Semiconductor Optoelectronics
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Lecture – 34
Semiconductor Laser-II Output Characteristics

We continue with semiconductor lasers and the output characteristics. Before I start the output characteristics, let me just discuss the answer for the quiz.

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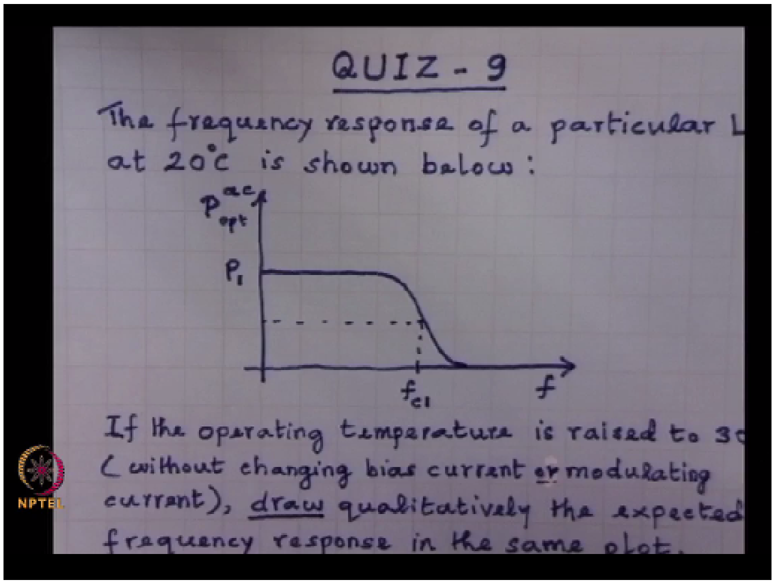

So this was the quiz question. The frequency response of a particular LED at 20 degrees is shown below. If the operating temperature is raised to 30 degree without changing bias current or modulating current or without any change, draw qualitatively the expected frequency response in the same plot. So what you see is when the temperature goes up from 20 to 30, 2 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 lower power and the second thing that happens is when the temperature goes up, tau decreases and the bandwidth is inversely proportional to tau. Therefore, decrease in tau, the carrier recombination time leads to an increase in band.

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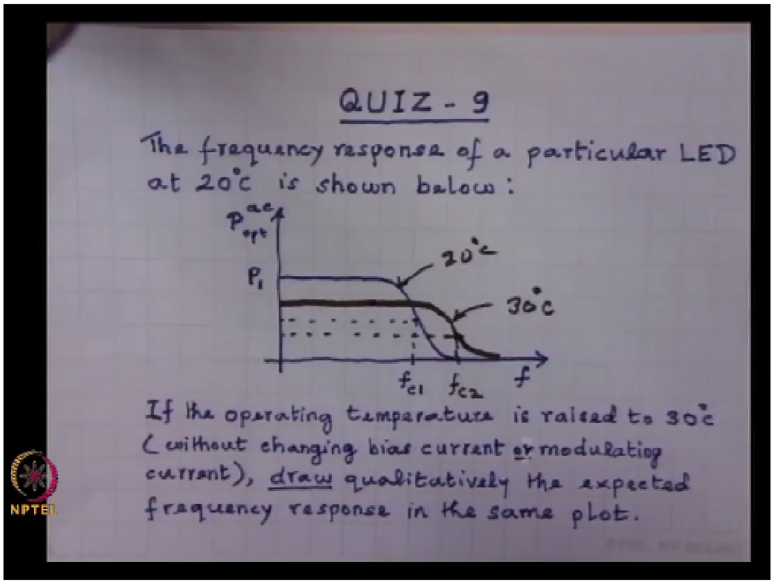

So these are the 2 changes that you had to show. So let me show it right here. So the expected curve now becomes like this and half of that, the half power, this is important to show that the cut-off now goes here. So this is fc2. So earlier this was for 20 degree Centigrade and this is for 30 degree.

So this is the expected answer that it will decrease here and it will increase here. This is because eta a decreases and 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 we were discussing about the threshold.

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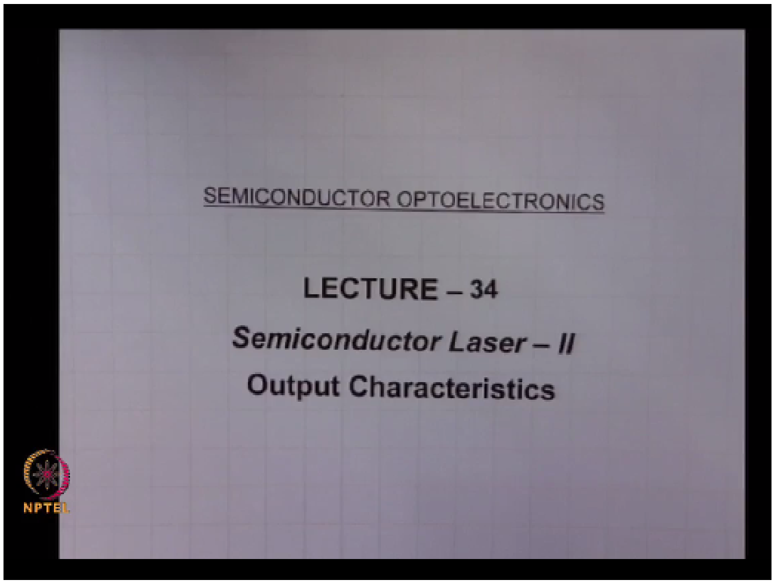

Threshold that is the output parameter, output characteristic where I versus, that is we have plotted here current in this axis, versus the optical power, here.

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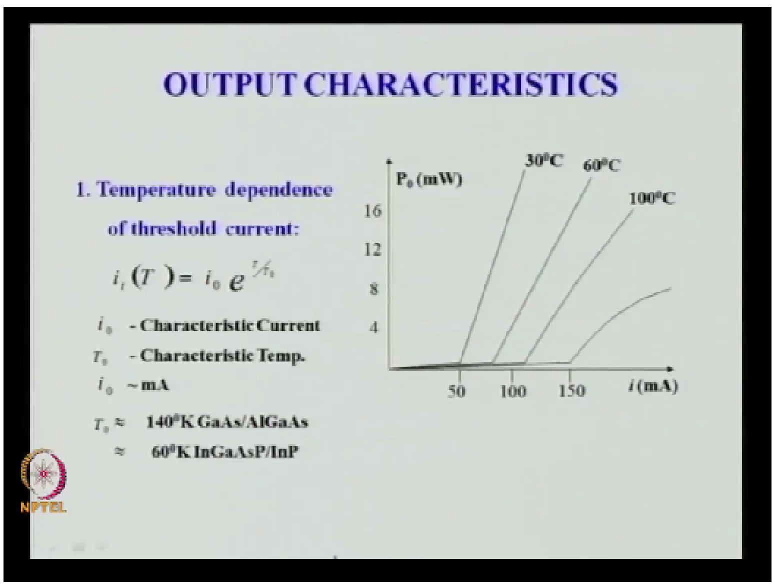

What we have got, we started like this.

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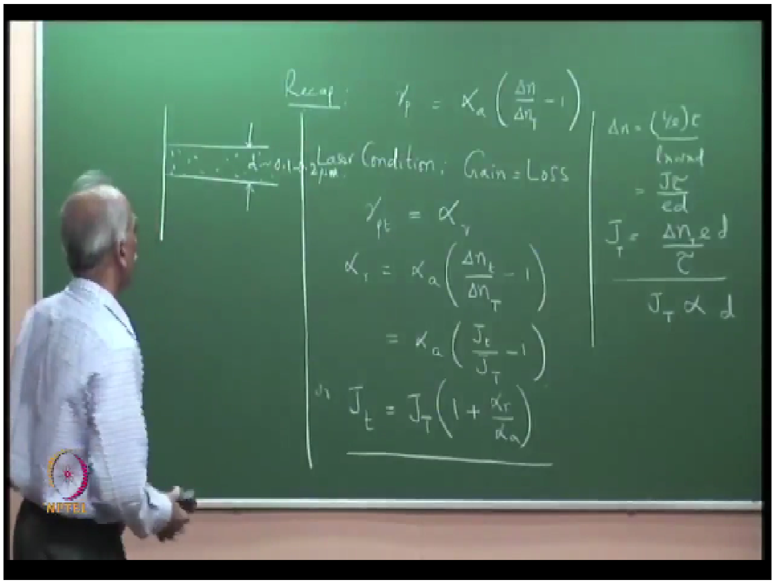

Just recall, recap, we had an expression for P gain coefficient, gamma P=alpha a*delta n/delta np-1. All the parameters we know, so delta n, very quickly, delta n=i/e*tau/l*w*d or this is nothing but i/lw is J, so it is J tau/e*d or we have J=delta n*e*d/tau. So J transparency, if I want to write J transparency, that will be equal to delta nt*e*d. So what you see is J transparency JT is proportional to, JT 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=loss, that means gamma P at threshold, gamma Pt=loss in the resonator alpha r, gamma Pt is given by this. So alpha r=alpha a*, I am substituting this, delta nt/delta nT. We have discussed in detail, this is threshold, this is transparency, -1 or delta nt/delta n is JT/, now this is equal to alpha a/J threshold/J transparency-1 or J threshold=, alpha a goes to denominator, so we have JT*1+alpha r/alpha a. This is the expression that we get by equating this gain coefficient equal to loss coefficient.

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=loss. In the case of semiconductor lasers, we have an optical waveguide there. The active medium, I am showing only portion of the semiconductor laser. So this goes down to cladding layers and then substrate and so on. I have just zoomed this active layer, this is that d which for a double heterostructures is about 0.1-0.2 micrometers for a double heterostructures.

I want to answer why this was 0.1-0.2. Why did not we said okay, in a homojunction, it was 1-2 micron and they reduced, they could reduce it down by going to 0.1-0.2, why did not they go further down, the threshold would have reduced to further. So why we have stopped 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 semiconductor lasers and that is called the confinement factor. I want to discuss about the confinement factor. Before I will proceed any further.

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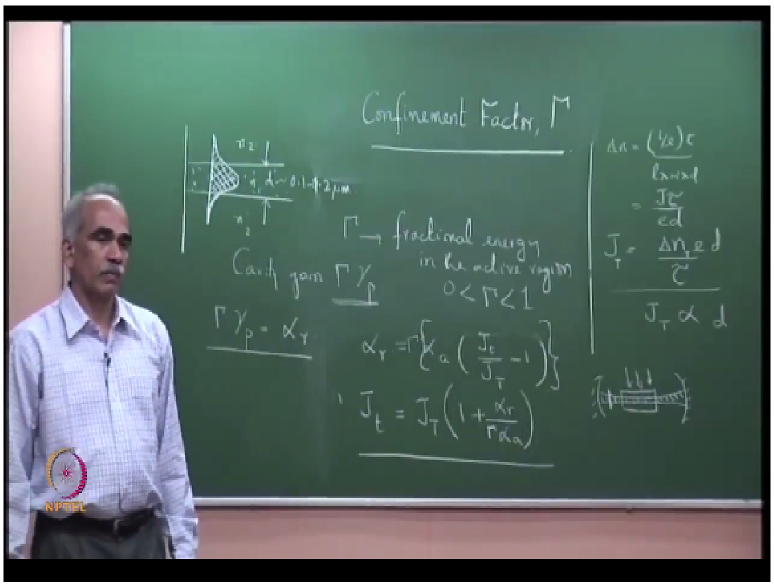

So confinement factor gamma. The laser diode, the active region forms an optical waveguide and therefore, there is an optical mode which is going back and forth. So this is the optical mode, the modal free distribution which is going back and forth. This is a dielectric waveguide of lower refractive index here, n2, n2 and this is n1. 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, I have shown just an expanded portion, the mode is going back and forth. As it goes back and forth in the laser resonator, the entire mode suffers loss. The alpha r, resonator loss coefficient, 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 in the active region, then the cavity gain is gamma*gamma p. Gamma is less than 1, 0<gamma<1. Gamma is this fraction. Please see, let me shade it the other way, 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 -infinity to +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 it is called confinement factor? We will come to that in a minute. Therefore, the cavity gain is gamma*p, so we should equate this is alpha r. In other words, our equation should have been gamma*gamma p=alpha r. Normally, in a bulk laser like the Nd:YAG laser, I showed you the Nd:YAG laser here, this is the mirror or any other laser, helium-neon laser or whatever.

The laser beam is well within the active region, it is well within the active region. So what I am showing is the Gaussian mode and this is the pump 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 cladding layer, high band bap material and therefore, we should equate this, this is the cavity gain.

Cavity gain=loss. So you substitute this here, cavity gain=alpha r which is I have to substitute this gamma times this equal to alpha r, so what you will get is Jt, I will write in the same expression, JT, there is a factor gamma which will come here. You can write again, so gamma*gamma p, this is gamma p, please see this is gamma p, so gamma*gamma p has to be equate to alpha r which gives you J threshold=JT* a factor gamma. Remember that gamma is < 1.

So what, there is quite a bit, we will see so on. So is this is the correct expression, we should take the confinement factor.

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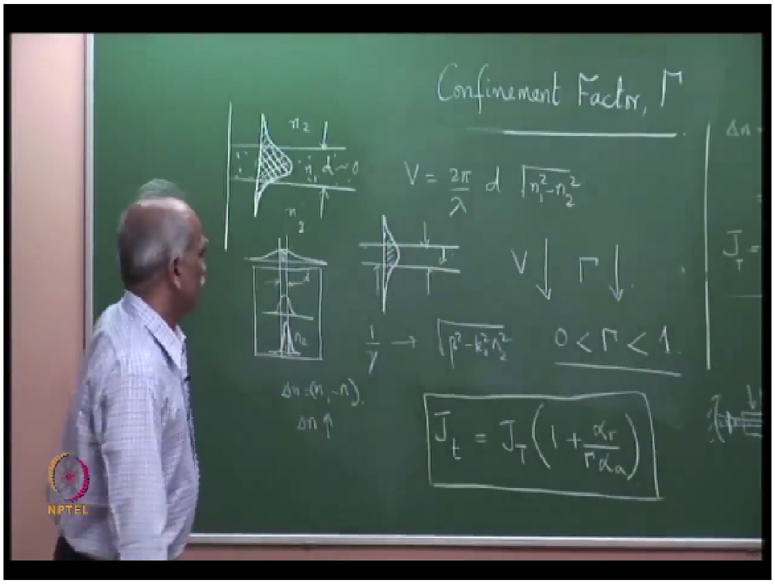

So the current expression contains Jt is equal to this gamma, okay, where gamma is the confinement factor and you will see something that if I have, this is the optical waveguide. The fractional energy which is inside or the confinement of a mode to the waveguide is determined by the V number. So the V number is 2 pi/lambda*d*square root of n1 square-n2 square. It is not a direct relation, the confinement gamma, 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 n1, n2, no change in n1, n2; n1, n2 is fixed. Wavelength of operation is the same and therefore if I reduce d, in this case, what will happen is, the mode will spread further. The mode will spread further. Actually those of you who have done a course on optical waveguide, will see that this length where this penetration depth is depending on 1/gamma and gamma here is square root of beta square-k0 square n2 square, where beta is the propagation constant.

Those who have not done a course, do not worry but those who have done a course, they know that the penetration depth is 1/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/gamma increases. In other words, the penetration depth increases if beta decreases that is if the thickness d decreases.

So those of you have 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 decreases, gamma decreases, the fractional energy decreases, the relation is not directly an analytical expression, where it has to be numerically obtained but V decreases, gamma decreases.

So if the waveguide becomes smaller and smaller, why am I bringing this concept, now this is our d; therefore, assuming that n1, n2 are the same for the same material, d decreases, V decreases. V is the normalised frequency, V decreases. V decreases, gamma decreases. What is its implication, keep this picture in mind and if d increases, alternatively one can also have, let me show the waveguide like this now.

So if I have a waveguide here of a fixed d, so this is d, fixed d, this is n1 and this is n2. Then let me say that the mode is like this. If n1-n2, that is n1-n2, if the difference n1-n2 or delta n, so if delta n goes up, d is fixed, but delta n goes up, then also V 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<gamma<1. 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 film, is very small. So gamma approaches 0, gamma approaches 1.

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 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, n1-n2 should be large. So several design flexibility or design criteria which are involved here.

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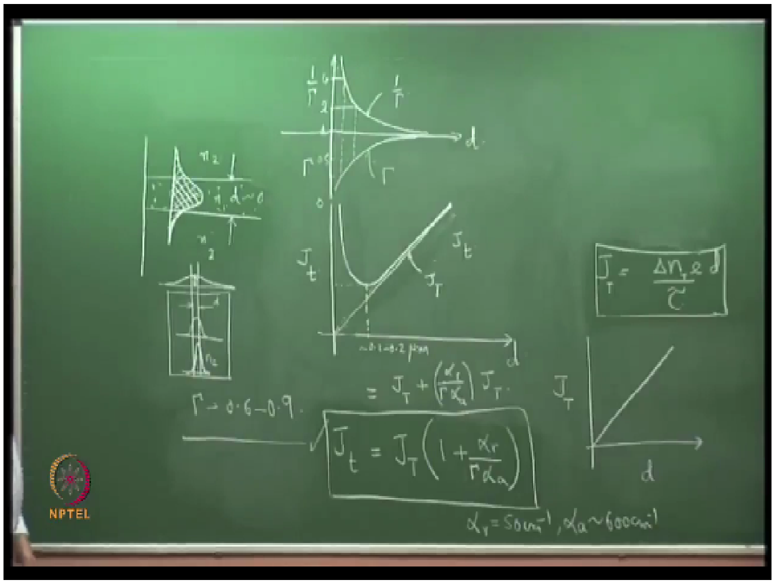

Now let me plot this gamma, how this gamma look like with d. So first thing is here, this is the expression, J and T is here, let me erase the rest of them. I want to plot and see the importance of this confinement factor in determining the threshold current. What I am now plotting is d versus gamma. 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 0-1. How would 1/gamma vary. When this is small, this is large. So this is going up, this here I am plotting 1/gamma. 1/gamma, minimum value is 1 because maximum value of gamma is 1; therefore, 1/gamma, minimum value is 1 and as this goes down, so this is 1/gamma, what kind of numbers for example if the scales are different to the 2 sides.

If this was 0.5, then we will have 1/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/gamma, this curve is 1/gamma, this curve is gamma, so variation of gamma, variation of 1/gamma. Why am I interested in 1/gamma, 1/gamma is here. if I plot JT, so JT versus d, what kind of graph will I expect.

JT that is transparency current versus d, I should get a straight line, right that d=0, JT is 0 and as d increases, JT increases, JT versus and what is J threshold, J threshold is JT+, so let me write this=JT+ this part which is alpha r and alpha a are constant, nothing to do with the material dimension there. So alpha r alpha a/gamma*JT. So 1/gamma is here, please see this, this is 1/gamma.

So if I want to plot Jt, 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,1/gamma is 1, so this factor is not there. This factor is just a constant alpha r/alpha a. Alpha a is the material absorption coefficient, alpha r is the resonator loss coefficient. So this is just a constant,*JT but if d increases, JT increases; therefore, at large values, I should have a graph, okay let me, so what I have plotted here is Jt, small threshold at large values.

Actual Jt is here, they should be merging closer and closer, just a minute. So what I have plotted here is JT, J capital T, the same curve I have put here. I want to plot the other curve namely Jt. As d decreases, here gamma decreases; therefore, 1/gamma increases, please see this, 1/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 50-60 centimeter inverse here and alpha a was about 600 centimeter inverse. You remember that we had put this as 0.1, alpha r/alpha a, that is how we had written 1.1, the transparency threshold current was 1.1 times transparency. So this factor was 1.1 without the gamma, but now there is a gamma coming in the denominator.

Therefore, when gamma becomes smaller and smaller, 1/gamma becomes larger, so the second term starts dominating and what happens is, this comes down here and then it shoots up. Why is it shooting up, because this is shooting up, 1/gamma is here, 1/gamma, so the second term is getting multiplied by 1/gamma, 1/gamma is shooting up and therefore this is shooting up. This minimum value is where you have lowest threshold current and this minimum value is approximately 0.1-0.2 micrometer.

I am writing 0.1-0.2 because it will also depend on the difference n1 and n2. For a given n1 and n2, it could be .1, 0.15, 0.2, that is why double heterostructures have a layer of 0.1 or 0.2 micron thick sandwiched between higher band gap materials. So what we have answered is the question, why d=0.1. Why did you stop there, why did not you reduce it further down. So normally, so this is the minimum, the threshold current is there, okay.

So this is the correct expression. Most of the semiconductor lasers have gamma between 0.6-0.9. For most practical semiconductor lasers, gamma is between 0.6 and 0.9. This is okay? So if that factor gamma was not there, it would have been going like this down. So the gamma was the one which stopped it there, okay. So let me continue with the PPT characteristics there. So this is a concept which was an important concept.

When I wrote the dimension of a semiconductor laser, we had written length around 300 micron. We should also ask a question why 300, why not 100, why not 500, we will answer that, okay. 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, okay.

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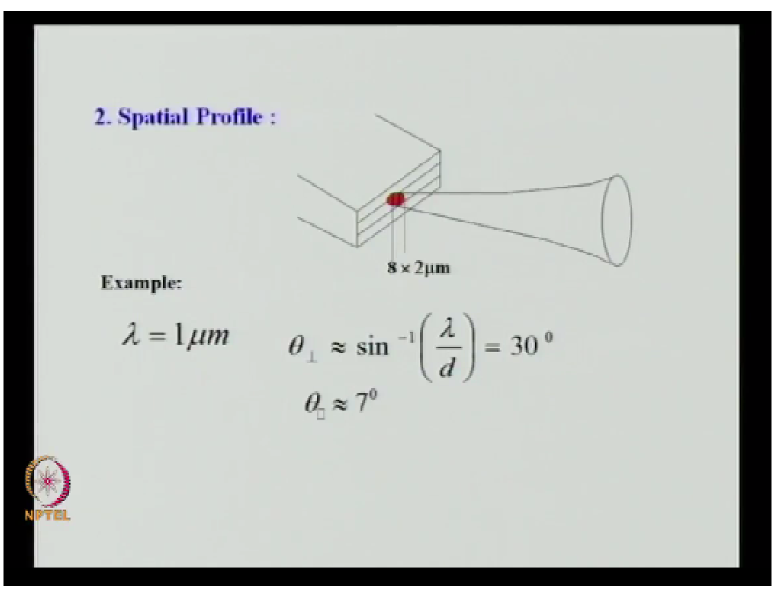

So output characteristic, this is the graph which we have discussed already and it is the first one, temperature dependence of the current. The second one is the spatial profile of the beam which is coming out, the beam that is coming out. Spatial profile of the beam, okay, right. So the spatial profile of the beam is here. So what is shown is the emission area here. Typical dimension is about 8*2 micrometer, the spot size. This is not the physical size.

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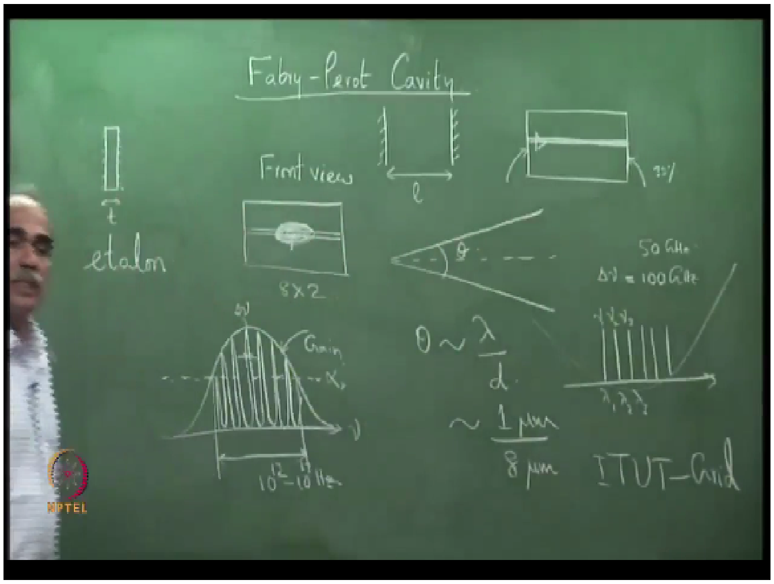

Please remember the double heterostructure is just, if you see the front view, we had a layer which was 0.2 micrometer here. So this was 0.2 but the spot, the laser spot which is generated because the field is spreading into the cladding also, there is a mass and tail, so the spot size is generally about 8 by 2, so 8*2, this is the front view, so it is an elliptic kind of a beam and therefore, what do we expect when it comes out, the beam, an optical beam which is compressed in this direction or narrower in this direction should be spreading more when it comes in this direction.

And it should be spreading less in the vertical direction and that is what you see. So what is 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

1D, the beam is coming like this out. So what is shown is theta is angle of divergence theta. The angle of divergence is approximately theta is approximately given by lambda/d and the lambda if you take 1 micron/d, so in this direction, it is the 8 micron, so 8 micron, so that is theta in radiance, 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. So this is theta perpendicular that is lambda/d, d has been taken as 2 micron in that direction. So it is 1/2 sin inverse half is 30 degree, so that is what is shown. This is the spatial profile of a beam of a laser output beam. Usually in applications, you 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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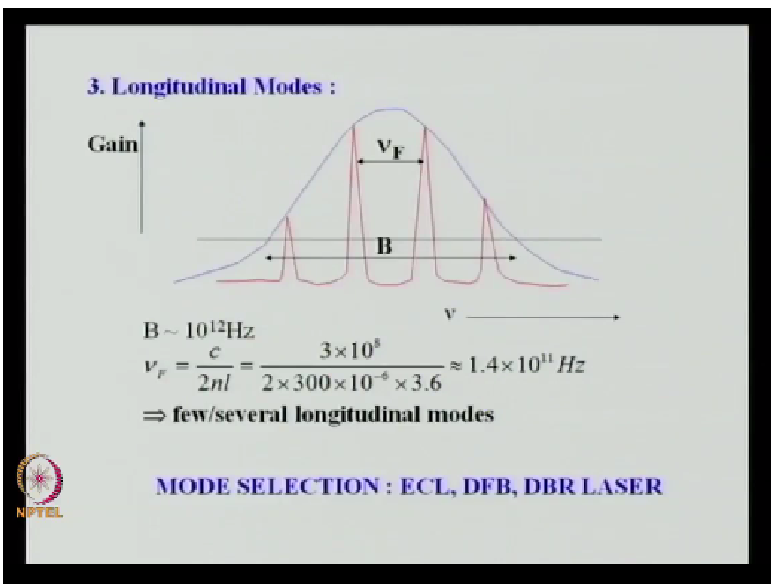

Third properties the longitudinal modes, we have had some discussion here. So what is shown is the blue line here, what we have shown is the gain profile, the gain profile here and this is the frequency axis. So you may recall that and this line here, horizontal line is the loss line. So recall what we had discussed that for all those frequencies where, so if this is the loss line, then for all those frequencies for which gain, gain of the amplifier, 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. We will discuss this a little bit more, there are couple of more slides which discussed this and I had also mentioned that why we are discussing this is because in many applications we need only 1 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 standing for external cavity laser. We have this in the next slide I supposed, external cavity laser. DFB standing for distributed feedback laser. DBR standing for distributed Bragg reflector laser. So we will see each one of these in detail.

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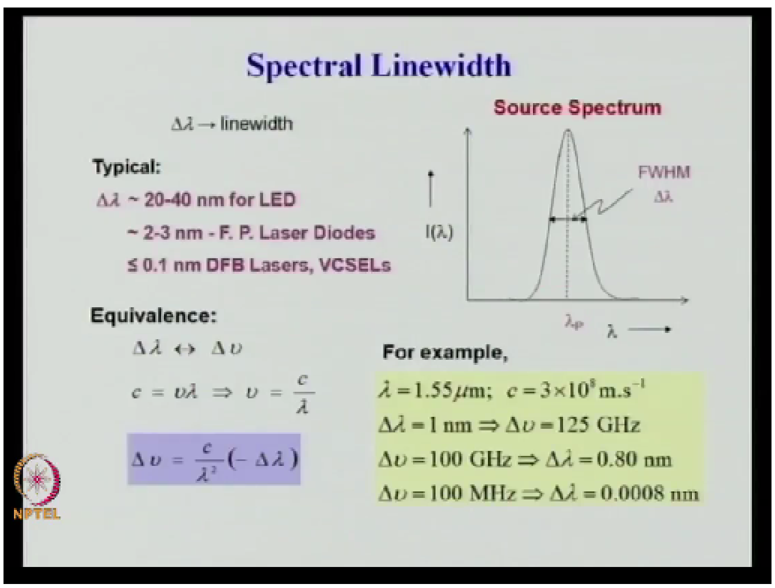

So let me discuss something about the spectral linewidth, some aspects we have discussed already but let me recall what we have discussed and what is its importance particularly from the point of your communication. For those students of optical communications, what is the importance of this spectral linewidth. So spectral linewidth is shown here, what is shown is the spectrum.

I of lambda versus lambda p versus lambda. Lambda p corresponds to the peak and this is the delta lambda. We have discussed this in great detail for LED and we have seen that delta lambda was of the order of 20, 30, 40 nanometers. So that is what is shown here. Delta lambda is tens of nanometre for LED but typical Fabry-Perot laser diodes, first time we are using Fabry-Perot laser.

What is a Fabry-Perot laser. Fabry-Perot laser is the normal laser diode that we use. Many of you may be knowing a cavity which has 2 high reflecting mirrors, a cavity formed by 2 high reflecting mirrors is called a Fabry-Perot cavity. So Fabry-Perot cavity and there are Fabry-Perot interferometers which are widely used in optics with large number of applications. A cavity formed by 2 mirrors separated by a distance d.

The intermediate region may have a medium also and a Fabry-Perot cavity which has a fixed distance like this, for example on a glass plate, parallel glass plate, you deposit highly reflecting coatings here. This is fixed, fixed t, a thickness a glass plate of thickness t with high reflecting mirrors coated. This is a fixed separation Fabry-Perot cavity. This is called an etalon, Fabry-Perot etalon, has many many applications including, we will see on users etalons for single frequency selection.

So this acts like a cavity with a fixed spacing. Here normally one can vary the cavity. So a semiconductor laser, the normal semiconductor laser with cleaved ends here which has a reflectivity of 32% where the mode goes back and forth, the mode is going back and forth, this forms a cavity and the normal semiconductor lasers 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 laser, okay. So I have used here Fabry-Perot laser diodes. Just to say that normal semiconductor laser 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 fibre communication.

The source in optical fibre communication is the DFB laser. VCSELs, vertical cavity surface emitting laser, we will discuss this in a little bit more detail. So these have extremely narrow linewidth. Usually in 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 oscillate only in one single longitudinal mode.

So 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 10 to the power of 13 hertz for semiconductor lasers. The nu F which is the free spectral range, free spectral range is the frequency range between 2 adjacent longitudinal modes.

The frequency separation between 2 longitudinal modes. I think we have a slide later which explains it more. So you can calculate some numbers are here, c 2*l is 300 micron, refractive index n is 3.6. So nu F frequency separation comes out to be 1.4*10 to the power of 11 hertz, a typical example and therefore B/nu 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 to single mode, so assume that here we have large number of modes oscillating like this. So this bandwidth here is 10 to the power of 12 to 10 to the power of 13 hertz. What about if I make the laser to oscillate in a single longitudinal mode, the width will be like this, the output, this multi-longitudinal modes and a single longitudinal mode can be observed on an optical spectrum analyser.

So in one of the future classes, I will show you, I will demonstrate and show you that these are not just theoretical concepts, you can actually see on an optical spectrum analyser, 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 analyser is not able to resolve, it will clearly show you just 1 line and the point is, the frequency separation here, this delta nu corresponding to this, 1 width here, 1 longitudinal modes is much smaller compared to this.

So the single frequency lasers have very narrow linewidth and consequently as given in this slide, the linewidth delta lambda is less than of the order of 0.1 nanometer. Many times much less than. 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 fibre communication.

If you substitute delta lambda equal to 1 nanometer, that gives you 125 gigahertz in this expression if you substitute or alternatively you will say delta nu is 100 gigahertz. Why have I put 100 gigahertz, because 100 gigahertz separation is the ITU-T grid for WDM, DWDM systems. Those of you may not be aware, many of you that in a DWDM system where you put large number of wavelengths or frequencies, nu 1, nu 2, nu 3 or lambda 1, lambda 2, lambda 3, the whole thing is in the 1550 nanometre window of optical fibre.

Low loss window of optical fibre, around 1550 you can pack large number of wavelengths, closely separated wavelengths, into a single mode fibre which makes the DWDM system. The frequency separation here, delta nu=100 gigahertz because this is the standard or you can go to 50 gigahertz is also permitted, this is called the ITUT grid, international telecom union, ITUT grid wavelengths or grid frequencies, these are standards, international standards and the separation is 100 gigahertz.

So if you take 100 gigahertz as the separation, it tells you delta lambda is 0.8 nanometer which means the separation between 2 wavelengths, please remember each wavelength is a channel, so 2 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 as the width. So if you have 2 laser diodes, they will simply overlap. So you have to have delta lambda, let me expand that. It is just interesting from the optical communication point of view.

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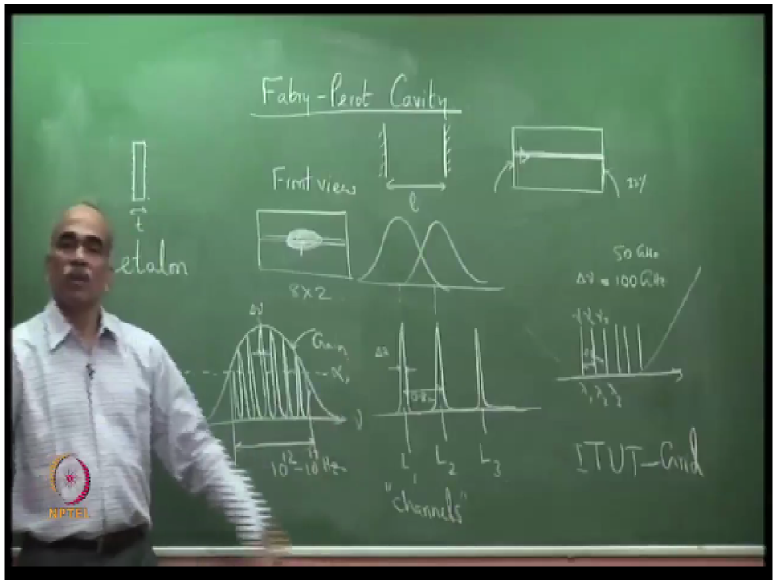

So each channel here, so this is the linewidth of the laser, this is the linewidth of the laser delta lambda. This is the channel separation. So there are lasers L1, L2, L3 are laser diodes which correspond to different channels, communication channel means a frequency over which you send signals. So these are wavelengths which are separated by 0.8 nanometer; therefore, the individual lasers linewidth, 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 linewidth of 3 nanometer, this has linewidth 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 the distributed feedback lasers have much smaller linewidth and therefore, there is no overlapping or no inter-symbol interference, alright. Some of the DFB lasers have 100 megahertz as the linewidth and you see what it corresponds to delta lambda is 0.0008 nanometer, there is no question of overlapping, this is 0.8 and this is 0.0008, very narrow.

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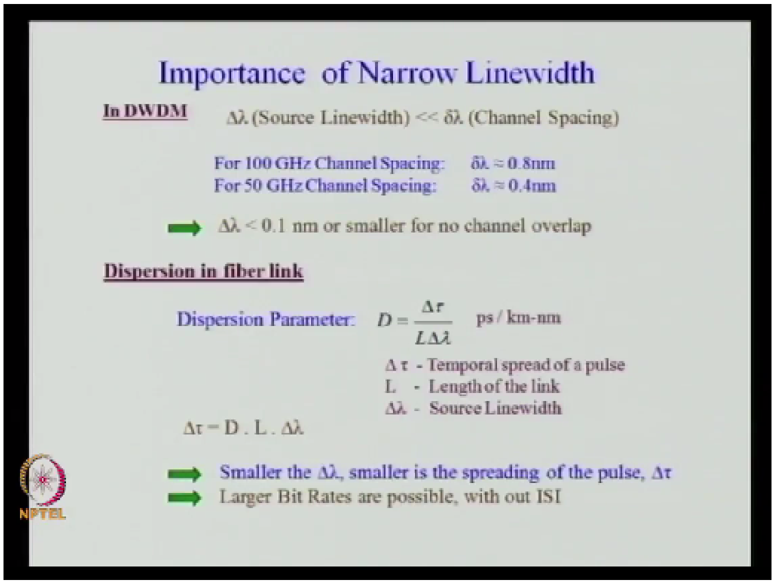

So to be familiar with the numbers, so there is a slide particularly this is importance of narrow linewidth in optical communication. There are importance of narrow linewidth in various applications, a smaller narrow linewidth gives you a higher coherence and a highly coherence sources are required for various applications but the importance which is discussed here is with the respect to optical communication.

So the same point which I have been discussing is here, delta lambda source linewidth should be much less than the channel spacing, for 100 gigahertz channel, spacing is 0.8 nanometer. If you take 50 gigahertz, it is 0.4 nanometer, implies delta lambda should be less than 0.1 or smaller for no channel overlap. I have already discussed, everything is on the board. Dispersion in fibre link, those who have studied a course on fibre optics, you know that there is the dispersion parameter called D.

Those who have not studied, does not matter, just this to correlate the interest of a fibre-optics people. D is here is given by an expression like this, the dispersion parameter. The units are picosecond per kilometre nanometre. Delta tau here refers to temporal spread of a pulse. L is the length of the link and delta lambda is the source linewidth in this expression and therefore delta tau which is the pulse spreading, the spreading in time is equal to the D*L*delta lambda.

Any given fibre is characterised by the parameter D. Typically if you take G6y-1 fiber, then that is about 17 to 18 picosecond per kilometre nanometre is the dispersion. So you can calculate that multiplied by the length of the link, 1 km link, 10 km link, larger the link, larger is the pulse spread, multiplied by the source linewidth. Larger the source linewidth, therefore larger is the spread. Smaller the source linewidth, smaller is the spread, as simple as that.

And therefore if you take a very narrow laser, very narrow linewidth laser, delta tau spreading will be extremely small. So smaller delta lambda, smaller is the spreading of the pulse and therefore larger bit rates are possible without ISI, inter-symbol interference that is when the bit starts overlapping, alright. So this is the importance in optical fibre communication and a small linewidth has many other applications where you need large coherence length, highly coherent sources.

Because the coherent time is inversely proportional to delta nu, namely the linewidth and therefore smaller the linewidth, larger is the coherence time, okay.

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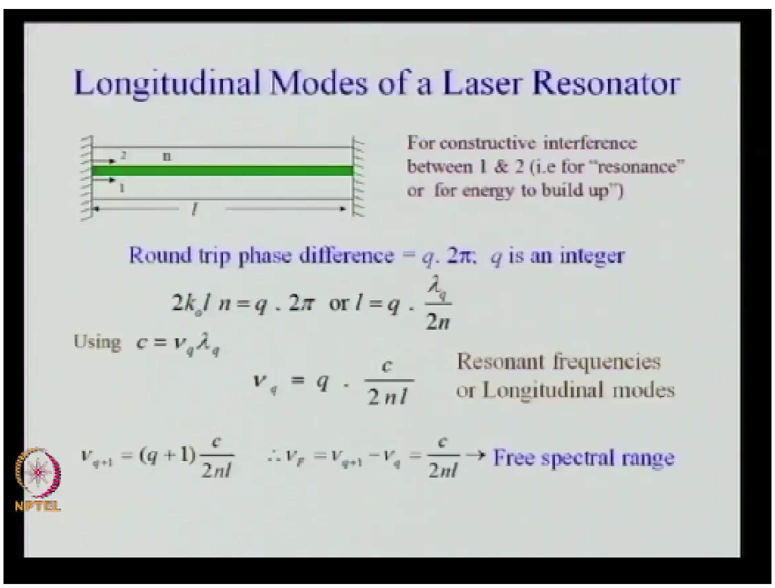

The longitudinal modes of a laser resonator, we have discussed this and therefore I quickly go through it. We already discussed this on the board for constructive interference between 1 and 2, which means after 1 round trip, that is for resonance or energy build-up, round-trip face must be integral multiple of 2 pi, we have discussed this in detail in lecture 33, 2 is an integer and therefore you get an expression for the resonance frequency nu q which is equal to q into this.

So therefore, if you put q+1 here, you get nu F, the free spectral range, nu q is the resonance frequency, so this is nu.

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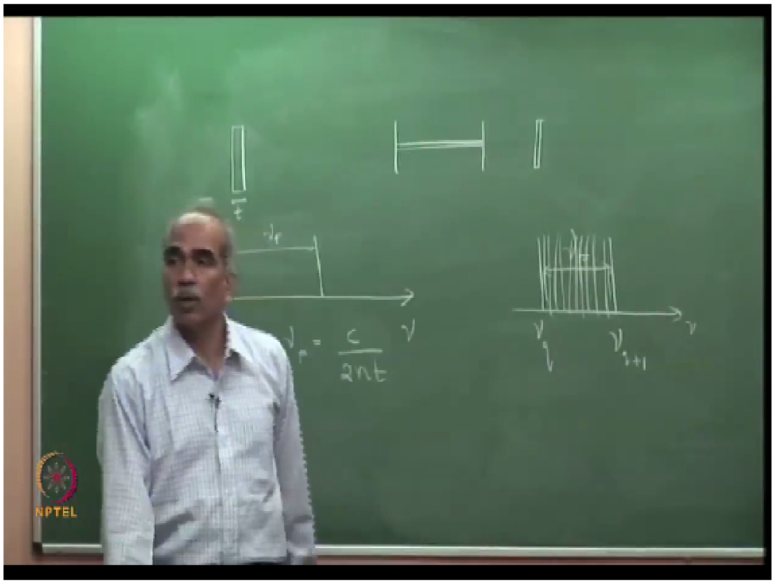

One resonance frequency is here, nu q. The next one is called nu q+1, thus q is an integer. This could be any number, 1500, so this will 1501, next resonant frequency. So free spectral range is this difference. This is nu F, free spectral range. The spectral range which is free. There is nothing there in between, it is easy to understand, free spectral range. So nu q-q1 is this, so that is the free spectral range.

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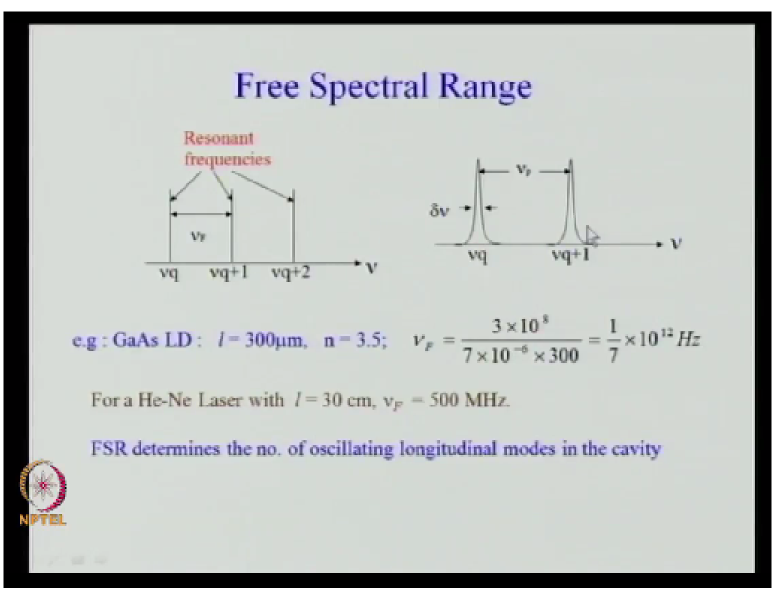

So here is the free spectral range again shown clearly and typical example of a gallium-arsenide laser diode, l is 300 micron, n is 3.5. This is what we had discussed earlier. I did not know that it was there again. For Heaney laser, if you take a Heaney laser, the common laser, l is very large, 30 centimeters here and nu F is 500 megahertz, very small, which means within this frequency range, there are large number of allowed frequencies.

If this was the nu F for a laser diode, for a helium-neon laser that would be very large number of. So the normal helium neon lasers which we use in the laboratory, has very large number of longitudinal modes. You have to specifically ask for a single frequency laser; otherwise, you will get only multi-longitudinal mode helium-neon lasers because the cavity is long, 30 centimeters or 20 centimeters and therefore nu F is very small, okay.

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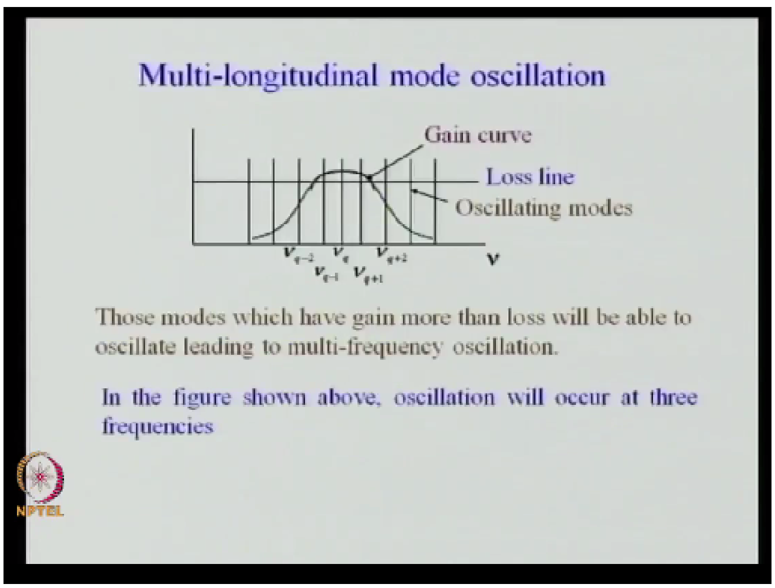

So little bit more about towards, we are going towards selection of a single frequency. So this we have discussed, there is a gain curve here. The vertical lines are allowed resonance frequencies of the resonator. So those modes which have gain more than loss, will be able to oscillate leading to multi-frequency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

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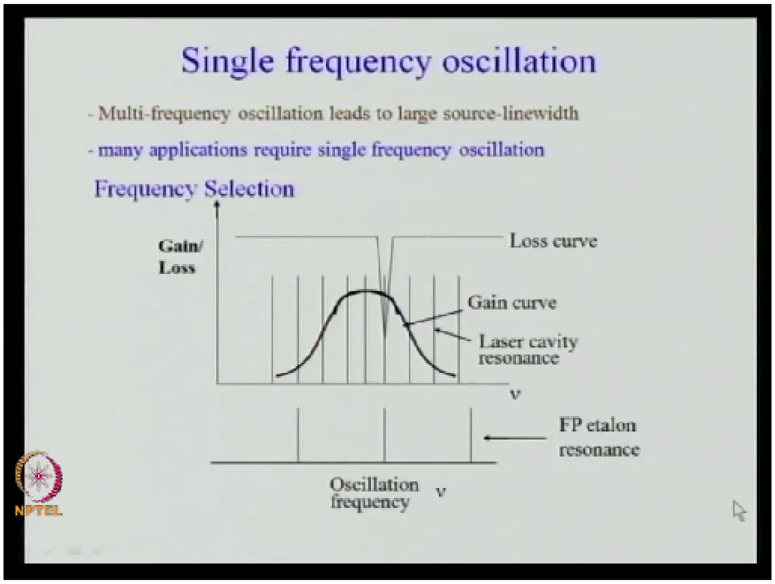

Single frequency oscillation. Therefore, if you somehow modulate the loss, here is the concept. If you somehow make loss very high for all frequencies but the required frequency, then that frequency alone will oscillate. So what is shown here is gain curve is the same but the loss line is now up except for 1 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 a dip here and therefore only this mode will oscillate, alright, okay.

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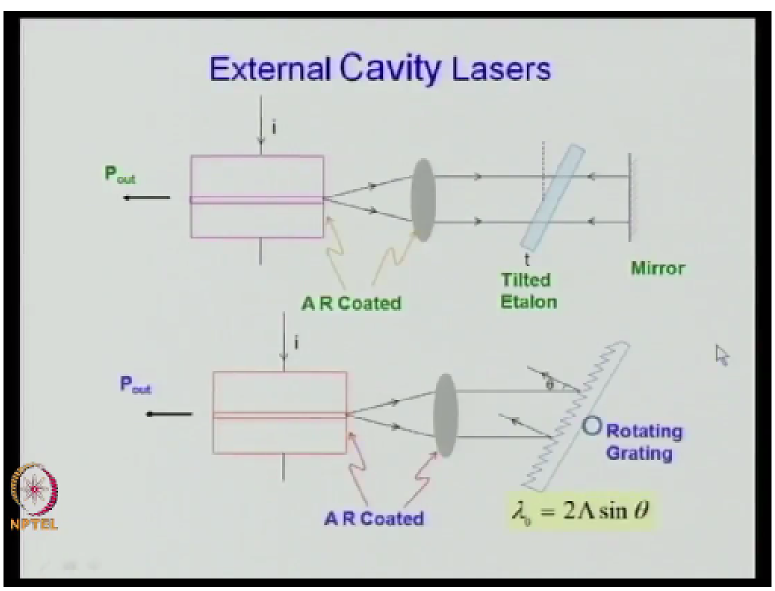

So let us go to external cavity laser, what is the actual mechanism, how do they do actually. So you see that there is a semiconductor laser. The end is (()) (50:43) but now antireflection coated because we do not want the laser to oscillate here like this. If you coat an antireflection coating, AR coating, that means there is no reflection coming from this end, not even 0.32. If you do not coat then 32% reflection is there but if you coat an antireflection coating here, then there is no reflection coming, 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, forget about this component for the moment and then you see it goes to an external mirror, this is the external mirror is forming the external cavity. This is external to the device here, external to the semiconductor chip here. So there is a mirror which reflects it back. So now where is the cavity, cavity is 32% reflection here and 100% reflection here.

There is nothing in between, no reflection in between, assuming that all surfaces are AR coated, okay, antireflection coated. Now in the cavity, you use a tilted etalon. I just brought you the concept of an etalon. What is that etalon. The etalon is a Fabry-Perot cavity with a small t. This t could be typically 5 mm 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=C/2n*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 it, this is normal etalon for bulk optics but in semiconductor lasers, t is already 300 micron, so if you want to use an 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 ts, then separation can be large.

So you have 2 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 couple of more minutes, we will stop and we will continue this discussion because it is a single frequency laser. The next class will be single frequency laser and we will discuss this in detail, alright. So let me stop here for the minute.