Fiber Optics
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Lecture - 36
Optical Sources and Detectors- IV

In this lecture let us continue our discussion on laser diodes. What we had seen in the previous lecture that the requirement for lasing is that we need to lift sufficient number of atoms from lower laser level to the upper laser level, and the upper laser level is metastable level.

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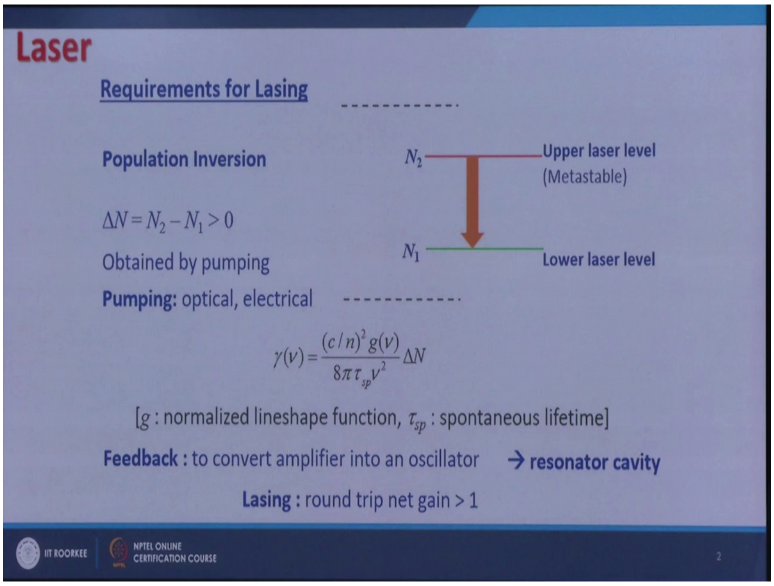

So, once we have the population inversion then the system can provide amplification by stimulated emission of radiation. However, this amplification should be sufficient enough to overcome the loss of the system, and once the gain coefficient is such that the gain of the amplifier is such that it is able to overcome the losses then oscillations will start or the lasing action will start and we will have laser.

Since we have an amplifier and to convert this amplifier into an oscillator, we need to provide feedback and in order to provide the feedback we enclose the active medium between a pair of mirrors, in this way we form a resonator cavity and this cavity has the losses. So, lasing good start when one round clip gain is greater than 1. So, let us now look at the resonator cavity.

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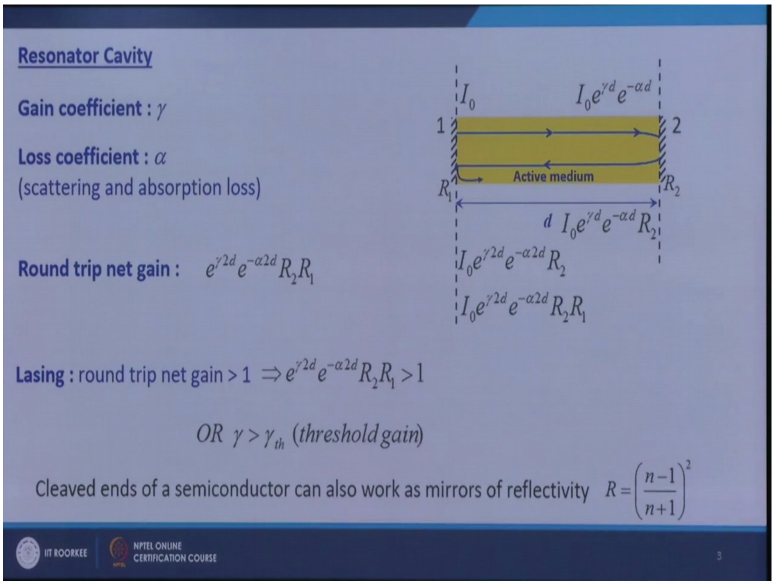

We have the active medium and let us say the length of this active medium is d, the gain provided by this medium is gamma, and the loss coefficient is alpha which constitutes scattering and absorption losses.

How to make it a cavity? We enclose it between 2 mirrors of reflectivities R 1 and R 2 mirror 1 of reflectivity R 1, and mirror 2 of reflectivity R 2, in a beam of light it starts from here and it goes through this active medium it makes a pass here, then it gets reflected from mirror 2 makes another pass from 2 to 1 and then get reflected from mirror 1. So, from here to here there is one round trip, and we should have the net gain of this cavity greater than 1 in one round trip. If in one round trip we have the gain greater than 1 then in successive round trips the gain will multiply, and it will give you a net gain which is always greater than 1 and we will have lasing.

So, let us find out what is the net gain. So, we start from here with intensity I 0 and by the time it reaches here just before hitting this mirror 2, the light intensity gets amplified by gain coefficient gamma and it is attenuated with loss coefficient alpha. The intensity just before hitting this mirror is I 0 times e to the power gamma d times e to the power minus alpha d. When it gets reflected from this mirror, then because of the finite reflectivity of this mirror 2 which is R 2, the intensity becomes I 0 e to the power gamma d times e to the power minus alpha d times R 2.

Now, this intensity starts from this mirror and then goes towards mirror 1 then just before hitting this mirror 1 the intensity will become I 0 e to the power gamma times 2 d times e to the power minus alpha times 2 d times R 2, and after getting reflected from mirror 1 it will be multiplied by this reflection coefficient R 1. So, after one round trip the net intensity the total intensity would of the light beam would be this. So, we start with I 0 and after one round trip the intensity becomes this. So, what is the gain? So, one round trip gain is of course, this divided by I 0. So, the one round trip net gain would be e to the power gamma times 2 d times e to the power minus alpha times 2 d times R 2 times R 1.

So, for lasing to happen this round trip gain should be greater than 1 which means this should be greater than 1 or I can say that the gain coefficient gamma should be greater than a particular value gamma t h which I call threshold gain. What is threshold gain? The threshold gain comes from the equality sign from here. So, from here I can get what is the threshold gain. Sometimes even if you do not put mirrors here mirror 1 and mirror 2 of reflectivities R 1 and R 2, then the cleave surfaces of this medium can also act as mirrors of reflectivity R is equal to n minus 1 divided by n plus 1 whole square, where n is the refractive index of this medium and outside medium is a R. So, this reflection coefficient is nothing, but the final reflection coefficient.

So, this reflectivity can also provide feedback to the cavity and if the round trip gain is greater than 1 then it will start lasing. So, what is the requirement for lasing? Requirement for lasing is gamma should be greater than gamma t h, what is the requirement for amplification? Requirement for amplification is there should be population inversion, but this is not sufficient. Our population inversion should be so much that the gain provided gamma should be greater than a threshold value, which is able to overcome the losses.

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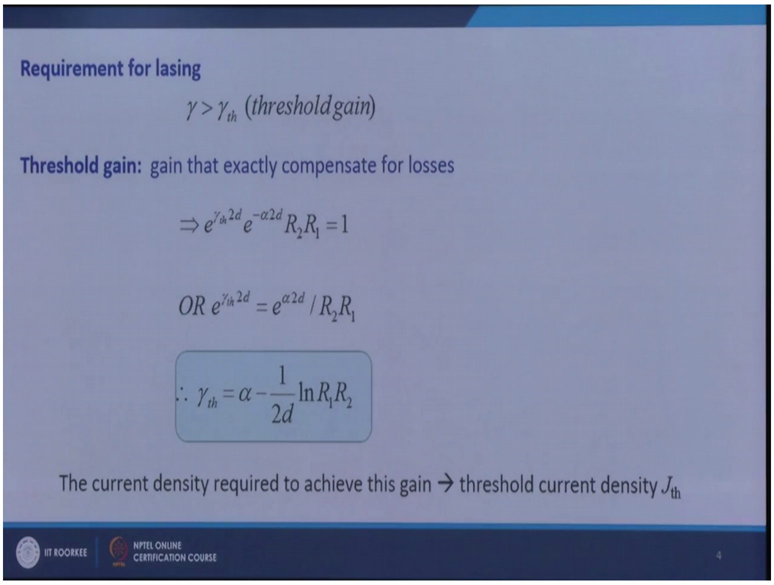

So, this threshold gain is that gain that exactly compensate for losses, which means that e to the power gamma t h if this equality sign is a gamma is equal to gamma t h, then e to the power gamma t h times 2 d times e to the power minus alpha 2 d times R 2 R 1 should be greater than should be equal to 1 or e to the power gamma t h 2 d should be equal to e to the power alpha 2 d divided by R 2 R 1 or I can write it in this fashion that gamma t h is equal to alpha minus 1 over 2 d log R 1 R 2.

So, what I see here this gain coefficient gamma t h is nothing, but the loss coefficient is scattering at absorption loss coefficient plus the finite reflectivity of the mirror, the loss coefficient due to finite reflectivity of the mirror. Please see that this minus sign does not mean that I am subtracting the loss due to finite reflectivities of the mirror from scattering and absorption losses no because R 1 and R 2 r smaller than 1. So, this log R 1 R 2 is minus. So, overall effect is this plus this. Correspondingly I should have a current density to acquire this much of gain and that current density is known as threshold current density, and correspondingly I should have threshold injection current.

So, what I should do in my laser diode? I should provide injection current and when I provide injection current if the injection current is low then the population inversion is not sufficient the gain coefficient is not sufficient to overcome the losses, and lasing does not start. When I slowly increase this current then as soon as the gain provided overcomes the losses, as soon as the gain provided is greater than gamma t h, the lasing starts.

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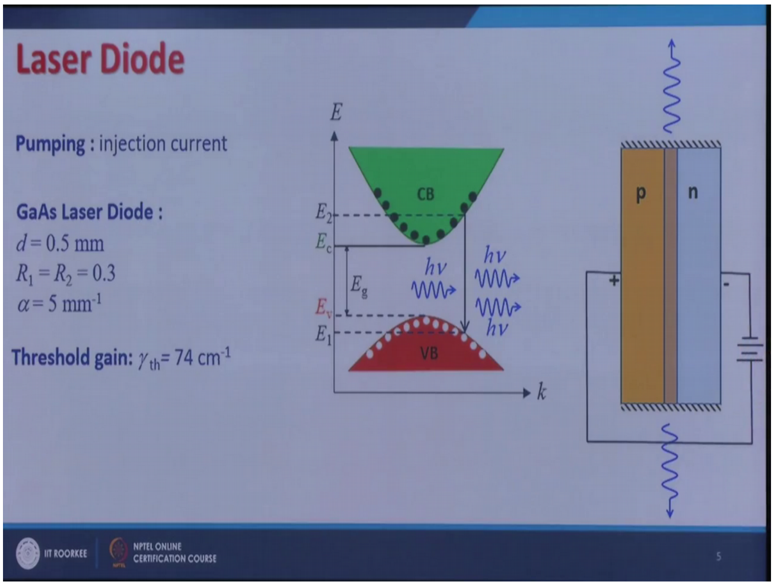

So, in a typical laser diode the pumping is by injection current. So, you provide forward bias current to this and when this current is greater than the threshold current or the game provided is greater than the threshold gain, then the lasing start. You have stimulated amplification and then because of feedback oscillation. So, laser starts working

Typically for gallium arsenide laser diode d is about half a millimeter, and if you do not put even the mirrors at the end of the cavity, the cavity is formed just by cleave surfaces then R 1 R 2 have typical value 30 percent, and scattering absorption loss coefficient is 5 millimeter inverse, then if you calculate the threshold gain then it comes out to be about 74 centimeter inverse. So, if I look at now the output power works the injection current characteristic of the laser diode, then what I would see initially when the current is low then I will have very small power coming out.

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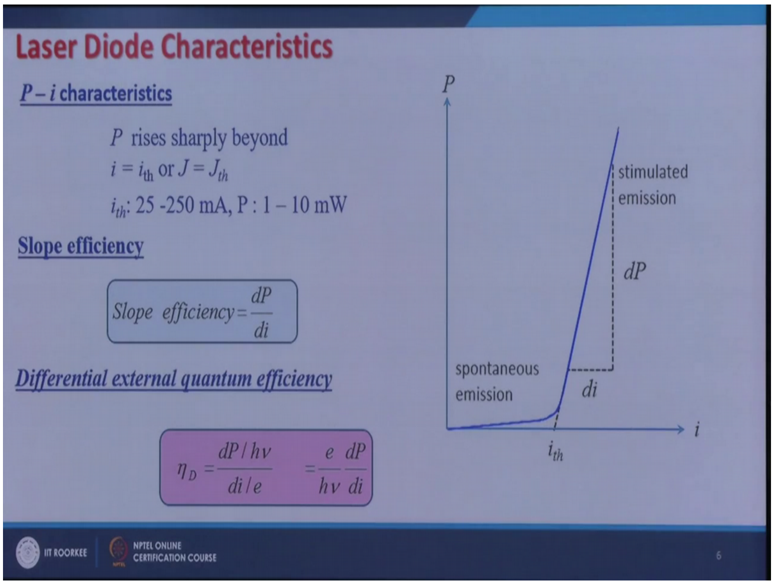

As I increase the current the power would increase, but is still it would not be very high and if I examine this then this radiation is not coherent radiation, which means this is not a laser this light is coming out due to the process of a spontaneous emission. So, in this region the laser diode works just like an LED. As soon as the current crosses the threshold value the power rises sharply and this is laser, this is laser action this is the power which is coming out of the process of stimulated emission.

So, this region below threshold this region is the region in which the laser diode operates as an LED, and in this region it operates as an LD or laser diode. Typically i t h is 25 to 250 milliamps and the output power that you get is 1 to 10 milli watts. And important characteristic of a laser diode is how much power would you produce per unit injection current. There is what is the slope of this line and this is known as slope efficiency denoted by d P over d i, another important characteristic is differential external quantum efficiency what it is? It is simply how many photons you would produce per unit injected electrons.

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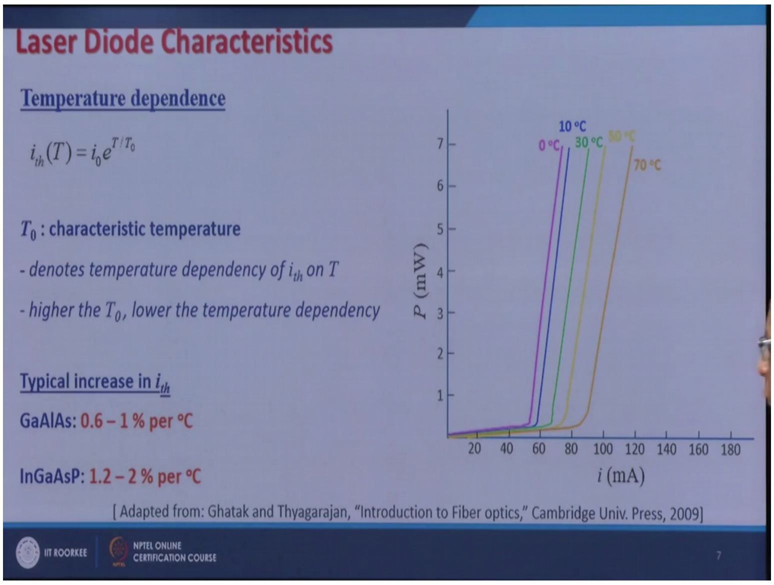

So, if you increase current around some value by an amount d i and correspondingly the output power increases by an amount d P, then the number of photons that are produced in this is d P over h nu, and the number of electrons injected per unit time are d i over e. So, this differential external quantum efficiency is the number of photons produced per unit time divided by the number of electrons injected per unit time, and it has to be smaller than 1 because we know that not all the electrons injected will result in radiative recombination.

So, not all the electrons injected will result into the photons. So, this gives you a finite is smaller than 1 differential external quantum efficiency. So, this I can write as by just rearranging the terms as e over h nu d P over di. So, I can write this as in terms of d P over d i or slope efficiency. Now what happens if I change the temperature of a laser diode? So, what I do I take a laser diode, and then see how the P i characteristics look like at 0 degree temperature, then I increase the temperature to 10 degrees, 30 degrees 50 degrees and so on and see the output characteristics the P i characteristics, and what do I notice is that when I increase the temperature the threshold current increases.

And if I fit an empirical relation between the temperature and the threshold current then this relationship fits very well this empirical relationship fits very well to the observed experimentally observed data and it is i t h at temperature t is equal to i 0 e to the power T over T naught, where i naught and t naught are the characteristics of a particular material or laser diode. T 0 is known as characteristic temperature and it denotes the temperature dependency of i t h on t of course, higher the value of T naught lower would be the temperature dependency.

Typically in gallium aluminum arsenide laser diode if I change the temperature by 1 degree, then i t h increases by 0.6 to 1 percent, and in indium gallium arsenide phosphide laser diode one degree change in temperature results in the change in i t h by 1.2 to 2 percent. Now let us look at output spectrum of a diode laser. So, I take a diode laser and observe its spectrum. So, what I do? I take a diode laser and couple its output to a spectrum analyzer, and then I slowly increase the current of this diode laser. So, initially when the current is small my optical spectrum analyzer shows this kind of graph.

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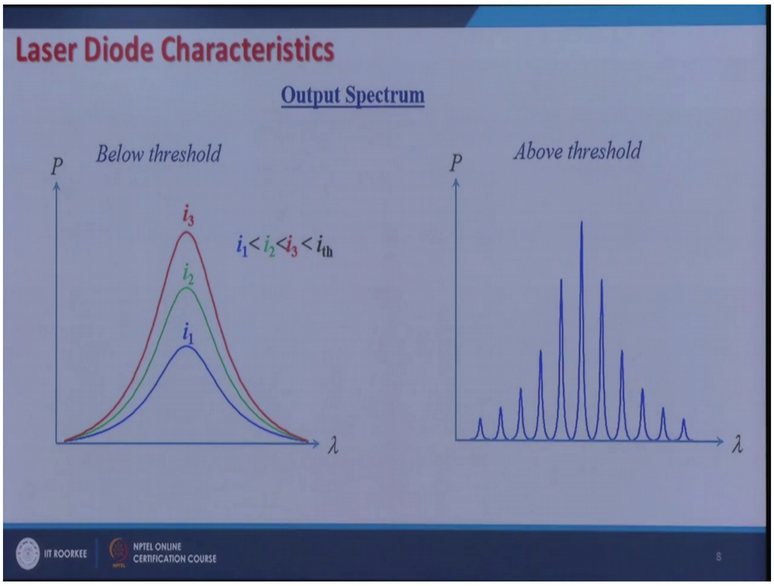

So, what I see? I see a very broad spectrum and the power level is not very high, when I increase the injection current then I again have the broad spectrum which slowly narrows down and the peak power increases, I further increase the injection current they spectrum again slightly narrows down and then the peak power again increases. But in all these values of current I m still below the threshold, and this is typical output characteristic of an LED. So, below threshold current I will get out of a spectrum which is similar to that of an LED.

When I increase the current beyond threshold then I see this kind of spectrum. So, this output in spectrum now transforms to these kind of sharp peaks equi spaced sharp peaks, and the power level is much much higher than the power level here. This is typical output spectrum of a diode laser, what would these peaks correspond to? These peaks correspond to multi longitudinal modes of the cavity it is nothing just fabry perot cavity actually. You have a resonator you have optical energy confined between 2 mirrors then you basically make a fabry perot cavity.

And you get an interference pattern something like this you will have certain frequencies you have certain frequencies which have 2 pipe a shift in a round trip and they go like this they are nothing, but just like if you take the analogy of a stretched string, then they are just like the modes of a stretched string what is the frequency of a longitudinal mode.

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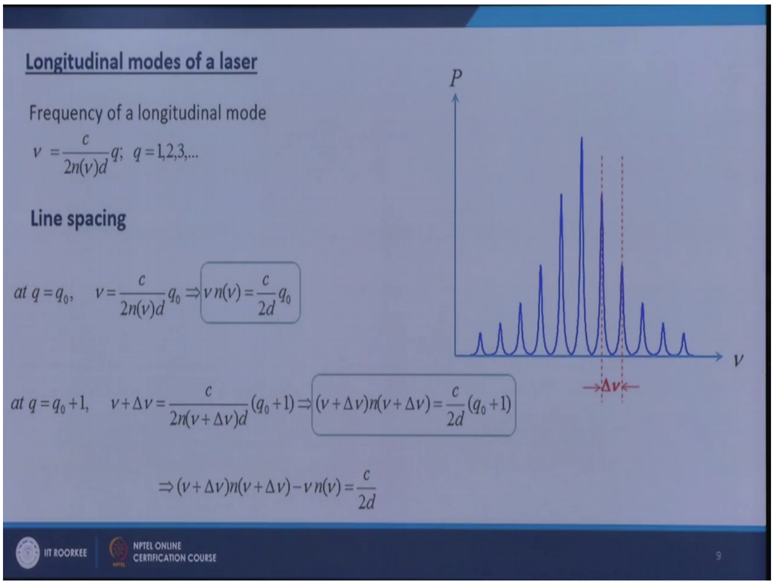

So, this can be very easily shown that the frequency of a mode can be given by c by 2 and d times q where q as an integer, and n is the refractive index of the medium and it is at frequency nu, d is the length of the cavity.

What is the spacing can I find the spacing between the 2 modes? Yes because I know what is the frequency of a mode then I can find out the spacing easily. So, if this particular line for example, occurs that the value of q is equal to q naught, then this nu would be c by 2 n nu d times q naught or if I just put all the frequency dependent terms on one side, then this nu times n nu would be equal to c over to d times q naught. The next one the immediate next one would occur it q naught plus 1 and let us say the frequency of this is nu plus delta nu that is line spacing is delta nu.

Then this new plus delta nu would be c by 2 n nu plus delta nu times b times q naught plus 1. Again I put all the frequency dependent terms on this side, and I get nu plus delta nu times n of nu plus delta nu is equal to c over 2 d times q naught plus 1. Let me subtract this from this and. So, I will get nu plus delta nu times n nu plus delta nu minus nu, nu is equal to c over 2 d, and now the task is to find out delta nu from this side.

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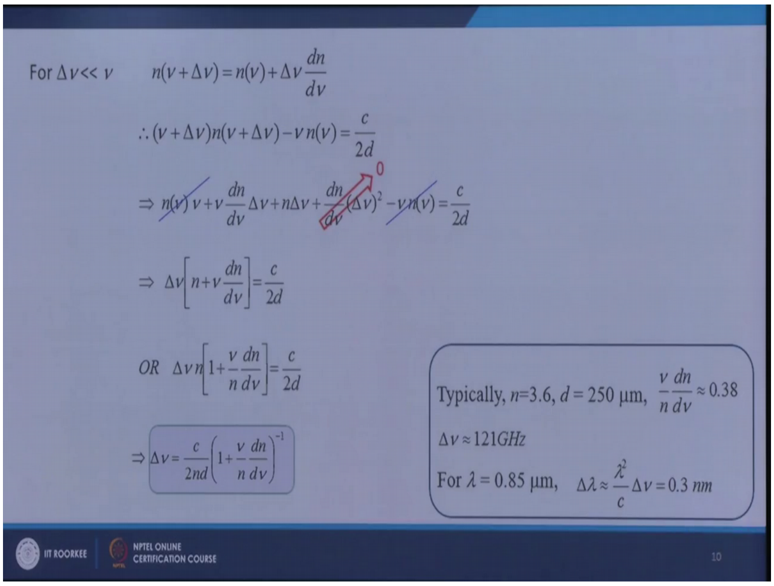

So, for that what I can do? I know this delta nu is much much smaller than nu then I can make a Taylor series expansion of n nu plus delta nu around n nu. So, it would be n nu plus delta nu d n over d nu, and I retain only first order term because the delta nu is much much smaller than nu.

Then this which I have in the previous slide nu plus delta nu times nu plus delta nu minus nu and nu is equal to c over 2 d. So, if I put this and nu plus delta nu here, and simplify then open the bracket then what do I get? I get this. Now I can see here that this n nu times nu would get cancelled from this term, and this delta nu is very small. So, this term I can approximate to 0 I can neglect this term. So, this gives me delta nu times n plus nu plus n plus nu times d n over d nu is equal to c over 2 d or if I take n outside. So, delta nu times n would be 1 plus nu by n d n over d nu is equal to c over 2 d or delta nu is equal to c over 2 and d times 1 plus nu over and d and over d nu inverse.

So, this is how I can get the line spacing; of course, if I neglect the dependence of refractive index of the medium on frequency then it is simply c by 2 and d, but if this dependence is strong enough then I will have to take this factor also into account. Typically n is 3.6, d is 250 micron and if nu over and d n over d nu is 0.38 around lambda is equal to 0.85 then delta nu would be 121 gigahertz.

If I put all these values here, I can also convert it into delta lambda because when I look at the spectrum in a spectrum analyzer I see power as a function of wavelength. So, it is more appealing to look into delta lambda as compared to delta nu.

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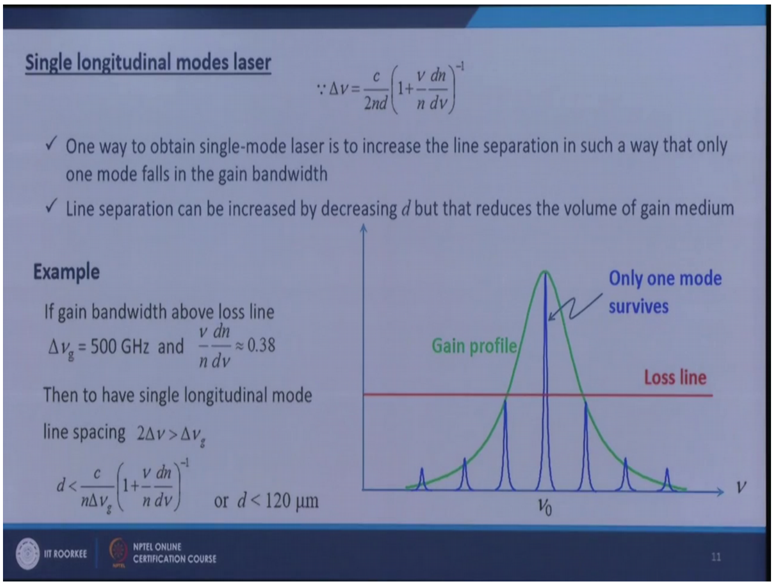

So, this delta lambda would be around 0.3 nanometers. How can I get a single longitudinal mode laser? Of course, now I have a laser, but it has got several lines, ideally I should have a laser which has only one wavelength and line width as narrow as possible. So, how can I have single longitudinal mode laser.

Well if I look at this frequency spacing line spacing then it is given by this. So, I can have a single longitudinal mode laser by 2 ways, one way is to increase the line separation. If I increase delta nu in such a way that only one mode crosses the loss line in the gain profile, then only one mode would oscillate. And how can I increase this line separation? I can increase this line separation by reducing the value of d, but the problem is that if I reduce the value of d, I also reduce the volume of the gain medium. So, I will have to increase threshold current.

If I look at this example here this green curve shows the gain profile and the red line shows the loss line. So, all the boards which are above this loss line will be oscillating. Now if I increase the line spacing such that, only one mode falls above this line then only this one will survive. Typical example is that if gain bandwidth above loss line is delta nu g that is this, which is 500 gigahertz and nu over and d n over d nu is 0 0.38, then to a single longitudinal mode line spacing is delta nu here delta nu here. So, this 2 delta nu should be greater than delta nu g then only one mode would be above this line.

Accordingly your d should be less than c over n delta nu g times this, and if you plug in all these numbers. So, this will give you the value of d which should be smaller than 120 micrometer. So, this reduces the volume of the gain medium significantly another way of doing.

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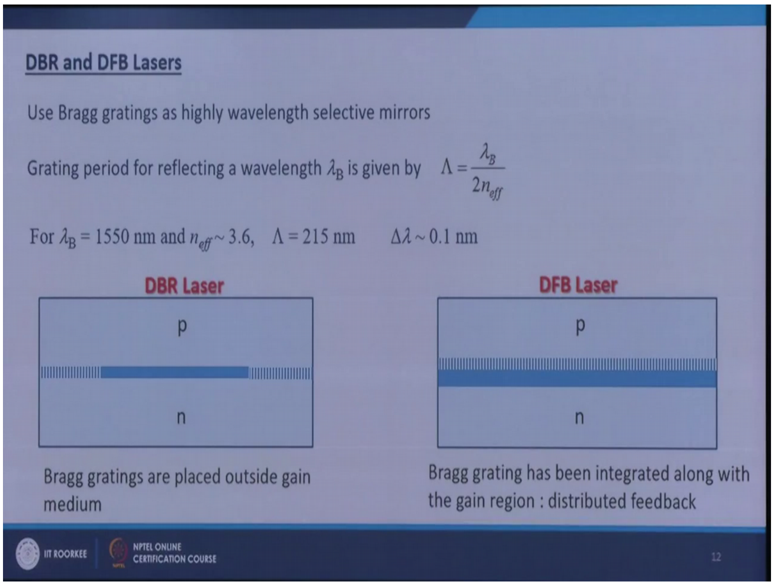

This is that you use mirrors which are highly wavelength selective. You use highly wavelength selective mirrors and we know from our previous knowledge of Bragg gratings, that if I have a Bragg grating then this Bragg grating reflect a particular wavelength and wavelength selectivity is very good ok.

I can have line width which is about 0.1 nanometer or 0.2 nanometers. So, I can put these kind of gratings Bragg gratings either at the end of the gain medium, outside the gain medium or I can integrate it over the entire gain medium. This kind of structure is known as distributed Bragg reflector DBR laser, and this kind of a structure is known as distributed feedback laser or DFB laser. What kind of periodicity you will require here? If you have lambda be around 1550 nanometer and an effective is typically 3.6 which is close to the refractive index of the medium, then the periodicity would be around 215 nanometers and typical line width you will get here is of the order of 0.1 or 0.2 nanometers.

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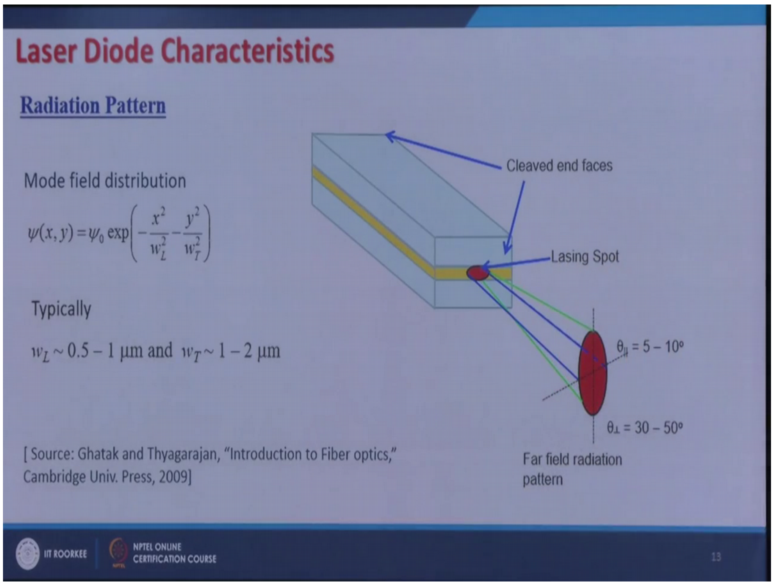

Another characteristic of a laser diode is its radiation pattern. So, how of course, we know the laser is highly directional, how directional the laser is that we get out of laser diode, how directional the laser diode is. So, if I look at this the light coming out of this then because of the structure of this, this is the multilayer structure and light is coming from a very thin region here very small region. So, this is the lazing spot and since it is a small then it diffract.

So, in this direction the dimensions are smaller. So, diffraction would be larger in this direction the dimensions are larger. So, diffraction would be less. So, accordingly I will have the radiation pattern which has peta parallel about f5 to 10 degrees, and theta perpendicular which is 30 to 50 degrees which is of course, much much better than that we get in the case of LED. The intensity pattern is Gaussian, so, if I look at the mode field distribution. So, it is given by psi x y is equal to psi 0 exponential minus x square over w L square, minus y square over w T square. So, in both the directions x and y direction I have a Gaussian, but the width is different typically w L is 0.5 to 1 micrometer and w T is 1 to 2 micrometer.

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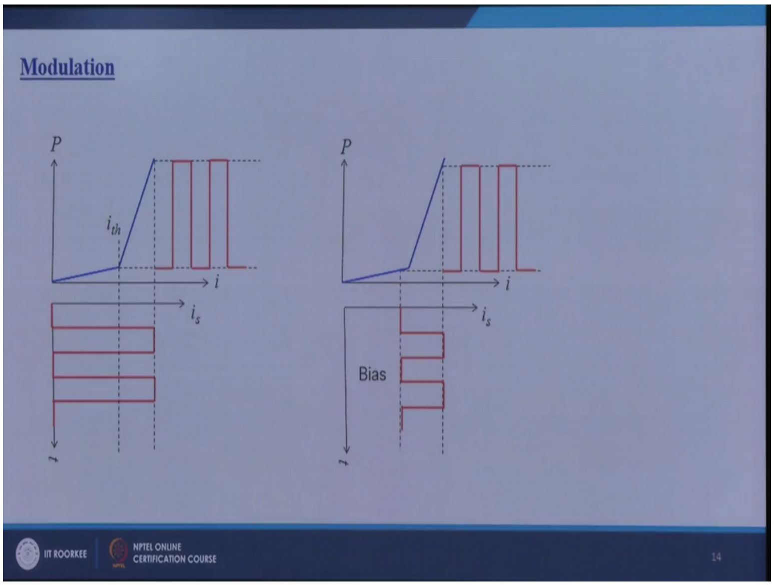

The last thing is that if I want to use this a this laser diode in communication, I need to modulate it. How do I modulate it? So, for that I look at P i characteristics and if my signal current goes like this, then when this signal current crosses this i t h my laser diode is switched on and when it goes below this then the laser diode is switched off, and accordingly I will get the modulated power like this. So, the current pulses will get converted into optical pulses, but here you see to switch this on I will have to increase the current to a much higher level.

So, my amplitude of the signal has to be very high. So, in order to avoid that what I can do? I can bias this laser diode around threshold and then write the signal over this, then it would be much more efficient. So, for efficient modulation of LD I should always modulate it near the threshold.

So, with this I finish the discussion on laser diode. In the next lecture I will start studying the photo detectors the receiver and of the communication system.

Thank you.