Semiconductor Optoelectronics
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Lecture - 35
Semiconductor Laser -II
Output Characteristics

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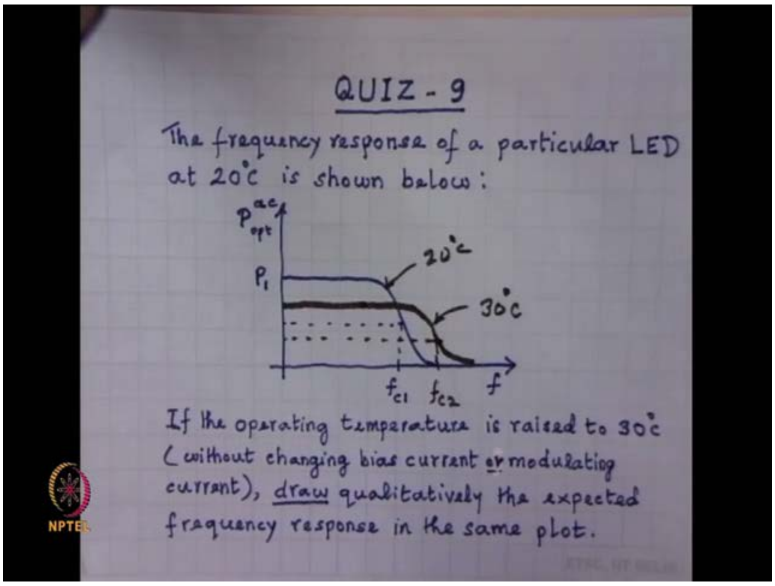

We continue with the semiconductor lasers and output characteristics. Before I start the output characteristics, let me just discuss the answer for the quiz. So, this was the quiz question. The frequency response of particular LED at 20 degree is shown below, if the operating temperature is raised to 30 degree without changing bias current or modulating current or without any change. Draw qualitatively the expected frequency response of the, on the in the same plot.

So, what you see is when temperature goes up from 20 to 30, two things happen; one is eta i drops down, the internal quantum efficiency drops down, which means the optical power generated drops down. So, naturally it will start now at a at a lower power, and the second thing that happens is when temperature goes up tau decreases and the bandwidth is inversely proportional to tau. Therefore, decreasing tau the carrier recombination time leads to an increase in bandwidth. So these are the two changes that you have to show, so let me show it right here.

So, the expected curve now becomes like this and half of that, the half power this is important to show that the cutoff now goes here. So, this is f c 2. So, earlier this was for 20 degree 20 degree centigrade and this is for 30 degree. This is the expected answer that it will decrease here and it will increase here. This is because eta i decreases this is because tau decreases. So, both points need to be shown. So, half mark for this point, half mark for this point. Most of you have got half mark. Alright so let us continue with the output characteristic. Before I take up the PPT there is an important point about we were discussing about, the threshold threshold that is the output parameter, output a characteristic were i verses that is a we have plotted here current in this axis verses the optical power here.

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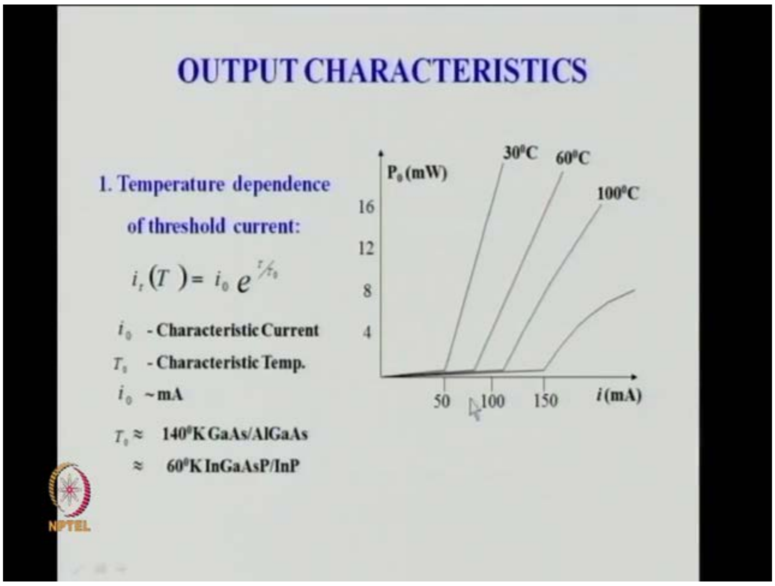

What we have got we started like this just recall recap we had, an expression for peak green co-efficient.

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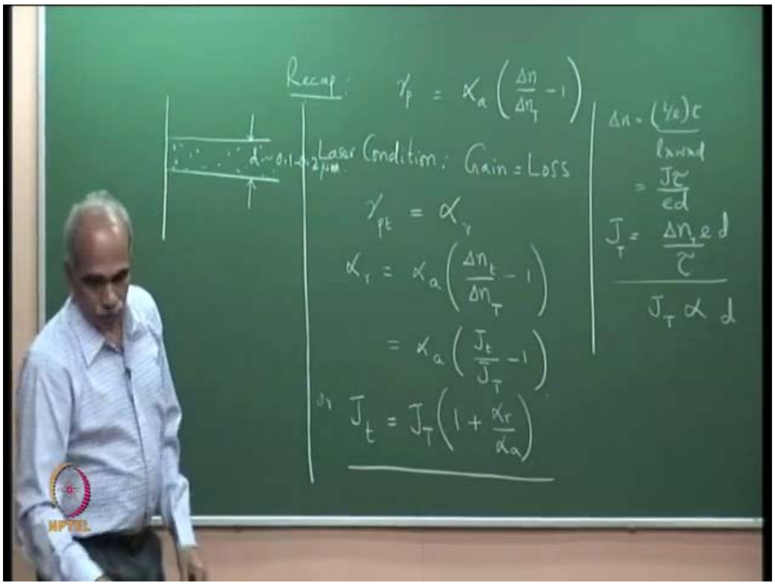

Gamma p is equal to alpha a into delta n by delta n T minus 1. All the parameters we know so delta n very quickly, delta n is equal to i by e into tau divided by l into w into d or this is nothing but i by l w is J so it is J tau by J tau divided by e into d or we have J is equal to delta n into e into d divided by tau. So, J transparency if I want to write J transparency that will be equal to delta n t into e into d So, what you see is J transparency J T is proportional to J T is proportional to d. Now, what we did is then we came to the laser equation. So, laser condition is laser threshold condition is, gain equal to loss. Gain equal to loss, that means gamma p at threshold gamma p t is equal to loss in the resonated alpha r.

Gamma p t is given by this. So, alpha r is equal to alpha a into I am substituting this delta n t divided by delta n capital T. we have discussed in detail this is threshold, this is transparency minus 1 or delta n t by delta n is J T by, so this is equal to alpha a divided by J threshold divided by J transparency minus one or J threshold is equal to alpha a goes to the denominator. So, we have J T into 1 plus alpha r divided by alpha a. This is the expression that we get by equating this gain co-efficient equal to loss co-efficient. However, there is an important point which we miss here or something that is unique to semiconductor lasers, but not in the case of bulk lasers. Gain equal to loss. In the case of semiconductor lasers, we have an optical wave like there.

The active medium I am showing only portion of the portion of the semiconductor laser so this goes down to cladding layers and then sub straight and so on. I have just zoomed this active layer, this is direct to d which for a double hit row structure is about 0.1 to 0.2 micrometer for a double heat row structure. I want to answer why this was 0.1 to 0.2. Why did not he said, in a homo junction it was 1 to 2 micron and they reduce they could reduce it down by going to point 1 to point 2, why did not they further down with the threshold would have reduce further. So, why we have stop here so I want to answer this question that why 0.1 0.2 micrometer. So, we do not have, we have not taken care of an important point which is applicable to semi conductor lasers and that is called the confinement factor. So, I want to discuss about the confinement factor before I proceed any further.

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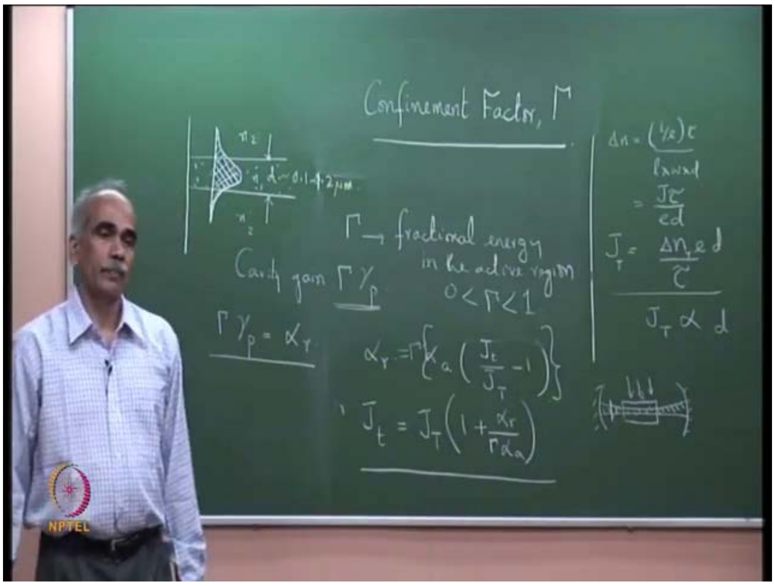

So, confinement factor gamma confinement factor gamma it so know, is that laser diode the active region forms an optical wave guide and therefore, there is a optical mode which is going back and forth. So, this is the optical mode, the model fee distribution, which is going back and forth. This is the dielectric wave guide of a lower refractive index here n 2 n 2 and this is n 1. As you see gain the available gain is in the active medium there is no gain outside therefore, the mode is going back and forth in the laser have shown a just an expanded portion the mode is going back and forth as it goes back and forth in the laser resonator, the entire modes suffers lots the alpha r resonator lose loss co-efficient is for the entire mode.

Entire mode means the entire field distribution, but the gain is coming only from the active region and therefore, the cavity gain is fractional portion. A fraction of the mode is experiencing the gain. So, if gamma is the fractional energy fractional energy in the active region in the active region then the cavity gain cavity gain is gamma times gamma. Gamma is less than 1, 0 less than gamma less than 1. Gamma is the fraction please see, let me shade it the other wave so you can see this is the portion which is inside the active region therefore, the total power in the mode which is going from minus infinity to plus infinity. Here and this is the energy or the power which is in the core and the ratio of this to the total is gamma that is what I have written as fractional energy of the mode the mode energy is distributed everywhere here and the fraction is this and this gamma is called the confinement factor.

Why this called confinement factor, we will come to that in a minute therefore, the cavity gain is gamma times p. So, we should equate this to alpha r in other words our equation should have been gamma times gamma p is equal to alpha r. Normally in a bulk laser, like the Nd:YAG laser I showed you the Nd:YAG laser here, this is the mirror and or any other laser helium, neon laser or whatever. The laser beam is well within the active region. The well, it is well within the active region. So, what I am showing is the Gowsigan mode and this is the pumped active region. The entire region, there is gain in the entire region and therefore, the entire beam which is going back and forth here, is seeing the gain medium, but here only the fraction which is inside the core is gain. There is no gain here outside.

It is the cladding layer high band gap material and therefore, we should equate this. This is the cavity gain. Cavity gain is equal to loss. So, you substitute this here cavity gain is equal to alpha r, which means have to substitute this. Gamma times this equal to alpha r. So, what you will get is J t, I will write in the same expression J t is the factor gamma which will come here. You can write again so gamma times gamma p. This is gamma p, please see this is gamma p so gamma times gamma p has to be equated to alpha r, which gives you J threshold is equal to j T into a factor gamma remember that gamma is less than 1 so what there is quite a bit. We will see, so what.

So, this is the correct expression. We should take the confinement factor. So, that current expression contains j t is equal to this gamma. Here by gamma is the confinement factor. I am use see something that if I have, this is the optical wave guide. The fractional energy which is inside or the confinement of a mode to the wave guide is determined by the V number.

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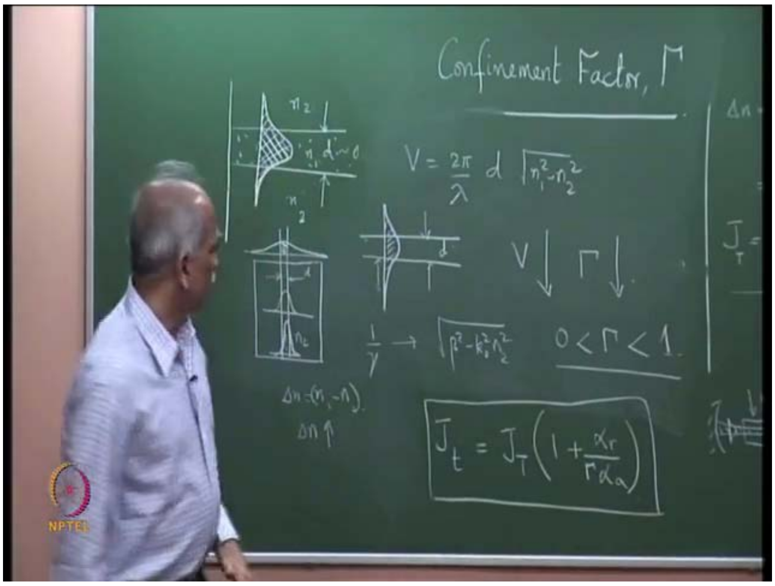

So, the V number is 2 pi by lambda into d into square root of n 1 square minus n 2 square. It is not a direct relation, the confinement gamma is a not, I cannot write analytically a direct expression for the dependence of gamma and V. But note this explanation V is this, if d is larger V is larger. So, in this if d is smaller. For example, let me show, a smaller d. same n 1 n 2, no change in n 1 n 2. n 1 n 2 is fixed.

Wave length of operation is same and therefore, if I reduce d, in this case what will happens is, the mode will spread further, the mode will spread further. Actually those of you have done a course on optical wave guide will see that, this length where this is this penetration depth is depending on 1 over gamma and gamma here is a square root of beta square minus k 0 square into 2 square. Where beta is the propagation constant those you have not done a course do not worry, but those you are done a course they know that the penetration depth is 1 over gamma and this is gamma is beta square, where beta is the propagation constant. If you reduce the thickness, beta decreases and therefore, this difference decreases. Therefore, gamma decreases therefore, 1 by gamma increases.

In other words the penetration depth increases, if beta decreases. That is if the thickness d decreases. So, those of you are not done a course do not worry about it, but keep this qualitative picture in mind that V can be reduced or increased by changing d and the refractive index difference. So, if you keep the refractive index difference fixed then V is proportional to d, if you change d then V changes. If V V decreases gamma decreases. The fractional energy decreases, the relation is not directly an analytical expression. It has to be numerically obtained, but V decreases gamma decreases so if the wave guide become smaller and smaller. Why am I bringing this concept. Now, this is our d therefore, assuming that n 1 n 2 are the same for the same material d decreases V decreases.

V is the normalized frequency V decreases V decreases gamma decreases. What is its simplification keep this picture in mind and if d increases alternatively one can also have let me show, the wave guide like this. Now, if I have a wave guide here of a fixed d so this is d fixed d this is n 1 and this is n 2 then let me say that the mode is like this. If n 1 minus n 2 that is n 1 minus n 2, if the difference n 1 minus n 2 or delta n delta n so if delta n goes up d is fixed, but delta n goes up then also we will go up if V goes up this will get more tightly confined. So, if I want to draw it here, this will get tightly confined like this, it will get tightly confined, if delta n goes up.

So, the fractional energy inside the core increases, which means gamma approaches 1 gamma is between 0 less than or equal to less than gamma less than 1. If if delta n decreases then let me draw here this time, If delta n decreases the same mode will spread like this weakly confined. This is for smaller delta n very weakly confined. Now, you see the fractional energy which is inside the core which is inside the guiding field is very small. So, gamma approaches 0 gamma approaches one. So, confinement factor is determined by d for a given material system or if you want d fixed then delta n can be or if you want to d very small like we will go further down to quantum well structures. d has to be reduced further and when you want d very small, if you want gamma to be reasonably good n 1 minus n 2 should be large.

So, several a design flexibility or design criteria which are involved here. Now, let me plot this gamma. How would this gamma look like with d? So, first thing is here. This is this is the expression J n T is here. Let me erase the rest of them. I want to plot and see the importance of this confinement factor in the, in determining the threshold current.

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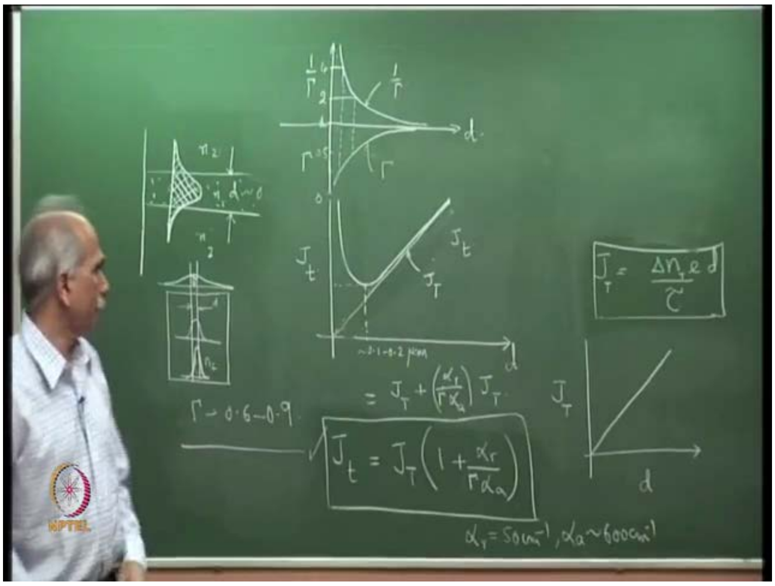

What I am now, plotting is d verses gamma. So, gamma minimum value is 0 maximum value is 1. So, for very small values of d like this, the mode is spreading gamma is closer to 0 so gamma starts from somewhere here. At 0 confinement will be 0 and it is approaching 1 as d increases gamma approaches 1. So, what I have plotted is gamma 0 to 1. How would 1 by gamma vary, when this is small this is large?

So, this is going up. So, this here I am plotting 1 by gamma. 1 guy by 1 by gamma minimum value is 1 because when gamma reach maximum value of gamma is 1. Therefore, 1 by gamma minimum value is 1 and as this goes down to this is 1 by gamma. What kind of numbers? For example, if this was the scales are different to the two sides. If this was 0.5 then we will have 1 by gamma as 2, this is 2. If this was 0.25 then here it is 4 and so on. The scales are different to this side, so please let me mark it like this. This is 1 by gamma, this curve is 1 by gamma, this curve is gamma, so variation of gamma variation of 1. Why am I interested in 1 by gamma?

1 by gamma is here. If I plot J T so J T verses d what kind of graph will I expect J T that is transparency current, verses d. I should get a straight line, right. Let d is equal to 0 J T is 0 and as d increases J T increases J T verses and what is J threshold? J threshold is J T plus So, let me write this is equal to J T plus, this part which is alpha r and alpha a are constant nothing, to do with the the material dimension there, so alpha r alpha a divided by gamma into J T. So, 1 by gamma is here. Please see this this is 1 by gamma. So, if I

want to plot J T how would it look if I want to plot J threshold this is small t J threshold as a function of d at large values of d at large values of d 1 by gamma is 1.

So, this factor is not there. This factor is are there, just a constant alpha r by alpha a. Alpha a is the material absorption co-efficient alpha r is the resonator loss co-efficient. So, this is just a constant into J t, but if d increases J t increases therefore, at a large values I should have a graph. Okay. Let me so what I have plotted here is. J t J small threshold at large values actual J t is here. They should be merging closer and closer. Just a minute. So, what I have plotted here is J T J capital T, the same curve. I have put here, I want to plot the other curve namely J T as d decreases as d decreases here gamma decreases. Therefore, 1 by gamma increases, please see this 1 by gamma increases, which means this term is becoming larger and larger initially this term was fixed very small.

Now, this term is becoming larger and larger. Why this is very small because we have some numbers you recall, alpha r was about 50 or 60 centimeter inverse here and alpha a was about 600 centimeter inverse. You remember that we have put this as point 1 alpha r by alpha a that so we have written 1.1. The transparency threshold current was 1.1 time transparency. So, this factor was 1.1 without the gamma, but now, there is a gamma coming in a denominator therefore, when gamma becoming smaller and smaller 1 by gamma becomes larger. So, the second term start dominating and what happens is this comes downs here and then it shoots up why this is shooting up because this is shooting up. 1 by gamma is here, 1 by gamma.

So, the second term is getting multiplied by gamma. 1 by gamma is shouting up therefore, this is shouting up. This minimum value is where you have lowest threshold current and this minimum value is approximately 0.1 to 0.2 micrometer. I am writing 0.1 to 0.2 because it will also depend on the difference n 1 and n 2. For a given n 1 and n 2 it could be 1.1 0.15 0.2. That is why double heat row structure have a layer of 0.1 or 0.2 micron thick sandwiched between higher band gap materials. So, what we have answer is that question why d is equal to 0.1? Why d is stop there? why did not you reduce it further down? So, normally this is the minimum. The threshold current is there. So, this is the correct expression. Most of the semiconductor lasers have gamma between 0.6 to 0.9 for most practical semiconductor lasers gamma is between 0.60 to 0.9.

This is, if that factor gamma was not there, it should have been going like this down. So, the gamma was the one which dropped it there. Let me continue with the with the PPT characteristics there. So, this is the concept which was an important concept. We have a, when I wrote the dimension of a semiconductor laser, we have detune the length around 300 micron. We should also ask a question why 300 why not 100 why not 500? We will answer that. We will answer it a little later, let me go further now. So, when numbers are given they are not arbitrarily chosen. There is a reason for every number. Only we have to know what is the reason? So, output characteristics this is the graph, which we have discussed already and this is the first one temperature dependents of the current.

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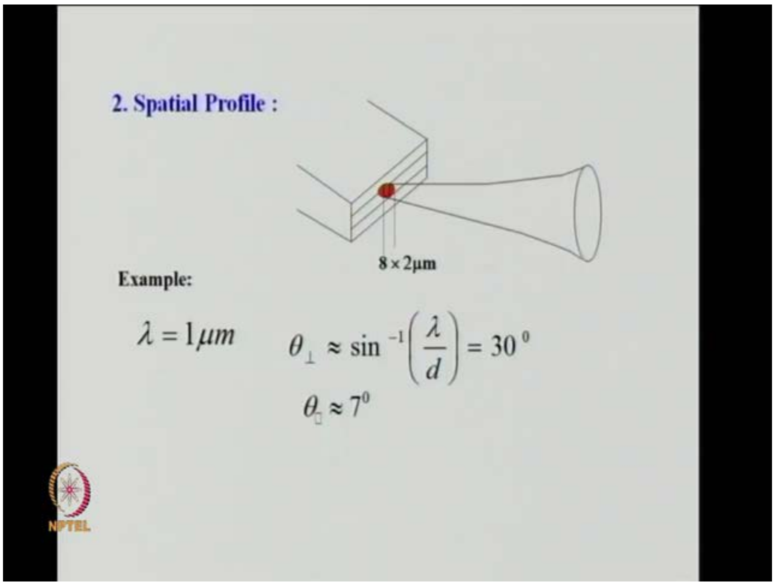

The second one is a spatial profile of the beam which is coming out, the beam that is coming out, spatial profile of the beam, right. So, the spatial profile of the beam is here. So, what I shown is the emission area here. Typical dimension is about 8 into 8 cross 2 micro meter. The spot size, this is not the physical size please remember that the double heat row structure is a just, if you see the front view we had a layer which was 0.2 micro meter here.

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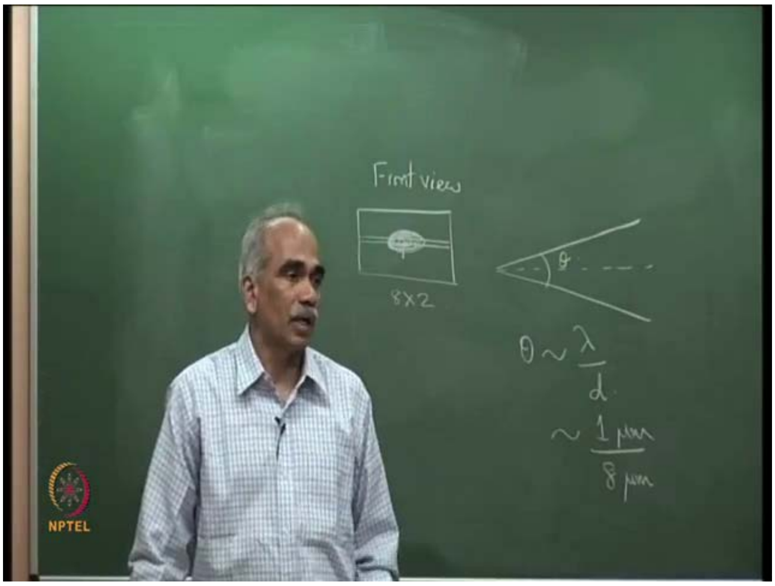

So, this was 0.2, but the spot the laser spot which is generated because the field is spreading into the cladding also that is an vane sine tail so the spot size is generally about 8 by 2 so 8 cross 2. It is the front view front view. So, it is a elliptic kind of a beam and therefore, what do you expect when it is comes out. A beam an optical beam which is compressed in this direction or narrower in this direction should be spreading more, when it is come in this direction and should be spreading less in the vertical direction and that is what you see and what I shown here is the ellipse here and the ellipse here they are complementary.

That is they are perpendicular to each other. The ellipse which is at the emission region and the ellipse in the far field so this is the beam which is coming out the beam is coming out far field means refraction has taken place and therefore, the beam cross section if you see, it is elliptical like this and this, in this direction it is theta perpendicular that is the angle of divergence. So, if I show in 1 d the beam is coming like this out and what I shown is theta is angle divergence theta. The angle of divergence, if is approximately theta is approximately given by lambda by d and lambda if you take 1 micron divided by d. So, in this direction it is 8 micron. So, 8 micron so that is theta in radiance. So, which is approximately 7 degree here.

So, this is for theta parallel, there is a compatibility problem. This is theta parallel parallel means parallel to the interface or parallel to the layers in this direction. Theta parallel and theta perpendicular is here. This is theta perpendicular, that is lambda by d. d has been taken as 2 micron in that direction so it is 1 by 2 sine inverse of is 30 degree so that is what it show. This is the spatial profile of a beam of a laser output beam. Usually in applications use see collimator laser beam coming out, that is because there are collimating lenses after the beam which comes out. One uses collimating lenses so that you have a parallel beam of light.

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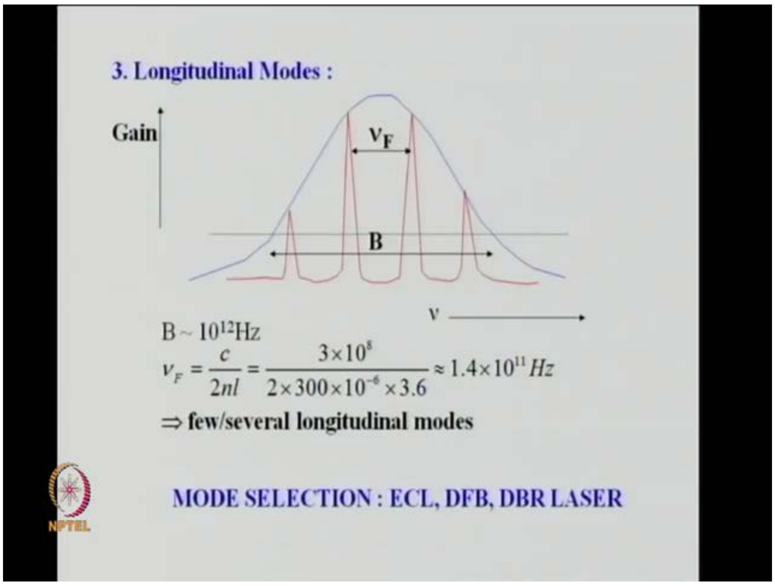

Third property is the longitudinal modes. We have had some discussion here. So, what is shown is the blue line here, what we have an shown is the gain profile the gain profile here and this is the frequency axis. So, you may recall that and this this line here, horizontal line is the loss line. So, recall what we had discuss that for all those frequencies, where so this is the loss line and then for all those frequencies for which gain gain of the amplifier.

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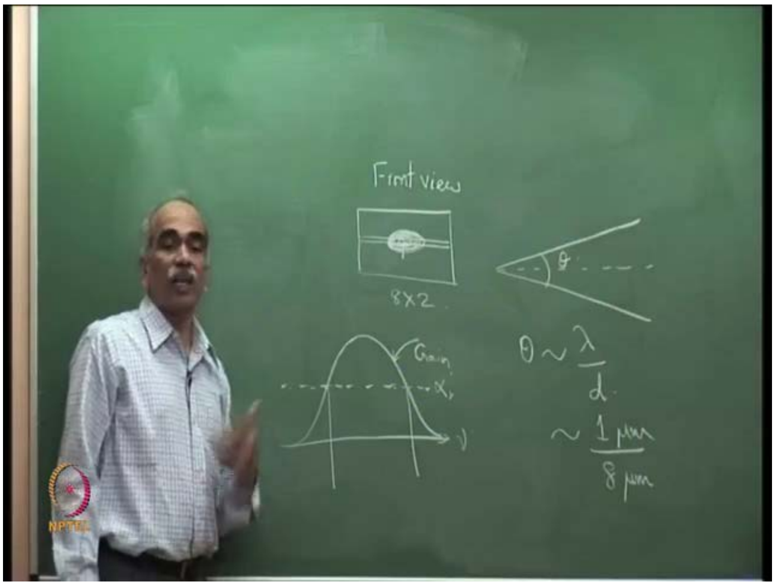

So, if gain is more than loss so this is alpha r the loss line. For these frequencies we can have oscillations and the resonance frequencies which will oscillate is determined by the laser. So, that is a, we will discuss a little bit more. There are couple of more slides which is discuss this and I had also mention that why we are discussing this is because in many applications we need only one longitudinal mode, so how to choose longitudinal mode, single longitudinal mode. There are different techniques to choose. So, what is indicated here is mode selection laser structures used for selecting a single longitudinal mode, ECL stands for external cavity laser. We have this in the next slide as suppose external cavity laser, DFB standing for distributed feedback laser, DBR standing for distributed brag reflected laser. So, we will see each one of this in detail.

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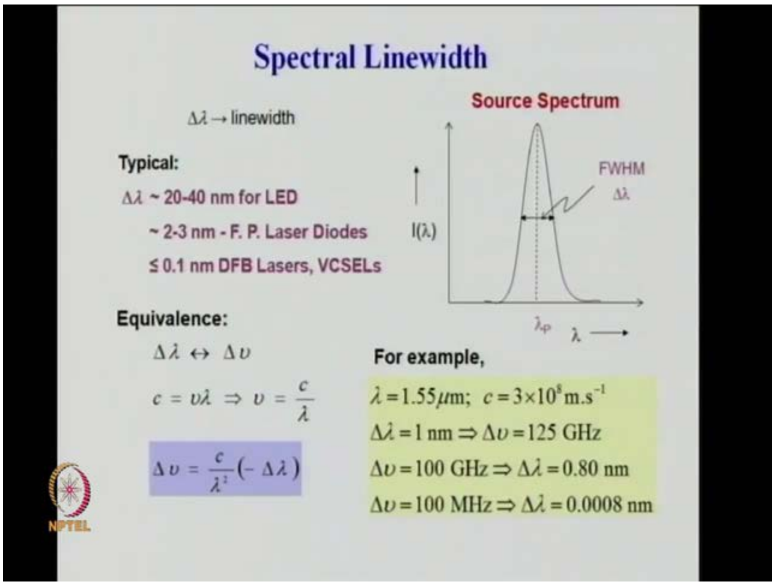

So, let me discuss something about the spectral line width some aspects we have discuss already, but let me recall what we have discussed and what is its impotency particularly from the point of you have communication for those students of optical communication. What is the importance of this spectral line width. So, spectral line width is shown here, what is showing is the spectrum I of lambda verses lambda p verses lambda. Lamda p corresponds to the peak and this is delta lambda. We have discuss this in the grade detail for LED and we have seen the delta lambda was of the order of 20 30 40 nanometers. So, that is what I shown here.

Delta lambda is tens of nanometer for LED, but typical Fabry-Perot laser diodes. First time we are using the Fabry Perot laser. What is the Fabry-Perot laser? Fabry-Perot laser is this normal laser diode that will use. Many of you may be knowing the cavity, which has two high reflecting mirrors. The cavity formed by two high reflecting mirrors is called a Fabry-Perot cavity.

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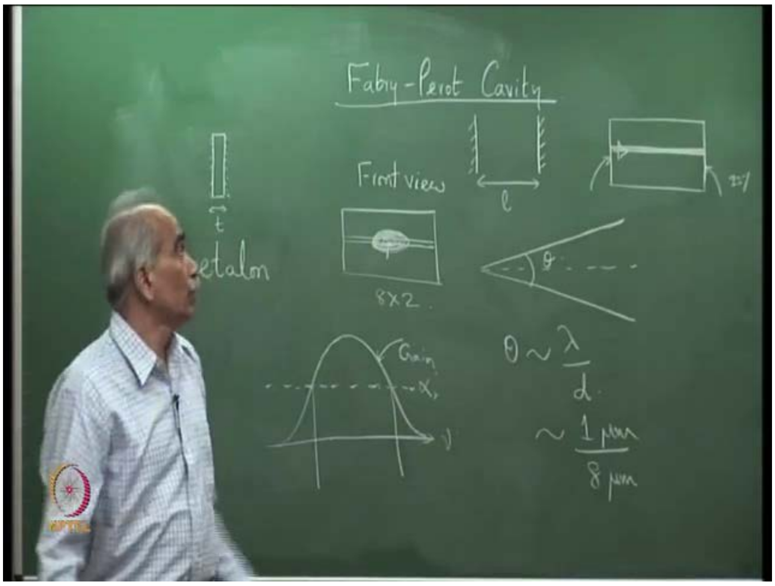

So, Fabry-Perot and there are Fabry-Perot interferometers, which are widely used in optics with large number of applications. A cavity formed by two mirrors separated by a distance d, the distance. The intermediate region may have medium also and Fabry-Perot cavity which has a fixed distance, like this for example, on a glass plate. Parallel glass plate. You deposit a highly reflecting coatings here this is fixed fixed t. A thickness a glass plate of thickness t with high reflecting mirror coated. This is the fixed separation Fabry-Perot cavity this is called an etalon. A Fabry-Perot etalon. Has many many applications, including we will see one uses a etalons in for single frequency selection.

So, this act like a cavity with a fixed spacing. Here normally one can vary the cavity. So, a semiconductor lasers, the normal semiconductor laser with cleaved ends here which has a reflectivity of 32 percent, where the mode goes back and forth. The mode is going back and forth, this forms a cavity and the normal semiconductor laser is sometimes called a Fabry-Perot laser. The laser diodes the semiconductor lasers are Fabry-Perot lasers. Some of the earlier books you will see the, theory of Fabry-Perot laser. Theory of Fabry-Perot laser means theory of the normal semiconductor lasers. I used here Fabry-Perot lasers diodes. Just say that normal semiconductor lasers diodes have delta lambda of about 2 to 3 nanometer and there are other semiconductor lasers, special semiconductor lasers like the DFB laser distributed feedback lasers which are used for all optical fiber communication, the source in a optical fiber communication is the DFB laser, VCSELs vertical cavity surface emitting lasers. We will discuss this in little bit more detail. So, these have extremely a narrow line width. Usually the Fabry-Perot, normal Fabry-Perot lasers oscillate in several longitudinal modes. We will see some numbers. They operate in several longitudinal modes. Whereas these ones can oscillates only in one single longitudinal mode. So, that the diagram that I have here. For example, in the previous slide I think there was a calculation. Yes, see this in, this slide you can see there are 1 2 3 4 oscillating modes within the bandwidth here.

The typical bandwidth is 10 to the power of 12 to the 10 to the power of 13 hertz for semiconductor lasers. The new F, which is the free spectral rang free spectral rang is the frequency range between two adjacent longitudinal modes, the frequency separation between two longitudinal modes. I think we have a slide later which explains it more. So, you can calculate some numbers are here, c 2 into l is 300 micron refractive index is n 3.6. So, new F frequency separation comes out to be 1.4 into 10 to the power of 11 hertz. A typical example and therefore, B by new F 10 power 12 by this number, will give you about 6 or 7 modes. So, normally a semiconductor laser operates in several modes of the order of 10 modes normal Fabry-Perot lasers, but if you cut down that into single mode.

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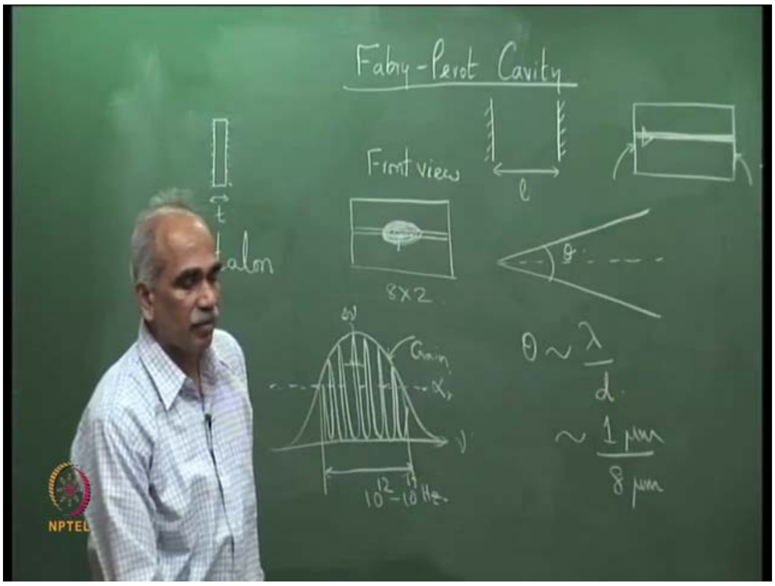

So, assume that here we have large numbers of modes oscillating like this. So, this bandwidth here is the 10 to the power of 12 to 10 to the power of 13 hertz. What about if I make that laser will oscillate in a single longitudinal mode, the width will be like this. The output, this a multi longitudinal modes and a single longitudinal mode can be absorbed on an optical spectrum analyzer. So, in one of the future classes, I will show you, I will demonstrate and show you that these are not just theoretical concept. You can actually see on an a optical spectrum analyzer. The multi longitudinal modes of a Fabry-Perot laser and when you use a single frequency laser, you will just see one line. The spectrum analyzer is not able to resolve, it clearly show you just one line and the point is the frequency separation here, this delta new corresponding to this.

One width here, one longitudinal mode is much smaller compare to this. So, the single frequency lasers have very narrow line width and consequently as given in this slide, the line width delta lambda is less than of the order of point 1 nanometer. Many times much less. Some calculations are made here, elementary calculations delta lambda relation between delta lambda and delta nu so delta lambda is given by this formula here and if you take some numbers for example, in the 1.55 micrometer window here, of optical fiber communication. If you substitute delta lambda equal to 1 nanometer that gives you 125 giga hertz. In this expression if you substitute or alternatively use a delta nu is a 100 giga hertz. Why have I put 100 giga hertz because 100 giga hertz separation is the itivity grid for WDM DWDM systems; those of you may not be aware.

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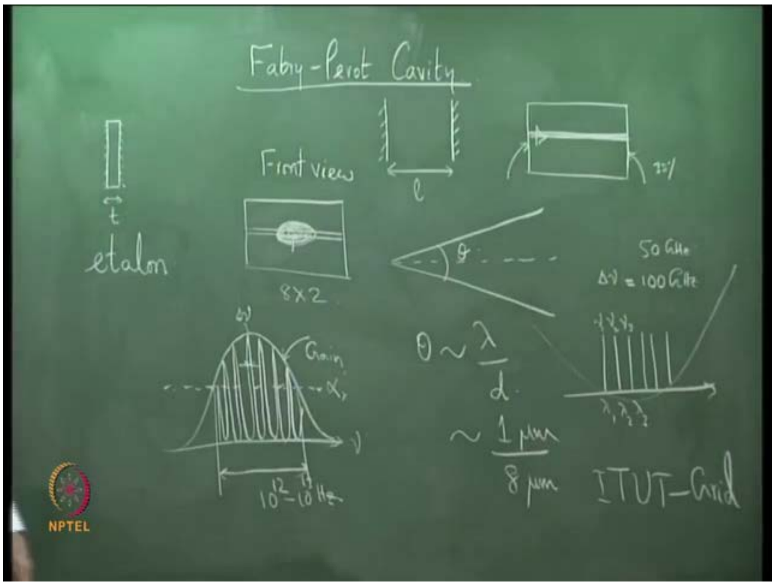

Many of you that in a DWDM system, where you put large numbers of wavelengths have frequencies nu 1 nu 2 nu 3 or lambda 1 lambda 2 lambda 3, the whole thing is the 15 50 nanometer window of optical fiber, low loss window of optical fiber around 15 50.

You can pack large number of wavelengths, closely separated wavelengths into a single mode fiber, which makes the DWDM system. The frequency separation here, delta nu is of the order of, is equal to is not a order 100 giga hertz because it is the standard or you can go to the 50 giga hertz. It also permitted this is called ITUT grade, international telecom union ITUT grid wavelengths or grid frequencies.

Sir, standards international standards and the separation is 100 giga hertz. If you take 100 giga hertz, as the separation it is tells you delta lambda is 0.8 nanometer which means the separation between two wavelengths. Please remember each wavelength is a channel. So, two wavelength separation here is 0.8 nanometer. What will happen if you use a normal laser diode? A normal laser diode has 2 to 3 nanometer has the width. So, if you have 2 laser diode, they will simply overlap. So, you had to have delta lambda. Let me expand that, it is just interesting from the optical communication point of view.

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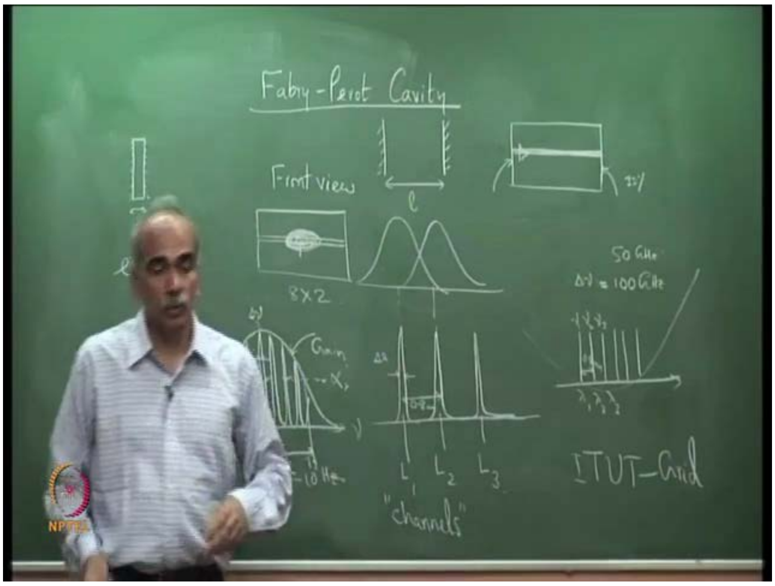

So, each channel here. So, this is the line width of the laser this is the line width of the laser. Delta lambda. This is the channel separation, so there are lasers l 1 l 2 l 3 are laser diodes, which corresponds to different channels, channels communication channel means a frequency over which you send signals. So, these are wavelengths which are separated by 0.8 nanometer. Therefore, the individual lasers line width delta lambda should be much smaller than this, otherwise they will simply overlap. Otherwise it will be like this. So, you have a channel here, a channel here this has a line width of 3 nanometer this has a line width of 2 nanometer. So, they will overlap. They should not be overlapping because you want to isolate the channels at the detection you have to isolate these channels.

So, they should not be overlapping. So, these should be very small and distributed feedback lasers have much smaller line widths and therefore, there is no overlapping or no inter symbol interference. Alright, here is some of the DFB lasers have the 100 mega hertz. As the as the line width and you see what it is corresponds to delta lambda is 0.0008 nanometer. There is no question of overlapping this is 0.8 and this is 0.0008 vary narrowly.

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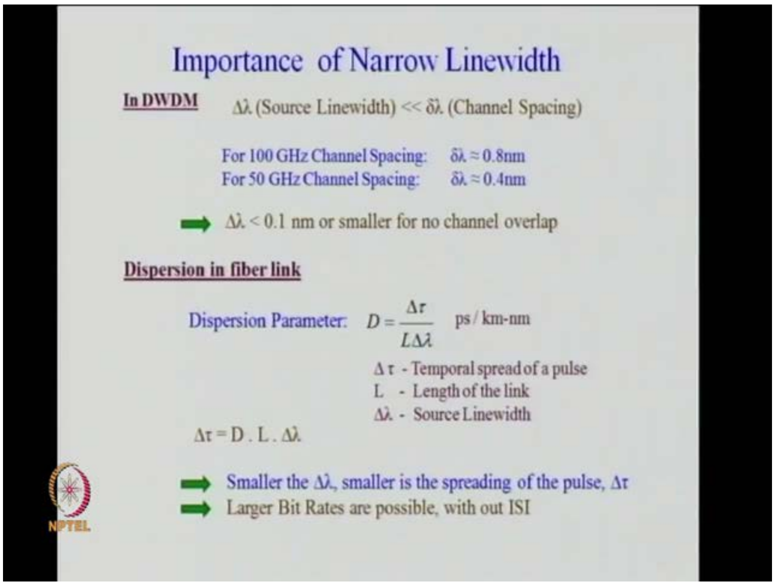

So, can be familiar with the numbers, so there is a slide particularly this is importance of narrow line width in optical communication. There are importance of narrow line width in varies applications. A smaller narrow line width gives you a higher coherence and highly coherent sources are required for the varies applications, but the but the importance which is discussed here is with respect to optical communication. So, the same point which I have been discussing is here, delta lambda source line width should be much less than the channel spacing for 100 giga hertz channel spacing is 0.8 nanometer if you take 50 giga hertz it is 0.4 nanometer implies delta lambda should be less than 0.1or smaller for no channel overlap.

I have already discussed, everything is on the board. Dispersion in fiber links. Those you have studied a course on fiber optics you know that there is the dispersion parameter called D. Those you have not studied does not a matter this is just a to correlate the interest of a fiber optics people. D is here is given an expression like this. The dispersion parameter. The units are picoseconds per kilometer nanometer. Delta tau here refers to temporal spread of a pulse, l is the length of the link and delta lambda is the source line width in this expression and therefore, the delta tau which is the pulse spreading, the spreading in time is equal to d into l into delta lambda. Any given fiber is characterized by the parameter D.

Typically if you take a G 651 fiber then that is a about 17 to 18 picoseconds per kilometer nanometer is the dispersion. So, you can calculate that multiplied by the length of the link. 1 kilometer link 10 kilometer link. Larger the link larger is the pulse spread, multiplied by the source line width. Larger the source line width therefore, larger is the spread. Smaller the source line width smaller is the spread as simple as that and therefore, if you take a very narrow laser, very narrow line width laser delta tau spreading will be extremely small so smaller delta lambda smaller is the spreading of the plus and therefore, the larger bit rates are possible without ISI inter symbol interference, inter symbol interference that is when the bits starts overlapping.

Alright so this is the importance in the optical fiber communication and the small line width has many other application, where you need a large coherence length, highly coherent sources, because the coherent time is inversely proportional to delta nu namely the line width. And therefore, smaller the line width larger is the coherence time.

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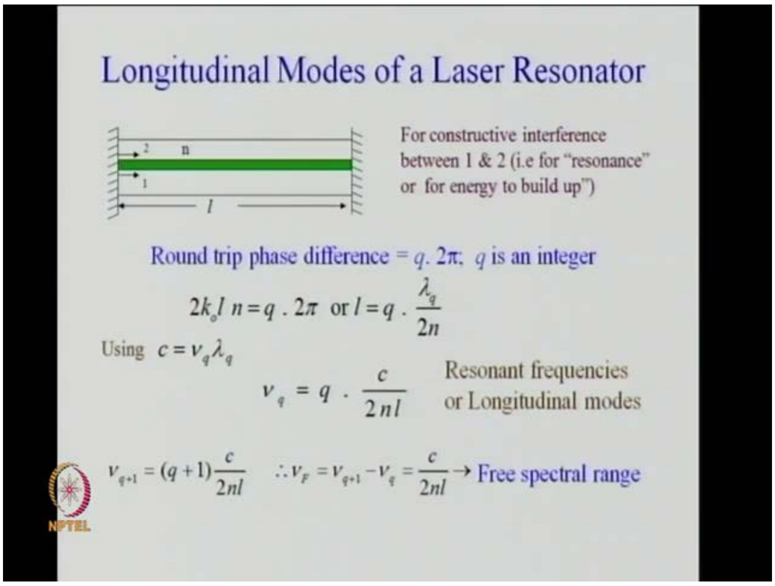

The longitudinal modes of the laser resonator, we have discuss this and therefore, I have quickly go through it. We have already discussed on this board. For constructive interference between 1 and 2, which means after one round trip. That is for resonance or energy build up. Round trip phase must be integral multiple of 2 pi. We have discussed this in detail in lecture 33. q is an integer and therefore, you get an expression for the resonance frequency nu q which is equal to q into this. Therefore, if you put q is equal to q plus 1 here q plus 1 here you get nu F the free spectral range. Nu q is the resonance frequency. So, this is new.

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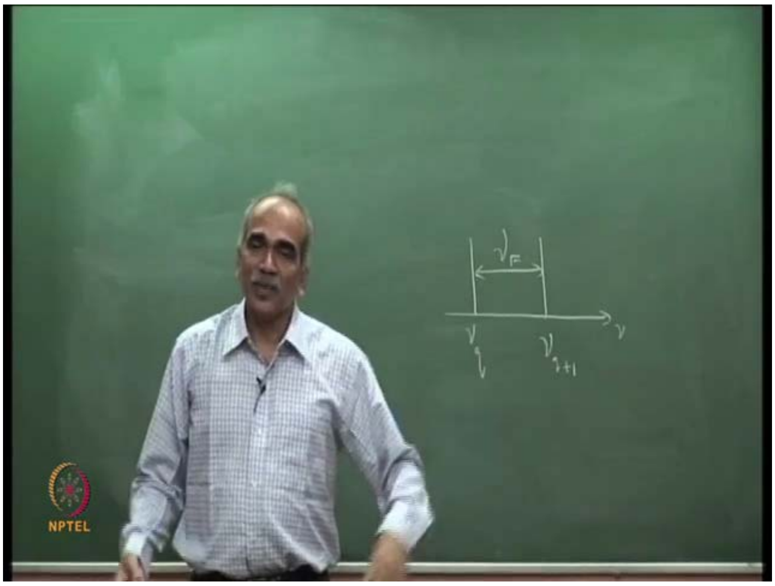

One resonance frequency is here nu q. The next one is called nu q plus 1 because q is an integer. This could be any number 1500. So, this will be 1500 and 1, frequency next resonance frequency. So, free spectral range this difference. This is nu f, free spectral range, the spectral range which is free. There is nothing there in between it is easy to understand free spectral range. So, nu q minus nu 1 is this. So, that is the free spectral range.

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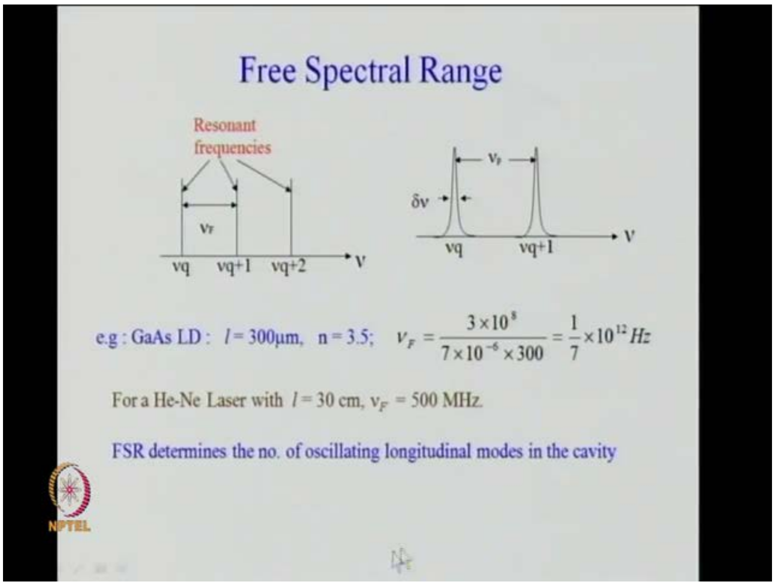

So, here is the free spectral range. Again shown clearly and typical example of gallium assonate laser diode. l is 300 micron n is 3.5. This is what we had discussed earlier. I did not know that, it was there again. For He-Ne laser, if you take He-Ne laser the common laser the l.

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Is very large 30 centimeter is here and nu F is 500 mega hertz very small. Which means within this frequency range there are large number of allowed frequencies. if this was the nu F for laser diode for a helium neon laser, there would be very large number of. So, the normal helium neon lasers, which we use in the laboratory has very large numbers of longitudinal modes. You have to specifically ask for a single frequency laser. Otherwise you will get multi longitudinal mode, helium neon lasers because the cavity is long 30 centimeters or 20 centimeters and therefore, nu F is very small.

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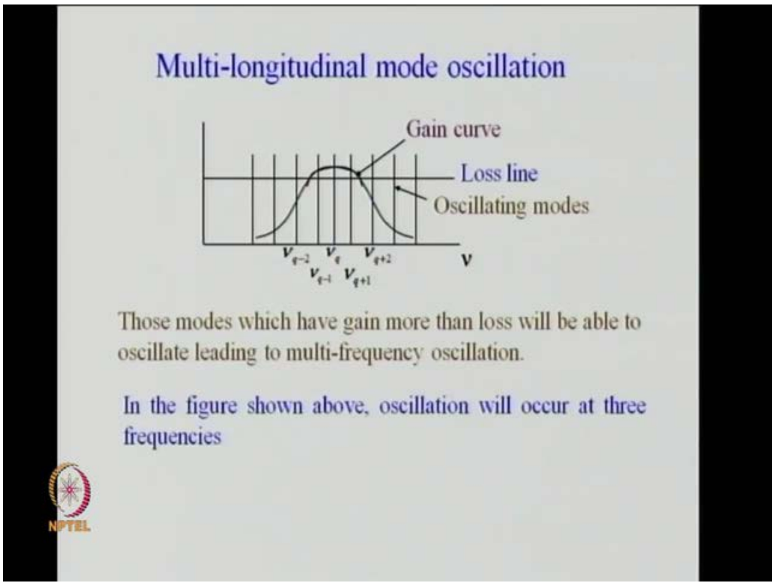

So, little bit more about towards, we are going towards selection of a single frequency. So, this we have discussed there is a gain curve. Here, the vertical lines are allowed resonance frequencies of the resonator. So, this those mode which have gain more than loss, will be able to oscillate leading to multi frequency oscillation of the lasers. So, in this frequency in this figure oscillation will occur at 3 frequencies because you can see 1 2 3. So, these frequencies gain is more than loss.

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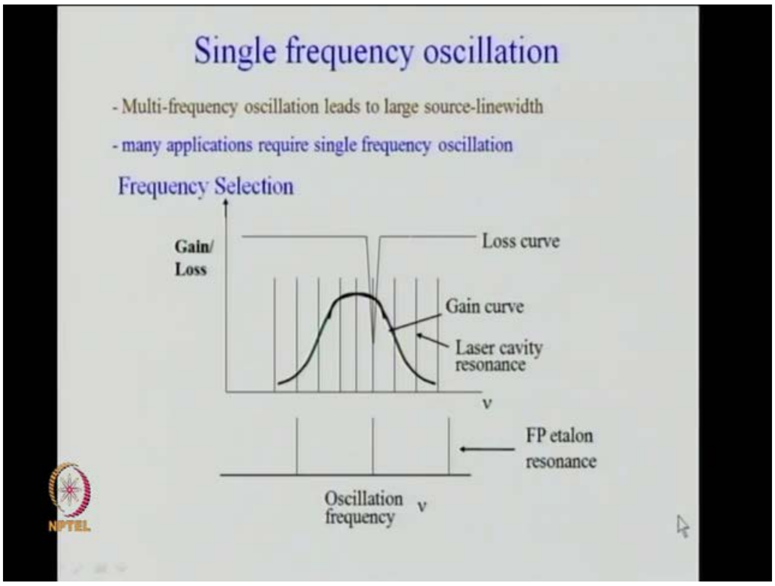

Single frequency oscillations, therefore if you somehow modulate the loss, here is the concept, if you somehow make loss very high for all frequencies, but the required frequency then that frequency alone will oscillate. So, what is shown here is gain curve is the same, but the loss line is now up. Except for one frequency where the loss has dropped. Why it has dropped, we will see. But if I make, this is just the principle principle of selecting a single longitudinal mode. You just make loss very low for that particular frequency like this. So, the loss curve has the dip here and therefore, only this mode will oscillate alright.

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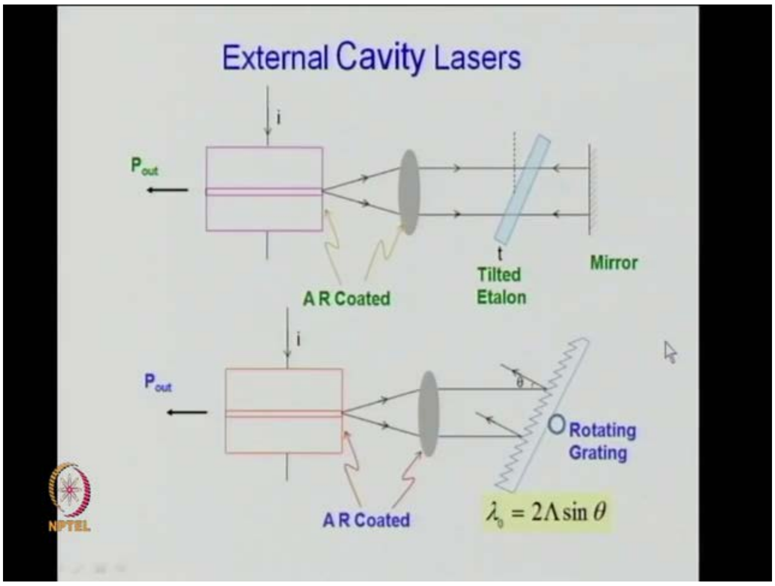

So, let us go to external cavity laser. What is the actual mechanism? How do they do actually? So, you see that there is the semiconductor lasers. The end is cleaved S, but now anti reflection coated because we do not want the laser to oscillate here like this. If you did not, if you coat an anti-reflection coating AR coating; that means there is no reflection is coming from this end not even 0.32. If you do not coat 32 percent reflection is there. But if you coat an anti reflection coating here, then there is no reflection coming. So, whatever comes which means, there is no feedback going from here.

So, the light completely passes through this. So, this lens is for collimating, making it parallel and in between so forget about the component for the moment and you see it goes to the external mirror. This is the external mirror forming the external cavity. This is external to the device here, external to the semiconductor chip here. So, there is a mirror, which reflect it is back. Now, where is the cavity? Cavity is 32 percent reflection here and 100 percent reflection here. There is nothing in between. No reflection in between. Assuming that all, are all surface we have coated anti reflection coated. Now, in the cavity you use a tilted etalon. I just brought you the concept of an etalon what is that etalon?

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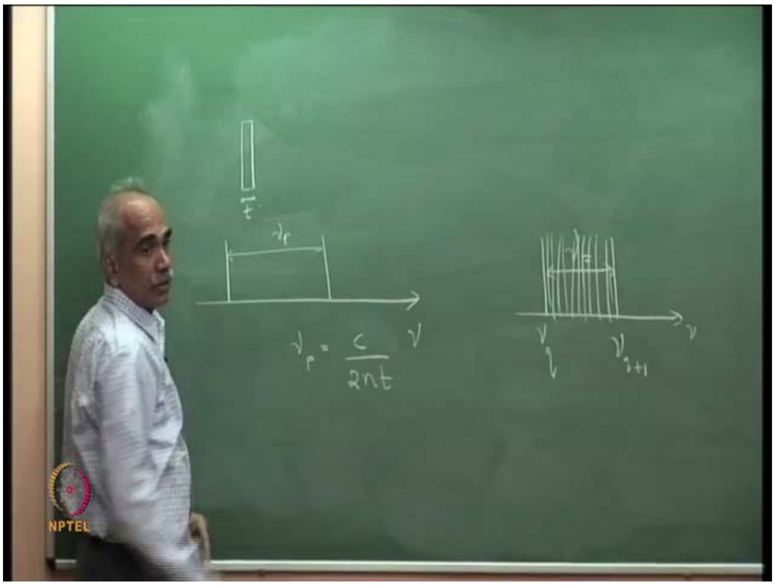

The etalon is a Fabry-Perot cavity with a small t. This t could be typically 5 millimeter t. If small t means what, this resonator it is a resonator with small t, which means it has frequency separation very large, nu F is very large. Why nu F is very large, because nu F is equal to C divided by 2 n into t. Small t and therefore, nu F is large. So, you have a small cavity. Therefore, nu F is very large. Of course, if you are looking at, this is normal etalons for bulk optics. But in semi conductor lasers t is already 300micron. So, if you want to use a etalon which has a larger spacing this t should be 10 micron or 20 micron or 50 micron much smaller t's, but if you take smaller t's then separation can be large.

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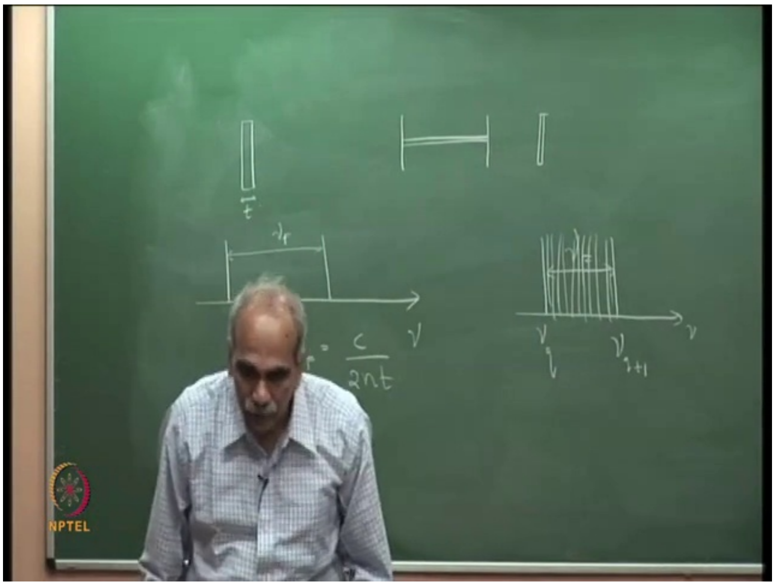

So, you have two cavities coupled. Please see this. This is one cavity, the laser semiconductor laser cavity and there is an etalon here. Why tilted I will tell you a little later. Just a couple of more minutes, we will stop. So, maybe we will continue this discussion because it is a single frequency laser. The next class will be single frequency lasers and we will discuss this in detail alright. Let we stop here for the minute.