide, as shown in Fig. 6.21.

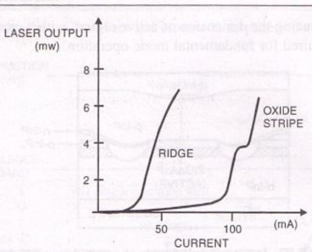


Fig. 6.20. Light output versus current characteristic.

However, room temperature CW threshold currents are between 70 and 90 mA with output powers of 20 mW for In GaAsP devices operating at a wavelength of 1.3 μm. Strong index guiding along the junction plane can provide improved transverse mode control in injection lasers. This can be achieved using a **buried heterostructure (BH)** device in which the active volume is completely buried in a material of wider bandgap and lower refractive index. Figure 6.21 shows the structure of BH laser.

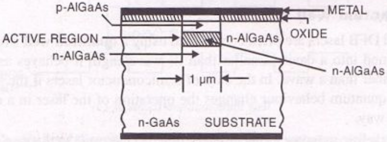


Fig. 6.21. Buried heterostructure laser structure : GaAs/AlGaAs BH device.

The optical field is well confined both in the transverse and lateral direction within these lasers. Confinement of injected current in active region is achieved through the reverse biased junctions of the higher bandgap material. The higher bandgap, low refractive index confinement material is AlGaAs for GaAs lasers operating in the 0.8 to 0.9 μm wavelength range while it is InP in InGaAsP devices operating in the 1.1 to 1.6 μm wavelength range.

A variety of BH laser configurations are available those offers both multimode and single mode operation. There devices provide lateral current confinement and leads to lower threshold current, that may be obtained with either weakly index guided or gain guided structures.

Figure 6.22 shows a more complex structure known as **double channel planar buried heterostructures (DCPBH) laser.** This device has a planar InGaAsP active region which provides very high power operation with CW output powers upto 40 mW in the longer wavelength region. Room temperature threshold currents are in the range 15 to 20 mA for both 1.3 μm and 1.55 μm emitting devices. Lateral mode control may be achieved by reducing the dimension of active region, with a cross sectional area of 0.3 μm^2 being required for fundamental mode operation.

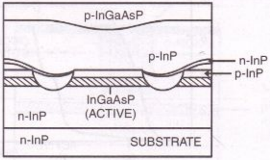


Fig. 6.22. In GaAsP/InP double channel planar BH device.

Parasitic capacitance, because of the use of the reverse biased current confinement layers can reduce the high speed modulation capabilities of BH lasers. There are two ways to overcome this problem :

- Regrowth of semi insulating material
- Deposition of a dielectric material

With the use of these techniques, modulation speeds in excess of 20 GHz has been achieved which are limited by the active region rather the parasitic capacitances.

6.7.3. Quantum Well Lasers

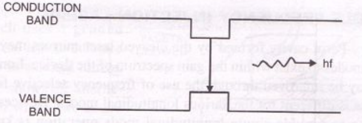
DBR and DFB lasers are often constructed using a **quantum well** structure. When light is confined into a cavity smaller than its wavelength it behaves as a particular (quantum) rather than a wave. In the case of semiconductor lasers if the size of cavity is restricted, quantum behaviour changes the operation of the laser in a dramatic and fundamental way.

- Most semiconductor lasers are very thin (20 microns) in the vertical direction. In quantum well lasers cavity height is reduced to around 10 or 20 nm.
- The width of the cavity does not need to be restricted but it should be narrow enough to prevent formation of unwanted lateral modes.
- Generally the cavity width is from 5 to 20 microns. To get sufficient gain, the cavity has to be many wavelength long.
- It is also difficult to manufactures lasers with cavities shorter than 50 microns while for other semiconductor lasers the cavity length is typically 200 to 250 microns. This cavity geometry is known as **quantum well**.

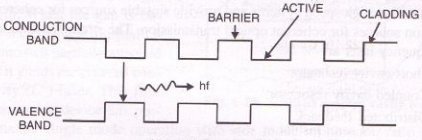
In recent years DH lasers have been fabricated with very thin active layer having thickness of around 10 nm. This special fabrication technique makes lasing action more efficient. In these devices the carrier motion normal to the active layer is restricted, resulting in a quantization of the kinetic energy into discrete energy levels for the carriers moving in that direction. This effect is similar to the **quantum well (QW) laser diodes.**

The quantum well technique modifies the density of energy levels available for electrons and holes. Like *p-n* junction, QW laser diode is characterized by the lower potential energy of its electrons and holes, thus making their recombination easier.

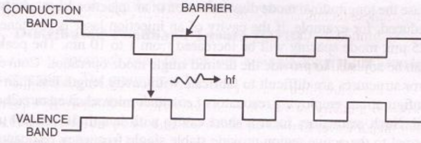
Therefore in these laser diodes less forward current is required to reach and sustain lasing action.



(a) Single quantum well.



(b) Multiquantum well.



(c) Modified multiquantum well

Fig. 6.23. Energy band diagram showing various types of quantum well structures.

Both **single quantum well (SQW)** having single active region and multiple active regions lasers have been fabricated. In latter structure, the layers separating the active layers are known as **barrier layers**. Figure 6.23 shows the energy band diagram for the active regions of these structures.

In a **multi quantum well (MQW)** the bandgap of the barrier layer differs from the cladding layer and is known as **modified multiquantum well laser.**

Better confinement of optical mode is obtained in MQW lasers as compared to SQW lasers, resulting in a lower threshold current density for these devices. The AlGaAs/GaAs material is widely used in MQW. It is demonstrated that the superior characteristics of **MQW devices over conventional DH lasers** give :

- better optical characteristics at lower threshold currents
- narrower line widths
- high modulation speeds
- lower frequency chirp
- less temperature dependence.

The main **advantages** of quantum well laser diodes are as follows :

(1) In QW laser diodes, current to light conversion is more efficient.
(2) Confinement of output beam in these diodes are better.

(3) By varying the thickness of an active layer, possibility of changing radiating wavelength is increased.

6.8. SINGLE FREQUENCY INJECTION LASERS

The Fabry-Perot cavity formed by the cleaved laser mirrors may allows several longitudinal modes to exist within the gain spectrum of the device. Longitudinal mode selectivity may be improved through the use of frequency selective feedback so that the cavity loss is different for the various longitudinal modes. Devices which employ this technique to provide single longitudinal mods operation is known as **single frequency** or **dynamic single mode (DSM) lasers**. Such laser reduces fiber intermodal dispersion within high speed systems and provide suitable sources for coherent optical transmission sources for coherent optical transmission. The strategies used to achieve single frequency laser are

(1) Short cavity resonator.
(2) Coupled cavity resonator.
(3) Distributed feedback.

6.8.1. Short and Coupled Cavity Lasers

To increase the longitudinal mode discrimination of an injection laser, cavity length should be reduced, for example, if the cavity of an injection laser is shortened from 250 μm to 25 μm, mode spacing will be increaesd from 1 to 10 nm. The peak of the gain curve can be adjusted to provide the desired single mode operation. Conventional cleaved mirror structures are difficult to fabricate with cavity length less than 50 μm, therefore configurations employing resonators *i.e.*, either microcleaved or etched have been utilized. Such resonators form a short cavity with length 10 μm–20 μm in a direction normal to the active region provide stable single frequency resonantor.

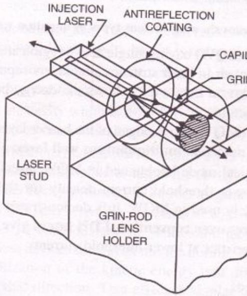


Fig. 6.24. Short external cavity laser using GRIN rod lens.

Multiple element resonators or resonators with distributed reflectors also give a loss mechanism. Mode selectivity in such a coupled cavity laser is obtained when the longitudinal modes of each Fabry-Perot cavity coincides. Figure 6.24 shows an example of three mirror resonator which uses a **graded index (GRIN)** rod lens to enhance the coupling to an external mirror.

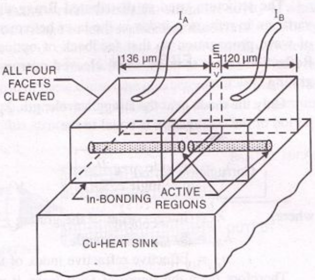


Fig. 6.25. Cleaved coupled cavity laser.

Figure 6.25 shows the alternative approach in which two active laser sections are separated by a gap of approximately a single wavelength. When the gap is obtained by recleaving a finished laser chip into two partially attached segments it yields the **cleaved coupled cavity (C^3)** laser. This four mirror resonantor device has provided dynamic single mode operation with side mode suppression ratio of several thousands. The single frequency emission of C^3 device can be tuned discretely over a range of 26 nm by varying the current through one section.

6.8.2. Distributed Feedback Lasers (DFB)

An elegant approach used to pick out a single longitudinal mode is to use a diffraction grating. The grating can be :

- Separate from the substrate.
- Etched into the portion of the substrate that extends beyond the laser cavity (Bragg reflecting laser).
- Etched into the substrate prior to the deposition of the semiconductor films (distributed feedback laser).

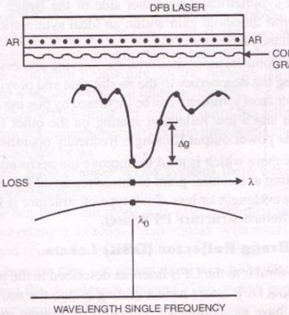


Fig. 6.26. Distributed feedback (DFB) laser (single frequency operation).

The structure used in distributed Bragg diffraction gating, provides periodic variation in refractive index in the laser heterostructre waveguide along the direction of wave propagation so that feedback of optical energy is obtained through Bagg Reflection rather than by usual cleaved mirrors. Figure 6.26 shows the corrugated grating structure.

Only the mode near the Bragg wavelength, λ_B is reflected constructively when the period of the corrugation is equal to the :

$$\boxed{\text{Corrugation period} = \frac{l\lambda_B}{2n_e}} \quad ...(6.30)$$

where,
λ = Integer order of the grating
λ_B = Bragg wavelength
n_e = Effective refractive index of the waveguide

Therefore from the figure of DFB laser, it may be observed that this particular mode will lase while the other modes exhibiting higher losses are suppressed from oscillation.

- First Order gratings (*i.e.*, $l = 1$) provide the strongest coupling within the device.
- Second order gratings (*i.e.*, $l = 2$) are sometimes used because their large spatial period eases fabrication.

According to the device operation, semiconductor lasers employing the distributed feedback mechanism can be classified into two broad categories :

- Distributed feedback (DFB) laser
- Distributed Bragg Reflector (DBR) laser.

In the DFB laser the optical grating is usually applied over the entire active region which is pumped.

When considering a DFB laser with both end facets antireflection (AR) coated, then two modes located symmetrically on either side of the Bragg wavelength will experience the same lowest threshold gain within an ideal symmetrical structure and will therefore lase simultaneously.

But practically the randomness associated with the cleaving process creates different end phases, thus removing the degeneracy of the modal gain and providing only single mode operation. Moreover facet symmetry can be increased by placing a high refraction coating on one end facet and a low reflection coating on the other (**known as hi-lo structure**) to improve the power output for single frequency operation.

Another technique is there which is used to improve the performance of the DFB laser. It modifies the grating at a central point to introduce an additional optical phase shift, typically a quater wavelength or less. Such type of structure is kown as **double channel planar buried hetero-structure DFB laser.**

6.8.3. Distributed Bragg Reflector (DBR) Lasers

DBR lasers are very similar to the DFB lasers as described in the previous section. The major difference is that DFB lasers have a grating within the active region of the cavity while DBR lasers have a partitioned cavity with the grating in a region that is not active.

The reason for this structure is that the refractive index within the cavity of a laser changes during operation because of change in temperature and electron flux. Change of refractive index in the grating region of course changes the operational wavelength of the device. If we put the grating into an inactive extension of the cavity then less wavelength variation occurs. Because of these causes the characteristics of the material immediately adjacent to the grating are not being changed by the laser's operation. Figure 6.27 shows a schematic of this structure.

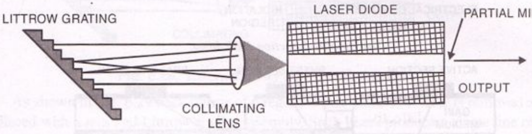


Fig. 6.27. DBR laser-schematic.

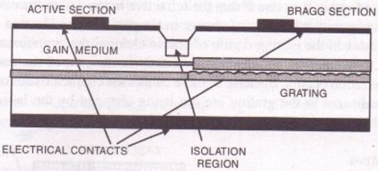
As in the DFB laser no end mirrors required as the grating can provide sufficient reflection. However end mirrors are always used in an asymmetric configuration. Typically this is 30% mirror on the back facet and either just a cleaved facet or a 4% mirror on the front (output) facet.

Typically DBR lasers produce a single line only with a line width of around .0001 nm. The major problem is that there can be significant absorption in the inactive region near the grating. This causes a loss in efficiency.

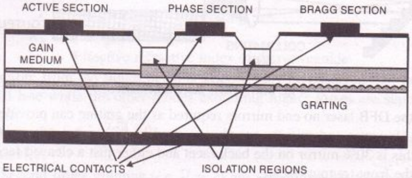
Tunable DBR Lasers

There are several situations where it is required to change (tune) the laser's wavelength.

- Some WDM systems required to tune the laser very quickly within a few tens of nanoseconds to a particular wavelength (or channel). A number of proposals for optical LAN and MAN networks require this ability.
- In other WDM situations we may want to establish a path through a wide area network by using wavelength routing. This would be appropriate in a wide area telecommunication backbone network where tuning is used to configure and re-configure routes through the network. In this case a tuning time of around a second would be quite acceptable.
- Still other WDM situations might require the setting up of "calls" across the network (like telephone calls). Set up time in this case can be perhaps a hundred microseconds or so.
- In early fixed channel WDM systems there were two main problems with laser wavelengths :
  (*i*) When lasers are made it is extremely difficult and costly to specify the wavelength exactly. Randomness determines the required wavelengths and rejects the rest but this is expensive.
  (*ii*) Over the time the materials of which the laser is made deteriorate a bit and the wavelength changes. This is fine in single-channel systems but anathema to WDM systems as wavelengths will start to run into one another.



(a) Tunable 2-section DBR laser.



(b) Tunable 3-section DBR laser.

Fig. 6.28.

In both of these cases a laser that can be tuned slowly over a relatively narrow range that can make a big improvement. So different systems require different kinds of tunability *i.e.*, range and speed.

Figure 6.28 shows two electronically tunable DBR lasers. One is a two-section device and the other has three sections.

The tunable 2-section device has a discontinuous tuning characteristic over a range of a bit less than 10 nm while the three-section device can be continuously tuned over the same range.

Operation (of the 3-section device) is as follows :

- Current in the left-hand section of the device flows through the gain medium and here lasing (amplification) takes place.
- In the centre and rightmost sections the electron flux within the cavity causes the cavity to change in refractive index within these sections.
- The change in RI causes the wavelength of the light emitted to change also.
- The right-hand section has the grating inside it (or rather immediately adjacent to it) and this is used for broad tuning.
- Fine tuning is accomplished by varying the current in the "phase section" (middle part) of the laser cavity.

A disadvantage of the 3-section device is that it requires relatively complex electronics for control.

External Cavity DBR Lasers

An interesting form of DBR laser can be constructed where the resonant cavity extends outside the laser chip itself. Since the length of cavity is extended thus the possible number of longitudinal modes increases exponentially. The major reason for the external cavity is that we can use a much stronger (more selective) grating.

Figure 6.29 shows the schematic of external cavity DBR laser.

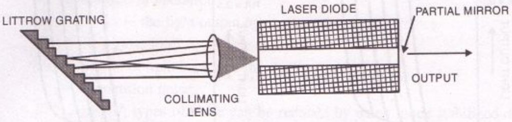


Fig. 6.29. External cavity DBR laser schematic.

As shown in Fig. 6.29 back mirror of a regular index-guided FP laser is removed and replaced with a lens and Littrow grating assembly. Such lasers produce a single line only with a very narrow line width (a few tens of kilohertz).

Here the **major problem** is that these devices are significantly more expensive than other types of high quality laser.

A **useful feature** is that we can mount the grating on a moveable platform (such as a piezoelectric crystal) and mechanically tune the device by tilting the grating. This provides a very wide tuning range but a relatively slow tuning speed.

6.9. INJECTION LASER CHARACTERISTICS

The injection laser is used for optical fiber communication thus its characteristics should be studied which may affect its efficient operation. Some major operating characteristics of the device which generally apply to all the various materials and structures are discussed here.

(1) Threshold current temperature dependence : Generally the threshold current tends to increase with temperature, the temperature dependence of the threshold current density J_{th} being approximately exponential for most common structures. It is given by

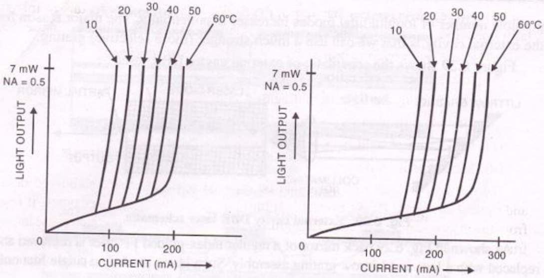
$$J_{th} \;\alpha\; \exp\left(\frac{T}{T_0}\right) \qquad ....(6.31)$$

where, T = Device absolute temperature.

T_0 = Threshold temperature coefficient (it describes the quality of material)

Figure 6.30 shows the variation in threshold current with temperature for two gain guided injection lasers. Both devices had strip widths of approximately 20 μm but were fabricated from different material systems for emission at wavelengths of 0.85 μm and 1.55 μm (AlGaAs and InGaAsP devices respectively).

For AlGaAs device T_0 is usually in the range of 120 to 190 K while for InGaAsP device it is between 40 and 75 K. The increase in threshold current with temperature for AlGaAs devices can be accounted for with reasonable accuracy by consideration of increasing energy spread of electrons and holes injected into the conduction and valence bands.



(a) AlGaAs device. (b) InGaAsP device.

Fig. 6.30. Variation in threshold current with temperature for gain guided injection lasers.

(2) Dynamic Response : When injection laser is used in high bit rate (wideband) optical fiber communication systems, its dynamic behaviour is critical. The application of a current step to the device gives **switch on delay**, sometimes followed by high frequency damped oscillations known as **relaxation oscillations (RO).** These transient phenomenon occur when the electron and photon populations within the structure come into equilibrium, as shown in Fig. 6.31.

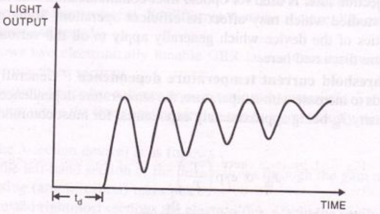


Fig. 6.31. Dynamic behaviour of an injection laser showing switch on delay and relaxation oscillations.

The **switch on delay** is caused by the initial build up of photon density resulting from stimulated emission. It is related to the minority carrier lifetime and the current through the device. The current term and thus the switch on delay may be reduced by biasing the laser near threshold.

When a current pulse reaches a laser which has significant parasitic capacitance after the initial delay time. The pulse will be broadened because the capacitance provides a source of current over the period that the photon density is high. The injection laser output can consist of several pulses because the electron density is repetitively build up and quickly reduced, thus causing ROs. The switch on delay t_d may last for 0.5 ns and the RO for perhaps twice that period.

(3) Noise : The noise behaviour of the device is an important feature of injection laser operation, especially in the case of analog transmission. The sources of noise are :

(*a*) Phase or frequency noise.

(*b*) Instabilities in operation

- kinks in the light output against current characteristics.
- self pulsation.

(*c*) Reflection of light back into the device.

(*d*) Mode partition noise.

(*b*), (*c*) and (*d*) types of noise can be reduced by using mode stabilized devices and optical isolators. **Phase noise** is an intrinsic property of all laser types, it results from the discrite and random spontaneous or stimulated transitions which cause intensity fructuations in optical emission. Each event causes a sudden jump in the phase of the electromagnetic field generated by the device. Figure 6.38 shows the spectral density of phase or frequency noise characteristic represented by $\frac{1}{f}$ to $\frac{1}{f^2}$ upto a frequency (*f*) of around 1 MHz.

At frequencies above 1 MHz the noise spectrum is flat or white because of quantum fluctuations and its major cause is line width broadening within the semiconductor lasers. The low frequency components can be easily tracked and is not a major problem within optical fiber communications.

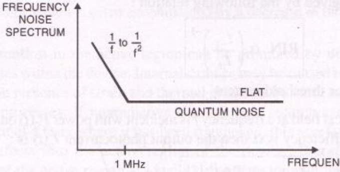


Fig. 6.32. Spectral characteristics showing injection laser phase noise.

Usually the **quantum noise** levels are low for injection lasers operating at frequencies less than 100 MHz unless the device is biased within 10% of threshold. The noise spectrum is flat in this region when the laser is operating above threshold *i.e.*, in wideband systems, quantum noise becomes more pronounced. This occurs mainly in the case of multimode device.

Amplitude or intensity fluctuations of the output from semiconductor injection lasers also leads to **optical intensity noise**. These fluctuations occur because of temperature variations or spontaneous emission contained in the laser output. The random intensity fluctuations create a noise source known as **relative intensity noise** (RIN) which is defined in terms of

- Mean square power fluctuations $\overline{\delta P_e^2}$.
- Mean optical power squared $(\overline{P}_e)^2$.

In general, the faster the device can switch, the narrower will be the range of channels over which it can switch.

Another point is that tunable lasers are seldom capable of continuous tuning over an unbroken range of wavelengths. When they are tuned they **jump** from one wavelength to another (corresponding to the resonance modes of the laser cavity).

6.11. FIBER LASERS

Fiber lasers are not used in major commercial areas but they offer a number of very interesting possibilities and working prototypes. They are very closely related to fiber amplifiers.

The concept is very simple. We can use a section of rare earth doped fiber as the gain section (cavity) of the laser. The mirrors can be made in various ways but the use of **In-Fiber Bragg Gratings (FBGs)** is very attractive because of their wavelength-selective nature. The laser is pumped with light of a wavelength appropriate to the lasing medium *i.e.,* 980 nm or 1480 nm for Erbium.

Figure 6.34 shows the fiber laser constructed from two FBGs and a length of Erbium doped fiber.

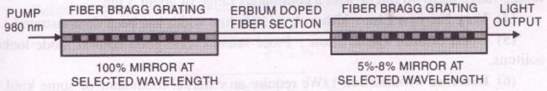


Fig. 6.34.

In-Fiber Laser Using FBGs. Depending on the detailed design the exit mirror might have any reflectivity (at the specified wavelength) between about 5% and 80%.

All it is an optical amplifier with mirrors on the end of the fiber to form a cavity.

- Input light from a pump laser operating at 980 nm enters the cavity through the left-hand FBG. Both FBGs are resonant (reflective) at a very specific wavelength.
- Spontaneous emission will commence in the erbium quite quickly.
- Most of the spontaneous emissions will not be in the guided mode and so will leave the cavity quite quickly.
- Most spontaneous emissions will not be at exactly the right wavelength to be reflected by the FBGs and so will pass out of the cavity straight through the FBG mirrors. But some spontaneous emissions will have exactly the right wavelength and will happen to be in the guided mode.
- In this case these emissions will be reflected by the FBGs and amplified in the cavity and lasing has commenced.

Various rare earth dopants can produce lasers in differing wavelength bands. In addition the type and composition of glass used in the "host" fiber makes an enormous difference to the operational characteristics of the lasing medium. This is because it plays a very important role in the energy state transitions necessary to support stimulated emission. The exact wavelength however is determined by the characteristics of the grating used :

- Nd^{3+} at 0.9
- Nd^{3+}at 1.08
- Pr^{3+} at 1.06 μm
- Er^{3+} at 1.55 μm

Another factor is the level of rare earth dopant used in the glass. Some glass hosts can not be doped to very high concentrations. For example, erbium in silica glass can only be used to a maximum of about 1% but it can be used at significantly higher concentrations in "ZBLAN" glasses. If we want the laser to be short *i.e.,* to minimize mode hopping a high dopant concentration is needed.

The **important characteristics** of this class of lasers are as follows :

(1) High Power Output : In communication applications power output of up to 50 mW is achievable. For other types of applications powers of up to 4 W in continuous operation or 10 W in pulsed operation are possible. This is a lot higher than is achievable with semiconductor lasers.

(2) Low Noise : Fiber lasers have inherently very low levels of Relative Intensity Noise (RIN).

(3) Tunability : Tunable versions have been constructed with a discontinuous tuning range up to 40 nm or with a continuous range of about 5 nm.

(4) Very Narrow Linewidth : A 10 kHz line width has been demonstrated.

(5) Good Soliton Generation : Fiber lasers create good natural mode-locked solitons.

(6) External Modulation : We require an external modulator of some kind as we can't control the output by switching the energy source on and off.

(7) Pre-selected Wavelengths : Since FBGs can be manufactured to very accurate wavelength tolerances and do not require an active temperature control (heaters and coolers) thus the device can be manufactured to an accurate wavelength without the need for post-tuning.

(8) Mode Hopping : Mode hopping is still a problem but can be eliminated if the device is physically short. If this characteristic is controlled, this type of laser could be a very suitable source for a WDM system.

Solved Examples

Example 6.1. An incandescent lamp operating at a temperature of 1000 K with an average operating wavelength is 0.5 μm. Determine the ratio of stimulated emission rate to the spontaneous emission rate.

Solution. Given that, $\lambda = 0.5\ \mu m = 0.5 \times 10^{-6}$ m

$$T = 1000 \text{ K}$$

$$f = \frac{C}{\lambda} = \frac{3 \times 10^{8}}{0.5 \times 10^{-6}} = 6 \times 10^{14} \text{ Hz}$$

Ratio of stimulated emission rate and spontaneous emission rate is given by

$$= \frac{1}{\exp\left(\frac{hf}{KT}\right) - 1}$$