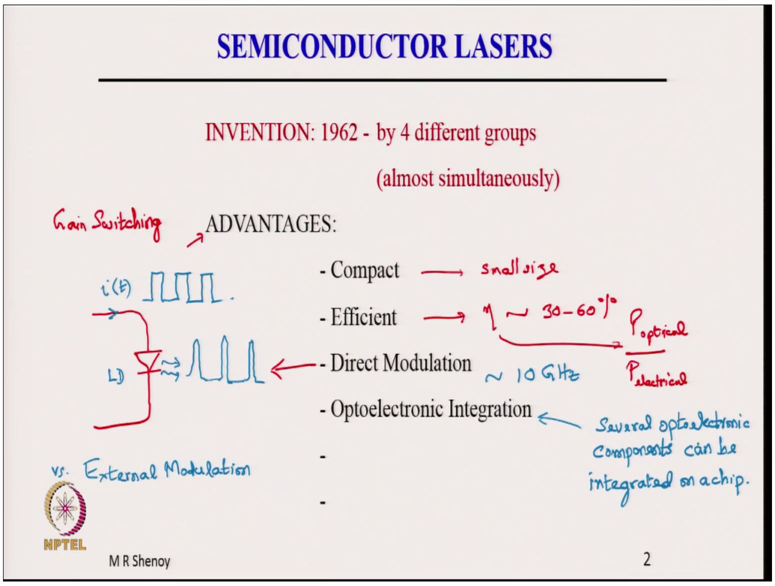
Introduction to LASER
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 35
Semiconductor Lasers

Welcome to this Mooc on Lasers. We have been discussing some laser systems and today we will discuss Semiconductor Lasers, one of the important class of lasers with a wide range of applications, particularly commercially and technological, industrial applications.

(Refer Slide Time: 00:43)



Semiconductor lasers were first invented in 1962 almost simultaneously by 4 different groups. The advantages of semiconductor lasers are, they are very compact. So compact which means small size, small size for the same level of power, very efficient. So, the power conversion efficiency is of the order of 30 to 60 percent typically. Efficiency here refers to the wall plug efficiency.

So, this refers to total optical power P optical divided by P electrical, the input electrical power. So, this is optical direct modulation, this I discussed when I discussed about pulsing lasers. So, direct modulation refers to modulation of the device, that is if you have a semiconductor laser here, it is gain switching. When we discussed about gain switching, I had given this example gain switching.

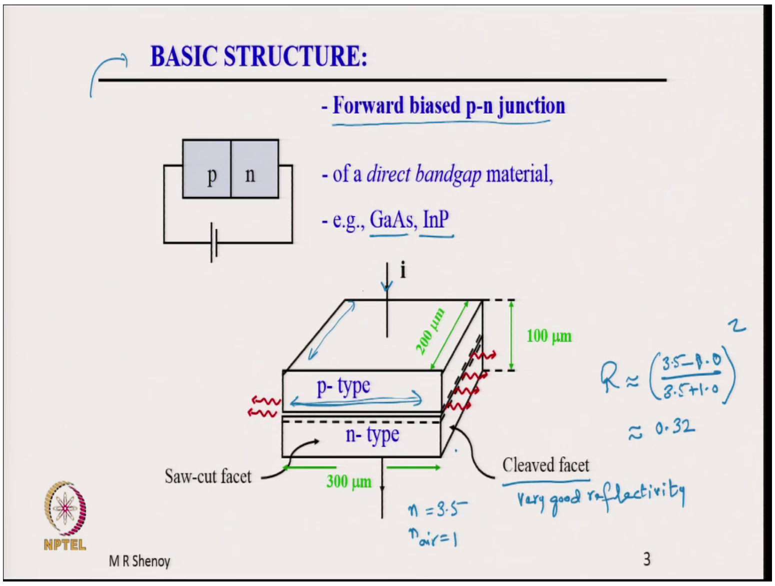
For example, a current i flows from here i of t, if this varies as a pulsed output, if this current let us say, a square variation a pulsed current here the optical output, which comes out from the laser diode. So, this is laser diode will also be in the form of pulses. So, we are switching the gain by switching the injection current. So that is called direct modulation as opposed to, we have also discussed external modulation so versus external modulation.

So, just recall that this is what we meant by so external modulation, where the laser gives a CW output, but you have an external modulator which pulses the output. The important point is direct modulation at speeds of the order of 10 gbps, 10 gigahertz, is possible for semiconductor laser diodes several gigahertz up to 10 gigahertz is possible, which no other laser can be modulated at such high speeds.

Optoelectronic integration, because these are semiconductor devices therefore, several optoelectronic components; several optoelectronic components can be integrated so optoelectronic components can be integrated on a single chip. That is what we mean by optoelectronic integration, so integrated on a chip.

So this optoelectronic components includes semiconductor lasers, photo detectors, modulators, wave guides, splitters, several components can be integrated on a single chip, that is referred to as optoelectronic integration. And semiconductor lasers being made on semiconductor substrates are compatible with optoelectronic integration. There are several advantage more advantages, which I have not listed here.

(Refer Slide Time: 04:58)



So, let us look at the Basic Structure, the basic structure, so it is a forward biased p-n junction. So, I have shown here a p n junction with a supply forward biasing; of a direct band gap semiconductor material, such as gallium arsenide or indium phosphide. And, the structure typically with dimensions looks like this. Typically, it is about 300 micrometer in length and about 200 micrometer in width and approximately 60 to 100 micrometer in height or thickness.

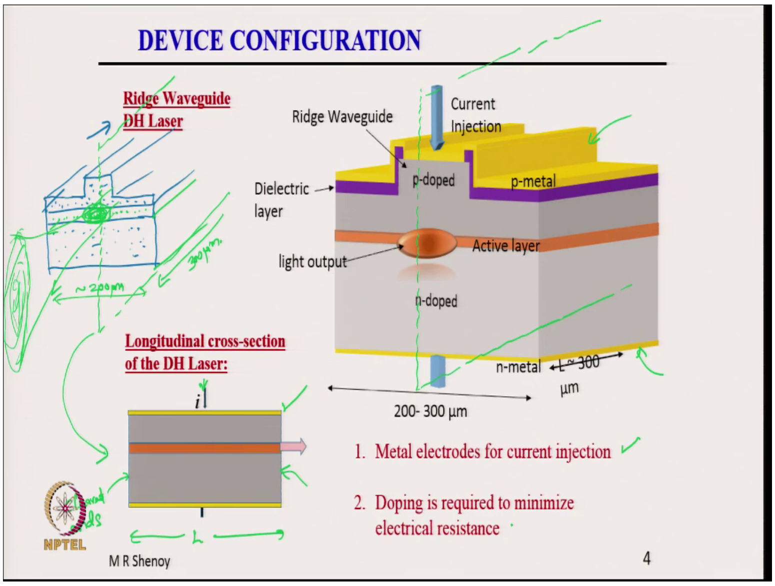
So, typical one piece of semiconductor laser, typical dimensions of these and current i, so current flows here, across the junction and at the junction region the electron holes recombine generating photons which result in lazing in the device under proper conditions.

So, as shown here, the laser generally has two cleaved facets, cleaved facets provide very good reflectivity, they give very good reflectivity. And usually there are no mirrors in a semiconductor laser. The cleaved ends itself for example, the semiconductor has a refractive index typically about n is equal to 3.5 and therefore, if you have a cleaved facet the interface between semiconductor and air, so n air is equal to 1 this would give a reflectivity of r approximately equal to n 1 minus n 2 square.

So, 3.5 minus 1.0. So, that is refractive index of air divided by 3.5 plus 1.0, that is n 1 minus n 2 by n 1 plus n 2 whole square n 1 minus n 2 by n 1 plus n 2 gives us the amplitude reflection coefficient and the reflectivity will be whole square which is approximately 0.32; that means, 32 percent reflectivity is provided by the cleaved ends.

Usually, the other two ends are saw cut facets. So that there is no reflection provided the reflectivity from the other two ends are poor. This is done because we would like the laser to build up in this direction, back and forth in this direction in the cavity, not in the perpendicular direction. If the two other ends are also cleaved ends the laser may build up in this direction as well. So, to avoid this, usually it has two cleaved facets.

(Refer Slide Time: 08:01)



The device configuration is shown here. Usually, these are nowadays it is usually ridge waveguide double hetero-structure lasers. So a ridge waveguide is a those of you who are not familiar, it comprises of layers like this, if I show the front end, this is the front surface here. So, the front surface, so this is the chip which is shown and over this there is an another layer which is grown with a raised ridge.

So, the structure looks like this. So I have drawn it here. So, that when I draw you get a better feel. So this is of one material here and the substrate here is, this is the substrate starting point so, usually n doped, and the intermediate layer which is here is a higher refractive index, lower band gap material which is sandwiched. So, that is the active layer. So this is the active layer. So the structure is like this. So, this is the active layer.

And the mode which builds up inside the laser in this direction, this is the spot modal spot which is shown here and the light is coming out in this fashion. So, this is the cone of light which is coming out. So the light is building inside the laser here and comes out as a cone of light. It is usually elliptic in nature because the spot here is elliptic and when it diffracts it gives an elliptic spot like this. So that is what is shown here.

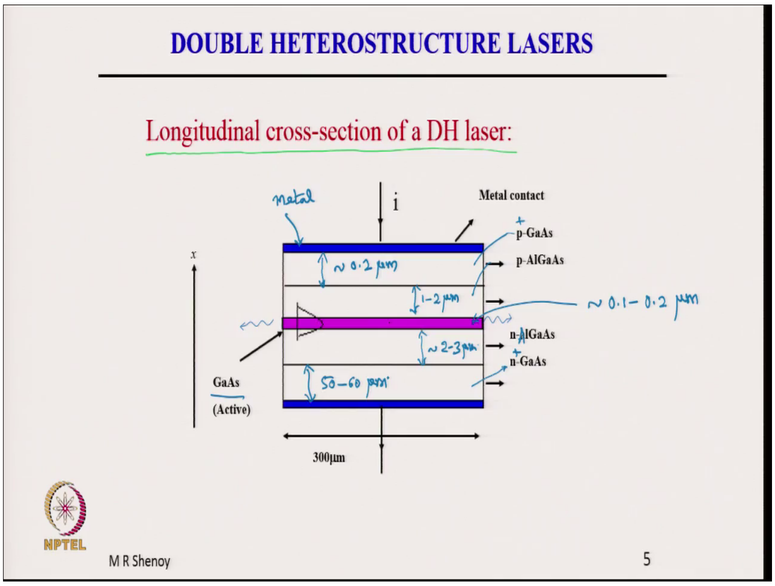
And on top we have gold layers here, for metal contact, current injection. So this is the gold layer. The width of the device here, this is approximately 200 micrometer and the length in this direction is approximately 300 micrometer. So that is what is shown. And now, if we take a longitudinal cross section like this, if we show a longitudinal section that is in this diagram here, so the longitudinal section if I take it would be on this plane here.

Then we will see the longitudinal section would look like this. That is what is written here, longitudinal cross section of a double heterostructure laser. We will discuss about the double heterostructure, but first what is shown here is a section which is along the length, in other words, this is the length laser length and these are the cleaved facets. So these are the facets which provide reflection. So facets cleaved ends so cleaved ends which provide reflection.

And here is the metal electrodes for injecting current through the device. Why I am showing this and explaining this is because, henceforth, we will primarily discuss with a structure whose longitudinal cross section is shown here. We would not be discussing the 3D structures which are shown here, but the longitudinal section is sufficient for us to understand the physics of working of these semiconductor lasers.

The metal electrodes are provided for current injection and doped structures are used, so doped semiconductors are used. Doping is required to minimize electrical resistance or increase the conductivity. So this is the typical device configuration of a semiconductor laser, a practical laser and henceforth, we will discuss with by taking the longitudinal section of the laser alright.

(Refer Slide Time: 12:17)

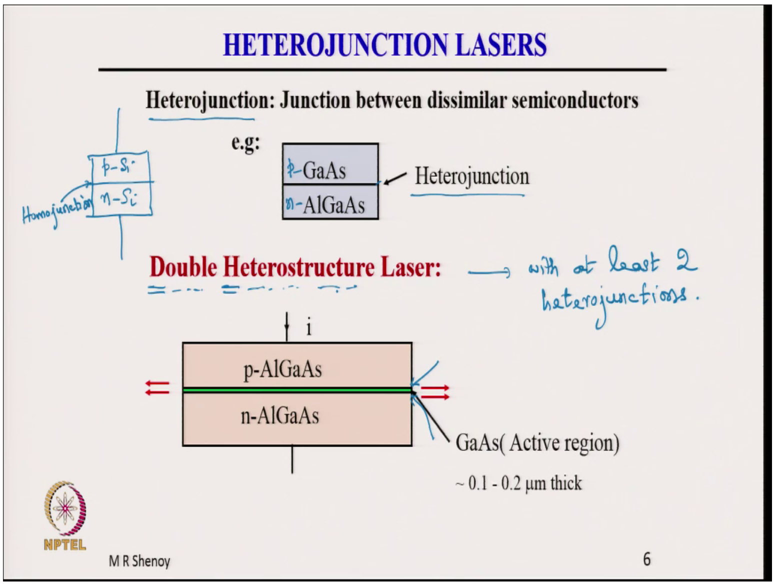


So, there is the Double Heterostructure longitudinal cross-section of a double heterostructure laser. I am yet to explain to you what is this double heterostructure. So, it comprises of an active layer here, which is typically of dimension 0.1 to 0.2 micrometer. A layer of thickness approximately this much.

And it has two cladding layers typically, 2 to 3 micrometer thick, 2 to 3 micrometer, this may also be 2 to 3 or 1 to 2 micrometer. And then, we have a p plus contact layer usually, so this is p plus contact layer. This is p aluminum gallium arsenide. This is n aluminum gallium arsenide so aluminum gallium arsenide. This is n plus gallium arsenide the substrate, and this is the gallium arsenide active intermediate region.

And this dimension, this contact layer may be of the order of 0.1 to 0.2 micrometer again and this is the metal. And this thickness is the substrate thickness could be generally 50 to 60 micrometer. So, the diagram that I have shown here is not to scale, but that is why I have written the typical dimensions in the longitudinal cross section of a double heterostructure laser.

(Refer Slide Time: 14:06)



Now, why double heterostructure? Let us see. These are heterojunction lasers, so heterojunction means junction between two dissimilar semiconductors. So, like gallium arsenide and aluminum gallium arsenide are two different semiconductors and the junction between them is called a heterojunction.

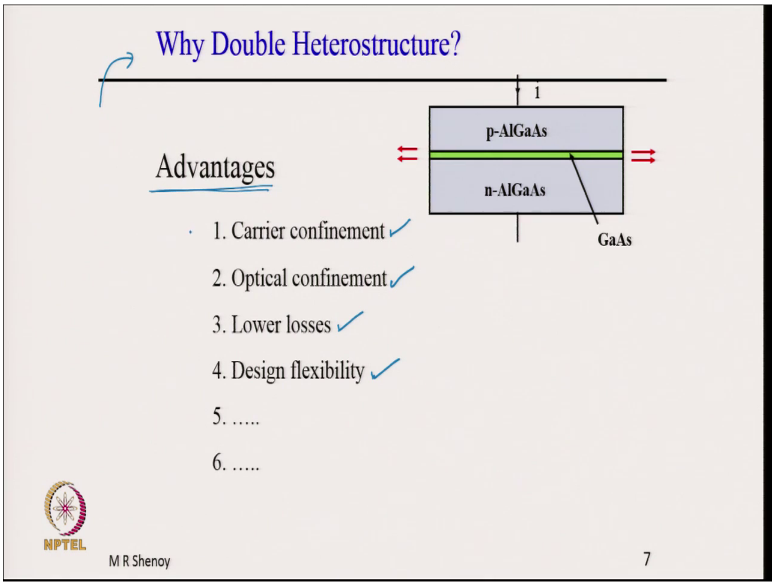
Normally in a diode that we have a electronic diode, we have a p type silicon here and an n type silicon. The material is silicon, one side is p doped and another side is n doped and we have a p n junction. This is a homo junction. So this junction between these two p and n sides is a homo junction in p n junction this is a homo junction.

But this one is a heterojunction because the materials are different. This may be p doped gallium arsenide, this may be n doped aluminum gallium arsenide, but the most important point is the junction is between two dissimilar materials and therefore, it is a heterojunction.

The DH that we have used in the earlier two slides stands for Double Heterostructure. A structure which has two heterojunctions with at least, there may be more with at least 2 heterojunctions is a double heterostructure. So in the simplest structure we see that there is n aluminum gallium arsenide, p aluminum gallium arsenide and intermediate layer is gallium arsenide.

Therefore, we have one junction which is here, a heterojunction and the second junction which is here. So there are two heterojunctions, and hence the name double heterostructure laser. It need not be laser, it could be a double heterostructure device, some other device, but we are interested in double heterostructure lasers and that is why we are considering double heterostructures.

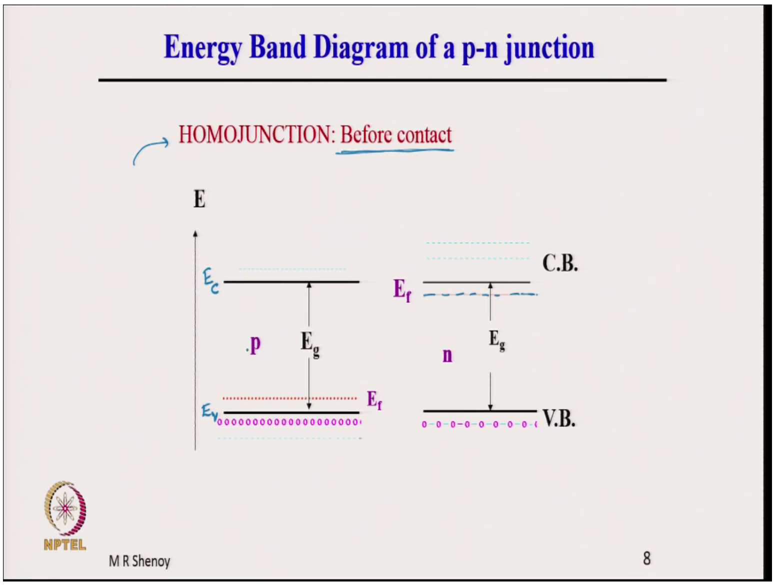
(Refer Slide Time: 16:27)



Now, why double heterostructure? There are many many advantages of a double heterostructure, but the most important ones I have listed here. These are the advantages. What do they mean? Each one can be explained. So, 1st carrier confinement, optical confinement, lower absorption losses and lot of design flexibility to use different materials and make lattice matched double heterostructures.

So, these details are beyond the scope of this course. Here we are looking at it as a structure, a laser system and therefore, nevertheless let me discuss a couple of points here, that is carrier confinement and optical confinement.

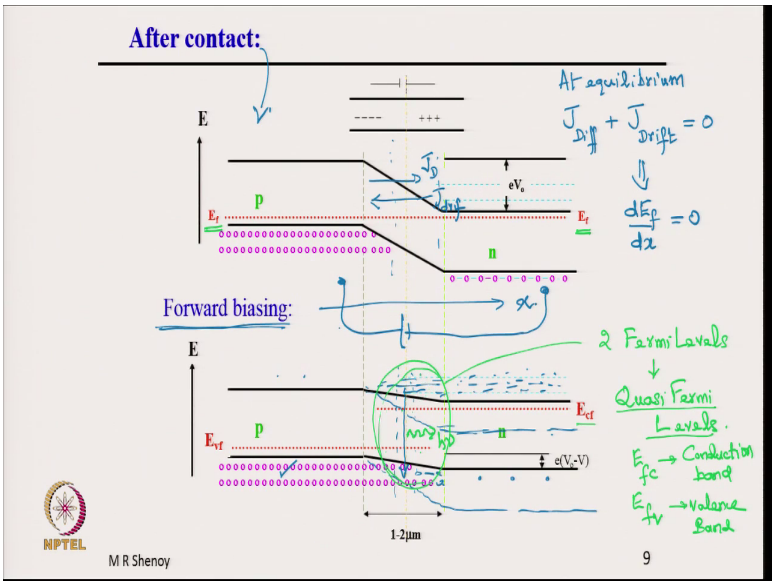
(Refer Slide Time: 17:28)



So, let us consider a homojunction device before contact, this is a p type semiconductor, n type semiconductor. As you can see, p type semiconductor has is the Fermi level which is close to the valence band. So, this is E v, this is E c and the Fermi level is close to the balance band it means, this is a p type semiconductor.

In the other case we have the Fermi level which is here, which is an n type semiconductor. Valence band and conduction bands are shown. Now, this is before contact. What we have shown here is the energy band diagram of a p type semiconductor and a n type semiconductor. It may be p silicon n silicon, before contact.

(Refer Slide Time: 18:20)



And, now when we make a contact then we know that there are carrier migration taking place because of concentration difference and the Fermi level gets aligned from this side. The diffusion current and the drift current compensate each other. So, if we have the diffusion current density J D and drift current density J drift then J drift plus, so J D that is J diffusion plus J drift. Hope most of you have studied a p n junction. So this must be equal to 0 at equilibrium.

That is when there is no bias, no external bias. And this requires that the Fermi level is aligned. This will give us that you can show this that dE f by dx is equal to 0, where x is this direction. So, this is x and dE f by dx must be 0 which means the Fermi level is aligned.

So this is after contact, without any bias. So this is just after contact. Now, if we forward bias now if we do a forward biasing, what happens? Forward biasing means we apply a p to this end and end to the other end. So we apply a p bias. So we are applying battery like this, so positive to this end p side and negative to the n side.

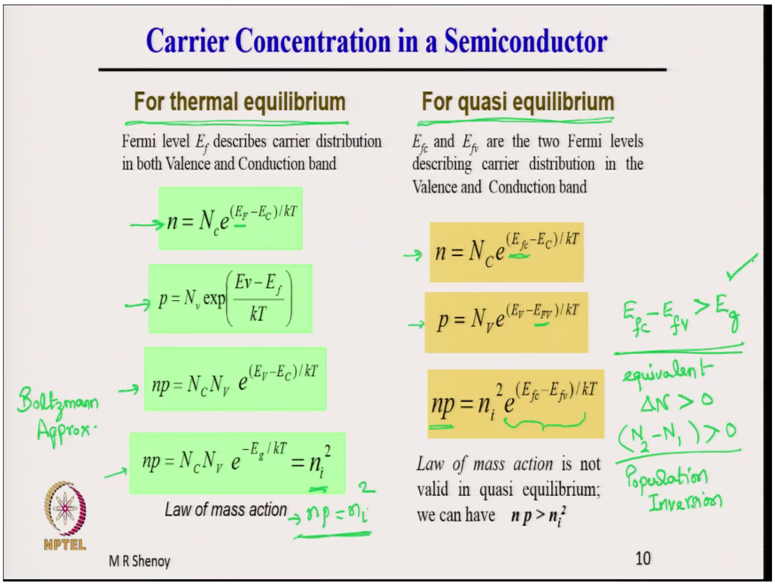
The potential energy of electrons on the n side increases and therefore, the band goes up. So originally the band was here like this, like this and now the band has gone up. And therefore, originally this is the so called depletion region, where there are very little electrons and holes in the depletion region.

But now, that we have forward biased the barrier is reduced as we can see here, so this is the barrier potential barrier here is reduced, and electrons can now come up to this easily as you forward bias. Similarly, the holes have also come up to this, and therefore in the junction region for example, in this region of space simultaneously at the same place same position x, we have holes and electrons.

Earlier, before away from the junction region here we had plenty of holes, but very little electrons. Similarly in the n side we have plenty of electrons. So, this is the dashed points are electrons and very few holes which are not even shown. Now, in the junction region after forward biasing in the same position we have plenty of holes and electrons and they recombine here resulting in the generation of photons.

And this is the mechanism of recombination which leads to generation of photons in the case of a light emitting diode for example. But, in the case of a rectifier diode or an electronic diode no light is generated but the recombination leads to flow of current across the junction, in a forward biased diode.

(Refer Slide Time: 22:14)



Now, what is to be noted is; one, here we had a single Fermi function or a Fermi energy level, but in this case we have two Fermi levels. If we see the junction region if we see this junction region there are two Fermi levels, one from the p side and one from the n side, and these are called the quasi Fermi levels.

So, two Fermi levels in the junction region, when you forward bias the diode and these are called quasi Fermi levels. And designated by E fc for the conduction band and E fv for the valence band. So, this is for the valence band and the other one is for the conduction band. In the original semiconductor before we biased, we had only one Fermi level which describes the distribution of carriers in both valence band and conduction band.

But when the semiconductor is in quasi equilibrium then it has two Fermi levels; one describing the distribution of electrons in the conduction band and the other one describing distribution of holes in the valence band. So, these are designated as E fc and E fv.

So, here is a little bit of just a little bit of mathematics from semiconductor physics. In thermal equilibrium for a given semiconductor the carrier density of electrons n is given by an expression like this; E f minus E c by k T this is under the so called Boltzmann approximation. Those of you who have studied semiconductor physics so Boltzmann approximation.

And p, the whole density is given by an expression like this and the product n into p is N c into N v into E to the power E v minus E c by kT or n p is equal to N into c into e power minus E g by kT. And, this can be shown to be equal to n i square where n i is the intrinsic carrier concentration and therefore, we write n into p is equal to n i square which is called the law of mass action in semiconductor physics.

When the semiconductor is in quasi equilibrium, this is important n the carrier concentration is given by N c into expression is similar, but see the difference here it is E f minus E c, now we have E fc minus E c. Because the distribution of n is described by a different Fermi function. Similarly, the distribution of p in quasi equilibrium is described by a different Fermi function; and therefore, n into p comes out to be n i square into E to the power E fc minus E fv by kT.

What we have seen is, there is an additional term. In other words, by creating a difference between the two quasi Fermi levels or by controlling the separation between the quasi Fermi levels, we can change the carrier concentration, the product can be changed by orders of magnitude.

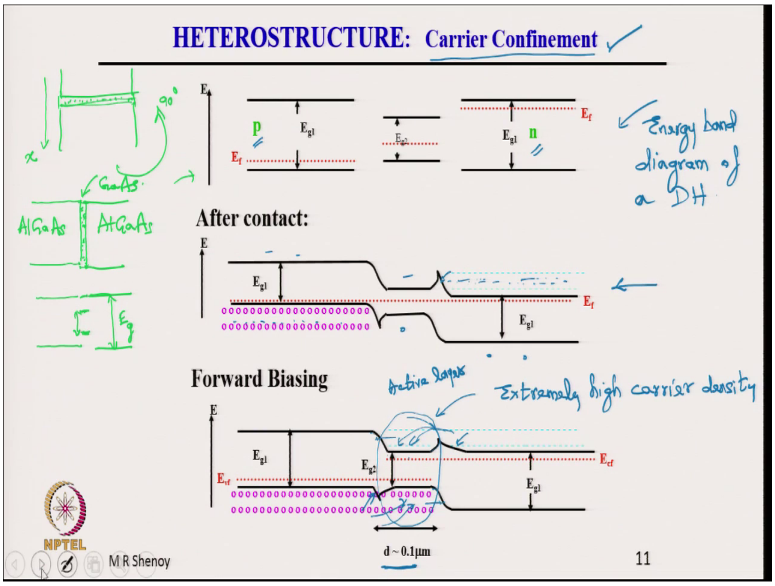
This is the idea behind forward biasing a diode. The law of mass action is not valid in quasi equilibrium and we can have n into p greater than n i square, indeed much much greater than n i square. Now, why did I recall this statistics in semiconductors? Because, the condition for semiconductor lasers, we would not be able to go into the details in this one lecture.

But for semiconductor lasers to lase, that is stimulated emission to take over E fc minus E fv must be greater than E g, the band gap of the semiconductor. The separation between the quasi Fermi levels must be greater than E g if we have to have stimulated emissions, dominating and laser action to take place. This condition is equivalent condition in the laser that we have studied.

So this is equivalent condition to population inversion delta N must be greater than 0 or N 2 minus N 1 we had written that N 2 minus N 1 should be greater than 0 or population inversion. So, this we called as population inversion in this course, so population inversion. What is the equivalent condition for semiconductor lasers? The equivalent condition for semiconductor lasers is E fc minus E fv greater than E g.

This is very important and that is why I had given the statistics carrier statistics because population inversion is the necessary condition for amplification by stimulated emission and the equivalent condition in the case of semiconductor lasers is E fc minus E fv greater than E g, in fact greater than h nu for light of frequency nu to get amplified by stimulated emission alright.

(Refer Slide Time: 28:57)



So, let me illustrate, why double heterostructure and what is carrier confinement? If we look at this, the double heterostructure comprises of recall that the double heterostructure comprises of a thin layer sandwiched between two layers of another type of semiconductor. So, this is a thin layer which is here sandwiched between two other layers of semiconductor.

Therefore, if this is the x direction or depth direction x. If I rotate this through 90 degree; so if I rotate this through 90 degree then I will have the material like this. So, the thin layer here sandwiched between two other layers of higher band gap material. This material here is a lower band gap material, gallium arsenide. This is higher band gap material, aluminum gallium arsenide and aluminum gallium arsenide, it is an alloy with different compositions of x.

So, let me not go into those details, but what is important is therefore, if I plot now the energy band diagram, it would look like this one has higher E g and the intermediate layer has a smaller E g like this, and then again we have higher E g like this. So, this is the E g of the intermediate layer, this is the E g, E g is the band gap so E g of the outer layers which is of higher band gap. So, that is what is shown in this diagram here.

Now, we are now showing the energy band diagram of a double heterostructure. So, what is being shown is energy band diagram of a double heterostructure energy band diagram of a Double Heterostructure DH. This first diagram is before contact, so this one is before contact and after contact because of carrier migration the band bending takes place and we get a energy band diagram which is something like this. How this comes, that is a another course to discuss it is not in our purview here.

And if we now forward bias what you note is after contact as before in the single p n junction, we have the Fermi level same all along in all three materials here. When you forward bias, if we forward bias then in the junction region please note this is p type this is n type.

This could be intrinsic or very lightly doped and therefore, in the junction region this is the junction region now, and in that region we have two Fermi functions and there is a separation E fc minus E fv. Note that, when the junction is formed, please see this intermediate diagram.

When the junction is formed without any bias there are plenty of electrons here these blue dashes are electrons representation. There are plenty of holes on the p side, very little electrons, very little holes. And in the junction region, there are hardly any electrons and holes, may be a very little electrons and holes.

When we forward bias, the potential barrier here is lowered, potential barrier is lowered both here and here this is the p side and this is the n side. So here and here, potential barrier is lowered. You can see there is a barrier which does not permit hole to go there. Here, there is a barrier, so this barrier here does not permit electrons to go to the left.

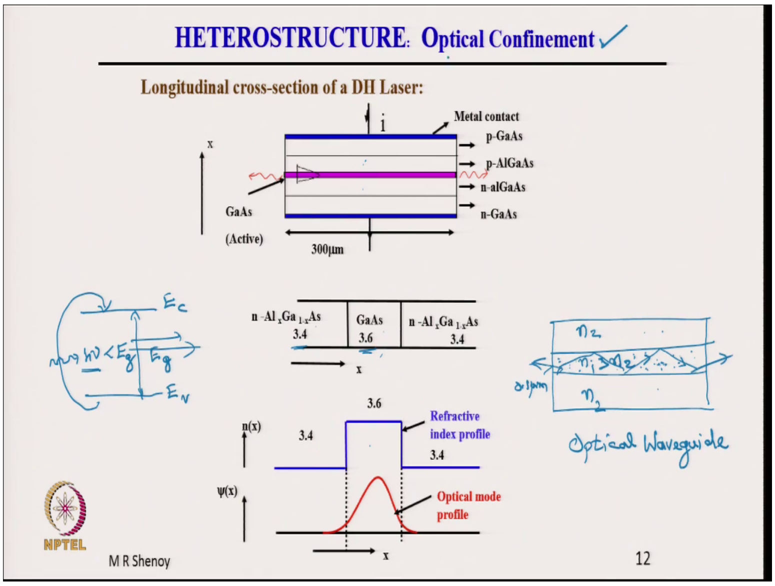
When the barrier is lowered because of forward biasing, the electrons move into this region and the holes move into this region. And we see that in the junction region there are plenty of electrons and plenty of holes in a very small very small layer, very thin layer. And therefore, the volume of the layer is extremely small.

If we look back at the homo junction, here, this separation is 1 to 2 micron. The normal depletion layer width in a p n junction is approximately 1 to 2 micron depending on the doping concentration. Now, we have made a double heterostructure where we have sandwiched a very thin layer of semiconductor between two other materials of higher band gap.

So, we had decided the thickness. So, we had decided the thickness to be 0.1 micrometer and therefore, the carriers are confined to a very small volume and this leads to extremely high carrier density; extremely high carrier density. That is number of carriers per unit volume. So for the same current and we will see, in the theory it can be shown that carrier density. The gain in the medium is proportional to the carrier density in the medium.

And therefore, carrier confinement, the point which is highlighted here carrier confinement refers to confinement of electrons and holes to the thin layer sandwiched layer. The electrons cannot move to this side because there is a barrier. The holes cannot move further because there is a barrier and therefore, the holes and electrons are confined to this thin layer which we call as the active layer. So, this is about the carrier confinement.

(Refer Slide Time: 35:48)



One more point which is optical confinement here. This is by chance, so this is rotated through 90 degree. A higher band gap material has a lower refractive index and the lower band gap material which is sandwiched layer has a higher refractive index, and therefore, it forms a refractive index distribution is like this, this is n of x, x is this direction the depth direction.

So, in the depth direction if you go, you have a refractive index variation like this. In other words, we have a layer of refractive index n 1 which is surrounded by a layer of refractive index n 2 and n 1 is greater than n 2. As you can see n 2 is 3.4 n 1 is 3.6. And what does this make? This leads to an optical waveguide.

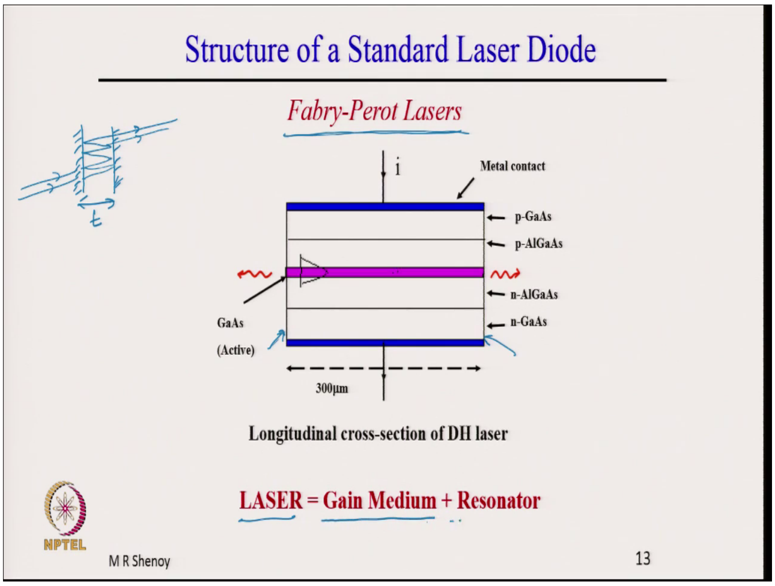
The energy which is generated here gets trapped because of total internal reflection and light comes out from the ends like this after total internal reflection. So, this is an optical waveguide and the light which is generated is confined to the layer. In the previous case, the carriers were confined to that layer and now we have light which is confined to that thin layer, it is the same thin layer which is of 0.1 micrometer here.

And this is the higher band gap material which has a lower refractive index and this is called optical confinement. This has great advantages because the light generated in this region cannot be absorbed by the region which is outside. The band gap of this region that is the core region here, gallium arsenide is smaller than the band gap of aluminum gallium arsenide.

And therefore, as you would know that if you have a semiconductor with E v and E c and the band gap E g here, then if a photon is incident of energy h nu which is less than E g then this does not get absorbed and it simply passes through. Because it does not have enough energy to take an electron from the valence band to the conduction band and; that means, the photon is not absorbed. That is what is true here, the light which is generated here.

The light is generated because carrier recombination takes place here, but the generated light gets trapped here and propagates without absorption and that is the meaning of optical confinement. There are many many advantages of a double heterostructure which has led to the grant of Nobel Prize for this discovery.

(Refer Slide Time: 39:17)

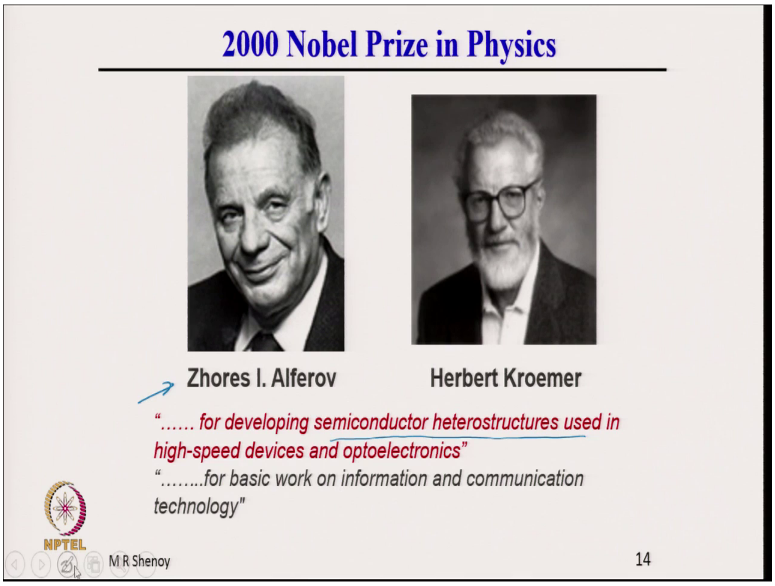


And therefore, the final structure of a standard laser diode is it is a double heterostructure these are called Fabry-Perot Lasers. Fabry-Perot simply says that it has two reflecting ends here. So, it is like the Fabry-Perot interferometer where you have two mirrors highly reflecting mirrors separated by a certain distance t or d. So, light which is incident on this gets reflected back and forth, back and forth and comes out here.

And this output shows the interference fringes, that is why its called a Fabry-Perot interferometer. Now, what you have is two reflector separated by a distance. So, exactly like that we have two reflecting surfaces which are separated by a gain medium and these are called Fabry-Perot lasers. The laser as before gain medium plus resonator.

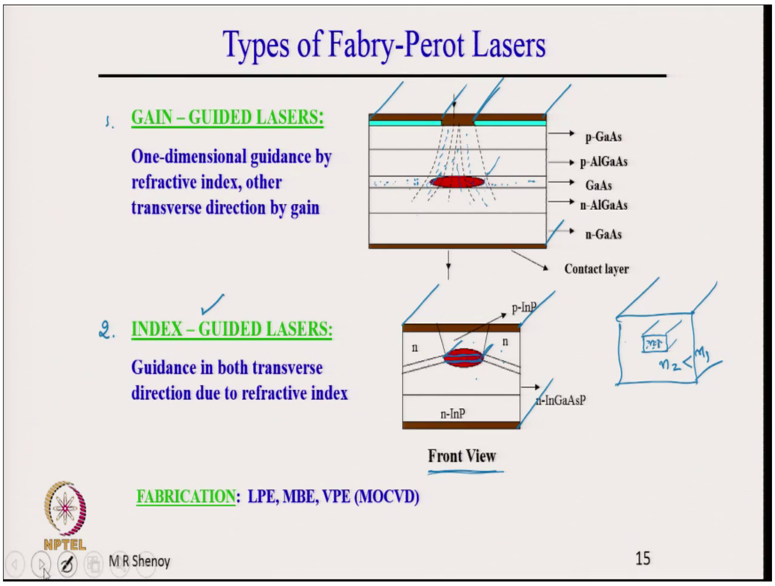
The physics of lasers the concepts and the idea of lasers that we had studied in this course for the bulk materials is also applicable to semiconductor lasers, because we have a gain medium here and two reflecting end surfaces which forms the optical resonator. And therefore, gain medium plus resonator forming the laser.

(Refer Slide Time: 40:53)



So, here is what I mentioned that the 2000 Nobel Prize in physics was given to Alferov and Herbert Kroemer. So, Alferov and his group for developing semiconductor heterostructures used in high speed devices and optoelectronics, so developing semiconductor heterostructures. And of course, Herbert Kroemer got for his basic work on information and communication technology.

(Refer Slide Time: 41:27)



The types of Fabry-Perot Lasers. So what is shown here is the front view. Front view means actually the laser continues like this. It is a only the cross section front end is shown. And there are two types of lasers broad classification; 1 is gain-guided laser and 2nd is index-guided laser.

So, gain guided laser simply has layered structure and the current flows, so what is shown here is a schematic representation of carrier flow direction. So the carrier flows over a certain region and it recombines, so this is the active region which is the thin layer that is sandwiched.

So, the carriers recombine here leading to the generation of light and the light propagates back and forth and builds up. So, the gain region is because of the carriers passing through this small region and hence it is called gain guided laser. So, all along the length here, the gain is provided just under the contact electrode which is here.

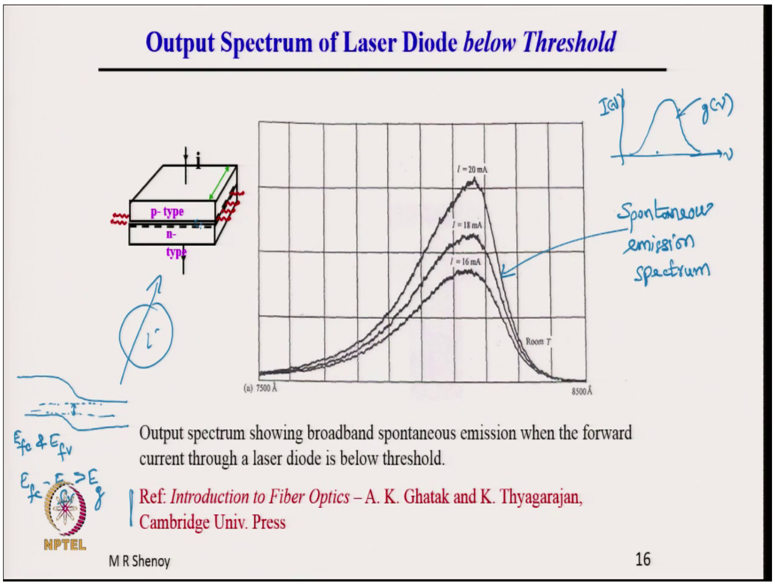
So, this actually continues like this, contact electrode and therefore, everywhere there is gain only under this strip and it is called a gain guided laser. In contrast, in index guided laser, there is the refractive index all around is lower the refractive index of the layer, here it is not visible because of the red color. The layer which is here has a refractive index which is higher and therefore, light is confined by refractive index.

If we have, for example, a cross section, I am showing a cross section like this, where let us say a rectangular waveguide. Where you have n 1 here surrounded by n 2 and n 2 is lower than less than n 1. So this is a channel here. So, light will all be trapped here inside this because of total internal reflection.

What determines this confinement? The refractive index and hence they are called index guided lasers. So the layers, there are different layers, it is not one layer n 2 surrounding because of other technological reasons, but all the layers which are surrounding this layer where light is generated has a refractive index lower than that of this layer.

And therefore, light is trapped here by total internal reflection to a region and hence it is called index guided laser. These are some of the fabrication techniques which are used to grow these layers, they are liquid phase epitaxy, molecular beam epitaxy and vapor phase epitaxy.

(Refer Slide Time: 44:27)



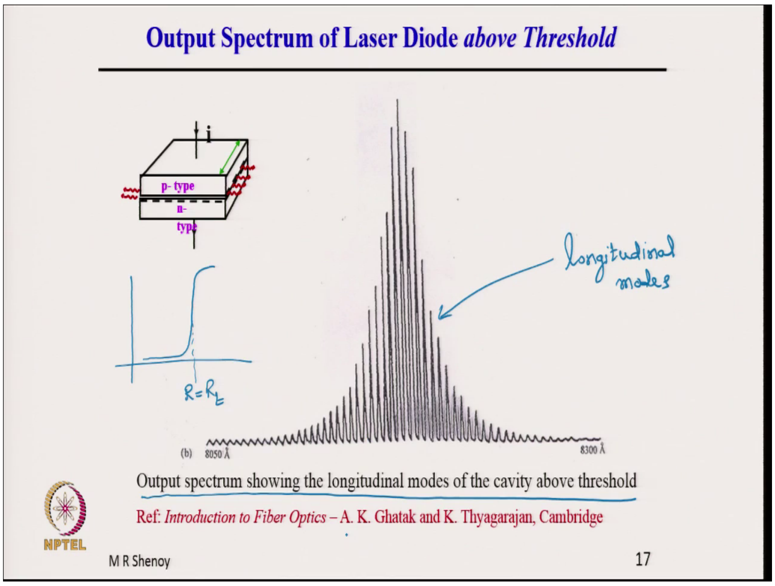
Now, I want to come to the output spectrum. So, what is shown is, so you have the laser diode, a double heterostructure laser diode and a current flows through this. Slowly you increase the current, so the current i. So, i is increased. So there is a current source and current is increased.

As current increases, initially we get output spectrum which is like this. What is shown here is the spontaneous emission spectrum. When the current flows there are electron holes recombining in the junction region giving out light. How does the current flow? Because you forward bias the p n junction. When you forward bias the p n junction the E v and E c, so let me show the energy band diagram here.

When we forward bias so the separation between E v and E c slightly increases. This is E fc and E fv so, E fc and E fv. The dashed lines that I have shown are the quasi Fermi levels E fc and E fv. A small difference occurs and therefore, there are carriers recombining and generating light and what you get is a spontaneous emission spectrum; spontaneous emission spectrum.

As the current increases, you can see the current is continuously increasing, the separation E fc minus E fv increases and when E fc minus E fv becomes, right now the difference is less than E g when E fc minus E fv becomes greater than E g then we will see that it suddenly starts lazing and you see the spectrum. So, this figure I have shown from this. I could have drawn myself by hand, but I thought let me show you a figure. So, please see this for more details.

(Refer Slide Time: 46:50)

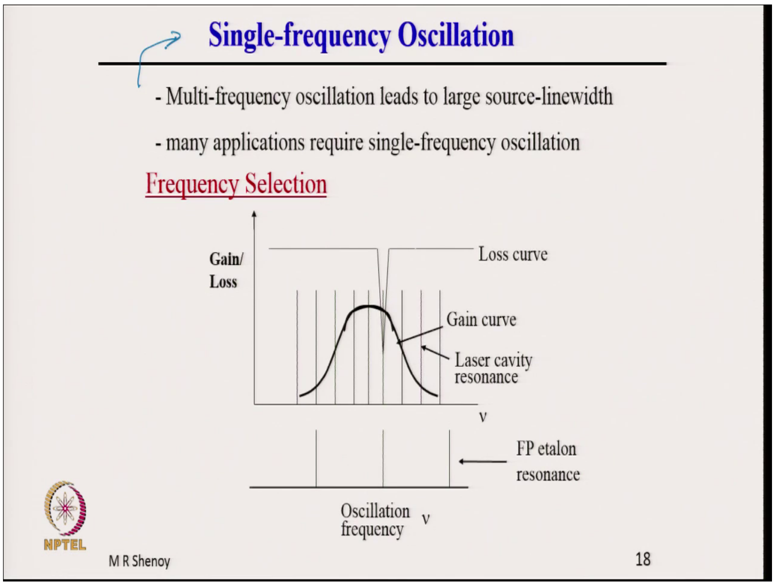


And when the current suddenly increases you see the output changes to this form. The output spectrum now shows longitudinal modes of the cavity. Earlier, what we saw here is a spontaneous emission spectrum. It is like the g nu spectrum, which is the spontaneous emission spectrum. We recall the g nu spectrum, so this is g of nu.

The laser line output intensity i of nu versus nu, if you plot what you get is g nu curve which is nothing but spontaneous emission spectrum. But, when the laser starts lazing, suddenly you see the laser is now lazing and what you have are the longitudinal modes of the laser. You can indeed see these modes. I will show you a diagram a little later. So, what is the difference?

The laser gives a certain output up to the threshold, you recall that the laser output changes around the variation of threshold, we had studied this variation of threshold, so around threshold R is equal to pumping rate is equal to R t. There is a sudden change in the output power. And also qualitatively the nature of the output also changes suddenly when it lases.

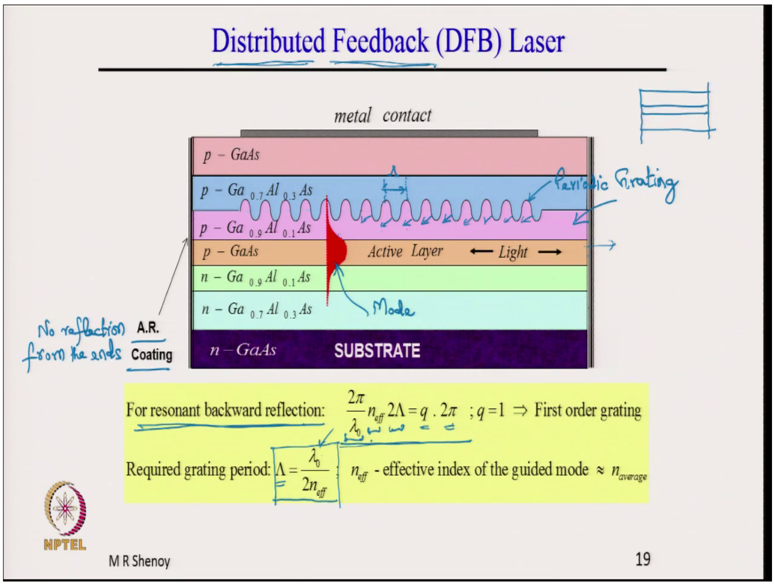
(Refer Slide Time: 48:24)



Now, I will briefly discuss about single frequency oscillation. So this is a diagram which I had discussed earlier. How to select a single longitudinal mode by specifically making the laws for that mode much smaller than the other modes, we can ensure that there is only one more lacing.

Let me not go into the details because we have already discussed this in detail. In the case of a bulk laser in particular, I had taken the example of intra cavity tilted etalons, use of intra cavity etalon to select a single longitudinal mode. A method which is used in semiconductor lasers is using a grating, which selectively provides feedback at one particular wavelength and that is given by the distributed feedback laser.

(Refer Slide Time: 49:19)



So, it is illustrated here. So, that is the laser and this is the laser cavity. It has two ends. This is the light which is generated. It is a mode, the fundamental mode, so the mode of the laser, mode which is propagating back and forth. Now, when the mode propagates, what we have seen is there is a tail, evanescent tail outside.

Unlike, the normal Fabry-Perot Lasers, in the normal Fabry-Perot Laser we had a thin layer sandwiched between two other layers, that is all. There was no grating. But in this case, specifically in the outer layer there is a periodic grating. So this is the periodic grating, so a periodic grating.

The periodic grating gives selective reflection back. It provides back reflection. So, for resonant backward reflection this condition has to be satisfied. That is k naught, k naught is 2 pi by lambda into n effective, which is the effective index of the mode multiplied by 2 lambda here must be equal to q times 2 pi.

Why 2 lambda? Because lambda is the period here, so this is lambda, probably not shown in the diagram. So this is lambda is the period of the grating. So, 2 lambda is round trip phase. So round trip phase must be equal to an integral multiple of 2 pi. Round trip phase is round trip distance multiplied by the effective index of the mode multiplied by the k naught.

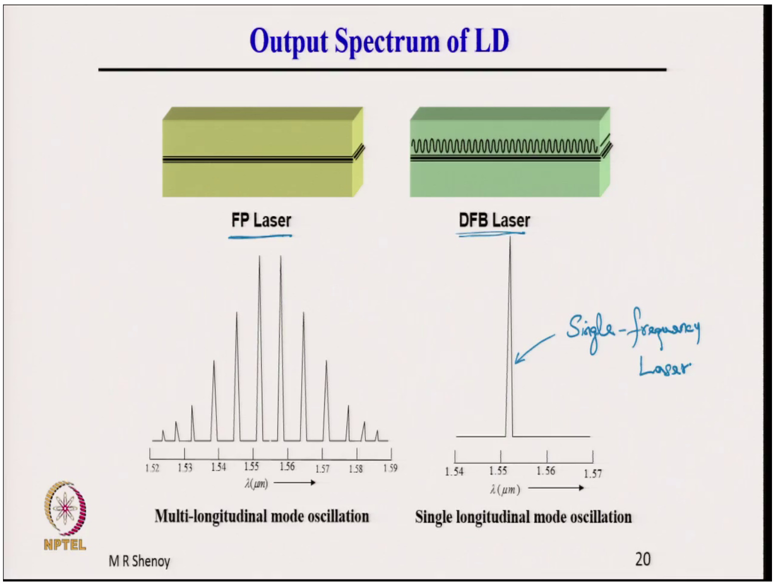
So, k naught into effective index multiplied by one period round trip 2 lambda must be equal to integral multiple of 2 pi. And if we put this condition, there is only 1 wavelength for which this condition is satisfied. The required grating period, if we use the grating period lambda then only one wavelength will have reflection coming back.

All other wavelengths will be lost. All other wavelengths will propagate here and go out, because there is an anti reflection ends are anti reflection coated. Means there is no reflection from the ends, no reflection from the ends. It is a very interesting laser, because the ends are coated with anti reflection coatings.

So, whatever reflection has to come, has to come because of the periodic grating. And the periodic grating will reflect only one wavelength or single frequency which satisfies the Bragg condition. This is called the Bragg condition, because it is a periodic structure. And when we do that then there is only one single longitudinal mode oscillating in the laser. And the feedback is distributed all along the length.

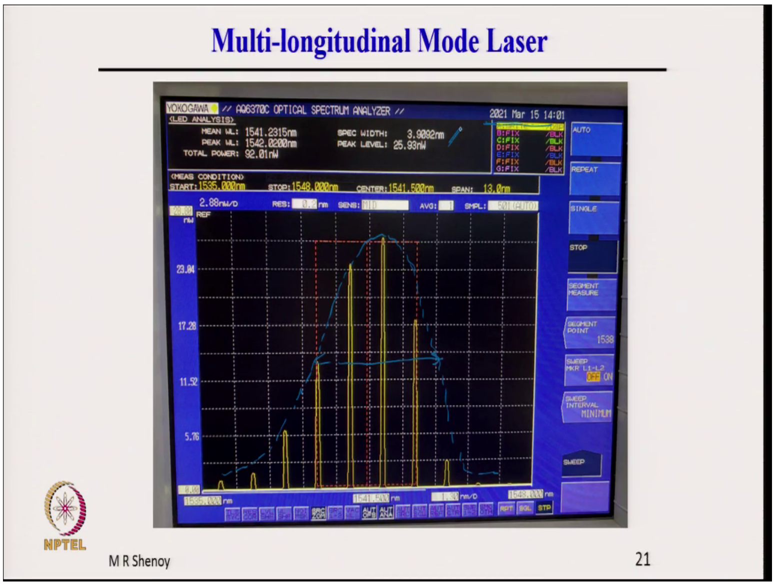
I have shown these arrows to simply say that the reflection comes for that one wavelength from every point not like other lasers where the reflection comes only from the ends. In this case, the feedback comes all along the length of the cavity and therefore, the name distributed feedback laser alright.

(Refer Slide Time: 53:18)



So, let me show the spectrum here. So, here is the spectrum of the laser diode. For a single frequency laser what are shown are the longitudinal mode in a normal Fabry-Perot Laser. The laser oscillates in several longitudinal modes. In the case of a distributed feedback laser the laser oscillates in one longitudinal mode or it is called a single frequency laser so single frequency laser.

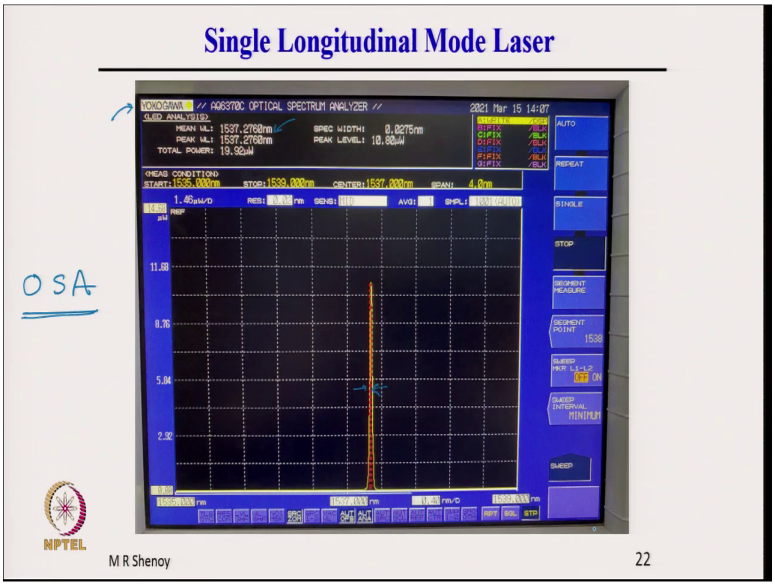
(Refer Slide Time: 53:59)



So, I decided that we should have a diagram of this. So what is shown here is the actual diagram of the output of a Multi-Longitudinal Mode. A semiconductor laser, which oscillates in several longitudinal modes. It may be interesting to see that, it is just today that we have recorded and we can see that the data which is written here, it tells the peak wavelength, the average wavelength, the total power and the overall width. The width is about 3.9 nanometer.

We can see the numbers which are written here. So numbers tell that the total width is about 12 nanometer and the width is calculated by taking the envelope of this and full width at half maximum of this envelope is about 4 nanometer. Maybe half may be somewhere here. So this may be approximately 4 nanometer, 3.9 nanometer which is shown here.

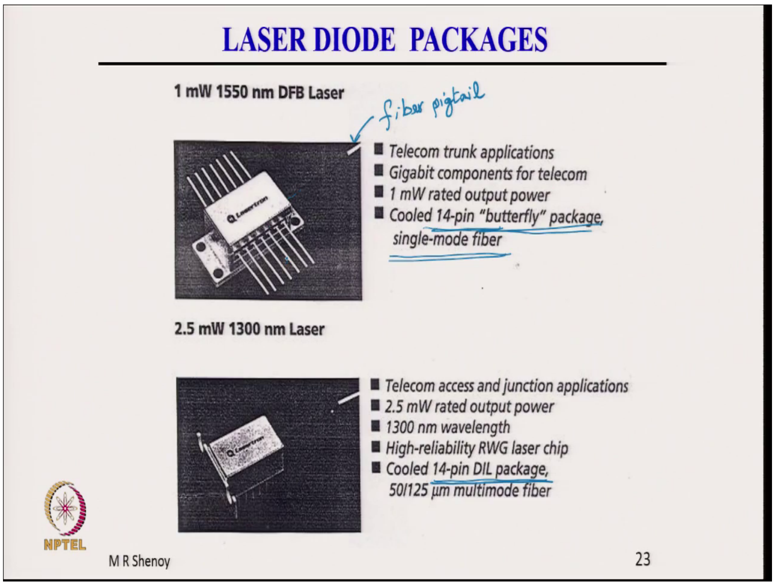
(Refer Slide Time: 55:05)



In the next photograph, we can see the output from a single longitudinal mode laser from a DFB laser. So, this is from a DFB laser and this is from a Fabry-Perot Laser, both are recorded today. So, we can see that the pulse width in this case, the width the separation here is 0.0275 nanometer. That is very very narrow. The line width of the single frequency laser is extremely narrow, and the wavelengths are shown here. So the wavelength is 1537.27 nanometers.

And this is the output from a single frequency laser or a single longitudinal mode. So, this is an optical spectrum analyzer OSA; Optical Spectrum Analyzer, output of an optical spectrum analyzer which is there in our lab. So, this is a Yokogawa make optical spectrum analyzer. All the parameters are there various resolution, width, peak, everything is analyzed and provided in this.

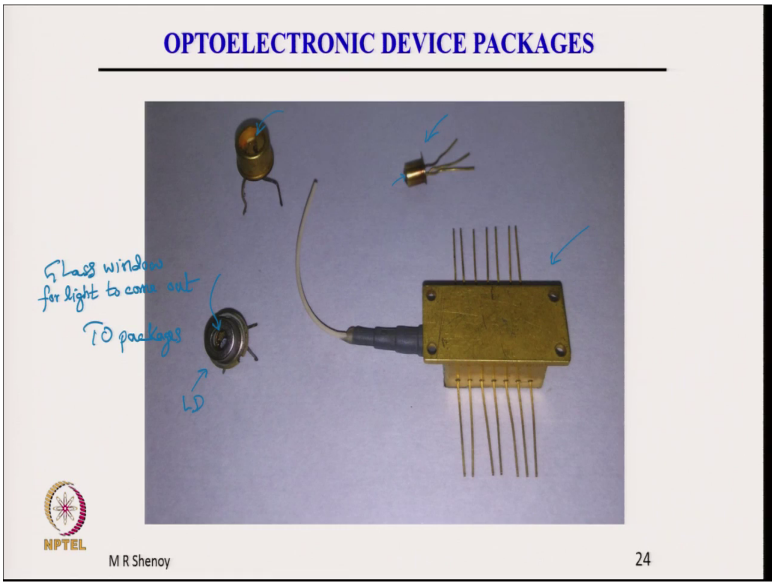
(Refer Slide Time: 56:21)



Now, finally, I want to show laser diode packages. How the packages look like. So, typical packages, this is called a butterfly package. It is a 14 pin butterfly package. This is from one of the companies data sheet. So, laser tron, so cooled 14 pin butterfly package. And the output comes out to a single mode fiber. This I will show in another diagram. So, we can see this is the sleeve and here is the fiber. So this is the fiber output. So, the fiber pigtail, this is called fiber pigtail, lasers with fiber pigtail.

And this is called a 14 pin DIL package Dual In Line package. Just like IC, where the pins are going vertically downwards. Here the pins are coming to the sides, like the wings of a butterfly. There are 14 pins which come out so; obviously, the connector for this is a different type, not like the normal IC sockets. So this has a different kind of connector and the leads come out like wings of a butterfly, hence the name butterfly package. These are widely used in optoelectronics.

(Refer Slide Time: 57:44)



And here is the last slide where we have taken a photograph from our lab different components. So this is a laser diode. So, this is an LD TO package. This is the actual butterfly package. So this is the butterfly laser diode you can see the 14 pins, 7 and 7 here. There are various reasons why such a package is used.

And these are just like in the normal transistors electronic transistors, but these are optoelectronic components. The difference that you see is in all optoelectronic component. At the top there will be a glass opening, a window for light to come out or light to be incident in the case of a photo detector.

So, here also you can see opening. Everywhere there is a opening, otherwise it would look just like an electronic component. These are the TO packages so, TO packages just like the electronic transistors. But, there is always a glass window for light, which differentiates between electronic and optoelectronic component. Glass window for light to come out in the case of a source or to be incident in the case of a photo detector.

So there, I will stop this talk. It is a very detailed there are detailed courses available. There is also an NPTEL Mooc on this area, which is called semiconductor optoelectronics, which discusses in detail the complete physics and the design, fabrication, structures and their characteristics. So with this we will stop the laser systems and in the next week we will take a couple of applications.

Thank you.