Hence in this case infinite Bandwidth.

Similarly if

Note: a function in frequency domain represents the sinusoidal function then if it has infinite Coherence time i.e. we can predict the signal at any time interval.

In practice, we have certain Bandwidth and certain Coherence time. But the important thing to be noted that they have inverse relationship.

So Higher Coherence in relationship means smaller Value of Tcoh and larger Value of Bandwidth. And if Tcoh is large, we can able to predict the Signal separately far and Bandwidth will be small.

Since the Dispersion is related to Spectral width of the Source, the larger the Spectral width closer to be a source for optical communication. So for a good source, the Spectral width is small as possible i.e. otherwise, the Bandwidth should be as small as possible (which in turn the Tcoh should be as large as possible).

Hence the source should be temporal Coherent.

Spatial C
Spatial coherence function \( R(A) = \int_{-\infty}^{\infty} A(x) A^*(A-x) \, dx \)

Power Radiation Pattern \( \leftrightarrow R(A) \)

In this function, the temporal coherence function is very small because signals are continuously varied.

And if I could ask about the relationship at a perpendicular direction to the direction of propagation.

Spatial coherence function

Power Radiation Pattern \( \leftrightarrow R(A) \)

If I have a function which is partially coherent in the plane perpendicular to the direction of propagation, it essentially means that radiation is not focused in the direction of propagation but goes in any other direction.

As we know, in case of LED, the generated photon can go in any arbitrary direction and only those photons within the critical angle cone can escape from the device. If by some means, we can create the photons within the critical angle cone, then most of the photons can come out. So it should be directed in proper direction, this improves the efficiency.

Similarly, if I have very focused radiation, then it can be launched essentially inside the optical fiber because, this will lie in the acceptance cone if it
Since width of Radiation Pattern related to Spatial Coherence
So we can summarize for increasing the Bandwidth
we required temporal coherency in the source. If I have
Spatial Coherency then it gives the highly directional
propagation, thus improves the light launching efficiency
So How can I defined the Coherency between two photons?
Two photons are coherent if and only if they have
→ Same Energy (i.e. frequency)
→ Same Phase
→ Same momentum Vector (It should move in the same
direction)
→ Same Polarization [If I look the Photon as Electromagnetic
and Magnetic field. It can have different behavior
with respect to time, which is characterized by the
parameter which is called as Polarization]
So it may be possible that photons are moving in the
same direction, with same frequency, but if their
Electric field perpendicular to each other then they
will not take part in the interference.

Polarization of photon: It is the Polarization of that
Electromagnetic wave, to which the photon belongs.
So Coherency can be defined as Triplet (E, k, p)
Let us consider a system of two energy levels.

Excited \( \rightarrow \) \( N_2 \rightarrow E_2 \) (higher energy level)

Ground \( \leftarrow \) \( \leftarrow \) \( \frac{N_1}{N_2} \) \( \rightarrow \) \( E_1 \) (lower energy level)

and the difference of these two energy levels

\[ (E_2 - E_1) = h\nu = h\nu_0 \]

Due to thermal excitation, the electrons occupy different energy levels and may have different densities of electrons. If I take the general nature of the density of electrons are generally related by Boltzmann relation.

Suppose the electron density is given by \( N_1 \) and \( N_2 \). Then by Boltzmann distribution

\[ \frac{N_1}{N_2} = e^{-\frac{h\nu_0}{kT}} \]

where \( h\nu_0 \) is the difference in energy i.e. \( E_2 - E_1 = h\nu = h\nu_0 \)

\( h \rightarrow \) Planck's constant

\( \nu \rightarrow \) Frequency of photon

\( k \rightarrow \) Boltzmann constant

\( T \rightarrow \) Absolute temperature

Hence, density of electrons exponentially decreases as we go to the higher energy level. Hence,

\[ N_2 = N_1 e^{-\frac{h\nu_0}{kT}} \]

So, one can take

Let us take \( T = 300K, \lambda = 0.7\mu m \)

\[ E_{ph} = (E_2 - E_1) = h\nu = \left( \frac{hc}{\lambda} \right) = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{7 \times 10^{-7}} \approx 3 \times 10^{-18} \text{ J} \]

\[ kT = 1.38 \times 10^{-23} \times 300 = 4 \times 10^{-21} \text{ J} \]

\[ \frac{E_{ph}}{kT} = 100 \]

So, \[ \frac{N_2}{N_1} = e^{-\frac{E_{ph}}{kT}} = e^{-100} \approx 10^{-32} \]

So, if we consider the energy level that corresponds to 0.7\mu m, then the ratio of electron density between upper level and lower level is \( 10^{-32} \).
which is essentially shown that the higher level is practically empty. Most of the Electrons are present in the lower level. This is the Natural Situation. So at thermal equilibrium at $T=300K$ the Electrons in the upper energy level is negligibly small. Compare to electron density at lower energy.

The Electrons lying in the upper energy level have tendency to relax to the lower energy state. So electrons in the upper energy level is called as electrons are in the excited state and the electrons present in the ground level relax in a ground level energy state.

We can say that if the Electrons in the Excited state naturally it has tendency to come down to the ground state, and when the transition takes a photon is y

released in this process.

Now since this process does not required anything else, because electrons have natural to relax in the lower energy level, this process is called as spontaneous process.

And whenever the spontaneous emission process takes place a photon released of frequency $\nu$.

The other process, suppose we take a material and shine light on the material, the intensity of light reduces, that means the part of light has been absorbed by the material. This energy excites the Electron from ground to level to higher level.

So if the photons are incident on the material and the Electron was there on the ground level, then this process called as absorption, will take away the energy from the photon, gives the energy to Electron and Electrons are excited to higher energy state and photon will
be lost. This is the natural process. As the light beam passes through the materials, it gets attenuated and numbers of photons will be lost. Energy of these photons are given to the electrons and electrons are excited and goes to higher energy state, and photons are lost.

In addition to these two phenomena i.e. Absorption and Emission, there is an another process which is the forced process. i.e. If I have the electrons in the excited state at higher energy level, and photon is incident on the system, then this photons may force the electrons to jump down and when the jumping takes place, the photon is released. So this original photons will force the electrons to jump and emit another photon. So this process does not takes place by its own but it is forced by a photon, and this process is called as Stimulated Process. And Postulate is that when this forced process takes place the additional photon released. Since it is completely under the influence of additional photon, so the property of original new photons are originally identical to the original photons.

So the two photons generated are essentially coherent. So the two photons now will be travelling in the same direction, same frequency and same polarization.

So when photon incident on a material, two process can take place. One is photon may get lost and electron can be lost. Or Photon may force the electron to jump from the excited state and released another photon which coherent with respect to the original photon.

So the Stimulated process is rather multiplicative process. So it can go very rapidly.

One can define these happening using certain parameters which is called as Einstein's Parameter.
So the process which does not depend upon the photon given by coefficient \( A_{21} \).

The process which takes place in the presence of photon, the coefficient is given by \( B_{21} \).

Now we can say that I have the electron density at higher energy level. The rate of electron deexcitation downward by its own nature, i.e., spontaneous nature is directly proportional to number of electrons in higher energy level.

Now we can formulate down essentially, we can say electron density in upper level \( N_2 \)

" " " lower level \( N_1 \)

So, we can write the equation for three process as follows:

**Spontaneous Process**

Rate of electron transition downward or rate of depletion of electrons in upper level which is given by \( -\frac{dN_2}{dt} \propto N_2 \)

So;

\[
\frac{dN_2}{dt} = -A_{21} \cdot N_2
\]

So after solving

\[
N_2(t) = N_2(t=0) \cdot e^{-A_{21} t}
\]

If we define the parameter, i.e., life time of electrons, i.e., spontaneous life time then

\[
A_{21} = \frac{1}{\text{Spontaneous life time}}
\]

Spontaneous life time

\[
\tau_{sp} = \frac{1}{A_{21}}
\]

So

\[
N_2(t) = N_2(t=0) \cdot e^{-t/\tau_{sp}}
\]

So this shows that naturally the electron decay with time this decay will be exponentially with characteristic life time \( \tau_{sp} \).
Since either two process takes place in the presence of photon

**Absorption Process**

Electrons are taken from the ground level to the upper level. So rate of electron decay will be proportional to $B_{12}$ and number of electrons present in ground, and also beta proportional to photon flux $P(f)$.

So we can write

$$\frac{-dN_1}{dt} = B_{12}P(f)N_1$$

**Stimulated Process**

In this case the transition goes from higher energy level to the lower energy level.

Again rate of change of electron will be proportional to $N_2$, flux density and $B_{21}$.

So we can write

$$\frac{-dN_2}{dt} = B_{21}P(f)N_2$$

So for three process simultaneously operated, two process bringing the electrons downward, one process an upward process taking the electrons from ground level to the excited level.

Since in thermal equilibrium as the number of electrons does not change i.e.

Hence total downward transmission must be balanced by the upward transmission.

So we can write the balance equation

$$A_{21}N_2 + B_{21}P(f)N_2 = B_{12}P(f)N_1$$

Hence we can get net photon flux

$$P(f) = \frac{A_{21}N_2}{(B_{21}N_2 - B_{12}N_1)}$$
\[ P(f) = \frac{A_{21}/B_{21}}{B_{12}/B_{21}} \]

So if all three processes - spontaneous emission, absorption, and stimulated emission - take place simultaneously inside the material, then there is net photon flux given by above equation.

Since they are in thermal equilibrium, so this photon flux can be equivalent to blackbody radiation. The coefficients \( A_{21}, B_{21}, N_1, \) and \( N_2 \) are called Einstein coefficients.

**LASER \Rightarrow 2**

Now we know that \( \frac{N_1}{N_2} = e^{-\frac{h\nu}{kT}} \)

So

\[ P(f) = \frac{A_{21}/B_{21}}{B_{12}/B_{21} e^{-\frac{h\nu}{kT}} - 1} \]

Now if I have a body at temperature \( T \), then this body gives the blackbody radiation, so we can say that the flux photon flux density must be same as that of photon flux density obtained by blackbody radiation.

Expression for blackbody radiation:

\[ P(f) = \frac{8 \pi m^2 g^3}{c^2} \times \frac{1}{(e^{h\nu/kT} - 1)} \]

\( n \rightarrow \) refractive index of medium to which the \( \nu \)
\( \mu \rightarrow \) radiation is coming
\( c \rightarrow \) velocity of light, \( f \) is the frequency of radiation
\( h \rightarrow \) photon energy
\( kT \rightarrow \) thermal energy
So when the three process are proposed the Black Body radiation takes place.

After comparing these equation:

\[ \frac{A_{21}}{B_{21}} = \frac{8\pi n^3 e^3}{C^3} \]

and

\[ \frac{B_{12}}{B_{21}} = 1 \quad \text{r.e.} \quad B_{12} = B_{21} \]

1. \( B_{12} \rightarrow \) Transition probability electron going from lower energy level to higher level.
2. \( B_{21} \rightarrow \) Transition probability electron coming down both in the presence of photon.

Above equation shows that these two transition probability are equal. That means the absorption process and stimulated processes are equiprobable.

Absorption process is very normal process and absorption i.e. if a light beam falls on the material it gets attenuated. So the photons lose energy, then there is absorption of photons. We never find the stimulated process in nature but always find the absorption process in nature. But observation process shows that these two processes are equiprobable.

One can ask why we find absorption in nature but never find stimulated emission in nature?

Answer is lies in Boltzmann distribution. Although the transmission probability are equal, the phenomena depend upon where the electrons are. In thermal equilibrium, the more number of electrons exist in ground state in comparison to fiber state. Even if photon have equal probability to force the electron upward and downward, but upward transmission majority takes place because more no. of electron at to exist in the ground level.

So the net result which is always seen is upward transmission of electrons and photons lost.
If we can create a situation where the no. of Electrons in higher energy state is larger than the no. of Electrons in lower energy state, now the stimulated process will be dominated over the absorption process.

If we want, the stimulated process should be dominated then essentially we have to change the natural level of Electrons in different energy level.

So by some mechanism, we have to transport the more no. of Electrons in higher energy level.

So for better seeing the stimulated, we have to change the natural. So we have to invert the population of Electron, and that process is called Population Inversion.

So by achieving the population inversion if the photons incident on the materials, then we can get stimulated emission of Radiation.

When we are looking for the interaction of photons between the energy level, where difference is exactly equivalent to the energy of photon, essentially we are looking about the Resonance phase. So this photons have some defining frequency.

So we have characteristic frequency i.e. Energy is difference between two energy level and one is frequency of photons.

When we have two system having the same natural frequency, there is exchange of power. Precisely same things happens. As the frequency of photons remains same as that of System frequency + Energy flows in exchange. Of course which energy takes place depends upon the where the more energy takes place.

Hence in case of Absorption, the incident photon is having the highest energy in comparison to Electrons, presents in the ground level, so energy transmitted from photon to ground level. Electrons and Electrons gets excited to the higher level of energy and photon lost.

But in case of Stimulated emission the no. Electrons is having the higher energy so energy is transmitted to photon and we get multiplication of photon.

Scanned by CamScanner
go the Phenomena like a force vibration phenomena.
and when the force vibration phenomena takes place
the emitted photons remains the same characteristics.
So what is the contribution of
What is the relation between spontaneous process and
stimulated process
So, \[
\frac{B_{21} P(t)}{A_{21}} = \frac{L}{(e^{hf/kt} - L)}
\]
Now if \( P_f >> kT \)
set \( A = 1.11m \) for which \( h\nu = 1.2eV \)
\[
\frac{P_f}{kT} = \frac{(1.2)}{(0.025)} e^{-\frac{hf}{kT}} \text{ e}^{-50}
\]
Hence stimulated emission practically from
Existing at room temperature under thermal
Equilibrium.
Let us concentrate on the two process in which the
Photon is required.
Stimulated process is multiplicative process. One photon
incident gives rise to two photons which has same
Characteristics. If the more electrons are available
here in high energy level it can pull two electron
this generates now four one of photon and one so on.
Whereas spontaneous process naturally Electrons tryly
to come down. The time constant for this process
is large then the time constant of stimulated process.
So the Process starts with high spontaneous process
as time progress it is dominated by slow process.
So In other discussion we will consider only above
absorption and stimulated emission.
One can ask a question if I want to make the
Population inversion. Since naturally electrons exist
in the ground level by some mechanism I have
to transfer the electrons in the upper level. What
should be the true mechanism.
Again I have to supply the energy to electrons, and after getting energy the electrons get excited to higher level.

So the energy has to given in terms of photons and energy must be exactly equivalent to energy difference between the two levels. Hence the frequency of photon should be same as that of photon that we count to generate by stimulated emission.

Simple two energy system can not create the laser.

We can create the system with more energy.

\[ \text{Level } E_3 \]

\[ \text{Band of Energy} \]

\[ \text{Level } E_2 \]

\[ \text{Level } E_1 \]

As we have band of energy, so by providing the incoherent beam, the electrons can be transported from \( E_1 \) to \( E_3 \).

Now if the life time of electron is relax from \( E_3 \) to \( E_2 \) is much smaller, then electrons get excited from \( E_1 \) to \( E_3 \) and very quickly comes from \( E_3 \) to \( E_2 \).

Now if \( \tau_{32} < \tau_{21} \) then the energy supplied to system corresponding to \( E_3 - E_1 \), then very quickly electrons comes to \( E_2 \) and since \( \tau_{21} > \tau_{32} \) it will weight at \( E_2 \).

Now if the photon incident with energy equivalent to \( E_2 - E_1 \) then it pull down the electron and we get the stimulated emission of radiation corresponding to energy difference \( E_3 \) and \( E_1 \).
So To create a layer we required at least 3 layer System. LASER-3.

As some times the three layer System is not enough.

So we can write

$$\frac{dP}{dt} = B_{21} P(f) (N_2 - N_1)$$

$$= \frac{c^2 k_f}{8 \pi f^2 n^3 c_s p} P(f) (N_2 - N_1)$$

$$\frac{dP(f)}{dt} = \frac{c^2 k_f}{8 \pi f^2 n^3 c_s p} P(f) (N_2 - N_1)$$

So differential equation for photon flux

$$\frac{dP(f)}{dx} = G P(f) \quad G \rightarrow \text{Gain constant}$$

$$P(f, x) = P(f, x=0) e^{Gx}$$

If $N_2 < N_1$ : $G$ is -ive

$$G = -\alpha \rightarrow \text{attenuation constant}$$

If $N_2 = N_1$ : $G = 0$ Transperancy (Net flow remains same)

If $N_2 > N_1$ , $G$ is +ive (Growth of photon flux) [Cherale]

As the photon travels more and more inside the material and if the population inversion is maintained then the photon flux goes on increasing exponentially.

So my objective is to make a mechanism that can make the photon to travel more and more inside the material and that can able to generate more numbers of photons that are coherent.

Let us have a look on Gain quantity

$$G = \frac{c^2 k_f (N_2 - N_1)}{8 \pi f^2 n^3 c_s p}$$

depends upon $f, n, c_s p - d (N_2 - N_1)$
For given parameter, the gain is inversely proportional to the frequency, i.e. lower the frequency, higher will be gain.

Hence that is why creating a Laser for low frequency or longer wavelength is easier in comparison to high frequency or shorter wave length.

Gain is also inversely proportional to the average life time. This means if T_sp is small, electrons are naturally willing to jump down, such as spontaneous process then high gain.

So we can say that for given population inversion the growth of photon flux density depends upon the frequency of radiation and average life time.

Hence in case of stimulated emission, if the stimulated photon is not there, then there is no chance of multiplicative generation of photons. Hence it requires a stimulated photon so that it can amplify the energy. Hence it is called as "light amplification by stimulated emission of radiation".

Hence this photon is need to supply externally that can be amplify.

But our aim that Laser should generate light.

Hence if the population inversion is created, then suddenly photon will be created due to the spontaneous process and this generated photon can be used as in stimulated emission. Now the photon generated by spontaneous emission is capable of generating the new photons by stimulated emission.

But the seed before stimulated emission should be internally generated by spontaneous emission. Since this stimulated process is just an amplification so whatever the characteristics generated by absorption photon will exist in the amplified photon.
So the thing is that if the photon generated by spontaneous emission is not coherent, then the photons generated by stimulated radiation will be not coherent. So if the photon generated by stimulated emission is not coherently feedback to the system then coherency in radiation will increase systematically. So we have to create a frequency selective mechanism so that coherency into the system can be increased.

Coming to the Semiconductor Material,

\[ G = \frac{\alpha^2 h (N_2 - N_1)}{8\pi f^2 n^2 \gamma_{sp}} \]

\((N_2 - N_1)\) injected carrier in P-N Junction under Forward Bussed Condition.

So the Gain function

Spectral width of Gain function will be much much smaller compare to \(N_2 - N_1\) function. LCD have large spectral width which is not good for Communication.

If we consider the same semiconductor material then and stimulated process is carried out then photon flux is going to reduce very much as exponentially Variation Pvt.

For LCD Spectral width = 70-100nm

Laser \(\alpha^2 h = 1-2\) nm

In case of LCD the photon can emerge in any direction thus very few photons goes into Optical Fibre. So the Efficiency of these devices very very small.

In order to create the Spatial Coherence in system we can make a mechanism that should select the photon to the travelling in certain direction and feedback to the system and reject all other photons.
Let us say I have medium, the photons are generated by the spontaneous emission and travel in any direction. Let one photon move in the desired direction. Let us put an mirror on this side so photon travelling in concerning direction will get reflected and proceed towards another feedback mirror. So photons moving perpendicular to the mirrors come back again and again. Whereas photon not moving in the perpendicular direction get lost. If the photons confine in the medium, it travels more in distance and number of photons increases. So in this process we have directed the amplification process to only in the direction perpendicular to the mirror.

What we want that some photons leak out through the mirror and the leaked photon must have the same characteristics to that of revolving photons inside the material.

Let us say if we start with \( n \) numbers of Bob photons and again come back to the same location and they travel the distance of 2L. Also its reflectivity of these mirrors are \( R_1 \) and \( R_2 \). Then the photon which had been started from this point which is \( N e^{-2L} \), but part of the photon going to leak from the two mirrors. Also it is possible that photons moving inside this may get lost due to some extra mechanism.

So we have stimulated process that provides the gain but there are some other process which may create loss to the photons.
So to gain $G$, attenuation constant $\alpha$.
So as the photon moves inside the material, we have net gain coefficient ($G - \alpha$).
Hence by taking this approximation, the photon gain due in the traversement of one trip is
$$N = N_0 e^{(G - \alpha)z} \times R_1 \times R_2$$
multiplied by reflection coefficient $R_1$ and $R_2$.
That as number of photon that present should at the starting should be same as that of No of photon travelled by one trip.
Mathematically
$$N = N_0 e^{(G - \alpha)z} \times R_1 \times R_2$$
So
$$R_1R_2 = e^{(G - \alpha)z}$$
This is the condition for the sustained oscillation inside the material. So if this condition satisfies the flux neither grows nor dies inside the material. This will give the constant radiation and radiated photon will have the same properties and it will be coherent. Intrinsically we have temporal coherency no putting this mechanism, we have the spatial coherency, it will be highly beam radiation.
$$R_1R_2 = e^{(G - \alpha)z}$$
So this is the very important condition for the sustained oscillation.
These are nothing but electromagnetic wave, and if these electromagnetic waves travels the distance of $2L$ then the phase change will take place.
So if the photon reaching after one round trip does not remains in phase with newly photon these two field fields cancel each other, and we will have the destructive interference. So for sustained oscillation we also must satisfies it.
So we are taking the consideration of EM waves travelling inside bounded dielectric medium. Which is nothing but waveguide.

Essentially this structure have resonant cavity. Therefore it is called as Fabry Perot Cavity

\[
\text{Completely Reflected}
\]

When Electromagnetic waves travels inside the bounded medium, it may not travel in free space but in mode.

We can say the phase constant in given direction \( \beta \) as

\[ \beta = \frac{2\pi}{\lambda} \text{Neff} \]

Neff > refractive index for particular mode = \( \frac{c}{\text{Velocity of mode}} \)

So the Net phase change in one round trip

\[ 2\pi + 2\beta L = 2m\pi \]  
For constructive interference

\( m = \text{integer} \)

\[ 2\beta L = \text{multiple integer of } 2\pi \]

So for sustained oscillation and constant radiation through the system we must have the two conditions

\[ R_1 R_2 e^{-(\alpha L)} = 1 \]

and phase condition

\[ 2\beta L = \text{integral multiple of } 2\pi \]

So

\[ \frac{2\pi \text{Neff}}{\lambda} L = 2m\pi \text{Neff} \]

\[ L = \frac{m\lambda}{2\text{Neff}} \]
So the length of this cavity should be a multiple of $A/2\pi n$.

$$L = A/2$$

As $m$ is an integer, so only discrete value of $A/2\pi n$ is satisfied. Even if the population inversion takes place, every frequency will not satisfy the phase condition.

So we can show

**Gain Spectrum**

If we want to create a single wavelength laser, we can assign the parameter such that only one phase condition satisfies for only one wavelength.

In Otherwise, only one mode can excite in the cavity and second mode can not excite laser will get only one wavelength.
In that case \( L = \frac{m_{1} \gamma}{\gamma_{eff}} \) should be such that even \( m=1 \) is not possible.

Thus practically if the value of \( L \) is very very Small (in range of \( 1 \mu m \)) then one can fabricate the laser of a particular wavelength.

**Laser - 4**

There are some specific type of laser which are commonly used in practice.

**Ruby Laser**

It is a solid state laser. It is one of the first one

\[
\begin{align*}
\text{Pumping} & \rightarrow 6300 \text{nm} \\
\lambda & = 6943 \text{ A}^{\circ} \\
A_{0} & = 6300 \text{ A}^{\circ}
\end{align*}
\]

So we have a Ruby rod which has energy level appropriate to generate the light in the visible range. Then by exposing the rod to some flashing light, the population inversion is created inside the material. So if look the energy level diagram for the Ruby, a ground state energy level, little spread energy level \( E_{2} A = 5600 \text{ A}^{\circ} \) and another energy level \( 4000 \text{ A}^{\circ} \).
and having 4th energy level, where an electron can make a transition and can get stimulated or spontaneous radiation.

So to create the population inversion, so that electron are transported to either second energy level or the first 4th energy level. Essentially energy has to supply either 5500Å or 4900Ås, and we create the population inversion. The life time of electron in the upper two energy level remains smaller in comparison (10^8 s) in comparison to the 2nd energy level (3 ms).

So the electrons quickly relaxed to the 2nd energy level, where the life time of electrons are quickly longer (3 ms).

As the life time in the 2nd energy level is quite longer, thus electron boils until the external photon comes and stimulate the radiation.

If we have feedback mechanism appropriate to λ = 6943Å, then that photon can stimulate the process and that photon can generate the light of wavelength λ = 6943Å. This is Red color in visible spectrum, eventually we get the red color light from the ruby rod. And we have laser acting 6943Å operating wavelength.

Since as the stimulation process starts, as it remains very fast and we may not have a population inversion after some time, so we have to keep replacing the electrons in the upper energy level, and.

So this generation of light takes place in the periodic manner.

The red light for the generation of light can be represented as follow.
So we can see the spikes, we do not get such continuous emission of light.

**He-Ne Laser**

This is the laser which is generally used in most of the pointers, which gives the red point.

As the name suggests, this laser is made from the gases, which remains the combination of He and Ne.

---

The construction mainly contains the small tube, which contains the mixture of He and Ne, and by passing the discharge through, essentially we transfer the energy of the discharge to the molecule, more precisely the energy is transmitted to the He molecule. Because the He molecule is having very less molecule, so directly energy can not be transmitted to the Ne molecule.

So we have combination pressure: 

- He → Pressure 1 torr (1 mm of Hg)
- Ne → Pressure 0.1 torr

The above have combination of energy here He and Ne.

So what the discharge does it supplies the energy to the He atom, and the He atoms are excited and they have very long life time in particular energy level. Since, we have mixture of He-Ne. These He atoms collide with Ne atoms.
excited to the higher energy level, so the population inversion here takes place in two steps, first excitation of He-atoms and then transfer of energy between the He and Ne atoms by proper atomic collision.

Now we get the Neon atoms which are excited in higher energy level and by using different transition of Ne atoms we can get laser in a appropriate wavelength.

So if we look the energy level diagram of the Neon, it is fairly complex, having various energy levels. So one can work out appropriate energy level that gives the light in a visible range i.e. red color.

There are differences that correspond to 6328 Å in red region, so this is the transition that makes different interest.

For this line, we have to make the feedback mechanism that would support the corresponding to wavelength 6328 Å and other wavelengths are suppressed.

As we have discussed, that longer the wavelength, more probability of losing action. So longer wave far.

So we have to create some absorbing structure to the longer wavelength.
So that the concern wavelength of 6328 Å can
simplify and finally electron can move battle down to
the ground state.

So by providing the positive feedback, by the mirror
as shown in figure, essentially one can generate the
red light from the mixture of He and Ne. So hence
Hence if we want to generate a light of proper material
and proper frequency which has energy level such
that certain energy differences corresponds to the
material two level energy differences.

But from the optical communication point of view, these
lasers are not very suitable. If we can somehow, we
wanted an optical source, which should be compatible
with electronic circuits. So that it can be carried
by the optical fiber.

So those lasers (Gas lasers) are not very suitable because
they are not compatible with the electronics circuits
which are used for the communication.

Essentially we go back to semiconductor laser. If we
take semiconductor material, and if we can make
the lasing action inside the semiconductor material
that would be compatible with the electronics
circuit.

So again the idea is same like LED. Inside LED we
have p-n junction, and by making the p-n junction
forward biased, the electrons and holes are injected
in a common region, they recombine and then we
are having the generation of light due to recombination
but then the photon generated, they can move in all
possible direction.

Hence LED have extremely low conversion efficiency
So now if we can create the mechanism inside the
p-n Junction, or inside the active region of p-n Junction
where recombination is taking place, and if we
make some kind of positive feedback mechanism inside the p-n junction, then they will remain for longer time inside p-n junction, they will create the stimulated emission and we will get directe generation of light inside the p-n junction.

Schematically take the p-n junction, then if we make a reflecting mechanism over the p-n junction, then photon will be trapped inside the region and stimulated radiation action will take place.

In fact by making the fabrication of LED in such a way that I have some kind reflecting boundary which will make the photon confine for longer time, the same LED can be converted into Laser.

So the principle is that a proper p-n junction material with proper polishing so that photons can be trapped inside the material, for stimulated radiation action, i.e., a highly polished LED can acts as a Laser.

So this is the device that will be very compatible with the electronic circuit.

A semiconductor-based Laser which is called as Laser diode is better widely used for the long-distance communication.

Initially the efficiency was very small, i.e., electric current flows, this provides the recombination between electrons and holes but most of photons get lost but there are linearity between the optical power and current flowing through the circuit. The same thing happens along with the Laser diode, because photons are confined so
for some current we are having high optical power. Again the relationship between optical power and currents are linear but the change in optical power so far small change in currents are more in comparison to the LED.

Characteristics of laser diodes

At low current stimulated emission still not overcome the losses inside device so the device starts functioning like LED. So for low current efficiency of device is very small. Once, we reach to a certain value beyond which the stimulated emission overcome the losses suddenly lasing action starts and we have large efficiency of device. So even for small change in current, we have the large change in output. Laser diode has typical characteristics that almost changes at threshold current. Below threshold current O/P power is very very small and device behaves as LED. Beyond threshold current we have large O/P.
LED can be easily used for analog communication due to linear characteristics over a wide range. So by changing the current we can get same behavior in the optical signal. Whereas in case of laser diode, there is sudden break in its characteristics and it shows like a switching action. Because of this characteristics, the device is more suitable for switching type of action.

In both the region, I have linear variation, but characteristics is not very stable for modulation. So the laser diode is not very suitable for linear modulation, rather suitable for switching types of action i.e. suitable for digital modulation.

Fabry Perot Resonator Cavity

In middle region recombination takes place, photons generated. Polishes are provided on the faces of device. Laser beam comes out of the middle region. Even though positive feedback has taken from the photons, exactly perpendicular to the mirrors, when tries to come out from this region, essentially, size of emerging beam remains in few microns, so we have deflection of beam not exactly emerges in perpendicular direction.
When the photon beam is come out from the narrow region, essentially, a beam of photon beam to come out from any small region is few percent. This cause the defraction of light, or to have the angular zone, in which the photon escaped outside because of the defraction of light. Angular width is typically much much smaller in comparison to the LED.

As we increase in current inside the device, essentially light characteristics changes.

If the device is biased to the zero current, then the switching time will be longer, because it will build the photon up to threshold current for the proper lasing action. Essentially we have the delay before switching this device. And this delay depends upon the biasing current with respect to the threshold current.

Get the device is biased with some input current, Ib. When I supply the digital data which is in the form of current, zero corresponds to Ib and I corresponds value higher then Ib.

As Ib current is not same as the threshold current. So delay time is given by

\[ td = T \ln \left( \frac{IP}{IP + (I - Ib)} \right) \]

So if the device is biased at threshold level Ib = Ith

then \[ td = 0 \]

But if the device is biased at the threshold current, then optical current corresponding to biased zero is not zero but at the threshold current. Hence the extension ratio that becomes smaller, which will have the implication for the bit error.
Second problem is that, if we biased the device at the threshold current, whether we are transmitting the pulse or not transmitting the pulse device current will always flow inside the device and because of that temperature of the junction increases and laser get heated. And threshold current is strong function of temperature of the device. So as the temperature increases, the threshold current also increases.

\[
\begin{array}{c}
I \\
T_1 \leq T_2 \leq T_3
\end{array}
\]

So automatically, it will introduce a delay. So in order to keep the delay less, either we can increase the biasing current according to the threshold current or keep the threshold current as constant.

But first method will behave like a positive mechanism for increasing the temperature of the device, which is not very desirable.

So for good operation, operation, the temperature of device must be stabilized, or in any other way laser must be operated in a temperature controlled condition.

Relaxation Oscillator

Suppose we are giving a switching pulse.
As soon as the current supplied to the laser, the population inversion is built, and because of the population inversion, gain in the system inversion is very large. Large numbers of recombine and we can get an optical pulse. But as soon as the stimulated pulse starts, the depletion region depleted with electron-hole pairs and gain falls. and Stimulated output also will reduce, so this phenomenon is called Relaxation Oscillation, and Frequency of Relaxation Oscillation

\[ f = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{\tau_p T_{sp}}} \left( \frac{1}{\text{Ith}} - 1 \right)^{1/2} \]

So one can ask, if I want to use the laser as a digital modulation scheme, what are the limits of the modulation frequency?

When the electron-hole pairs are injected inside the region, then as long as the electron-hole pairs exist, we can not switch off the light. So this time time depends upon the life time of electrons of the carriers.

In this laser device we have three life time.

\[ \tau_s \quad \rightarrow \quad \text{Spontaneous life time} \]

\[ \tau_t \quad \rightarrow \quad \text{Stimulated life time} \]

\[ \tau_p \quad \rightarrow \quad \text{Third life time} \]

Life time is twice the photons are generated inside the P-N region even if the carrier is laser. Even if the current is stopped inside the device unless the photon is lost inside the region, we can not create.

So upper limit is decided by the \( \tau_p \) time at which the photon exist inside the cavity. Which is called as the Photon life time inside the cavity (\( \tau_{ph} \)).

\[ \tau_{ph} = \left( \frac{c}{n} \right) \cdot \text{Atth} \]

So the \( \tau_{ph} = \frac{c}{n} \left( 1 + \frac{1}{2} \cdot \frac{\nu}{c} (R_1 R_3) \right) \{ 2 - 3 \text{ ps} \} \)

\( \text{Atth} - \text{Gain at which Oscillation just sustained} \)
Laser 05

Noise Performance of the Laser Cavity

When we get the light output from the laser, the output power does not remain absolutely steady-state. There are always some fluctuation due to this fluctuation, the light gets reflected, and this reflection behaves as a noise when we try to get the electrical signal from the another side.

Here we analyze the mechanism by which noise produces inside the optical fiber.

1) Reflection Noise +

As the name suggest this is something to do with the reflection of the signal.

```
Laser → 0
```

Laser emits the light, when this light couples to the optical fiber, then the light is reflected from the tip of the fiber.

Now some part is partly reflected back to the input signal, so if the optical fiber is perfectly aligned to the laser, then the reflected light goes straight back to the resonance cavity.

The phase of the reflected signals depends upon the distance between laser and tip of the optical fiber. Since the wavelength of the reflected signal is in micron so separation in the range of micrometers can change the phase of reflected rays.

Now if due to the thermal vibration, the tip of the optical fiber varies, by fraction of micrometers, the phase of reflected signal varies substantially and the signal goes in resonance cavity, because the phase difference arises may affect the signal in both manner.

As a result, the gain of the system depends upon the phase of the reflected signal returned from the...
tip of the optical fiber. So, because of the temperature
variations, or fluctuations, the output of lasers also
fluctuate. This noise, what is called as the reflection
noise.

2) Mode Partition Noise
We have seen that in a typical laser, there are many
frequencies which get amplified. So, you lose are having
the amplification spectrum. Those frequency which
satisfy the phase condition are getting amplified. So, we do not get a single frequency in a
laser, but we get a set of frequency, generated by
typical Laser.
As we know that the Fabry-Perot Laser Spectrum are
as follow

![Graph of Mode Partition Noise]

Separation between the lines is typically in the order
of 10⁻⁶ m, and thus fall 2 nm-3 nm.

So, time resolved laser spectra can be represented as
follow:

![Graph of Time Resolved Laser Spectra]
Though the average spectrum is given by ideal function but power may varies for different time slot and keeping the total power constant. Distribution of power among different frequency with respect to time keep varies. Which causes the variation and this Noise is called as Mode partition Noise.

3. *Speckle Noise* + Since large numbers of frequency generated through the laser, and when the laser is coupled with the optical fiber all the frequency are guided inside the optical fiber and hence they traveled with different velocity because of dispersion inside the optical fiber. When we reach the either side of the optical fiber, the interference of Electric field takes place inside the optical fiber. So typically we can see the interference phenomena. This generates an specific pattern of electric field due to constructive and destructive interference, this pattern is called as Speckle Pattern. Speckle pattern is redistribution of power in the Optical fiber cross-section, keeping total power constant. But the detector would not have the same response at all the points of fiber cross-section. Dark region detector receives more power but from bright region receives more power. But due to thermal fluctuation, this phenomena keep changing as a function of time. So the Pattern keep varies with respect to time. Since detector receive time varying response, therefore current through the photo detector slowly varies with respect to time - this is called as Speckle Noise.
The Amplification region is not having the uniform surface. So we have two waves in the opposite direction having the same propagation constant. And let the Perturbation period \( \Delta \). We will have the strong coupling between these two fields. If the difference between two propagation constant, since it is moving in the two opposite direction; hence it is \( 2\pi \), that will be equal to \( \frac{2\pi}{\Delta} \).

Hence if \( 2\pi = \frac{2\pi}{\Delta} \), then these two modes will be strongly coupled. In other words, feedback from one to another will be strongly. So, now from here, essentially we can find the wavelength for strong coupling.

So, from all other frequency, which are supported by the the above condition will get amplified. Hence whole Spectrum will not show the Amplification, but only few wavelengths are amplified. So, by proper selection, we can select the particular wavelength.

Hence we can represent the Spectrum as follows:

The Frequency width becomes few hundred of Mega Hertz or Gigahertz.
Light Emitting Diode (LED)

Let us consider a Semiconductor material. The Semiconductor material is characterized by band diagram.

The band diagram contains two energy levels called Conduction band and Valence band, and it is separated by forbidden energy band gap, which is given by energy \( E_g \).

Electrons present in the Conduction band and vacancy of electrons, which is called as photon present in the Valence band. They can recombine, and when the recombination takes place, then there is a possibility the energy equivalent to energy band gap can release in terms of photons.

Firstly, we are looking the light as a quantum of energy. Hence light is a collection of photons. If photon has energy is, it is equivalent to multiplication of Plank's constant and frequency of energy.

Essentially when the transition of electrons takes place from Conduction band to Valence band, the energy can be released in the form of photons.

Then there is a possibility that whatever the energy released, they does not remain in terms of photons. It may go into some other forms. And if it happens, then we will not get the emission of light.
Whenever the electron-hole recombination takes place, we may get emission of photons, or we may not get emission of photons.

If a photon is released, then the recombination process is called as a Radiative recombination process and if the photon is not released, i.e., the energy goes into some other forms, then this recombination process is called as Non-radiative Recombination process.

The Ratio of Recombination that generates the photons to the total Recombination is essentially called as Efficiency of Light Emitting Diode.

One can ask a simple question, that we are taking semi-conductor material, then as every type of semi-conductor material responsible for generation of photons due to electron and hole recombination.

Here, we essentially divide the semi-conductor material in two categories: (i) Direct Band gap semi-conductor, (ii) Indirect Band gap semi-conductor material.

Essentially, it can be characterized by looking at the energy band diagram of the semi-conductor material in the energy momentum space.

So in first case, the maximum of valance band is aligned with the bottom of conduction band. The other possibility we may have, where the bottom of conduction band is not aligned with the maximum of valance band.
So in this case, we are having the difference in the momentum.

We are having the holes in the valence band and electrons in the conduction band.

In first case when the electron hole recombination takes place, only one process is involved, that is the energy difference between the carriers. So these can combine, and can release the energy in terms of photon which is equivalent to the energy difference between the conduction band and valence band.

These type of material is called as a Direct band gap semi-conductor material.

But in second case, the conduction and valence bands are not aligned in a space, then the recombination of electrons and hole has to take place, the two process has to take place, i.e. first of all the energy difference due to momentum has to release, then the recombination process takes place.

Since we are having two processes involved in this case, the probability of taking place to processes simultaneously is much smaller. In comparison the first material that involves only one process. Hence in second process the generation of photons remains much smaller. These type of material is known as Indirect band gap semi-conductor material.

So the first requirement is the identification of the semi-conductor material, which is of direct band nature.

Inherently Ge and Ga both are Indirect band gap semi-conductor material. So both of these material can not be used as light emitting diode.

The most thoroughly investigated material, which are direct band gap are GaAs. This material is having the high efficiency of generation of photons.
A question arises for the direct band gap material. What will be the wavelength array of photons?

So let us considering two energy level:

**Direct Band gap material**

\[ E = (E_2 - E_1) = \hbar \nu = \frac{hc}{\lambda} \]

\[ A (\mu m) = \frac{(1.24)}{E (eV)} \]

For GaAs = 1.4 eV

\[ \Rightarrow \lambda = 0.8 \mu m = 800 \text{nm} \]

So if I know the energy difference between the two level, then I can easily calculate the wavelength of energy emission.

In first generation of optical communication system, the optical window is essentially 800 nm wavelength, essentially low loss medium. Window and the sources was GaAs.

But now a days we are looking for the emission around 1310 nm and 1550 nm.

Instead of using Single GaAs, we can use ternary material such as Ga\textsubscript{X}Al\textsubscript{1-X}As.

In Ga\textsubscript{X}Al\textsubscript{1-X}As, by mixing them in different proportion, essentially the band gap of energy material manipulated and also by depending upon the value of mole fraction, the material can be direct band gap or indirect band gap.

Now if \(x\) lies between 0 to 0.37 for Ga\textsubscript{X}Al\textsubscript{1-X}As, then energy of the band is given by \[ 1.424 + 1.266 x + 0.268 x^2 \]

And for these value of x, the material is direct band gap material.
Sunday, 5th Dec 72

and y = 2.27, then too one can manipulate the energy band gap as

$$E_{CV} = 1.35 - 0.8y + 0.32y^2$$

In this manner too one can manipulate the wavelength from 0.824m to 1.854m. This is boundary which is our interest.

Now a question arises, if the emission hole recombination process takes place, what kind of emission process takes place.

Although the semiconductor material is characterized by the band gap:

$$E_C$$

$$E_g$$

$$E_F$$

Electrons and holes are not sitting on the edge of these band gap. Any electron in the conduction band can recombine with any hole in the valence band. So there is an equal probability that any electron present in the conduction band can recombine with any hole in the valence band. With this assumption, one can ask a question: there is a distribution of electron in conduction band and distribution of holes in the valence band. And if any electron can recombine with any hole, what type of spectral distribution from the semiconductor material can be expected.

Presence of electron in conduction band depends upon the two things:

1) Whether the energy level of conduction band corresponding to the electron energy.

2) Even if the energy level present, whether it is occupied by the electron.
Essentially, if it is asked that what is the density of electrons in the conduction band, then it depends upon the two things — (i) energy density function in conduction band for electrons and (ii) occupancy of energy level by the electrons.

So essentially, we have the two functions: the energy density function and energy occupancy function by the electrons.

Similarly, the same things happen in the valence band.

So, first, we have to calculate the electron density inside the conduction band and hole density inside the valence band and then probability of photon generation will be multiplication of these densities.

\[ S_c(E_2) = \text{Distribution of Energy State in Conduction Band} = \frac{4\pi (2m_0)^{3/2}}{h^3} \left( \frac{E_2 - E_0}{2} \right)^{1/2} \]

Similarly,

\[ S_v(E_1) = \text{Distribution of Energy State in Valence Band} = \frac{4\pi (2m_0)^{3/2}}{h^3} \left( \frac{E_1 - E_v}{2} \right)^{1/2} \]

So, when \( E_2 = E_0 \), the \( S_c(E_2) = 0 \), and as \( E_2 \) goes higher and higher, and distribution of energy states goes higher and higher.

Similar things happen with the valence band.

Now, once the energy state is given, what is the probability that particular energy state is occupied by the particular electrons?

This essentially is given by the Fermi distribution. If I know the Fermi distribution, then I can know the probability of occupying the particular energy distribution.

If we take intrinsic semi-conductor material, then Fermi distribution will take place at the mid-point of \( E_0 \) and \( E_0 \).
Then, I can get the Fermi-distribution
\[
F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}
\]

Hence, to find out the electron availability inside the conduction band, we have to take the expression

Now we have to make the availability of electron and holes inside the material by the p-n junction

![Diagram of p-n junction with electron and hole movement]

So if the p-n junction is forward biased, then electrons and holes are injected through the p-n junction and the electrons and holes recombine inside the depletion region and then that may produce the photons.

So if the material is doped with the impurity, then the Fermi energy level shifts.

If I take - the n-type material, Fermi energy level remains close to the conduction band, and for p-type of material, the Fermi level will be very close to the valence band.

Let us take the p-type of material and whose Fermi level is given by \( E_{FP} \).

\( E_{FP} = \)

From the occupancy of energy level in \( E \) valence band is given.
But we are looking for the availability of the hole.
So we are looking for function:
Probability of absence of electrons in the valence band is:

\[ 1 - F(E) = \frac{l}{1 + e^{(E-E_P)/kT}} \]

Material is not heavily doped the Fermi level shifts towards the valence band.
So if we taking the Semiconductor material which is p-type:

Since \( E < E_F \)

So \( L >> \frac{(E-E_F)/kT}{E_F} \)

\[ 1 - F(E) \approx 1 - 1 + e^{(E-E_F)/kT} = e^{(E_E_/E_F)/kT} \]

n-type material:
Let us say that Fermi distribution of electrons \( E_F \)

\[ F(E_F) = \frac{l}{1 + e^{(E-E_F)/kT}} \]

\( E < E_F \)

\( E_F \approx \frac{(E-F_E_/E_F)/kT}{E_F} \)

Thus \( \frac{(E-E_F)/kT}{E_F} \)

\[ F(E) \approx \frac{l}{1 + e^{(E_E_/E_F)/kT}} \]

The above expression shows that the probability of electron present in Energy level \( E_2 \).
Let us assume that energy density function is

\[ n(E_2) = \exp\left(\frac{E_2 - E_F}{kT}\right) \]

Probability of holes in the valence band is

\[ P(E_v) = \exp\left(\frac{E_v - E_F}{kT}\right) \]

Then the probability of photon generation is

\[ \lambda \propto n(E_2) \cdot P(E_v) \]
\[ \lambda \propto \exp\left(\frac{E_2 - E_F}{kT}\right) \cdot \exp\left(\frac{E_v - E_F}{kT}\right) \]
\[ \lambda \propto \exp\left(\frac{E_2 - E_v}{kT}\right) \]
\[ \lambda \propto \exp\left(\frac{-E_2 - E_v}{kT}\right) \]

Let \( \lambda \) be constant for a given doping.

LED - 2

We have assumed that variation of energy density in a conduction band and valence band very slowly, so we can assume it is constant.

So if we take a P-n junction material with the forward biased condition, the electrons and holes are injected through the P-n junction. Hence electron-hole recombination takes place inside the P-n junction and energy is emitted from the in the form of photons.

Then we have seen that probability of photon generation.

Look at the energy diagram.
As any electron can recombine with any hole and correspondingly gives the photon out. So we may have various pairs of electrons and hole pairs that can combine and emit same energy and frequency of photons.

So if I want to to know the spectral distribution generated by a particular semi-conductor material, then I have to add up all the electron hole pairs, which has the energy difference same as the photon energy in which we are interested.

Hence \((E_2 - E_1)\) is nothing but the photon energy which we are looking for. So for a desired wavelength of photon \(E_2 - E_1\) must be constant, but then we have to integrate the quantity \(\int \frac{(E_2 - E_1)}{kT} \) for all possible energy.

\[\text{Integrate}\]

So we can integrate

\[
\text{Total no. of photon } \propto \int_{E_2}^{E_2 + \Delta \text{ph}} \frac{\text{d}E}{E - E_2} = \int_{E_2}^{E_2 + \Delta \text{ph}} \frac{\text{d}E}{E - E_2}.
\]

\[
\propto \left[ \frac{E_2 + \Delta \text{ph} - E_2}{E - E_2} \right] \left[ \text{E}^{\frac{E_2}{kT}} \right] - \text{E}^{\frac{E_2}{kT}}
\]

\[
\propto \left[ \frac{E_2 + \Delta \text{ph} - E_2}{E - E_2} \right] \left[ \text{E}^{\frac{E_2}{kT}} \right] - \text{E}^{\frac{E_2}{kT}}
\]

\[
\text{No. of photons } \propto (\text{Eph - E}_g) \cdot \text{E}^{\frac{E_2}{kT}}
\]

Model is true for energy greater than \(E_g\).
No. of photons $\propto (E_g - E_g) \cdot e^{(E_g - E_g)/kT}$

Spectral distribution of LED

Now when the photon energy equal to $E_g$, then power, no of photon generated is zero. As the photon energy increases, the number of photon generated increases, it reaches to the maximum value when photon energy $E_g + kT$ and after that it exponentially decreases and for large photon energy power again back to the zero. So it looks like asymmetric distribution. The maximum power

Hence the maximum energy can be achieved at little higher than the band gap energy.

Second analogy is that effective width of the function, that gives the spectral width of light emitted by the LED. This width is approximately $2kT$.

So for different type of material the $E_g$ changes but the spectral width remains $2kT$ and it does not depends upon $E_g$.

So we can say that, when we go for different material, the peak wave length and frequency changes but spectral width remains constant as far as the environment temperature is constant $T$.

This is not good because, the spectral width, which is one of our crucial parameter is not in our control at all, and it is purely decided by the operating condition.
Due to impurity, spectral width may vary \(-1.5\kappa T - 3.5\kappa T\) but still the variation is independent of \(E_p\).

**LED Spectral Width**

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta E_p}{E_p} = \frac{2\kappa T}{E_p}
\]

<table>
<thead>
<tr>
<th>(\lambda)</th>
<th>(\Delta \lambda)</th>
<th>(\Delta \lambda / \lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850 nm</td>
<td>30 nm</td>
<td>3.6%</td>
</tr>
<tr>
<td>1310 nm</td>
<td>70 nm</td>
<td>5.5%</td>
</tr>
<tr>
<td>1550 nm</td>
<td>100 nm</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

So, here we can notice that as we go for longer and longer wavelength, the spectral breadth of source increases and hence dispersion in the optical system also increases. So dispersion at 1550 nm is almost 2 times the dispersion for 850 nm wavelengths.

Hence LED has one of the major problems, that it has very large spectral breadth. That is why if we use LED as a source in optical communications, the data rate will be very small. In 10 MHz - 100 MHz, beyond that the dispersion will be unmanageable.

Second point, the spectral distribution of LED is highly asymmetric but for practical LED the spectral curve is almost symmetric.

Because of the presence of impurity, there may be forbidden energy band gap between conduction band and valence band. There may be possibility of recombination, even if the energy is less than the gap.

The second aspect of semiconductor material is the efficiency issue. It is seen that when Electron hole recombination takes place, there are two processes which are there: Non-Radiative recombination process and Other one is Radiative recombination process.
So when we create a P-N junction and Electrons and Holes are injected into the depletion region, the recombination takes place and every recombination we may not get the 20 Photon out. This information is captured by Quantum Efficiency.

Recombination Process

\[ \text{Radiative Recombination Process} \quad \text{Non-radiative Recombination Process} \]

\[ \text{Radiative Recombination Process: Responsible for light generation} \]
\[ \text{Wastage of Recombination} \]

Quantum Efficiency is the conversion of the electrical energy in the photons.

Quantum Efficiency is divided into two parts:

1. **Internal Quantum Efficiency**
   \[ \eta_{\text{int}} = \frac{\text{Number of Photons Generated}}{\text{Total number of Electron-Hole Recombination}} \]

2. **External Quantum Efficiency** (Capturing of Photons generated)
   \[ \eta_{\text{ext}} = \frac{\text{Number of Photons Guided to the Fiber}}{\text{Total number of Photons Generated}} \]

Internal Quantum Efficiency decided by intrinsic properties of the materials and may be the fabrication process.

The External Quantum Efficiency, which are something related to the Collection of photons by the Fiber.

Hence the Total Quantum Efficiency is the product of the Internal Quantum Efficiency and External Quantum Efficiency.

Let us discuss what are the factors that affect the Quantum Efficiency of LED.
Firstly suppose we have any region where some carriers are injected. The Rate of Change of Recombination or Rate of Disappearance of Carrier would be proportional to the Carrier Density. So we can write:

\[-\frac{dn}{dt} \propto n\]

\[n(t) = n_0 e^{-t/\tau}\]

\(\tau\) is the life time of the injected Carrier.

So Recombination Process can be characterised by \(\tau\) (life time).

\[\frac{dN}{dt} = \frac{N}{\tau}\]

So too have:

\(\tau_{rr}\) is life time against Radiative Recombination

\(\tau_{nr}\) is life time against Non-Radiative Process.

Total Radiative process is characterised by total life time

So we can say Total rate of Recombination:

\[-\frac{dn}{dt} = \frac{dn}{dt}\left|_{_{\text{total}}}\right. + \left[-\frac{dn}{dt}\right|_{\text{NonRad}}\]

\[\frac{n}{\tau} = \frac{n}{\tau_{nr}} + \frac{n}{\tau_{rr}}\]

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

So effective life time is essentially decided by \(\tau_{nr}\) and \(\tau_{rr}\).

Hence Smaller of two decide what is the effective process of Carrier when they are depleted inside the P-n Junction.
\[
\eta_{int} = \frac{-\eta_n}{\frac{\eta_n}{\eta_f} \text{ rad}} - \frac{-\eta_n}{\eta_f} \text{ total}
\]

\[
\frac{(\eta_n/\tau_{th})}{(\eta_n/\tau_{tr})} = \frac{\eta/\tau_{tr}}{\eta/\tau_{th} + \eta/\tau_{tr}}
\]

\[
\eta_{int} = \frac{L}{1 + \frac{\tau_{th}}{\tau_{tr}}}
\]

Now if \( \tau_{tr} \ll \tau_{th} \) then

\[
\eta_{int} = 1
\]

But if \( \tau_{tr} \) is comparable to \( \tau_{th} \) then efficiency drops very rapidly.

Hence what is its physical meaning, that when both the processes are operating simultaneously, if \( \tau_{tr} \ll \tau_{th} \) that is before an electron-hole recombination under the non-radiative process the electron-hole recombination for radiative process takes place, then this gives the rise in quantum efficiency. Now the non-radiative process does not have a chance to show its effect.

So for good radiative recombination process, \( \tau_{tr} \ll \tau_{th} \)

\( \tau_{tr} \) depends upon the intrinsic parameters.

\( \tau_{th} \) depends upon the doping.

For GaAs \( \tau_{th} \approx 100 \) ns.

For pure material \( \tau_{th} \) remains large, and most of the recombination takes place due to radiative process.

Due to impurity \( \tau_{th} \approx 100 \) ns.

As a result \( \eta_{int} \approx 0.5 \)

Only 50% of electron hole recombination gives us the light or photon generations. It is fairly good conversion process.