**BASIC TERMS AND DEFINITIONS:**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Light amplification by stimulated emission of radiation; a coherent source of light with a narrow spectral width.</td>
</tr>
<tr>
<td>Light-emitting diode (LED)</td>
<td>A semiconductor device that emits incoherent light formed by the P-N junction. Burrus (well) and edge-emitting diodes are used with systems operating up to 622 Mb/s over multimode fibers.</td>
</tr>
<tr>
<td>Light source</td>
<td>The fiber optic transmitter in an optical loss test set (OLTS) that uses one or more LEDs or lasers at specified wavelength. Lasers used in communication systems must be stabilized and operating in continuous wave or modulated at 2 kHz.</td>
</tr>
<tr>
<td>Laser diode</td>
<td>A semiconductor diode that emits light in a narrow spectrum; typically over 90% of the light output power concentrated within one angstrom.</td>
</tr>
<tr>
<td>Laser-optimized multimode fiber</td>
<td>The ISO/IEC 11801 standard defines two types: the OM3 50/125 fiber, with an effective modal bandwidth of 2,000 MHz-km at 850 nm, and the OM4 50/125 fiber, with 4,700 MHz-km bandwidth.</td>
</tr>
<tr>
<td>External Quantum Efficiency</td>
<td>The external quantum efficiency is defined as the number of photons emitted per radiative electron-hole pair recombination above threshold.</td>
</tr>
<tr>
<td>Internal Quantum Efficiency</td>
<td>The internal quantum efficiency is the fraction of the electron-hole pairs that recombine radiatively. If the radiative recombination rate is ( R ) and the nonradiative recombination ratio is ( R_{nr} ), then the internal quantum efficiency is the ratio of the radiative recombination rate to the total recombination rate.</td>
</tr>
<tr>
<td>direct band gap Materials</td>
<td>In some materials a direct transition is possible from valance band to conduction band. Such type of materials is called as direct band gap materials. Ex. GaAs, InP, InGaAs.</td>
</tr>
<tr>
<td>In-direct band gap Materials</td>
<td>In some materials a direct transition is not possible from valance band to conduction band. Such type of materials is called as indirect band gap materials. Ex. Silicon, Germanium.</td>
</tr>
<tr>
<td>population inversion</td>
<td>Under thermal equilibrium, the lower energy level ( E_1 ) of the two level atomic systems contains more atoms than upper energy level ( E_2 ). To achieve optical amplification, it is must to create non-equilibrium distributions of atoms such that population of the upper energy level is greater than lower energy level i.e. ( N_2 &gt; N_1 ). This condition is known as population inversion.</td>
</tr>
</tbody>
</table>
Concepts

Lasing conditions and resonant Frequencies
The electromagnetic wave propagating in longitudinal direction is expressed as –

\[ E(z, t) = I(z) e^{j(\omega t - \beta z)} \]

where,

- \( I(z) \) is optical field intensity.
- \( \omega \) is optical radian frequency.
- \( \beta \) is propagation constant

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

\[ I(z) = I(0) e^{[-\Gamma g(h \nu - \alpha(h \nu)) z]} \]

\( \Gamma \) is optical field confinement factor or the fraction of optical power in the active layer.

\( \alpha \) is effective absorption coefficient of material. \( g \) is gain coefficient.

\( h \nu \) is photon energy.

\( z \) is distance traverses along the lasing cavity.

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

\[ I(2L) = I(0) e^{[-\Gamma g(h \nu - \alpha(h \nu)) L]} \]

The condition of lasing threshold is given as
1. For amplitude : \( I(2L) = I(0) \)
2. For phase : \( e^{-2\beta L} = 1 \)
3. Optical gain at threshold = Total loss in the cavity.

\[ \Gamma g_{th} = \alpha_t \]

Now the lasing expression is reduced to –

\[ \Gamma g_{th} = \alpha_t = \alpha + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) \]

\[ \Gamma g_{th} = \alpha_t = \alpha + \alpha_{end} \]

LED Structures

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

**Double Heterojunctions (DH)**

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

![Double heterojunction (DH) emitter](image)

The crosshatched regions represent the energy levels of freecharge. Recombination occurs only in active InGaAsP layer. The two materials have different bandgap energies and different refractive indices. The changes in bandgap energies create potential barrier for both holes and electrons. The free charges can recombine only in narrow, well defined active layer side.

A double heterojunction (DH) structure will confine both hole and electrons to a narrow active layer. Under forward bias, there will be a large number of carriers injected into active region where they are efficiently confined. Carrier recombination occurs in small active region so leading to an efficient device. Antoer advantage DH structure is that the active region has a higher refractive index than the materials on either side, hence light emission occurs in an optical waveguide, which serves to narrow the output beam.

**LED configurations**

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

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

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

**Fabry – Perot Resonator cavity of LASER**

Lasers are oscillators operating at frequency. The oscillator is formed by a resonant cavity providing a selective feedback. The cavity is normally a Fabry-Perot resonator i.e. two parallel plane mirrors separated by distance L,
Light propagating along the axis of the interferometer is reflected by the mirrors back to the amplifying medium providing optical gain. The dimensions of cavity are 25-500 \( \mu \)m longitudinal 5-15 \( \mu \)m lateral and 0.1-0.2 \( \mu \)m transverse. Fig. 3.1.10 shows Fabry-Perot resonator cavity for a laser diode.

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

**Quantum Efficiency and Power**

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

\[
\eta_{\text{int}} = \frac{R_r}{R_r + R_{nr}}
\]

Where
- \( R_r \) is radiative recombination rate.
- \( R_{nr} \) is non-radiative recombination rate.

If \( n \) are the excess carriers, then radiative life time

\[
\tau_r = \frac{n}{R_r}
\]

and non-radiative life time

\[
\tau_{nr} = \frac{n}{R_{nr}}
\]

The internal quantum efficiency is given as –

\[
\eta_{\text{int}} = \frac{1}{1 + \frac{R_{nr}}{R_r}}
\]

\[
\eta_{\text{int}} = \frac{1}{1 + \frac{1}{\tau_{nr}}}
\]
The recombination time of carriers in active region is \( \tau \). It is also known as bulk recombination life time.

\[
\frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_{nr}}
\]

Therefore internal quantum efficiency is given as –

\[ \eta_{int} = \frac{\tau}{\tau_p} \]

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

\[ R_p = R_{nr} = \frac{1}{q} \]

\[ \eta_{int} = \frac{R_p}{I/q} \]

\[ R_p = \eta_{int} \cdot \frac{1}{q} \]

Optical power generated internally in LED is given as –

\[ P_{int} = R_p \cdot h \nu \]

\[ P_{int} = \left( \eta_{int} \cdot \frac{1}{q} \right) \cdot h \nu \]

\[ P_{int} = \left( \eta_{int} \cdot \frac{2}{q} \right) \cdot h \nu \]

\[ P_{int} = \eta_{int} \cdot \frac{h \nu I}{q} \]

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

\[ \eta_{ext} = \frac{P_{int}}{n (n+1)^2} \]

The optical output power emitted from LED is given as

\[ P = \frac{1}{n (n+1)^2} \cdot P_{int} \]

**Lensing Schemes for Coupling Improvement**

When the emitting area of the source is smaller than the core area of fiber, the power coupling efficiency becomes poor. In order to improve the coupling efficiency miniature lens is placed between source and fiber. Microlens magnifies
the emitting area of source equal to core area. The power coupled increases by a factor equal to magnification factor of lens.

Important types of lensing schemes are:
1. Rounded end fiber.
2. Spherical – surfaced LED and Spherical-ended fiber.
3. Taper ended fiber.
4. Non imaging microsphere.
5. Cylindrical lens,
6. Imaging sphere

Fig. 4.4.1 shows the lensing schemes.
There are some drawbacks of using lens.
1. Complexity increases.
2. Fabrication and handling difficulty.
3. Precise mechanical alignment is needed.

Fiber Splices
A permanent or semipermanent connection between two individual optical fibers is known as fiber splice. And the process of joining two fibers is called as splicing.

Typically, a splice is used outside the buildings and connectors are used to join the cables within the buildings. Splices offer lower attenuation and lower back reflection than connectors and are less expensive.

Types of Splicing
There are two main types of splicing
Fusion splicing.
Mechanical splicing / V groove
(ii) **Extrinsic Losses**

Extrinsic losses occur due to mechanical misalignment at point of joints. They are,

(a) **Lateral Misalignment**

This misalignment occurs when the, fibers are displaced along the face of fiber and hence the core overlapping area is reduced from circular to elliptical form hence power loss from emitting fiber to the receiving is given below,

\[
\text{MMGI Fiber:} \quad \text{Loss}_{\text{lat}} = -10 \log \left(1 - \frac{d_1}{3a_1} \right)
\]

\[
\text{SM Fiber:} \quad \text{Loss}_{\text{lat}} = -10 \log \left( \exp \left( \frac{d_2}{\lambda n_0} \right) \right)
\]

![Lateral Misalignment Diagram](image)

(b) **Angular Misalignment**

For a perfectly matched fiber, if point of joint at which core axis of fiber 1 is at an angle with the core axis of fiber 2 then angular misalignment occurs and the result is same as due to numerical aperture mismatch.

![Angular Misalignment Diagram](image)

\[
\text{For MMGI Fiber:} \quad \text{LOSS}_{\text{ang}} = -10 \log \left(1 - \frac{\text{sin}^2 \theta}{\lambda a_1^2} \right)
\]

\[
\text{LOSS}_{\text{ang}} = -\log e^{-\frac{\theta^2}{\lambda a^2}}
\]

![Angular Misalignment Diagram](image)

Where \( \theta \) = \( \text{arc} \text{tan} \frac{\text{angle}}{\lambda} \).

(c) **End separation Misalignment**

When two fibers are separated longitudinally by a gap of ‘S’ between them, then longitudinal end separation misalignment occurs.
Surface Emitting LEDs:
Primary active region is a small circular area located below the surface of the semiconductor substrate, 20-50µm diameter and up to 2.5µm thick. Emission is isotropic and in lambertian pattern. A well is etched in the substrate to allow the direct coupling of emitted light to the optical fiber. Emission area of substrate is perpendicular to axis of optical fiber. Coupling efficiency optimized by binding fiber to the substrate surface by epoxy resin with matching refractive index.

Edge Emitting LEDs:
Primary active region is a narrow strip that lies beneath the semiconductor substrate. Semiconductor is cut and polished so emission strip region runs between front and back. Rear face of semiconductor is polished so it is highly reflective while front face is coated with anti-reflective. Light will reflect from rear and emit through front face. Active Regions are usually 100-150µm long and the strips are 50-70µm wide which are designed to match typical core.
fibers of 50-100µm. Emit light at narrower angle which allows for better coupling and efficiency than SLEDs.

**Population Inversion**

The lifetime of an atom in excited state is of the order of $10^{-8}$ seconds. So, before an excited atom can be stimulated to emit a photon, it is most likely to make a spontaneous emission. The photons emitted by a spontaneous emission are not coherent.

The ratio of the number $n'$ of excited atoms to that of $n$ in the ground state is given by the Boltzmann's equation.

$$\frac{n'}{n} = e^{-\frac{W}{kT}}$$

- $W$ = Energy difference between excited state and ground state;
- $K$ = Boltzmann constant
- $T$ = Kelvin temperature.

Consider three level system in which three active energy levels $E_1$, $E_2$ and $E_3$ are present and population in those energy levels are $N$, $N_1$ and $N_3$ respectively. In normal conditions $E_1 < E_2 < E_3$ and $N_1 > N_2 > N_3$.

$E_1$ is the ground state, its lifetime is unlimited. $E_3$ is highest energy state, its lifetime is very less and it is the most unstable state. $E_2$ is in excited state and has more lifetime. Hence $E_2$ is a meta stable state. When suitable form of energy is supplied to the system in a suitable way, then the atoms excite from ground state ($E_1$) to excited...
states ($E_2$ and $E_3$). Due to un stability, Excited atoms will come back to ground state after the Life time of the respective energy states $E_2$ and $E_3$

If this process is continued then atoms will excite continuously to $E_2$ and $E_3$

Because $E_3$ is the most unstable state, atoms will fall into $E_2$ immediately. At some stage the population in $E_2$, will become more than the population in ground state.

This situation is called population inversion and is shown in figure 4.11

There are several ways of pumping a laser and producing population inversion necessary for stimulated emission to occur. Most commonly used methods are as follows.

There are several ways of pumping a laser and producing population inversion necessary for stimulated emission to occur. Most commonly used methods are as follows.

- Optical pumping
- Electric discharge
- Inelastic atom to atom collision
- Direct conversion
- Chemical reactions.

**3dB modulation bandwidth of LED:**
The expression for the 3 dB modulation bandwidth of LED in optical communication maybe obtained in either electrical and optical terms. If we consider the associated electrical circuitry in an optical fiber communication system to use the electrical definition, where the electrical signal power has dropped to half of its constant value due to the modulated portion of the optical signal. Hence, this corresponds to the electrical 3 dB frequency at which the output electrical power is reduced by 3 dB with respect to the input electrical power. We can also consider the high frequency 3 dB point, when the optical source operates down to D.C.

The expression for the electrical bandwidth can be obtained from the ratio of the electrical output power to the electrical input power in decibels and is given as
\[ \text{RE}_{\text{dB}} = 10 \log_{10}(\text{Electrical output power} / \text{Electrical input power}) \]

\[ = 10 \log_{10} \]

\[ = 10 \log_{10} \]

The electrical 3 dB points occur when the ratio of electrical powers shown in above expression is \(\sqrt{2}\) Hence, it follows that this must Occur when,

Thus this expression depicts that the bandwidth of the electrical regime may be defined by the frequency when the output current has dropped to \(\sqrt{2}\) (or) 0.707 of the input current of the system.

Optical bandwidth can be obtained from the ratio of the optical power output to optical power input in decibels \(\text{RO}_{\text{dB}}\) is given by

\[ \text{RO}_{\text{dB}} = 10 \log_{10} \]

\[ = 10 \log_{10} \]

Hence, the optical 3 dB points occur when the currents is equal to 0.5,hence Therefore In optical regime the bandwidth is defined by the frequency at which the output current has dropped to 0.5 of the input current to the system.

The Modulation bandwidth of LED is generally determined by three methods . They are

1. The doping level in the active layer,
2. Due to the injected carriers, the reduction in radiative lifetime.
3. The parasitic capacitance of the device.

If we assume that the parasitic capacitance is negligible, then the speed at which an LED can be directly current modulated is fundamentally limited by the recombination lifetime of the carriers,

\[ P = \text{Optical output power of the device} \]
\( \omega = \) Angular modulation frequency.
\( \tau = \) Injected carrier lifetime in the recombination region

(i) D.C. optical output power for the same drive current

**LASER:**
The key processes involved in laser action are as given below.

(i) Absorption.

(ii) Spontaneous emission.

(iii) Stimulated emission.

These three key processes are represented by 2-energy level diagrams.

Where, \( E_1 = \) Energy of ground state.
\( E_2 = \) Energy of excited state.

**Absorption**

When transition occurs between two states, then it involves the emission and absorption of energy in the form of photon energy \( h\nu_n = E_2 - E_1 \)

In the above figure we can see that electron in \('E_1'\) absorbs the photon energy and is excited to state \('E_2'\) when photon of energy \( h\nu_n \) is incident on the system.

(ii) **Spontaneous Emission**

Charge carriers are unstable in excited state so they try to come back in stable state and this is possible by emission of radiation. This emission takes place when energy \( h\nu_v \) is released. As it occurs without any external stimulation, it is known as spontaneous emission.
Stimulated Emission

Here in this type of emission when a photon of energy $h\nu_{12}$ is striking on system while the electron is still in its excited state, then the electron is stimulated so that it drops on to ground state and gives a photon of energy $h\nu_n$ and the emitted photon will be in phase with incident photon. The resultant emission is called as stimulated emission.

**Direct Recombination:**
In direct band gap materials, the minimum energy of the conduction band lies directly above the maximum energy of the valence band in momentum space energy. In this material, free electrons at the bottom of the conduction band can recombine directly with free holes at the top of the valence band, as the momentum of the two particles is the same. This transition from conduction band to valence band involves photon emission (takes care of the principle of energy conservation). This is known as direct recombination. Direct recombination occurs spontaneously. GaAs is an example of a direct band-gap material.

**Indirect Recombination:**
In the indirect band gap materials, the minimum energy in the conduction band is shifted by a $k$-vector relative to the valence band. The $k$-vector difference represents a difference in momentum. Due to this difference in momentum, the probability of direct electron-hole recombination is less.

In these materials, additional dopants (impurities) are added which form very shallow donor states. These donor states capture the free electrons locally; provides the necessary momentum shift for recombination. These donor states serve as the recombination centers. This is called Indirect (non-radiative) Recombination.

Nitrogen serves as a recombination center in GaAsP. In this case it creates a donor state, when SiC is doped with Al, it recombination takes place through an acceptor level. when SiC is doped with Al, it recombination takes place through an acceptor level.

The indirect recombination should satisfy both conservation energy, and momentum. Thus besides a photon emission, phonon emission or absorption has to take place.
GaP is an example of an indirect band-gap material.

**LED Materials:**
An important class of commercial LEDs that cover the visible spectrum are the III-V. ternary alloys based on alloying GaAs and GaP which are denoted by GaAs$_{1-y}$Py. InGaAlP is an example of a quarternary (four elements) III-V alloy with a direct band gap. The LEDs realized using two differently doped semiconductors that are the same material is called a homojunction. When they are realized using different band gap materials they are called a heterostructure device. A heterostructure LED is brighter than a homoJunction LED.

**Source Output Pattern**
Consider the following figure 5.1.1, which shows a spherical coordinate system characterized by $R, \theta$ and $\phi$ with the normal to the emitting surface being the polar axis. The radiance may be a function of both $\theta$ and $\phi$, and can also vary from point to point on the emitting surface. Surface emitting LEDs are characterized by their lambertian output pattern, which means the source is equally bright when viewed from any direction. The power delivered at an angle $\theta$, measured relative to a normal to the emitting surface, varies as $\cos \theta$ because the projected area of the emitting surface varies as $\cos \theta$ with viewing direction. The emission pattern for a lambertian source thus follows the relationship.

![Fig 5.1.1 Dimensional Spherical Co-Ordinate System](image)

Figure 5.1.2, shows the radiation pattern for a lambertian source. The complexity of emission pattern is still increases, when we consider edge-emitting LEDs and laser diodes. In the planes parallel and normal to the emitting junction plane of the device. The radiances of these devices are given by, $B(\theta, 0^\circ)$ and $B(\theta, 90^\circ)$. Generally, these radiances can be approximated as,

$$\frac{1}{B(\theta, \phi)} = \frac{\sin^2 \phi}{B_0 \cos \theta} + \frac{\cos^2 \phi}{B_0 \cos \theta}$$
Where,

\( T \) = Transverse power distribution coefficient
\( L \) = Lateral power distribution coefficient.

For edge emitter \( L = 1 \) and \( T \) is significantly large value.