Lecture: 18

Optical Sources:
Introduction to LASER Diodes
The basic principles of operation of a LASER as an optical source for high speed long-distance optical communication are based on stimulated emission in an environment of population with a positive optical feedback which endows the LASER with optical oscillatory characteristics and, thus helps the LASER to emit a highly coherent optical output. However, there are different ways that have been proposed to achieve the above configuration for a LASER and consequently, there are different types of LASERs too.

The very first and most primitive type of LASERs is the Ruby Laser. It is a solid state LASER consisting of a solid ruby rod exposed to a flashing light as shown in the figure 18.1 below:

![Figure 18.1: A Ruby LASER arrangement](image)

The winding shown in the above figure is actually the filament of the flashing light that is used to pump the electrons from the ground state to the excited state in order to maintain the population inversion condition. To understand the working of a ruby LASER, let us look into the energy level diagram of Ruby (Figure 18.2).

![Figure 18.2: Energy Level Diagram of Ruby](image)
A flashing light pumps electrons from the ground state \((E_0)\) to the two excited states \(E_2\) and \(E_3\) and create a condition of population inversion. Electrons from these levels undergo a fast decay to the energy level \(E_1\) where the electrons wait to get stimulated down to the ground state by emitting photons. The emitted photons have wavelength of about 6943 Å which corresponds to Red colour in the visible spectrum. As the electrons decay down to the ground state by emitting photons, the population inversion condition weakens and the rate of photon emission decreases. The pumping light is then flashed to pump the electrons to the excited state and maintain the population inversion condition and the rate of photon emission increases. Hence, in the output waveform of the ruby LASER, this rate of increase and decrease of the photons would be seen, rather than a constant output. However, this process happens very rapidly due to the tiny time constants as indicated in the figure 18.2. Therefore, in the ON state, the waveform consists of very narrow spikes which almost appear to be a continuous pulse of light as shown in figure 18.3 below.

The second type of LASER that was investigated is the Helium-Neon LASER (He-Ne LASER). A mixture of the two gases, Helium and Neon are taken in definite proportions and is used as the material for emitting photons in this type of LASER. The proportion of helium in the mixture is more than neon. The pumping mechanism used in a He-Ne LASER is an electric discharge passed through the mixture of the gases enclosed in a tube with Brewster Windows on the two sides. Mirrors are provided at the two ends of the tube. This arrangement would be clearer from the diagram below. He-Ne LASERS are widely used as pointers in seminars and presentations, etc. This is, however, only one use among numerous others.
To understand the working better, let us have a look into the energy level diagrams of Helium and Neon as shown in the figure 18.5 below. The He-Ne LASER has a peculiarity in its working. The peculiarity lies in the mechanism of pumping electrons of Neon to the excited state in order to create population inversion. In order to pump the ground state Neon electrons to the excited state, the ground state electrons of Helium are pumped to the excited state by passing an electric discharge. The excited He electrons then collide with the ground state Ne electrons and transfer their energy to the Ne electrons via collision and thereby pump the Ne electrons to the excited state. These excited Ne electrons cause a situation of population inversion in the gaseous mixture and the corresponding radiation too. The reason behind the above indirect transfer of energy to Ne is the small atomic cross-section of Ne which makes direct energy transfer a bit difficult to realise. The above discussion shall be clearer from the diagram below:

![Figure 18.5: Helium-Neon Energy level diagram](image)

The electric discharge excites the He atoms to the excited states $E_1$ and $E_2$ as shown in the above figure. These excited atoms then collide with the ground state atoms of Ne and, in the process, transfer their energy to the Ne atoms thereby exciting the Ne electrons to the excited states as shown in figure 18.5. Thus, the process of creation of population inversion, in this case, is a two-step process. The energy level diagram of Ne, as seen from the above figure, is fairly complicated. The excited state electrons in Ne get de-excited to various lower energy level states and out of these de-excitations, one gives an output which corresponds to coherent light of 6328Å (~red colour). The corresponding de-excitation is from $E_2$ to $E_4$ which gives the output coherent red light. So the feedback mechanism should be tuned to the above wavelength of interest and it must be ensured that maximum number of de-excitations occur between $E_2$ and $E_4$. We already are familiar with the fact that longer wavelengths can be lased faster and easier than shorter wavelengths. This causes the de-excitation probability through 1.15µm and 3.39µm to increase and consequently the output optical power would decrease. In order to prevent these
parasitic de-excitation from entering the feedback mechanism, absorbing elements must be employed to absorb the radiations corresponding to 1.15µm and 3.39µm wavelengths. These elements prevent the parasitic wavelengths to be amplified via feedback and in turn increase the desired de-excitation from E₂ to E₄. So, by proper design considerations, a feedback mechanism can be implemented which ensures the achievement of the above objectives.

Besides the above two types of LASERs, there are various other types of LASERs such as CO₂ LASER, Argon-ion LASER, Kr and Xe LASERs etc. Different LASERs have different optical output power levels too. To have overall view of commercially available LASERs, let us have a look into the following figure:

![Figure 18.6: Different commercially available LASERs](courtesy: Wikipedia)

The above discussion, thus, converges down to three basic steps that initiate the manufacture of any type of LASER. These three steps are as follows:

1) Recognize the suitable material that is capable of stimulated radiation at the particular desired wavelength.
2) Devise a proper and energy efficient population inversion creation and maintenance mechanism.
3) Design a proper and accurate feedback mechanism for maximum coherent optical output.

From the viewpoint of optical communication, Gas LASERs are not that compatible with the electronic circuitry of the system because for communication purposes, the light from the LASER needs to be modulated at optical frequencies. Hence the preferred material for manufacture of electronically compatible LASERs is semiconductor. Use of semiconductor even enables the laser to be designed on the same substrate as the supporting electronic circuitry of the system. For a semiconductor LASER, the basic structure consists of a forward biased p-n junction into which electrons and holes are injected to create population inversion and a stimulated emission is initiated due to stimulated radiative recombinations. So the
first two steps of the LASER design procedure have been, thus, achieved with a direct band-gap semiconductor material. However, the light generated due to radiative recombinations at a p-n junction is highly incoherent as seen in case of an LED. So a proper feedback mechanism to ensure and enhance coherency in the optical output, has to be designed. This can be done by slight manufacturing modifications in a basic LED as shown in the figure 18.6 below:

Figure 18.6: Basic structure for Semiconductor LASER

As seen from the above figure, a forward biased p-n junction with finely polished reflecting surface around the depletion region of the device can act as a LASER. These reflecting surfaces serve as a source of frequency selective optical feed-back in the semiconductor LASER as already discussed. The generated photons due to radiative recombinations at the junction, and having the desired wavelength, undergo multiple reflections between these surfaces and get exponentially amplified before they are emitted out. So, if a LED is slightly modified, such that it has finely polished depletion region serving as reflecting boundaries for the generated photons, the LED can be indeed converted into a LASER. In principle, a forward biased p-n junction made out of a direct band-gap semiconductor material with properly polished reflecting regions, at the depletion regions of the junction, will act as a LASER. This type of LASER is highly compatible with the supporting electronic circuitry of a long-distance optical communication system. This is why a particular type of semiconductor LASER called the LASER diode is used in almost all long-distance optical communication systems.

As the name suggests, the LASER diode is, in principle, a diode accompanied with a lasing capability. Since, the fundamental structure in a LASER diode is indeed a p-n junction; there is a linear relationship between the injected current and the optical power output as in case of a LED. The only difference is the higher value of efficiency that accompanies this emission. And the reason for this sudden increase in efficiency is the feed-back mechanism which increases the gain of device and the coherency in the optical output and as whole the total efficiency of the device increases. At low input drive currents, the slope of the power vs current curve is very low indicating the low efficiency of the basic diode. As the input drive current increases, a point arrives when the slope abruptly increases and the device
efficiency increases to a very high value. This particular value of current at which the slope of the curve increases abruptly is called the threshold current ($I_{th}$) of the device. The threshold current indicates the start of the stimulated emission process which begins to dominate and nullify the losses in the device due to the material properties and other factors by amplifying the output optical power at a much higher rate than the basic diode. This discussion would be clearer with the help of the following figure 18.7.

Figure 18.7: Output characteristics of LASER diode

As seen from the characteristics, for a small change in the input drive current to the device in the lasing region of the characteristic, there is a very large change in the output optical power from the device. This sudden increase occurs as soon as the input current reaches the threshold value. Hence, the device acts more like a switch which switches between high and low optical intensities. This observation renders the LASER diode to be suitable for digital modulation schemes unlike the LED which is its analog counterpart. The digital modulation schemes has two levels viz. HIGH and LOW indicated by 0(LOW) and 1(HIGH) digits which are called as ‘bit’s (binary digits) of data. If the input drive current to the LASER diode is below $I_{th}$, the optical output will be very low indicating the LOW (0) condition and if the input drive current is made higher than $I_{th}$, the optical output peaks to a large value indicating the HIGH(1) condition. However, the transition from the low optical intensity to a high optical intensity via population inversion is not instantaneous and takes a finite amount of time known as the switching time of the LASER diode. Hence, there is a delay introduced in the switching of the device which depends on the relative difference between the input bias current and the threshold current. If the diode is biased to 0 at LOW state, it would take comparatively longer time to switch to the HIGH state than that when the input bias current at LOW state is kept
reasonably near to the threshold current value, $I_{th}$. An ideal digital modulator requires infinitesimal switching delay so that the transition from 0 to 1 state could be instantaneous and the device could support high data rates.

If the input bias current under LOW state is ‘$I_B$’ and in case of HIGH state is ‘$I_P$’, then the delay 't$_d$' introduced into the switching of the device is given as:

\[
t_d = \tau \ln \left( \frac{I_P}{I_P + (I_B - I_{th})} \right)
\]

(18.1)

Here ‘$\tau$’ is the carrier lifetime against stimulated emission. The equation clearly shows that for the delay to be zero, the current $I_B$ must be equal to $I_{th}$ which would mean biasing the device at the threshold current. Although in principle this concept looks promising, yet in practice there are two main difficulties in biasing the LASER diode at its threshold current.

One of the difficulties is that, when the diode is biased at the threshold level the device has some amount of optical output (although very low in comparison to the HIGH state) because of which the digital 0 is not the actual desired optical LOW. This causes the extinction ratio (ratio of the output optical power at HIGH level to the output optical power at the LOW level) to decrease and this decrease leads to enhancement of bit errors in the data transmission.

The second difficulty encountered in biasing the LASER diode at the threshold current is that even during the LOW state some amount of current will always flow through the junction. This flow of current even during the LOW state does nothing but raises the temperature of the p-n junction and as a whole the device gets heated up. Now, the threshold current itself is an exponential function of the temperature. This would be clear from the figure 18.8 below:

![Figure 18.8: Variation of threshold current with temperature](image)
threshold current due to rise in temperature, we need a mechanism which not only
monitors the junction temperature but also maintains it at a constant value in order
to stabilize the threshold current. This mechanism would, hence, enable us to have
very small switching delay in the device. Compared to the LED, thus the LASER
diode needs a more complicated monitored operating environment.

There is yet another undesirable effect that has been noticed in optical output
when there is a transition from optical LOW to optical HIGH. During the transition
from LOW to HIGH, the optical output performs some oscillations before coming to
the steady state in HIGH condition. These oscillations are called the relaxation
oscillations of the LASER diode. This would be clearer from the following diagram.

![Figure 18.9: Response of a LASER diode](image)

The frequency of the relaxation oscillations is given as:

\[ f = \frac{1}{2\pi \sqrt{\tau_{ph} \tau_{sp}}} \left( \frac{1}{I_{th}} - 1 \right)^{1/2} \]  \hspace{1cm} (18.2)

In the above expression, ‘\( \tau_{ph} \)’ is the lifetime of the photon inside the material
before emission, ‘\( \tau_{sp} \)’ is the carrier lifetime against spontaneous emission
and ‘\( I \)’ is the input drive current flowing through the device. If the frequency of the input drive
current exceeds, the frequency of relaxation oscillations, the modulated optical signal
would be noisy and unreliable as it would contain lot of fluctuations resulting from
relaxation oscillations. In other words, the time period of the input drive current pulse
must be greater than the time period corresponding to the pulse of frequency given by equation 18.2, in order to have a reliable optical output.

The maximum modulating frequency that the LASER diode can be subjected to, depends upon the lifetime of the generated photon before it is lost, either by emission or by absorption inside the material. There are three different types of lifetimes associated with the device which are as follows:

1) **Carrier lifetime against spontaneous emission** (\(\tau_{sp}\)): This lifetime indicates the average time between two spontaneous emissions in the device. For typical LASER diodes, this lifetime is generally of the order of about a few nanoseconds (\(10^{-9}\) seconds).

2) **Carrier lifetime against stimulated emission** (\(\tau_{st}\)): This lifetime indicates the mean lifetime between two stimulated emissions in the device and so has to be smaller than the spontaneous lifetime. For a practical LASER diode, the carrier lifetime against stimulated emission is of the order of about tens of pico-seconds (\(10^{-12}\) seconds).

3) **Photon lifetime** (\(\tau_{ph}\)): This is the lifetime that indicates the average duration for which the generated photonic flux remains active before it is lost, either by emission or by absorption. In fact, this is the lifetime that determines the maximum modulating frequency to which the device can be subjected to for a reliable optical data transmission. This is because, once the photonic flux is generated via stimulated emissions, there remains very little control over the photonic flux as it grows exponentially in between the two reflecting surfaces and hence its value cannot be altered. Control is restored only when the excessive photons giving the peak overshoot in the relaxation oscillations die out either by emission or by absorption and the optical output assumes a steady state value. The expression for the photon lifetime is given as:

\[
\tau_{ph} = \frac{c}{n} G_{th} = \frac{c}{n} \left\{ \alpha + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right\}
\]  

(18.3)

In the above expression, ‘\(n\)’ is the refractive index of the semiconductor material, ‘\(G_{th}\)’ is the threshold gain given by equation 17.7 which is the gain required to obtain sustained photonic flux oscillations between the two reflecting surfaces with reflection coefficients ‘\(R_1\)’ and ‘\(R_2\)’, ‘\(L\)’ is the length of the Fabry-Perot resonant cavity and ‘\(\alpha\)’ is the photonic attenuation constant of the material of the device. For a practical LASER diode, the value of the photon lifetime is usually about 2-3 pico-seconds. In other words, the highest digital modulating frequency that the LASER diode can be subjected to is the frequency corresponding to the time period ‘\(\tau_{ph}\)’ which is given by the above equation.