Advanced Optical Communications

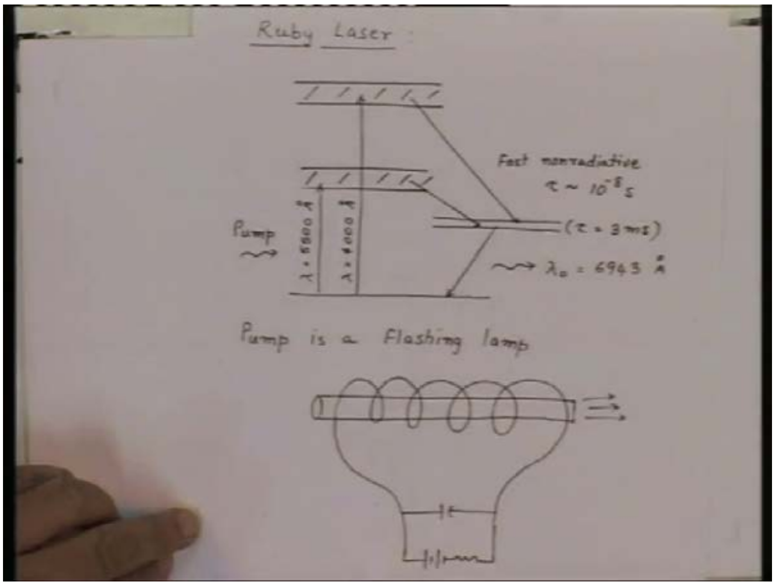
Prof. R. K. Shevgaonkar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 18

Laser – IV

In previous few lectures, we develop the principles of lasers. We found that for laser action we require what is called population inversion and then we require certain feedback in to the system. So that the photons which are generated they are trapped inside a region. What is called a cavity and through this positive feedback mechanism certain frequencies built up in to that region and you get essentially generation of light at certain frequencies. So, if you want to use laser as an oscillator, then we have to have population inversion and then we require positive feedback mechanism. So that certain frequencies built up inside the system with this basic understanding. Now, let us see some specific types of lasers which are commonly used in practice.

(Refer Slide Time: 01:28)



The one laser which you see is the solid state laser, which is a ruby laser, is one of the first one to be investigated. So, you have a ruby rod which has energy levels appropriate for generation of light in the visible range and then by exposing this rod to some flashing light the population inversion is created inside this material. So, if you look at the energy level diagram for ruby you have a energy level state which is the ground state then you are having a little spread energy level here corresponds to a wavelength which is 5500 angstrom. And then you are having another energy level here which corresponds to 4000 angstrom and then you are having another energy level here. Where the electron can make a transition and you can get the stimulated or spontaneous radiation.

So, to create a population inversion essentially, the ruby robs is pumped so that the electrons are transported from this ground state to either this state which is rather broad energy level or to this state. So, essentially the energy has to be supplied at a wavelength either 5500 angstrom or at 4000 angstrom and you create population inversion either at this level or at this level. Then the lifetime of the electrons in these 2 level is rather small is typically of the order of about 10 to the power minus 8 seconds. So, the electrons quickly relax to the energy levels, which are these energy levels where the lifetime is relatively longer it is of the order of about 3 mille second.

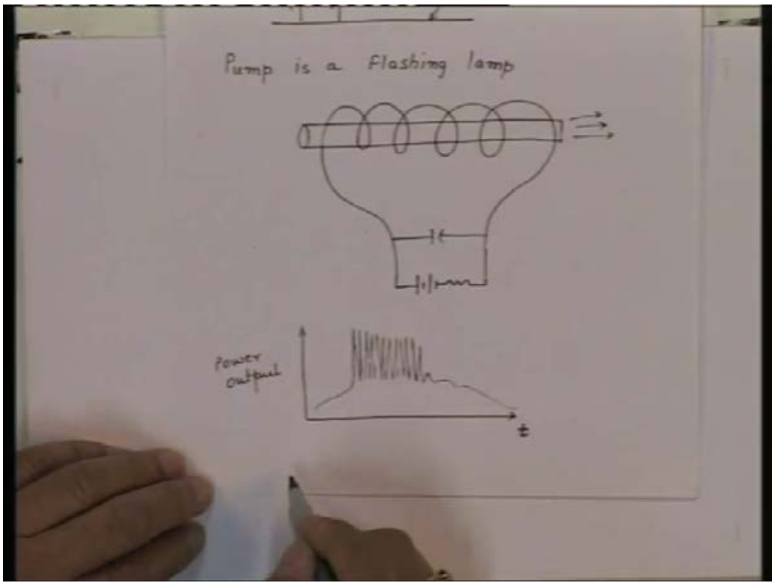
So, the electrons are transported from the ground state to this higher energy level states by pumping mechanism and then through the non radiative process the electrons very quickly relax to these energy levels. And since we are having a lifetime of electrons much larger in this energy level essentially, the electrons wait till the photon comes here and can stimulate the process of the downward transition. So, if you now have a feedback mechanism which is appropriate corresponding to this energy level difference then that photon can trigger the stimulated process and you can get a generation of light at a wavelength which is 6943 angstrom.

So, this is red colour invisible spectrum. So, essentially we get a red blue coming from the ruby rod or you have a laser which is acting at 6900 angstrom or in red colour of the visible spectrum. Now, as we mentioned earlier also that whenever we create a population inversion since this process is a very rapid process once the stimulated process starts very quickly. The population inversion depletes that means most of the electrons again collapse down to the ground state and you do not have a population inversion.

What that means is that we have to keep replenishing the electrons in the upper energy level and when the electrons accumulate in this level very quickly they collapse down.

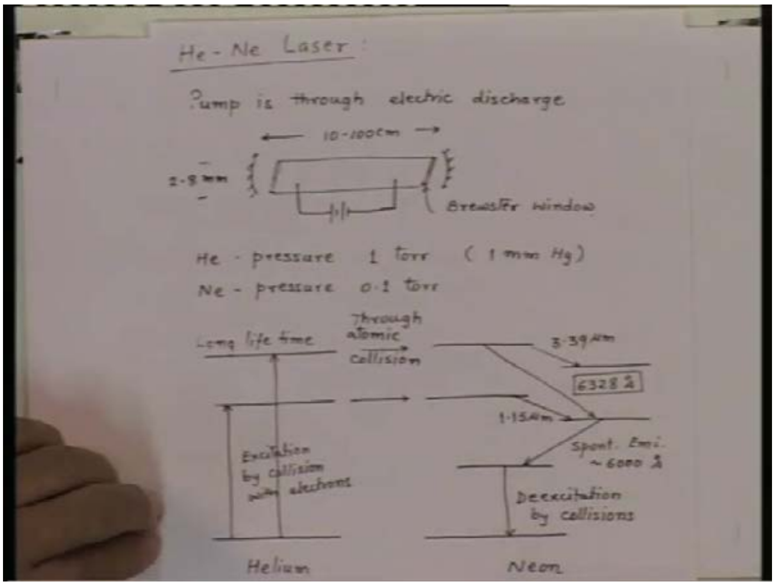
And essentially, what we get is an intense pulse of light and after that pulse again you have a less population in the upper level so they variation decreases again the population builds up and again you have an intense pulse of light and so on. Of course this thing takes place at a very short time scale.

(Refer Slide Time: 05:41)



So what we get is an optical power if I plot as a function of time we essentially, see some kind of spikes which are very closely spaced. We do not get as such a continuous light coming from this you get essentially, the pulses which are very narrow pulses and are very closely spaced. So, it appears almost as if the continuous light is generated from the ruby rod. So, this is one of the very first lasers, which you have studied and investigated for generation of red light.

(Refer Slide Time: 06:25)



He - Ne Laser :

Pump is through electric discharge

He - pressure 1 torr (1 mm Hg)

Ne - pressure 0.1 torr

Then, another laser which we see in laboratories is what is called the helium neon laser either this is the laser which is used in most of the pointers which gives you red spot. So, the entire pointers, which are used for seminars and all that essentially, use what is called the helium neon laser. So, as the name suggests this laser is made from the gases, which is a combination of helium and neon. So, the configuration is as follows we have a small tube here, which contains a mixture of helium and neon and by passing a discharge through this tube. Essentially, we transfer the energy from the discharge to the molecules and the energy actually is transported to the helium molecules.

Because the neon molecules have very low cross sections so directly the energy cannot be transported to the neon molecules. So, we have a combination here say helium pressure is one torr which is one millimeter of mercury and the neon pressure is 0.1 torr. We are having very small neon and then we are having a combination here for the energy levels which match here for the helium and neon. So what the discharge does is essentially supplies energy to the helium atoms and the helium atoms are excited and they have very long lifetime in these energy levels.

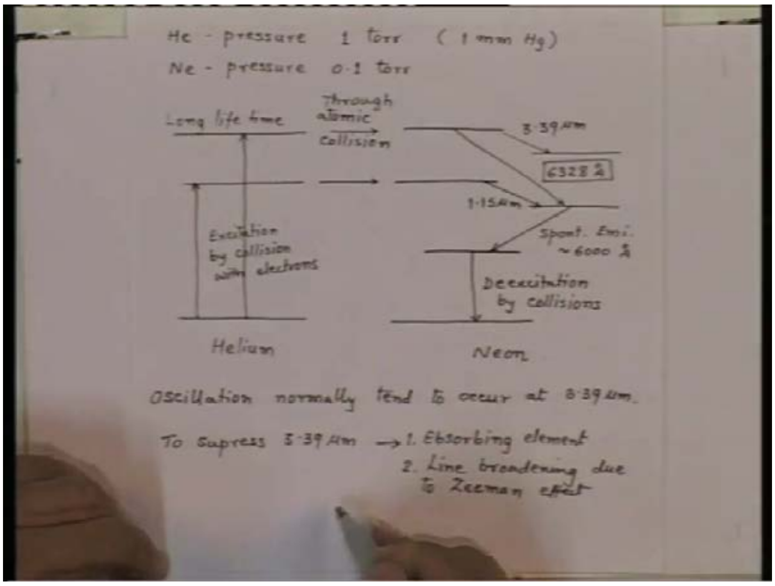
But since we are having a mixture of helium and neon this helium atoms collide with the neon atoms and impart energy to the neon atoms. So, in that process essentially, the neon atoms are excited to the higher energy level. So, population inversion process in this case e 2 step first you have excitation of the helium atoms and then by collision of the helium atoms with the neon you get excitation of the neon atoms. Now, we got the neon atoms which are excited to the higher levels and by using different transitions of the neon atom we can get the laser in an appropriate wavelength.

So, if you look at the energy level spectrum of neon it is fairly complex you are having many energy levels say you have a ground state and then you are having one state here another here, another here and then you are having another state here, another state here and so on. So, one can work out appropriate energy levels, which can give the light in the visible range in the red colour. So, you see that this is the difference from here to here if you see that corresponds to 6328 angstrom or in the red region so in fact this is the transition which is of interest.

So, now the process is as follows we supply energy to this which is helium then the neon items are excited in this level which can either relax to this level or can relax to this level or can make a transition to this level. Now, since this difference is very very small this corresponds to a wavelength of 3.39 micrometer this difference corresponds to 1.15 micrometer this one corresponds to about 6000 angstrom and so on. Now, we are interested in this transition because it that is where the lifetime is longer so we can have a stimulated emission corresponding to this transition.

So, first of all we have to create a feedback mechanism which would support wavelength corresponding to this transition and other wavelengths have to be suppressed. Whereas, we saw earlier where longer the wavelength there is more possibility of lasing action. So, longer wavelengths get easily excited or lased compared to the shorter wavelengths. So, in fact these are the wavelength which will get more easily lased compared to this one in which we are interested in. So what essentially, we have to do is we have to create some what are called the absorbing structures, which will absorb these frequency. So, there is no feedback corresponding to these wavelengths or this wavelength.

(Refer Slide Time: 11:32)



He - pressure 1 torr (1 mm Hg)

Ne - pressure 0.1 torr

Oscillation normally tend to occur at 3.39 μm.

To supress 3.39 μm → 1. Ebsorbing element
2. Line broadening due to Zeeman effect

And this is the wavelength which will get amplified there will be positive feedback for this and once the electrons come here again they will decay from this to this by the spontaneous emission. And then this is what is called the de excitation mechanism by which electrons again will relax to the ground state. So, by providing a positive feedback by using this kind of mirrors and so on. Essentially, one can generate red light from the mixture of helium and neon. So what it appears then is that if you want to generate light at certain frequency or certain wavelength.

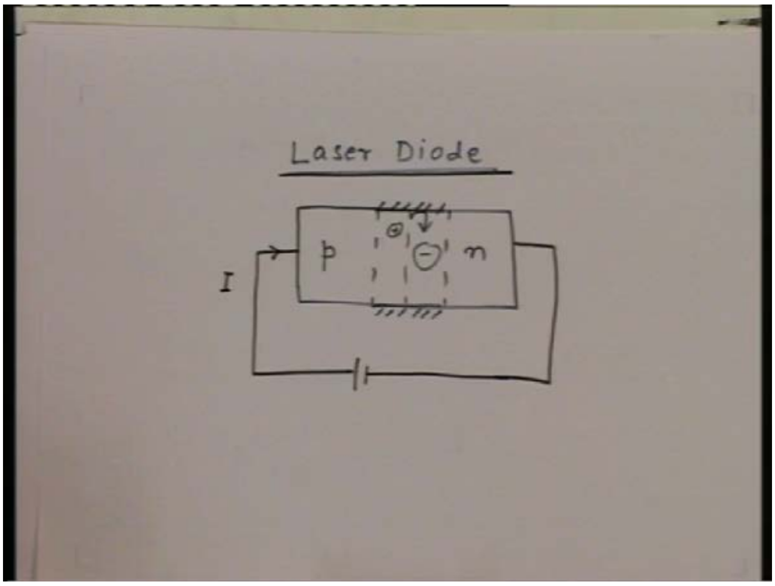
First we have to identify the proper material which has energy levels such that certain energy differences corresponding to the frequencies or the wavelengths. in which we are interested in then we have to find the mechanism by which electrons can be transported to higher energy level. So, in first case as we saw in ruby case directly energy was supplied to the ruby rod from the flash lamp. And the electrons get excited when we got population inversion whereas, in case of helium neon laser the energy was supplied to helium first through the discharge and then through the collision process. The energy from the helium atom was transferred to the neon atom and then we got population inversion so actual lacing action is taking place inside the neon gas.

But we want helium so that efficiently energy can be supplied to the system which can create population inversion inside the neon atom. So, these are the popular lasers there are many lasers in practice. We have carbon dioxide laser you have argon and laser and various types of lasers are there and you can have the power levels, which could vary over a very wide range. But what we have seen from optical communication point of view these lasers are not very suitable, but if you recall we wanted an optical source which is compatible with the electronic circuit. Because ultimately this source has to be modulated information has to be put on the source so that it can be carried over optical fibers.

So, these lasers which are gas lasers are not very suitable for optical communication because they are not very compatible with the electronic circuitry which is used for communication. So, essentially again we go back to a laser which is semiconductor base. So, if we take a semiconducting material and if you can create a lasing action inside the semiconducting material that essentially, would become compatible with the electronic circuit. So, again the idea is same which we had for l e d so inside l e d we had a p n junction and by making the p n junction forward bias essentially, electrons and holes were injected in a common region.

They recombine and then you are having generation of light because of recombination, but then this photon which we have generated inside l e d they were moving in all possible directions. So, there was efficiency factors associated with this so the l e d had a extremely low conversion efficiency. Now, if we create a mechanism inside the p n junction or inside the active region of the p n junction where recombination is taking place and if we make some kind of a positive feedback mechanism. Then the photons which are generated inside the p n junction they will remain there for longer time and when they remain there for longer time they will create stimulated action and we will get generation of light inside the p n junction.

(Refer Slide Time: 15:55)



So, in fact schematically if we see if we take a p n junction and you are having a depletion region here, where the recombination of electrons and hole takes place. And the light let us say is trying to come out from this side or this side if we create certain reflecting regions here. Then the photons which are generated inside these regions would get reflected by this. So, the photon will be trapped inside this region and then we will have a stimulated amplification of light.

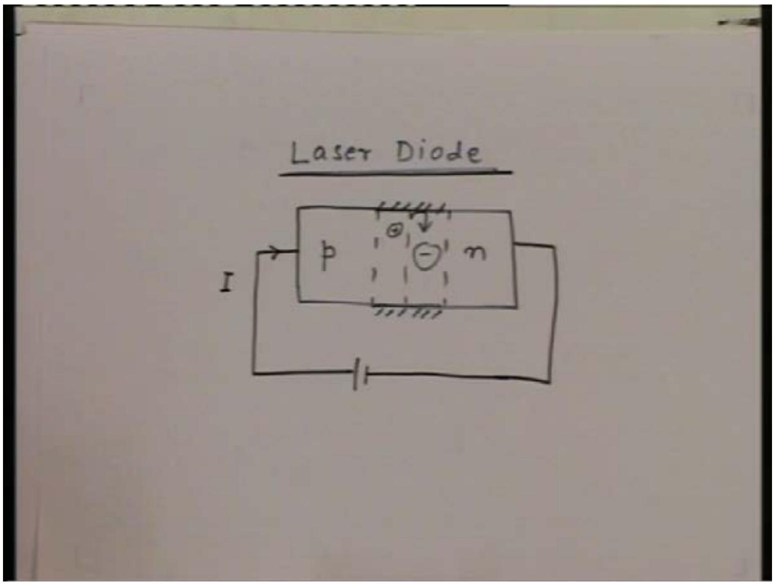
So, in fact by making the fabrication of l e d in such a way that I have some kind of reflecting boundaries which will make the photon confine for longer time inside the depletion region the same l e d can be converted inside a laser. So, in principle a forward bias p n junction made of a direct band gap material with proper polishing of the surfaces so that the photon can be trapped will act like a laser. So, this is the device which will be very compatible with the electronic circuitry and that is why a semiconductor base laser what is called the laser diode that is a device which is mostly used in long distance optical communication.

So, first thing to note here is that initially, when the feedback was not there as we saw the efficiency of conversion is very very small. That means we had the current when which flows in to p n junction and because of that current the electrons holes recombine in this region and the photon get generated. But most of the photon gets lost and very little light essentially, comes out of it but there was linearity between the optical power and the current which is flowing inside the device.

The same thing is happening in this case also here inside the laser diode that again the current is injected and as the current increases all the losses which are there inside this device. The stimulated gain takes over those losses and the photon are confined inside the region. So, stimulated process gives you amplification of light and once the stimulated process dominates over the losses then the efficiency of device suddenly increases. Because once the stimulated process starts the photons are not going arbitrary in all directions they will essentially, move in specified directions because of this positive feedback mechanism.

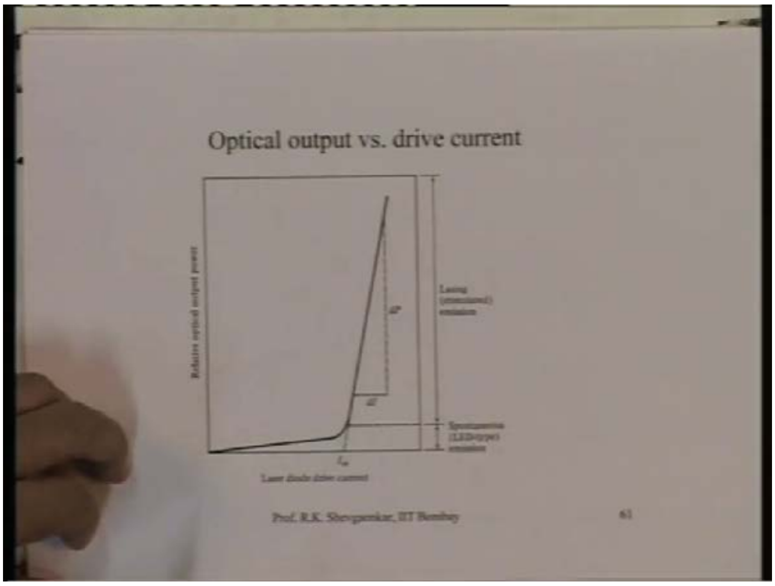
And you will see that now for the same carrier injection of a same current you will get much higher optical power. So, again the relationship is linear that you will have a optical power which is proportional to the current. But the change in optical power now, is much larger for the same change in current compared to what we used to get for l e d because the efficiency of l e d was very very small. Now, if I look at the characteristic of the laser diode essentially, the characteristic would look something like this.

(Refer Slide Time: 15:55)



So, firstly I take this device what is called laser diode (No audio from 19:50 to 19:58) and this is the p n junction which is forward bias we have done some polishing here so photon is confined in this. So, we want to find out what is the optical power in relation to what is the current which is flowing inside this device is current I. So, we can get what is called the output characteristic of laser diode which will look something like this.

(Refer Slide Time: 20:31)



Optical output vs. drive current

Prof. R.K. Shevgaonkar, IIT Bombay

So, we can have what is called the optical output versus the drive current which is the current which is flowing inside the laser diode. So, I am plotting here the current and here. We have optical power now at low current since the stimulated emission process has still not overcome the losses inside the device. So, device will start functioning like l e d so we have a linear relationship between the current and the optical power but the slope of this is very small because efficiency of the device is very very small.

Once you these two ways sudden threshold current beyond which the stimulated process overcomes the losses inside the device suddenly the lasing action will start stimulated process is dominate and then you will have a large efficiency inside the device. That means for your small change in the current we will have a very large change in the output of the optical signal. So, laser diode has a typical characteristic which almost breaks at this current which is what is called the threshold current.

So, below threshold current the optical power is very very small and the mechanism below this current is the spontaneous mechanism because the device is more or less working like l e d. Whereas, beyond the threshold current the device goes in to lasing action and then we are having the stimulated emission in this region and the efficiency of the device is very very large. So, as we saw in case of l e d the output characteristic is a linear characteristic you get the light output which is proportional to the current and this relationship is fairly linear over a very wide range.

So that device could very well be used for the analog communication because we have a linear relationship between the current and the optical power. So, by changing the current you get same behavior in the optical signal whereas, when we go to the laser diode here. Then we are having a sudden break at this point or we have a action which is more like a switching action. So, if the current is less than threshold value I have very low optical power something like this and if I have a current which is more than the threshold value then we have a optical power which is very large which is suddenly here.

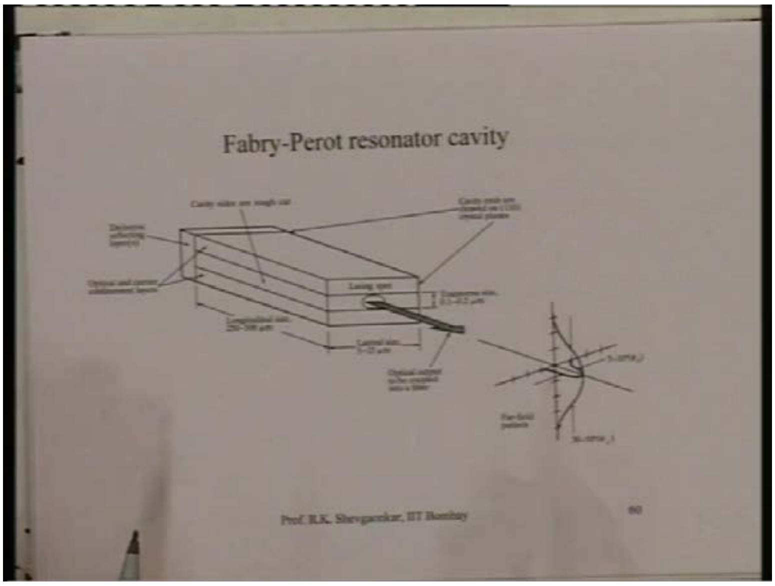
So, we will see that because of this characteristic essentially, this device is more suitable for switching kind of action because by reducing the current below threshold. Suddenly the device gets more or less switched off whereas, if the current exceeds the threshold current. Suddenly you see a large optical output from the device one can say that in both the regions here also. I have a linear variation and here also we have a linear variation but you would note that this linear variation is more stable whereas, here in the small fluctuation in the current will give me very large fluctuation in the light output.

So, though this characteristic is linear here it is not very stable characteristic. In the sense that I can use this for the linear modulation so the laser diodes intrinsically are not very suited for linear modulation process. They are rather suited for the switching kind of modulation whereas, the l e d is a device which is more suited for the linear modulation and that is the reason. When we go for analog modulation normally the l e d s are preferred because they have linear characteristic whereas, laser diodes are more suited for the digital modulation which have more like a switching action.

So, if I consider a data 0 and 1 and if I give the currents corresponding to 0 which is 0 and if I have a current corresponding to 1which is greater than threshold. Then you will see that the light output essentially, will swing that means 0 and suddenly some very large value. So, you will get an optical output which will switch by changing the current between 2 levels 1 below threshold and one above threshold. So, then it is important to note that the laser diode is a good device for long distance communication because it is a laser.

So, it has a very narrow spectral width it has a good efficiency but at the same time this device is not very suited for the linear modulation or for analog modulation. But since most of the optical communication is taking place as a digital modulation process this device is very suited for long distance optical communication. So, basically what we find here? Now, is that the laser diode is a very good device which can be suited for long distance optical communication with the digital modulation process. So, schematically if we now see how the light is coming out essentially we have a multilayer structure.

(Refer Slide Time: 26:18)



Fabry-Perot resonator cavity

Prof R.K. Shevgaonkar, IIT Bombay

60

And in this region the recombination takes place and the photons are generated we provide some kind of a feedback or polishing on this phases of the device and the laser beam comes out of this. Now, note here that even though the positive feedback has taken place for the photons which are travelling exactly perpendicular to this boundary. You have the mirrors and we get the reflection which will be coming exactly perpendicular to this when the photons try to come out of this region they are coming for a very narrow region from here they try to come out. So, essentially we have a beam of photon which is coming out of a very small region here and since the size could be of the order of few microns you have a diffraction of light.

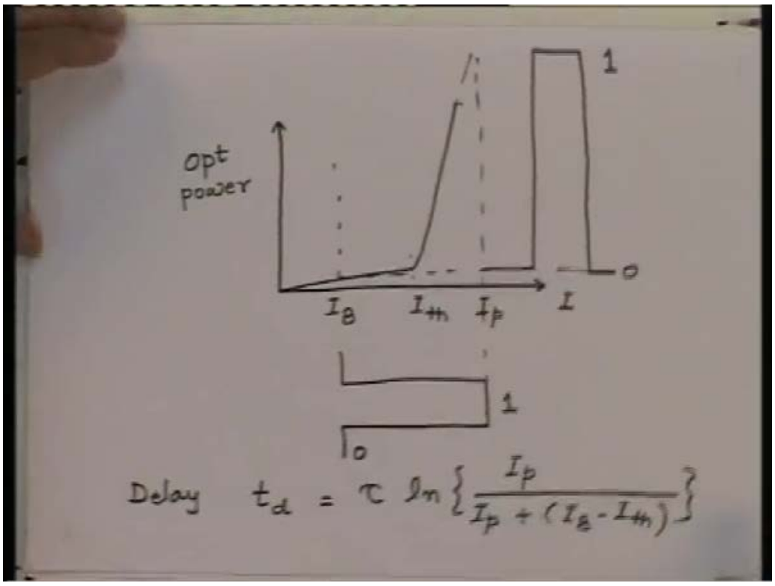
So, we do not have a beam which is exactly moving in this direction, but we have a angular zone in which the photons are escaped outside because of the diffraction of the light from this small region. Nevertheless the angular width which you will get from this device will be much smaller compared to l e d. So, you get typically few degrees cone you can get from this device whereas, as you remember the angular cone over which the power was coming from l e d used to be essentially 180 degrees. So, the laser diode essentially, gives you a beam which is reasonably narrow.

So, I can use this mechanism to find whether my laser diode has gone in to switching action in to lasing action. So, let us see if I take a laser diode and slowly increase the current inside the laser diode and keep looking at laser diode at an angle before the threshold. Since the laser diode works more like an l e d the light comes over a very wide angle. So, you can see the light very dim, but you can see from a tilted angle from the l e d after the current crosses the threshold value suddenly the process turns in to the stimulated process. So, the angular cone is no more one 80 degrees, but suddenly gets narrow like this.

So, from this direction it looks as if the device is switched off because now the radiation going in to a narrow cone. Then I have to own a device properly and look in to the device to really see the radiation coming out of that. So, as we increase the current inside this device essentially, the light characteristics change the angular cone changes also the nature of the light changes because in l e d the light is incoherent whereas, in laser diode the light will be coherent. The another important aspect of this thing now is that when we supply the digital data to the laser diodes then the photons will get excited inside this.

But then if the laser initials when the current is not a point if the current is brought 0. Then when we switch on the current the population inversion has to build to it is value which corresponds to this threshold current and beyond that only you will see the stimulated emission. What that means is that if the device is biased at 0 current then the switching time will be longer because it will take some time to build the population inversion and once you reach to that population threshold value beyond that only you will get a stimulated emission. So, essentially what we are saying is that we are having a delay associated with this switching this device and the delay will depend upon the biasing current with respect to the threshold current now the idea is as follows.

(Refer Slide Time: 30:44)



Suppose I consider this is the current I and this is the optical power the characteristic is like that and this is the threshold current which is I t h. And let us say we have biased this device at this value which is I B that means when I supply the digital data which is in the form of current the 0 corresponds to this current and one corresponds to a value which is higher than this. So, this is my 0 level and this is the 1 level as a result of this we will get the optical output corresponding to 0 level which will be this and corresponding to one level you will get an optical output which will be like that something like this. So, this is the 1 level.

So, by supplying this current which is the digital pulse where 0 corresponds to this biasing current and one corresponds to the current which is higher than the threshold current. You will get an optical pulse for which you will have a certain optical power corresponding to 0 levels and some optical power high power corresponding to 1 level. Now, what we are saying is because this current is not same as the threshold current. When this one signal comes it requires certain time to first build the population inversion up to this value and beyond that only the device can go in to lasing action.

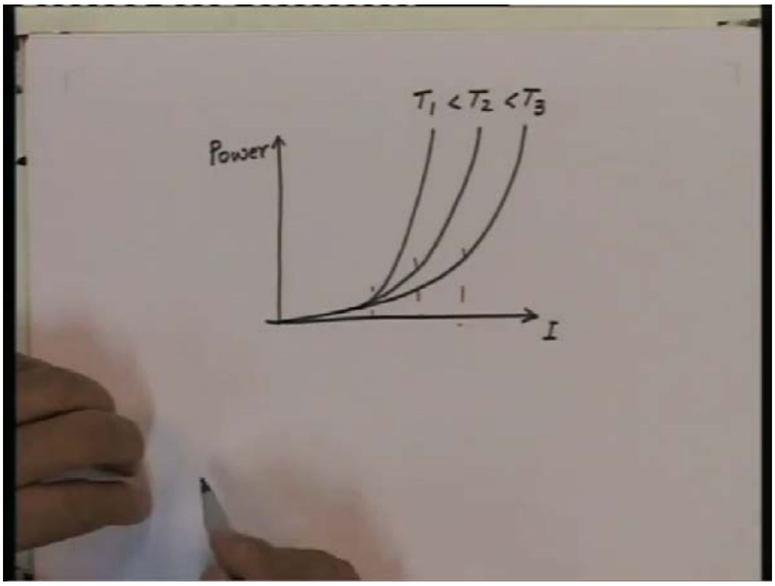
So, this delay in the switching action or getting the device in to lasing action is given by say t d phase. The delay that is equal to the lifetime of the photons l n log of the peak current which is this current. So, let us say this current is I P divided by I P plus I B minus I t h. So what do we find here is that if the device was biased at the threshold level then I B minus I t h would be 0 then this will be l n I P upon I P which is one so the delay will be 0.

What that means is if the device was biased at the threshold current that means it is just ready to get in to lasing action. As soon as the switching pulse comes you get a stimulated emission and you get a light pulse out. So, ideally what should happen if you want to have the delay very very small is that we should bias the device at the threshold current. So, the 0 level of digital should not correspond to the current which is 0 but it should correspond to a level which is I threshold then only you will get a switching time which will be very very small in this case it will be 0.

But this has two problems. Now, first we what we will notice is that if the device was biased at the threshold current then we have the optical level corresponding to 0 that is large. So, the 0 is not really 0 from our optical power point of view that is one problem or in other words what that means is that the what is called the extension ratio. Which is the ratio of the 1 level to 0 level that becomes smaller and later on we will see when we go for the calculation of the errors this will create certain problems. So, biasing the laser at the threshold current will reduce the extension ratio which will have implications for the bit errors.

The second problem is that if the laser diode is biased at the threshold current whether we are transmitting the pulse or not transmitting the pulse some current will always flow inside the device. And because of that the temperature of the junction will increase and the laser will get heated. Now, the temperature of the junction increases the major problem is that threshold current is rather a strong function of the temperature of the device. So, as the temperature of the junction increases this threshold current also increases in fact there is exponential relationship between the threshold current and the temperature.

(Refer Slide Time: 36:58)



So, if we ask how the threshold current will vary as a function of temperature this is power at some temperature. I have a characteristic which will look like that if the temperature increases the thing will become like this like this and so on. Where this is T 1 less than T 2 less than T 3 and so on temperatures. So, effectively what it means is that the threshold current is increasing as I go for high and high temperatures. So, initially let us say if we had biased the laser at certain point here then because of the current flow or the time the junction temperature will increase. When the junction temperature increases the threshold current will increase.

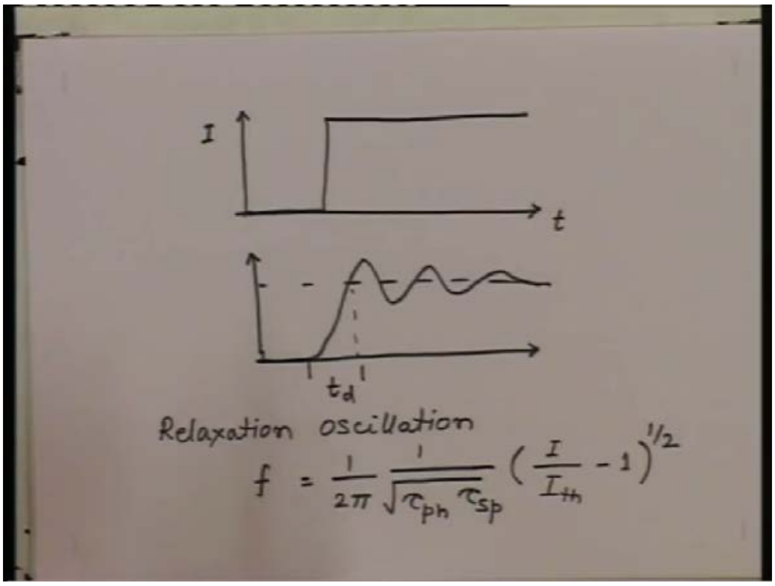
So, the biasing current will become smaller than the threshold current. So, it will introduce essentially a delay. So what that means is that if you want to have the delay very very small either we should track the threshold current. So, keep changing the biasing current so that threshold current and difference between threshold current and biasing current is small or make the threshold current stable. So that once it is biased at that point this difference I B minus I t is negligibly small in the first situation if you track the threshold current you will see that. If we put the biasing current here and temperature increases the threshold current will increase.

If I increase the biasing current again to come to threshold current we will be essentially, pumping more current in to the junction which will increase the temperature still further which will drift the threshold current still further and so on. So, you will have some kind of positive mechanism here, which is not very desirable because then the junction will get overheated and even laser will get damaged. So, for a good operation of the laser essentially, what we need is that this temperature of the device must be stabilized or in other words what it means is that the laser must be operated in a temperature controlled condition.

So, the junction temperature has to be monitored and there has to be some kind of a automatic feedback which will cool the junction so that it is temperature is maintained at some constant value. When that happens then of course, the threshold current will be equal to the biasing current and then we will have a very small delay inside this device. So, the operating conditions for the laser diode are not as simple as they are for the l e ds. So, l e d device you just take at p n junction which is biased appropriately and it will start working whereas, when we go for the laser diode then we require a much better temperature controlled environment.

So that it is threshold current can be properly regulated and then we can get that is slightly operation from this device. So, these are certain operational aspects corresponding to the laser diode when we use in to practice. Then another aspect of the laser diode is what is called the relaxation oscillation.

(Refer Slide Time: 40:50)



Relaxation oscillation

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{\tau_{ph}\tau_{sp}}} \left(\frac{I}{I_{th}} - 1\right)^{1/2}$$

What that means is that suppose we give a switching pulse which is something like that as I said these are function of time and this is the current which is supplied to the laser.

Now, as soon as this current is supplied to the laser you see that the population inversion will build and because of this population inversion building you will see suddenly the gain in to the system will be very large. So, you will see that large number of electron holes will get recombined and you will get essentially, a pulse of light. But as soon as the stimulated process starts then the depletion region will be depleted with the electron holes so the gain on the system will fall and the stimulated output also will reduce. So, for this current application we do not get an optical power which will be just like this you will see some kind of oscillation which will take place and after sometime it will get a stabilized value.

So, you will get population inversion or you will get more electron hole pair which will recombine will give you light, but when they start giving more light do you have short of electron hole pairs which will reduce the gain so again you will have a electron hole pair accumulation and so on. So, you will see light more than what is expected in stable condition then gain increases so the population or the electron hole pairs will reduce again the gain will fall down. So, you will get some kind of oscillations like this and after sometime then you will get the stable output.

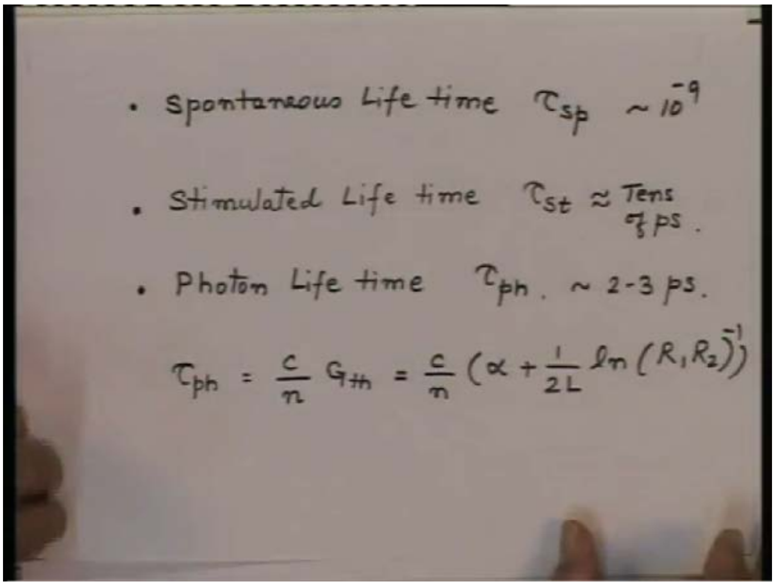
So, you have a delay which will be associated with this that is what we already talked about this is t d, but you have this phenomena of oscillation also which is related to this is what is called the relaxation oscillation of the laser. In fact we will see that if this was not a constant thing like this suppose it was a pulse the optical output will not be a pulse like thing it will be a some kind of a repel. Which will be riding on that pulse and later on you will see that this essentially, contributes to again some kind of noise in to the a optical communication system and which will affect your system performance.

So, this phenomena is what is called the relaxation oscillation (No audio from 43:26 to 43:32) and the frequency for this relaxation oscillation f is equal to 1 upon 2 pi 1 upon square root of tau photon which is the lifetime of the photon inside the laser multiplied by tau spontaneous into I upon I threshold minus one to the power half. So, in fact this is the frequency beyond which essentially, the laser modulation will be a problem because you it will not be able to respond properly it will not stabilize. So, if you consider a pulse period which is much larger compared to this period of oscillation then you will get a stable output here, but if that period is smaller compared to this.

Then essentially, you will not get a flat top pulse, but there will be a some distortion which will be on the pulse. So, this is the phenomena which is some kind of putting some kind of restriction on the operation of the lasers I bring it I do switch the laser on and off for the digital modulation. So, one can then ask now that if I want to use the laser for digital modulation scheme what are the limits of the modulation frequencies. What is going to now decide? What are the highest frequencies to which the laser can be modulated?

So, you will see essentially, what we are talking about here is that once the electron hole pairs are injected inside the region. Then as long as the electron hole pairs remain inside this region once they are injected we will not be able to change. The light output even if we switch off the current externally and the lifetime which we have here is essentially decided by the stimulated lifetime of the carriers. So, at low currents when the stimulated process has still not started the carrier lifetime will be decided by the spontaneous process so, in fact in this device.

(Refer Slide Time: 46:07)



- Spontaneous Life time $\tau_{sp} \sim 10^{-9}$
- Stimulated Life time $\tau_{st} \approx$ Tens of ps.
- Photon Life time τ_{ph}. $\sim$ 2-3 ps.

$$\tau_{ph} = \frac{c}{n} G_{th} = \frac{c}{n}\left(\alpha + \frac{1}{2L} \ln (R_1 R_2)^{-1}\right)$$

We have 3 lifetimes first is the spontaneous lifetime of the carriers (No audio from 46:10 to 46:17) as said tau spontaneous, second lifetime is when the stimulated process starts and as you have seen this process is much faster compared to the spontaneous process. So, the lifetime of the carrier recombination will reduce substantially and that will be the stimulated lifetime. (No audio from 46:36 to 46:49) The third lifetime is that once the photon is generated inside this. Even if the carriers vanish even if I stop the current in the external circuitry unless the photon is lost from this region either it is absorbed again inside the material or has left the cavity. We will not be able to change the photon flux.

So, ultimately the upper limit and the frequency will be decided by how long the photon resides inside this cavity. So, we have and what is called the photon lifetime inside the cavity which is tau photon. And how long the photon resides inside the cavity essentially, depends upon what is the threshold gain for the lasing inside this device. So, this tau photon tau p h is equal to c by n where n is the refractive index of the material into the threshold gain of your device G t h and threshold gain is the gain at which the oscillation just sustain say as you have seen earlier from that condition for the positive feedback this quantity would be equal to c by n into alpha which is the absorption inside the material plus 1 upon 2 L log of 1 upon R 1 R 2 minus 1 like this.

So, this is the absorption coefficient of the material this is the length of the region where lasing is taking place and these are the reflectivities of the 2 mirrors of the cavity. So, you will see that the spontaneous lifetime is rather long so it could be the order of about nanosecond. So, of the order of about 10 to the power minus 9 the stimulated lifetime is much smaller compared to this one. So, it could be of the order of about let us say 10s of picoseconds. And this photon lifetime if we calculate for the typical cavity which we use this could be of the order of about 2 to 3 picosecond.

What that means is that for a typical device we cannot have the radiation or the modulation which can change shorter than 2 to 3 picosecond because once the photon is generated. You will not be able to change the photon flux within this time which is the photon a lifetime. So, if you take inverse of this quantity we will get the highest modulation rate for a laser diode which will be typically of the order of about few 100 gigahertz in practice you can get the modulation that which could be the order of about few 10s of gigahertz. But ultimately this is the factor which we decide which is the highest rate at which the laser can be modulated.

So what essentially, we have done in this lecture we have try to investigate if we use the semiconducting material for giving the stimulated emission. Then what are the problems which we will face in realizing this. So, we saw that the same p n junction which is used for l e d. If we do some kind of a polishing on the edges of this p n junction so that the photons are confined in the depletion region. Then this photon can trigger the stimulated process and one can get the coherent radiation from the same p n junction. Then we studied the output characteristic and we saw that there is a break in the output characteristic.

So, intrinsically the laser diode is more suitable for digital kind of modulation with the biasing current as close to the threshold current as possible. We also saw that to have low switching delay the biasing current and the threshold current have to be controlled. And the laser has to operate in a temperature controlled environment then one can get the stable optical output with a very low delay and then from the lifetime of the photons and the carriers inside the p n junction. We essentially, try to establish the highest possible modulation rate which can be used for modulation of a laser diode.