Optical Wireless Communications for Beyond 5G Networks and IoT
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Lecture - 04
Optical Sources (LASER)

Hello, everyone. So, today, we will continue with the Optical Sources. Last time, we had discussed about a light emitting diode, today we are going to discuss about another type of optical source which is called as LASER.

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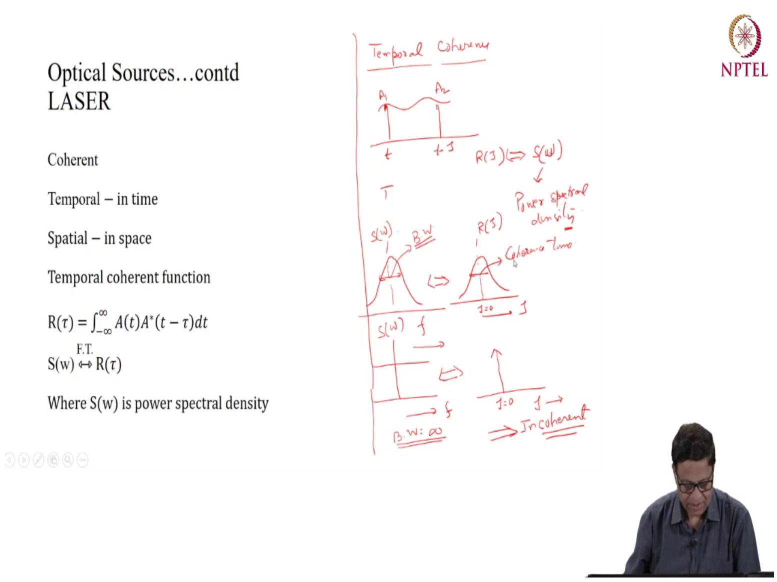

So, under this topic we will study about LASER characteristics, we will study about how LASER operates and what are the typical bandwidth of a LASER diode and what is a modulation bandwidth and we will understand different types of laser, types of noise it produces so on and so forth.

So, let us start our discussion with laser. So, LASER first of all is a coherent source of light. So, we need to first understand what is coherency and the coherency can be of two types. One is temporal coherence which is in time the other one is spatial coherence which is in space. So, let us try to understand temporal and spatial coherence.

So, temporal coherence: suppose there is a waveform something like this it has some amplitude A 1 at time t and at time t minus tau it is A 2. So, let us define a coherence a temporal coherence function as how this A 1 and A 2 are correlated. Temporal coherence function can be defined as R tau is equal to minus infinity to infinity A t into A conjugate t minus tau dt.

Now, we will see that this coherence function which is R tau forms a Fourier transform pair with S omega which is power spectral density this we should recall from signal and system of course, power spectral density ok. So, if R tau is something like this. This is tau is equal to 0, this is R tau; that means, if you correlate when tau is equal to 0 that correlate with the point itself then it has maximum R tau and as the tau increases the r tau value goes down.

So, if you get a curve like this then this is actually called as the coherence time where the value of R tau has fallen by some factors that depends on the definition whether it is 90 percent or 50 percent. So, that tells you the coherence time and this coherence time and if I take the bandwidth of this sorry, the Fourier transform of this Fourier transform of this.

Then this is sort of Gaussian. So, you will get a similar curve Gaussian curve here. So, this is f and this is actually the bandwidth. So, now, let us try to understand with some limits with extreme limits. For example, if you have the correlation function something like this and it is 0 for rest of the time, it is maximum at tau is equal to 0 which means these this waveform correlates only with itself with the same point otherwise it is 0. There is no correlation with any other point in this waveform.

So, and if I take the Fourier transform of such a thing, it basically gives you a flat response that is f and this is S omega, this was S omega. So, the bandwidth is actually infinite and which means the source is incoherent in time, right. So, now, let us try to understand the coherent in we can take the reverse of it that is let me explain with the next in the next page.

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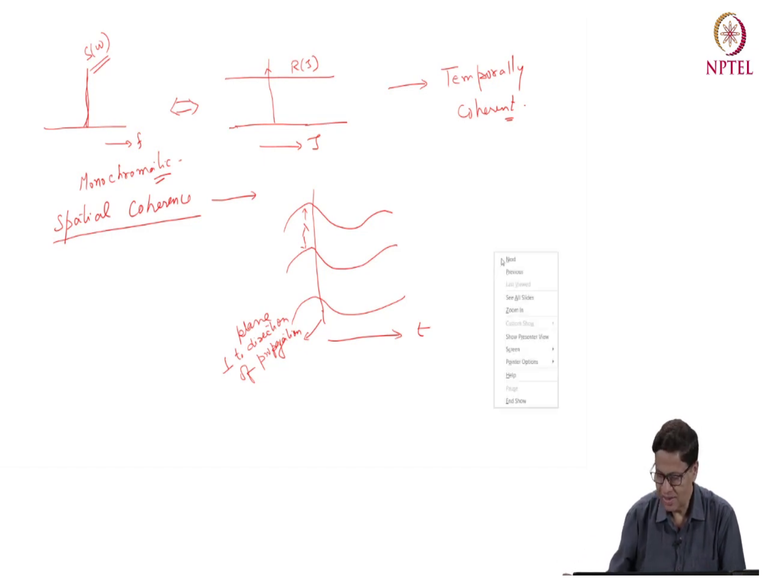

If I take the reverse of this that is I have this is my tau and R tau is same for all values of tau and if I take the Fourier transform of it this is f. So, this will give me a single line single frequency. So, this is S omega. So, if the coherence the R tau the correlation function is flat for all values of tau and if I take the coherence, then I get a single line.

So, this source is actually monochromatic and the source will be called as temporally coherent ok. So, now, let us try to understand the spatial coherence. As I as explained you earlier that the coherence is of two types, temporal coherence and spatial coherence, I have discussed the temporal coherence and then let us discuss the spatial coherence.

So, if I have a waveform which is something like this in I am saying in spatial domain and this is a plane which is plane perpendicular to direction of propagation and this is separated by say lambda wavelength. This is the t.

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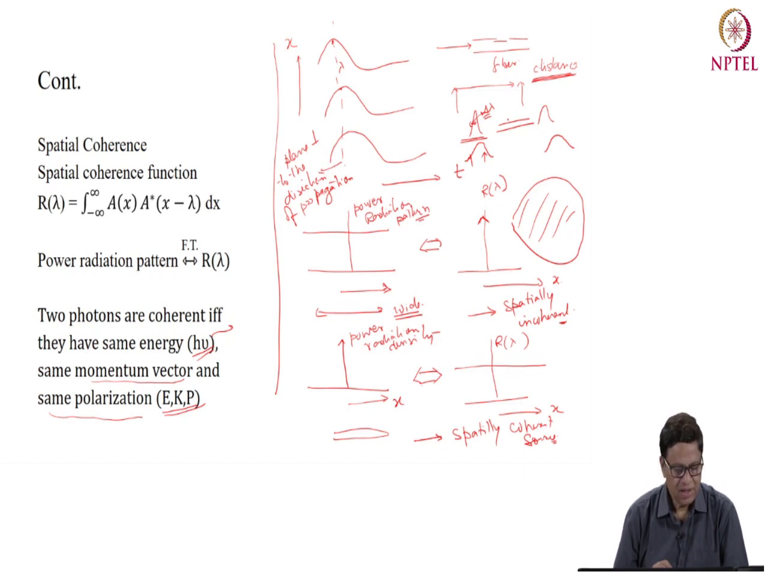

Now, if I take if my coherence function the coherence function in this case will be defined as R lambda is equal to A x into A conjugate x minus lambda. So, let me explain in front in this sheet itself. So, let me redraw again. This is some wave form and this is a plane perpendicular to the direction of propagation plane perpendicular to the direction of propagation and the spacing between these two points is say lambda and this is t.

So, as you see the spatial coherence function is defined as R lambda A x into A star x minus lambda this direction is x. Now, if I take the coherence R lambda plot R lambda versus x and if it is a; it is something like this that it is you know 0 at all value of x and it has maximum at x is equal to 0.

And, if I take and we know that the Fourier transform of spatial coherence function is how the power is radiated or power is spread or what is the pattern of power in a spatial domain which we can call as power radiation pattern R lambda. So, if I plot R lambda, then this will be it will be flat here. So, let me call this as power radiation pattern power radiation pattern.

So, this R lambda and power radiation pattern they form a Fourier transform pair. So, when the R lambda is has a impulse kind of characteristic, then the power radiation pattern is actually wide. The power is emitting in all the directions, so, wide emission of power.

So, the power which is coming from the source is emitted in all directions. So, this kind of source is actually spatially incoherent spatially incoherent because in some cases we want the power to be directional and we do not want that power should be spread in all the directions.

So, on the other side if you have R lambda which is constant over all values of x and if I take the Fourier transform of this, this will give me a impulse kind of thing. So, this is power radiation pattern not density you can write. So, this is in space x and it gives you highly directional power in one particular direction.

So, in this case the power is actually emitted in all area; whereas, in this case the power is emitted in a very very narrow or it is focused or it is directional. So, this kind of source is called as spatially coherent source. So, we have understood the difference between temporal coherence and spatially coherence.

So, the photons which are emitted they will be called as coherent if and only if they have the same energy h nu which basically tells that it has single wavelength, same momentum vector it tells about the power radiation direction that the power is highly directional and it should be same polarization. So, it should follow this triplet the energy and the momentum and the polarization.

So, LASER devices in generally they follow they are coherent both in time and in space which means they are spatially as well as temporally coherent. And, the benefit of spatially coherent is that the light is in one direction. So, you can couple maximum light in the fibre, right and if you have for example, you know a free space link and this is the receiver here and you want that they should all the light should get focused on the receiver.

So, you are looking for a very very coherent spatially coherent light so that it is directional and falls on to the receiver. So, spatially coherence is the property of temporal coherence is. So, this is the property of spatial coherence is used here. So, this is it give you the actually advantage in terms of distance.

So, if your light is directional, not spreading in the in all the directions then it will give you advantage of that you can cover a long distance and more light or more light can be covered in to the fibre. So, which gives you ultimately a long distance communication. If the LASER is temporarily coherent; that means, it is emitting almost monochromatic source, but in actual practice you do not have monochromatic source. So, it is roughly there is some bandwidth delta lambda.

We will discuss about this delta lambda little later. So, but the advantage of narrow spectral with delta lambda is that in the fibre the wavelengths which are there inside this delta lambda they when they travel inside it. So, they may not be you know significant amount of dispersion. If this is wide for example, you know because each wavelength will travel at different will travel at different velocity which will arrive at different times.

So, you will see you know spreading of pulses whereas, if it is narrow you have only few wavelengths and they are very close to each other and they travel almost with the same velocity. So, you may not get you know dispersion of pulses. So, you can have high data rate.

So, temporally coherent and spatially coherent are both useful property which can give you a long distance communication and which can give you high data rate communication.

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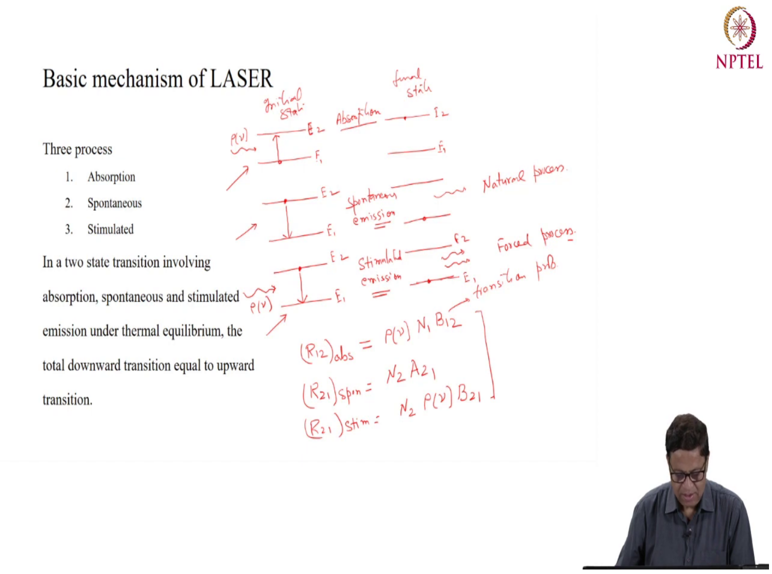

So, after understanding the coherency part, now let us try to understand the basic mechanism of LASER diode. So, there are three processes which are happening in matter and those processes are absorption – I will discuss little in detail about this absorption process; spontaneous process and stimulated process.

Let us understand what are these processes. So, the absorption processes is the absorption process is actually if you consider A 2 level system with energy E 1 and E 2 and there is some flux density say rho nu is falling on the matter this is E 2. Then the electrons electron from low energy state will go up because of this rho nu. So, the final state will be this is E 1, this is E 2, the electron has come here. So, this process is called as absorption.

The 2nd process is spontaneous. This spontaneous what happens? Again, let us consider two energy level system E 1, E 2, the electron which is there in the excited state naturally or spontaneously falls down to the low energy state and in the process it will emit energy. So, this energy and electron has come here. So, this is the final state and this was initial state. So, this process is called as a spontaneous emission. This is a natural process natural process happening all the time natural process.

The 3rd process is stimulated. So, what happens in stimulated? Again, let us consider two level system E 1 and E 2, and if the light flux density falls rho nu falls on to this matter then electron from here is actually forced to come down to lower energy state. And, in the process it is emitting more photons. So, this is E 2, this is E 1.

So, this process where you are forcing the electron to come down as a result of this input flux density is called as stimulated emission. This is a force process, you are forcing electrons to come down forced process. So, in a two state which I have discussed here, the transition involving absorption, spontaneous and stimulated emission under thermal equilibrium, the total downward transition is equal to upward transition in a steady state situation.

So, in this case it is upward transition, in this case this is downward, in this case also this is downward. So, upward transition is equal to downward transition, ok under steady state or under thermal equilibrium. Let us write some basic equations which we will not solve those equations, but I have just mention about those equations.

So, if I consider for example, the absorption part then the absorption rate R 12 is equal to rho nu that is a flux density falling on to it and it is proportional to the number of electrons in the E 1 level which is say N 1 and the probability is the probability that electron is here and is absorbed is given by B 12. These are transition probabilities. So, this is transition probability.

Similarly, I can write for a spontaneous emission. So, spontaneous emission will be R 21 because it is coming from two E 2 to E 1. This is spontaneous. This will be it is proportional to actually a number of electrons in higher energy state that is E 2 which is N 2 and the transition probability is A 21. So, this is the transition probability of going from higher energy state to lower energy state which we call it as spontaneous emission.

The third rate is stimulated. So, the stimulated will be again R 21 stimulated and it will depend how many electrons you have in the higher energy level that is N 2 and rho nu is your flux density and the transition probability will be B 21. So, these are the three basic equations and then you know to solve for different transition probabilities A 21, B 12, B 21 we will have to equate all the you know downward transition equal to the upper transition and then using some mathematics you can find out the values of A 21, B 21 and B 12.

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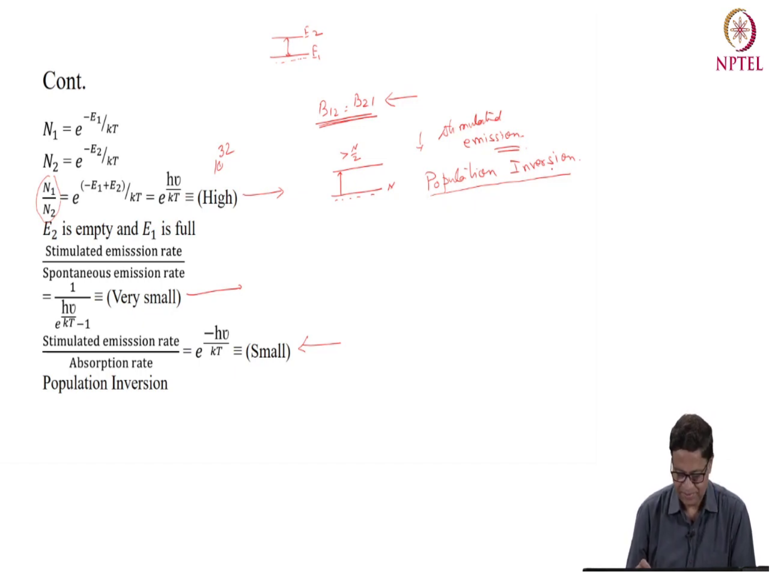

So, now, let us understand some interesting facts which are happening. So, if you see the number of electron density at energy E 1 is given by e raise to the power minus E 1 by kT where k is a Boltzmann constant and T is the temperature. Similarly, for N 2 it is given by e raise to power minus E 2 by kT. So, if I take the ratio of N 1 by N 2, it will give me e raise to power minus E 1 plus E 2 divided by kT which is nothing, but h nu.

This this difference is h nu here and if you put the values of Plancks constant and some typical frequency and Boltzmann constant and temperature you will see this value is very very high. So, the I think I have the order of 10 raise to the power 32 its quite high which actually means that at steady state or under normal conditions all the electrons are here at the E 1 level practically there is nothing at E 2 this is what it means. E 2 is empty, and E 1 is full.

Now, I try to calculate the stimulated emission rate versus spontaneous I find out the ratio of stimulated emission rate and spontaneous emission rate. So, again this is actually given by a formula 1 by e raise to power h nu minus h nu by kT minus 1. So, we have already earlier seen that e raise to power h nu kT is very very high. So, 1 divided by some you know big quantity gives you very very small.

So, what basically it means that stimulated emission rate is actually not happening practically right because this ratio is very small. So, under normal conditions there is no stimulated emission happening. So, this is another interesting way, this is one in fact. The another fact is this.

And, now, if I find out a ratio of stimulated emission rate with respect to absorption rate this gives you this gives me e raise to power minus h nu by kT and since this was e raise e raise to the power h nu by kT by putting you know typical values of h nu and k and T this is going to be very very small which means the stimulated emission rate is also negligible you know as in comparison to absorption rate.

So, earlier when we were discussing about those probabilities A 12 and B 12 and B 21 it can also be found that B 12 is equal to actually B 21 then; that means the probability of stimulation and the probability of absorption actually they are equal. But, this condition is not there at the moment, we have to create this condition, right. So, right now stability emission rate and absorption rate this ratio is quite small.

So, you have to create a condition and we understood from earlier analysis that B 12 is equal to B 21 that is the transition probability of stimulated and absorption they are same. But, it is not happening naturally. So, if you want that you know stimulated emission should dominate then you have to create that condition.

And, how do you create that condition? You pump some of the electrons from here to the higher state and in fact, you suppose this is n number of electrons roughly and you should pump greater than n by 2, then the stimulated emission will dominate stimulated emission will dominate.

So, what actually I have done essentially by lifting the electrons from the ground state to the higher state more than half? I have done population inversion. So, the moment I achieve this population inversion the stimulated process takes over, stimulated process dominates and we get stimulated emission.

This is the basic principle of LASER, say you have to create, you have to pump, you have to give energy using a pump and transfer more than half of the electrons from the ground state to the higher state and then when flux density falls on to the matter it forces those electrons to come down and they all emit photons and this process is called as stimulated emission and the LASER is based on this process.

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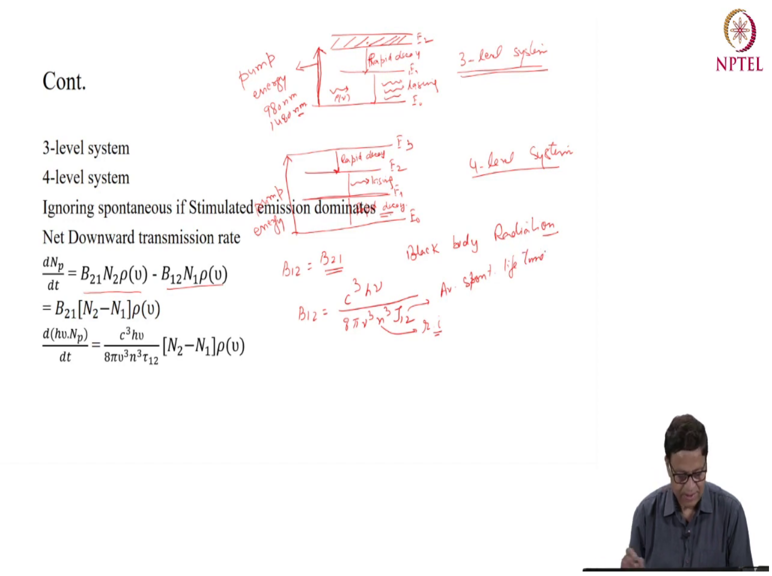

So, basically there are different types of LASER system, we will discuss the 3-level system first. So, 3-level system is basically you have three levels here; say this is energy E 0, E 1, E 2. So, first you give some pump energy, it can be a source another source of light so that the electrons are lifted and they are lifted to energy level E 2. In E 2 they stay here for very very less time and then there is a fast decay or rapid decay to E 1. And, from E 1 the electrons they fall on to the ground state and they emit your energy.

So, this is an example of a typical 3-level system and this is actually pump energy pump energy and this is corresponding to this frequency or this wavelength. So, typical pump energy which is used as in 980 nanometres or 1480 nanometres you know there are different wavelength which are possible that depends on the material which you are using. So, by using pump energy you are shifting the electrons from the ground state to higher energy state and they stay there for very small time.

So, there is a rapid decay to the lower energy state that is E 1 and from E 1 to E naught there is a emission of light and this is your input signal rho nu. So, it will force all those electrons which are there in the E 1 state to fall down to E g E naught and then emit more number of photons. So, this is basically a 3-level system.

One can also use 4-level system. Here in this case you have to practically you know pull at least half of the electrons to the higher state. So, you require more amount of pump power or pump energy, but if you have a 4 level system this criteria of high pump energy is relaxed. So, let us understand this. So, suppose there are 4 level systems starting E 0, E 1, E 2, E 3. So, this is your pump energy and then there is a fast decay rapid decay here.

So, even if one electron has come here in this point at this point there is already population inversion with respect to E 1 there is already population inversion, right. So, you require less amount of pump energy to create population inversion and the moment the this is the lasing part the electron will fall to E 1 and emit light.

So, this is lasing operation here. I forgot to write here as lasing and then from E 1 again there is a rapid decay. So, this is an example of a 4-level system. The advantage of 4-level system is that you require less pump energy to create population inversion which is a requirement for lasing.

So, let us after understanding this 3-level system, 4-level system. Let us now try to understand the temporal coherency part which we had discussed what why a LASER source is a temporal coherent. So, now, once you have achieved a stimulated emission I can always ignore spontaneous emission because now stimulated emission is dominating. So, spontaneous emission is much much less as compared to stimulated. So, I can simplify my analysis by ignoring spontaneous emission.

So, the net downward transmission rate will be that is rate of N p number of photons generated with respect to time is minus this minus this. So, one of them is stimulated the other is absorption and we are ignoring or neglecting the spontaneous emission. So, this is the rate and as explained you earlier that if you are solving those Einstein relations which I had given you in the beginning then basically this B 12 is equal to B 21.

That means the probability the transition probability of absorption and transition probability of stimulated they are actually same. So, this B 12 can be taken common. So, this becomes N 2 minus N 1 rho nu and if I multiply by h nu N p, then I get this equation this actually comes from the fact when you start when you also consider black body radiation theory black body because this matter is emitting some light.

So, this can be equated to a black body radiation and if you equate these Einstein Einstein relationship with black body relations then you get the value of B 21 which is written here. This will be c cube divided by 8. So, the value of B 21 or B 12 will be c cube h nu over 8 pi nu cube n cube tau 12; where c is the velocity of light, h is Planck's constant and nu is the frequency, n is the refractive index of the material and tau 1 is the average spontaneous time lifetime average spontaneous lifetime of the photon.

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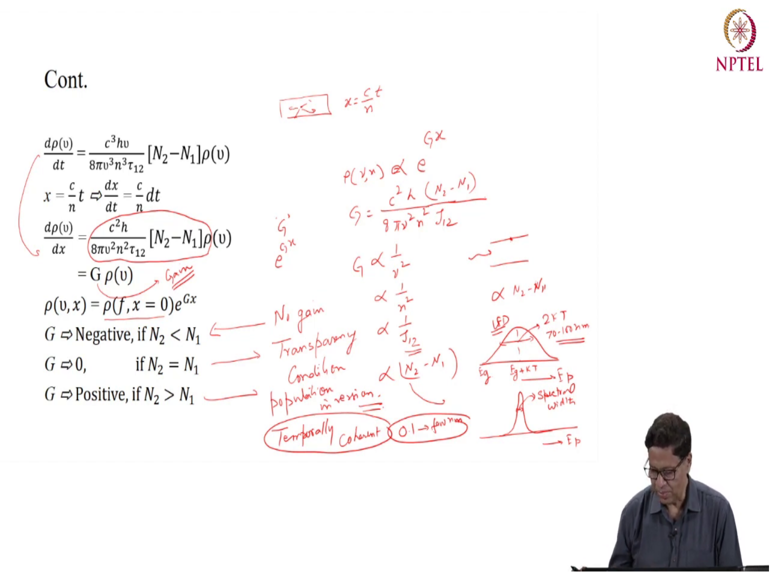

So, this becomes rate of flux density that is d rho nu because N p into h nu is flux density flux density rho nu d rho nu divided by dt is equal to this. And, since the photon which is generated inside a material is moving in all the directions. So, this can be written as in the form of dx, where x the distance travelled is c by n and is refractive index into time. So, if I differentiate dx by dt, I get c by n. So, so this becomes actually this dt will not be there, ok.

And, so, you can write this as this equation as d rho nu by dx is equal to c square h 8 pi nu square n square tau 12 N 2 minus N 1 into flux density. So, this whole thing can be written as a G which is actually called as the gam. And, if I solve this equation, so, this will becomes flux density as a function of distance inside the inside the cavity LASER cavity and function of frequency.

So, this is given by some constant rho f at x is equal to 0 into e raise to power Gx. So, notice here that G the gain factor is writing on exponential is writing on the exponential. So, so the power as a function of x is proportional to e raise power Gx, it is growing very rapidly because this G function is coming at the in the exponential.

And, if you see this G function the G is actually c square h over 8 pi nu square n square tau 12; that means, the gain is actually proportional to inversely proportional to nu square also inversely proportional to n square refractive index and is also inversely proportional to the average spontaneous lifetime of the photon.

Which means actually what it means that if tau 12 is small G is high which means if you consider 2-level system and if this tau 12 is very very small; that means, it is you know spontaneously falling to ground state very rapidly and you know this is aided by the input flux density. So, that is why this gain is actually the spontaneous is actually adding to the gain. So, it explains why G is proportional to tau 12.

So, this is the; this is how the flux density will grow inside the cavity which is e raise to the power Gx. So, now, let us try to understand you know G this particular G this G sorry I did not write the other things N 2 minus N 1 also right, sorry. So, this G is this and G is proportional to N 2 minus N 1. So, this G will be negative if N 2 is less than N 1; that means, the number of electrons in N 2 is less than at N 1 that is at energy E 2 as compared to E 1. So, that means, there is no gain here no gain.

If G is 0 which means number of electrons in the E 1 state and the E 2 state on an average the same so, the gain is unity. So, it is a transparency condition neither gain nor loss transparency condition if G is positive; that means, N 2 is greater than 1. This is a condition of population inversion you have more number of electrons at higher energy that is at E 2. So, this is a condition for population inversion.

So, G is positive if N 2 is greater than N 1 and it is a condition of population inversion. So, if you recall last time when we were discussing about light emitting diode, the gain or the power which was getting generated from LED was proportional to N 2 minus N 1 and it gave me something like this though this was E p h and this was 2 k T and it had a peak at band gap energy plus k T and this E g was 0 here this is E g.

Whereas in case of LASER diode, if I plot the same curve E p h and because G is riding on the exponential and the power is increasing at exponential rate so, the same curve will become very narrow. And, this in this case this is the spectral width of the LASER diode because of this whole stimulated emission process. So, this is the spectral width.

So, the spectral width of a LASER diode is very very low and typical LASER diode has a spectral width of 0.1 nanometre to few nanometres; whereas, in the LED case we had discussed or we had calculated the order of 70 to 100 nanometre. So, we can now say that this source is temporarily coherent. So, we have done some analysis and understood why the spectral width in case of LASER diode is very less and the source is temporarily coherent.

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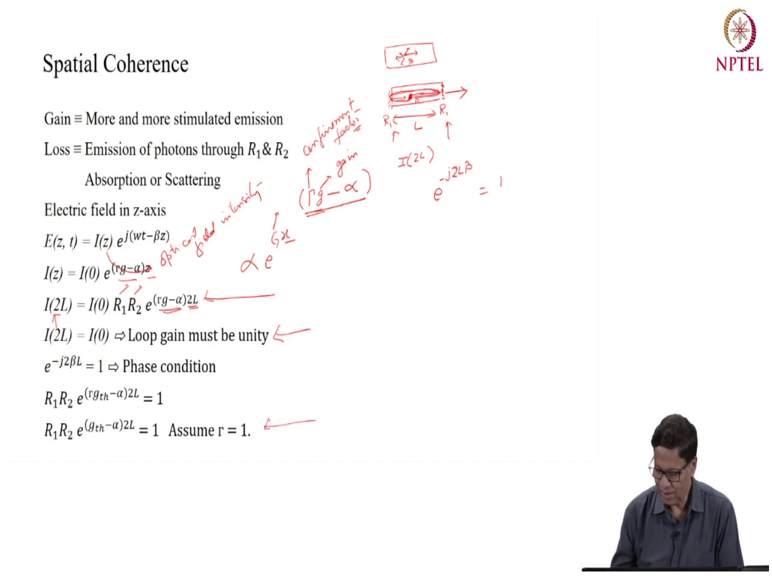

Now, let us see the other part that is a spatial coherence. So, inside a LASER cavity for example, the electron is moving with some propagation constant beta. And, it is actually going in all the directions whereas; we want some useful light to come out of through one of the facet of this structure.

So, in order to do that two mirrors are kept at the end and the electron which is for example, generated here has some propagation constant beta strikes this mirror gets reflected, strikes this mirror, gets reflected comes back here and in the process some of energy comes out because the reflectivity of the mirror is such say this is R 1, this is R 2 that some percentage of the light comes out, the other is stays inside the LASER cavity.

So, in order to have spatial coherence we want to have you know high gain that is more and more stimulated emission, so that it compensates for the loss and the loss is happening because of you know some light is coming out of this R 1 or R 2 and some absorption happening inside the material, some scattering happening inside the material. So, we want to have to want to want to have some sustained oscillation and want to have continuous output.

So, I need to ensure that you know LASER acts as a oscillator not as an amplifier. So, in order for this to have sustain for LASER to have sustained oscillations we want to use this LASER as an oscillator and for that we need to have some few conditions to be satisfied that we will understand.

So, first let us understand what is the electric field in the z-axis. This is given by E z, t I z this is optical field intensity optical field intensity into e raise power j omega t minus beta z if the electric fluid is in the is in the z-axis. And, this I z 0 is given by e raise power tau g minus alpha z where tau g, g is the gain and this is the confinement factor how the light is confined confinement factor. And, this basically gives you some idea about the gain the total gain in the system.

And, then there is some loss happening which is say alpha and this loss is some light coming out of the mirror some light is getting absorbed, some light is getting scattered. So, this is actually the net gain. So, I z as a function is a function of because earlier just now we I mean we had seen in the last lecture that the growth of flux density is e is to power G x.

This is how the flux density is growing, where G is the gain. So, in our case the net gain is tau g minus alpha which is here and x this is this was in x and this is in z direction. So, this is how the optical field intensity is growing I z is equal to I naught into E gamma G minus alpha z.

And, if you see you know that this distance is L, if it travels a distance of 2L which means the photon suppose a photon is generated here, it travels this distance gets reflected from the mirror, comes here, again reflected from the mirror comes back to the same position. So, basically it has travelled a distance of 2L which is here.

So, this I 2L will be I 0 into the total distance this is 2L and this is the net gain and these are the reflectivity of the two mirrors because it has encountered two reflections one at this point and another at this point. So, this is the optical field intensity after traversing a distance of 2L is equal to I naught the initial which is when it was generated in the middle and R 1 R 2 reflectivity of the mirror into e raise to power g which is the net gain into 2L.

So, for LASER to be as LASER to act as an oscillator, we need to satisfy two conditions: one is the loop gain must be unity that is I 2L is equal to I 0, the intensity when it has traversed distance of 2L should be equal to I 0. So, this is one condition. The other condition is a phase condition which happens typically in oscillator. So, E raise to the power minus j 2L this is a distance into the propagation constant should be 1. So, these two conditions should be satisfied. It will ensure that the LASER operates in a continuous in a continuous fashion or it is in an oscillatory mode.

So, if I put use one of the condition that is I 2L is equal to I 0 and put in this equation here I get R 1 into R 2 e raise to power gamma g th, this is the threshold gain because this is the gain which I require for oscillation. So, this g becomes g th g threshold minus the loss into 2L is equal to 1 and know without you know losing any loss of generality I can assume this gamma to be 1.

So, this is slightly you know becomes little easier and modified R 1 into R 2 e raise power g th minus alpha into 2L is equal to 1. So, this is one of the condition.

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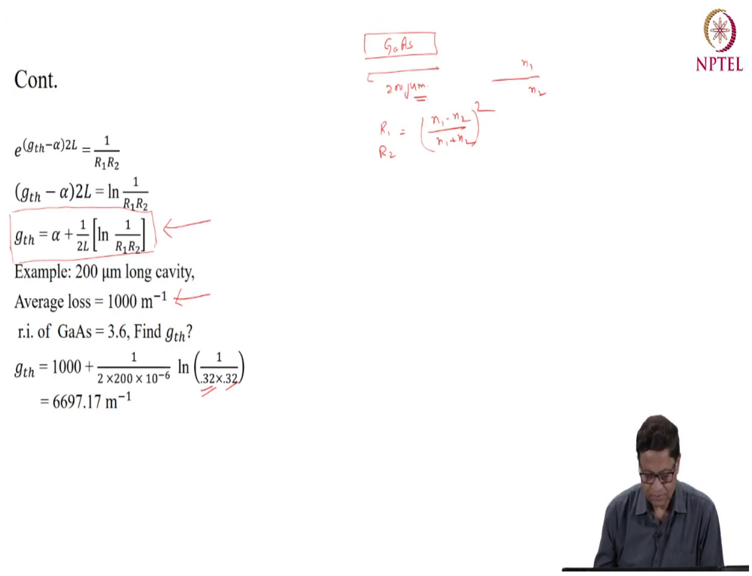

So, this is rewritten here and I can find out the value of g th by taking log natural both sides. So, this gives me g th minus alpha into 2L is equal to log natural 1 by R 1 R 2 and this is the expression for the G threshold that is a gain required which is alpha, the loss happening inside the cavity LASER cavity plus 1 by 2L into log natural 1 by R 1 and R 2.

So, let us try to find out the some typical value of g th. So, suppose I have a LASER cavity and the length is say 200 micrometers and the average loss that is alpha is given by 1000 meter inverse, this is per unit distance. So, and the material of this LASER cavity is gallium arsenide. The refractive index is about 3.6; then we need to find out what is the g th required for sustained oscillation.

So, if you put in these values in this expression here, you get g th as recall that R 1 and R 2 can be calculated as n 1 minus n 2 over n 1 plus n 2 whole square. This is how you find out the reflection the reflection coefficient. So, this is n 1, this is n 2, then this is interference, right. So, by putting some typical values of R 1 and R 2, I get g th as 6697.17 meter inverse or per unit meter. So, this is the value for the g th.

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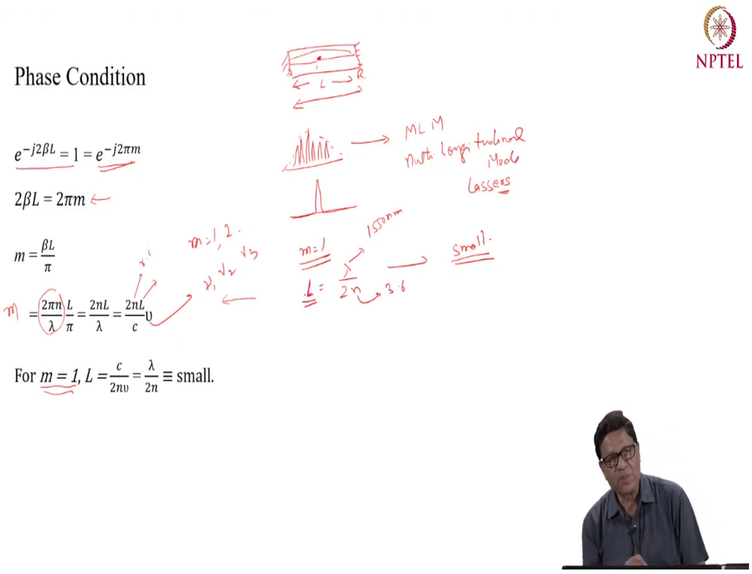

Now, let us try to understand the phase condition. We have understood about the gain part and now let us try to understand the phase condition. So, as I explained that the phase is for a distance of 2L. So, whenever suppose this photon is generated, it gets reflected from here, it gets reflected from R 1 and then travels and then again reflected and R comes back to this the total distance covered is 2L. So, the phase condition is that E raise to power minus j 2L into beta should be equal to 1.

So, this can be written in this form. This one is equal to e raise to power minus j 2 pi m. So, this gives you 2 beta L is equal to 2 pi m, where m is some integer and if you see m is equal to beta L by pi. So, I get this value of beta L by pi. So, this condition will not be satisfied for all the frequencies. So, this will be only then I can write this actually little more in in new form and in the frequency form.

So, beta L is actually 2 pi n by lambda that is beta into L by pi and if you simplify what you get is 2 n L divided by c into I, where L is the cavity length and n is the refractive index and mu is the frequency and this is m. So, this m can take some value m is equal to you know 1, 2 and so on and so forth; that means, this condition will be satisfied only by some few frequencies which are say nu 1, nu 2, nu 3 it is not satisfied by all the frequencies.

So, so what happens actually in an actual LASER diode? You get you know different frequencies here they may change in amplitude but you get different frequencies which are governed by these equations. And, if you take you know envelope of this so, this is something like this, right. So, this kind of LASER where you know many such m are excited and the dimensions are such that many modes are excited, such kind of LASER is called as MLM lasers or Multi Longitudinal Mode lasers.

So, suppose I want only and this will have some bandwidth or some spectral bandwidth spectral width. So, suppose ideally I want you know a single you know wavelength or to be excited; that means, I should have m is equal to 1, only in that case I will be able to get only one mode. So, if I take m is equal to 1, then and put the value of 1 here then I get some L as lambda by 2n, and if you put some value of lambda you know say 1550 nanometer and n you assume to be 3.6.

So, this L is actually very very small I mean one can construct a laser, but this L is going to be very small when this L is very small it cannot I mean such kind of source cannot emit high power. Otherwise it will get burned because you know the power generated per unit area will be very high. So, if you want to have a single mode LASER then one has to keep the LASER cavity length very very small and which you may not get good enough power if your L is very small.

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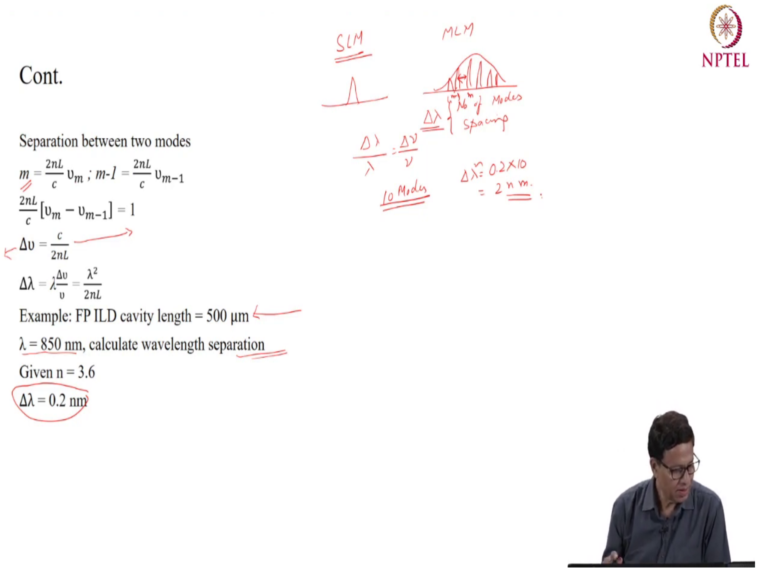

So, now let us try to find out the separation between two modes. So, as I told you there are SLN if it has only one mode that is called a single longitudinal mode, the other one which I had explained is multi longitudinal mode where you have you know many modes and single mode will have something like this.

So, now if I want to find out what is the spacing between these two modes and once I know this is spacing n number of modes so, then I can find out the spectral width. So, number of modes and spacing if I know these two factors, then I can find out what is the delta lambda or the spectral width of the LASER diode. So, to try to find out the separation between two modes m is equal to 2nL divided by c nu m corresponding to mth mode, this is what we did just now.

And, if you want to see m minus 1 mode this is say m mode this is m minus 1 this one. This will be given as 2nL divided by c nu m minus 1 and if I find out the difference between n m minus nu m minus 1 it will be something like this c by 2nL and I can write this in terms of delta lambda by using expression delta lambda is equal to lambda is equal to delta nu over nu.

So, this is in delta nu and I want in terms of delta lambda because normally the spectral width is expressed in terms of delta lambda or in terms of nanometer. So, this will be delta lambda square divided by 2nL. So, if I take a simple example and to give you some idea about delta lambda.

So, suppose I have a Fabry–Pérot injection LASER diode with a cavity length of 500 micrometers and lambda is equal to 850 nanometer I mean this is a lambda I am trying to I am trying to I am trying to I am trying to work at lambda is equal to 850 nanometer. So, I need to calculate what is the wavelength separation given the refractive index of the material is 3.6.

So, a simple calculation will give you delta lambda as 0.2 nm and suppose 10 modes are supported by that diode; that means, m is equal to 1 to 10, then the total spectral width will be actually roughly 0.2 into 10 or 2 nanometers.

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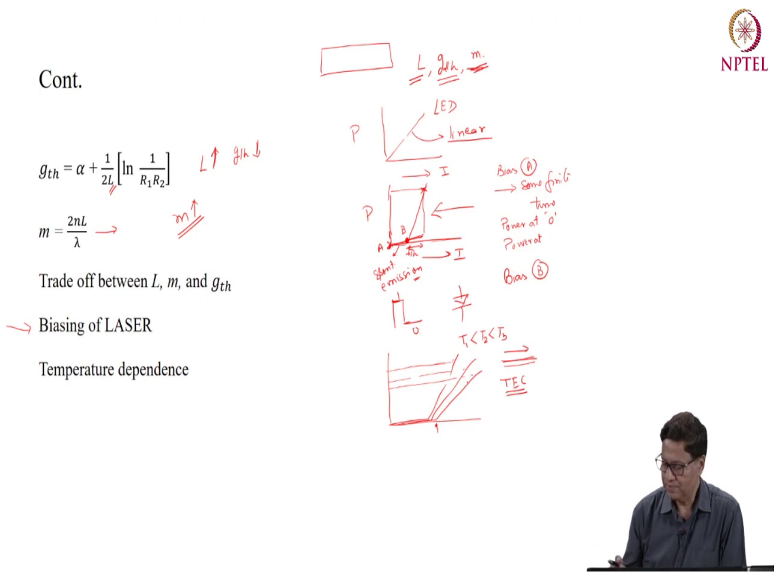

So, this explains about the spectral width. And, now let us try to find out what is a trade off while designing a LASER diode. So, there are three things which is in the hands of designer the length of the cavity and g th and m. So, as you see there is a trade off between L sorry L g th h and m.

So, if you increase L suppose the L increases then g t if L increases g th will increase g th will decrease and if L increases in this expression if you see the m is increasing. That means the number of modes which are supported are increasing which actually effectively is increasing your spectral width, right and when L increases you know you have larger cavity.

So, more power can be generated, right, but then at the cost of m is also increasing. So, the number of modes are increasing, effectively the spectral width is increasing and g th. So, if you see you know there is a interplay between these three quantities that is the cavity and the threshold required for population inversion and the number of modes. So, there is a trade off between these three quantities.

Now, let us try to understand how do we bias a LASER. So, if you see the characteristic of a LED for example, that is if I change the current here and the power here it is almost linear whereas in case of LASER diode when I am changing the current and this is the power. So, initially you know population inversion has not happened. So, spontaneous emission may be happening in the divided.

It may be acting for some time when there is a small amount of current, there will be very little power which is actually this is a spontaneous region spontaneous the population inversion has not occurred till this point spontaneous emission. As soon as you are able to achieve the population inversion, the stimulated emission kicks in and as soon as the stimulated emission kicks in there is a sharp increase in power.

So, there is some threshold I th after that there is a sharp increase in power. So, this is a typical characteristic of a LASER diode. So, you say threshold device after a certain threshold there is a increase in the power whereas, in the case of LED it was almost linear. So, now, when you are using this LASER diode where should I bias my LASER whether I should bias my LASER at this at this point say I call it point A or I call this point somewhere here as point B.

So, if I bias at point A so, there are two issues. You know in order to go from non lasing condition to lasing condition it will require some time some finite time is required some finite time which will actually limit your data rate the rate at which you can moderate your LASER diode. So, this is an issue if you bias at point A.

Although you get good extinction ratio extinction ratio is in the sense power when there is no emission or at says 0 and power at 1, because when you are modulating your LASER diode. Suppose this is your LASER diode and you are modulating with some 1 0 1 0. So, whenever there is A 1 it is emitting you know this amount of power or whatever maximum power and where ever it is 0 it is emitting this power. It is emitting this power which is there corresponding to point A.

So, the ratio the extinction ratio is defined as power at 1-level divided by power at 0-level. So, extinction ratio is good here because the power at 0-level is almost 0 is almost 0 and power at 1-level is quite high. So, that ratio is very high or extinction ratio is very high. So, at the receiver when you are decoding it becomes a little easier because the difference between two power levels is quite high. So, you are able to find out the difference between logical 0 and logical 1.

But, the issue is that you know going from 0 to 1 it takes some finite time so, which may affect your speed with which you are modelling the LASER diode. Suppose, I bias at point B bias at B your extinction ratio has gone down because you know power at this point and this point you require very less amount of I to go to 1 power. So, you have to be really very very operate in a very controlled environment.

And, moreover when you are biasing at B you are always some current is flowing in the device is always some because you are biased at B. So, always there is some current flowing in the device. So, there are two issues, but the time to go from 0 to 1 is very very less. So, there is a compromise that the extinction ratio might be little low and always some current is flowing.

But, as far as modulation bandwidth of the diode is concerned you are able to achieve much higher value as compared to if you if you bias your LASER diode at point A. So, ideally in practice you bias the LASER near the knee point because your main concern is to modulate the LASER at high speed.

So, you modulate near the knee region which is close to B. So, this is how you bias your LASER and also the characteristic which I have drawn here is function of temperature. So, as temperature increases for example, this is T 1, this is middle one is T 2, T 3 and this is increasing order. So, with increasing order your threshold also changes threshold value and the characteristic also changes.

So, in order that you get constant output power from the device you have to use some mechanism so that you control the junction temperature of the LASER diode and you do not if it is not controlled then the output power will change because you know these are different powers you are getting at different temperatures.

So, for maintaining the same so, there are some techniques which makes the junction temperature constant. So, one of them is use of thermoelectric cooler. So, it basically senses the temperature and accordingly pushes more current or less current depending upon the temperature and the power output is held constant. So, this is this highly temperature dependence. So, some mechanism should be there to arrest this variation in power with respect to temperature.

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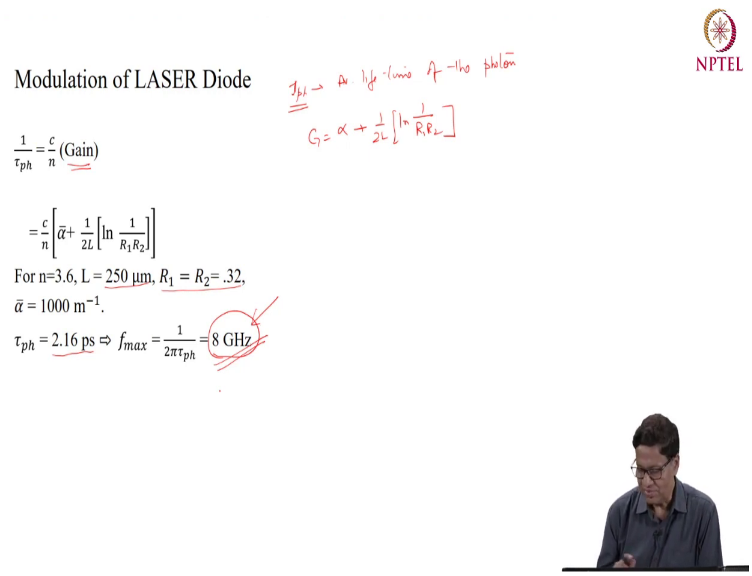

Now, let us understand about the modulation of LASER diode. So, the modulation of the LASER diode is given by is defined as follows. So, 1 by th h where tau p h is the average lifetime of the photon either it comes out of the device or it gets absorbed. So, you find out the average lifetime. So, the tau p h is called as the average lifetime of the photon before it comes out or gets absorbed inside the material. So, that 1 by t ph is tau p h is given by c by n into gain.

And, gain we have seen for the lasing condition was G was equal to alpha plus 1 by 2L log natural R 1 over R 2. So, for n is equal to 3.6 for gallium arsenide, suppose I take cavity length as 250 nanometer takes typical reflectivity as 0.32 and the attenuation or the loss part is 100 meter per inverse and plug in in these values will give me tau p h as 2.1 picosecond.

And, if I take just the frequency response of the inverse of this, it gives me typically 8 gigahertz you know I can modulate the LASER diode at this speed. I mean this is as far as direct modulation is concerned. If you want to have further high this thing there are other techniques using indirect modulation. But, typically you can modulate with LASER diode at very high frequency of the order of 8 gigahertz.

This was not the case for LED. LED you were able to modulate only few tens of megabits per second whereas, for LASER it is in terms of gigahertz.

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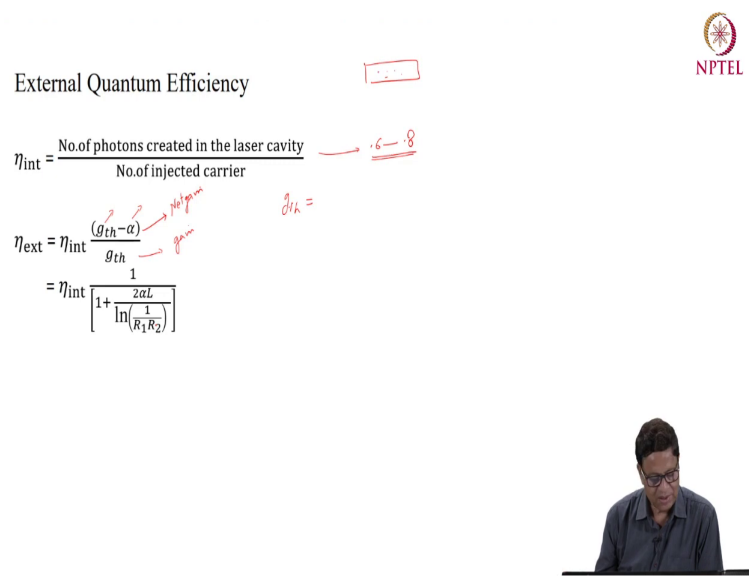

So, now, let us try to understand the external quantum efficiency of LASER diode. So, the internal quantum efficiency is actually defined by number of photons created in the LASER cavity, how many photons are created in the LASER cavity and divided by the number of injected carriers. So, this gives me an internal n int internal, this is of the order of 0.6 to 0.8 and the eta external that is external quantum efficiency is eta internal into the net gain.

This is the net gain because there is this is the gain part, this is a loss part and divided by the gain part. This gives me external quantum efficiency and I know the expression of g th which we have done earlier and using that expression of g th, we can find out this ratio. And, after doing some calculations what you get is eta external into internal frequency which is of the order of 0.6 to 0.8 1 by 1 plus 2 alpha L log natural 1 by R 1 R 2. So, this is the typical external quantum efficiency of a LASER diode.

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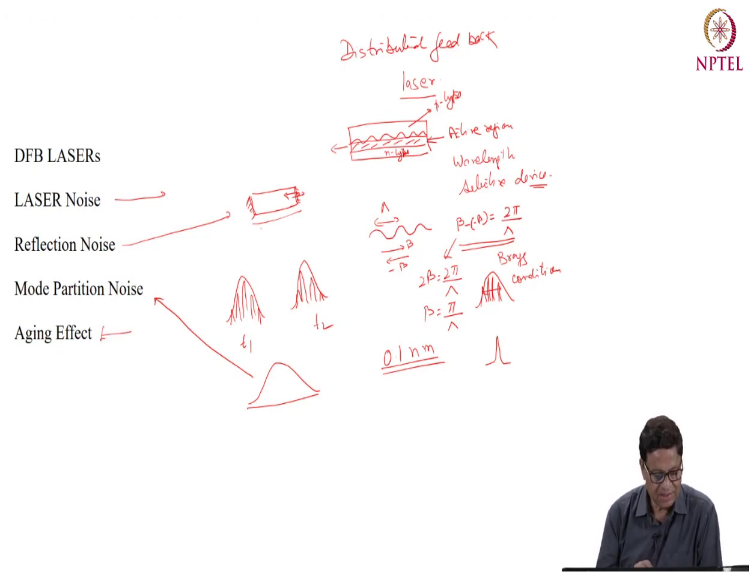

Now, let us understand briefly about the some types of LASER which are frequently used in communication and also during the course optical wireless communication we will see you know similar kind of lasers are used for optical wireless communication also.

So, one of the common type is DFB or distributed feedback. Feedback laser. So, what happens in distributed feedback LASER you have this is your LASER cavity and this is your say n-type, this is your active region and this is a p-type material and you construct a some sort of grating here. And, the property of this grating is that depending upon the spacing or the period of this grating some particular wavelength of the light is reflected back and others are transmitted.

So, basically what I am doing here I am making this as a wavelength selective device wavelength selective device. So, what is happening here? I mean this is my grating and say this period is capital lambda. So, and this direction is beta propagation constant and this direction is minus beta. So, if the reflected light is if it meets this condition there is beta propagation and the reflected part will be minus of minus beta.

If this is equal to 2 pi over lambda then there is a coupling of the light. So, the light only which is defined by this expression only that particular wavelength will be reflected back the rest of the part is reflected in the other direction which means I have achieved some sort of you know filtering or I have made the devices wavelength selective only 1 particular wavelength.

So, I am trying to make the LASER you know spectral width very very narrow. I mean the initially it has wide bandwidth I mean multi modes, but I want to make it single mode kind of laser. So, for making the single mode, I will be using this some grating structure which is embedded in the device.

And, then if this condition is satisfied which is what is called Bragg condition that particular wavelength which is defined by this that is 2 beta is equal to 2 pi by this is the period of the grating and beta is becomes pi by lambda. So, that corresponding to this beta that particular frequency or particular wavelength is reflected back. So, such kind of LASERs are called as distributed feedback. So, the feedback is you know distributed throughout the region.

So, such kind of lasers will have very very narrow spectral width of the order of 0.1 nanometer. Of course, the power will go down, but then you get very very narrow spectral width lasers. So, these are the commonly used lasers for high data rate applications whether it is you know free space optical wireless communication or optical communication using optical fiber.

The LASER also has some sort of noise. So, electron those photons which are generated either through stimulated or through some spontaneous process sometimes they you know their phase is different. So, it results in some sort of noise both in frequency and phase. So, this is referred as LASER noise and also you know as I explained you the LASER structure has some mirror.

So, some of the light goes out and some is reflected back into the materials if it is coupled you know through some fiber or somewhere then the light might get reflected back. So, this will generate some sort of noise which is called as reflection noise or. So, this is another type of noise which is produced in the LASER.

And, the third one is mode partition noise. Mode partition noise is as I explained you earlier, the LASER emits you know for a multi mode MLM LASER multi mode longitudinal mode lasers. There are many modes. Suppose, this is at time t 1 at t 2 you know the power in these modes will change may change.

So, it will become something like this or something like this something like this is a t 2, but if you take the average at different times you get I mean almost a steady power as far as envelope is concerned. But, within the device you know this power is continuously changing for all these modes. So, because of this you know some sort of noise is generated into the LASER diode which is called as the mode partition noise.

And, the third one is aging effect because you have some mirrors here the life of the mirror you know with constant reflection and constant continuous operation. This reflectivity is affected it may go down. So, this results in some sort of you know reduction in the power output. So, this is another point one should consider the aging effect of the LASER. So, these are the some of the impairments which happen in case of LASER

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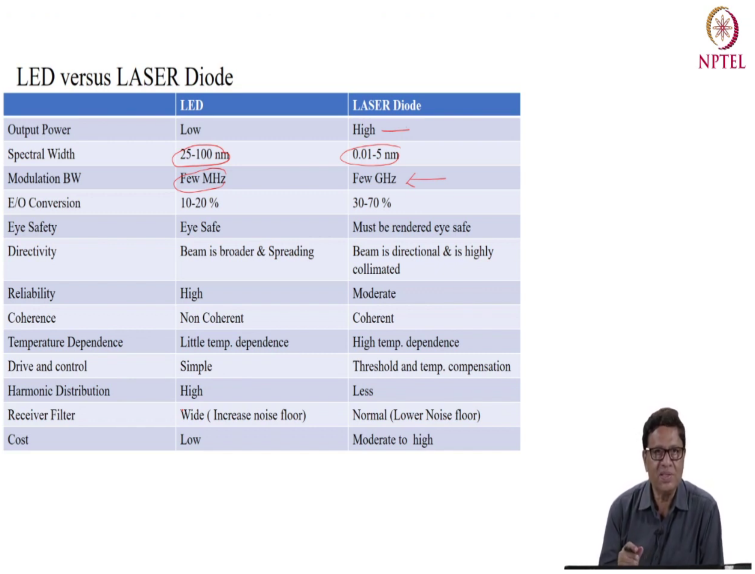

LED versus LASER Diode

	LED	LASER Diode
Output Power	Low	High
Spectral Width	25-100 nm	0.01-5 nm
Modulation BW	Few MHz	Few GHz
E/O Conversion	10-20 %	30-70 %
Eye Safety	Eye Safe	Must be rendered eye safe
Directivity	Beam is broader & Spreading	Beam is directional & is highly collimated
Reliability	High	Moderate
Coherence	Non Coherent	Coherent
Temperature Dependence	Little temp. dependence	High temp. dependence
Drive and control	Simple	Threshold and temp. compensation
Harmonic Distribution	High	Less
Receiver Filter	Wide (Increase noise floor)	Normal (Lower Noise floor)
Cost	Low	Moderate to high

So, finally, if I compare the difference between LED and LASER diode, it is listed here. So, if you see the output power in LED is of the order of you know my typical is microwatts whereas, LASER diode can give you high power, right. I am talking about a semiconductor Laser, but there are other lasers, gas lasers and all that they emit very very high power, but typical semiconductor LASER which can give you know few tons or few hundreds of milli watt.

The spectral widths is very high in LED which will restrict your transmission rate; whereas in LASER diode for df B for example, is 0.01 nanometer, but without DFB or normal lasers will give you some few nanometers, still very low. So, you can get a longer distance communication using LASER diode because the spectral width is low, the dispersion will be low.

The modulation bandwidth is few megahertz whereas, for LASER diode we also saw is about few gigahertz. Electrical to optical conversion in case of LED is very low 10 percent 20 percent. Laser diode is about 30 to 70 percent. As far as eye safety is concerned it is eye safe because power output is not very high.

And, LASER diode is should be made you know eye safe because if the power is high then it might damage the eye. So, depending upon what is the exposure time and what is the wavelength and what is the power, there are some safety eye safety levels are defined. So, the LASER power if you are operating in a environment where human beings are there has to be controlled and it has to be within those safety limits. So, it must be rendered eye safe.

The directivity of the beam is broader and spreading because it is a Lambertian source we discussed in in discussion when we are discussing LED that beam is broader and is spreading; whereas the LASER diode is spatially coherent and that is why the beam is directional and is highly collimated.

The reliability of LED is very high LASER is moderate because there are some mirror element. So, which make the reliability little low as compared to LED, but even then the reliability of a typical LASER diode is quite high. The coherence – LED is a non-coherent source we had a good discussion about the coherency part and, LASER diode is coherent. We discussed both the temporal coherence and the spatial coherence.

Temperature dependence – there is no temperature dependence in case of LED; whereas, the LASER diode is highly temperature dependent. The output power is highly temperature dependent and you should have some mechanism to control the temperature if you want to keep the power output constant.

The drive and control for LED is very very simple whereas, for LASER diode you have to keep the threshold constant, you have to keep the temperature constant. So, there is additional control secretary required to make threshold and temperature compensation. So, it is little complex as compared to LED. Harmonic distortion in LED is high where LASER diode because it is essentially a single source of light ideally. So, it is quite less.

Receiver filter is wide because the light is getting emitted from you know in a wide direction. So, the receiver which you use actually if you want to collect the whole light it should be wide angle so, it will have it will collect more noise as well. So, the noise floor actually increases when you are using LED and the c as a pair for communication; whereas, LASER diode is highly directional.

The receiver which you are going to have is also very very narrow. So, the noise collected is also less. So, basically the noise flow gets reduced when you are using LASER diode. And, the cost of course, is LED is low and LASER is somewhere moderate to high.

So, we have this concludes our discussion about the sources. So, we have discussed both LED and LASER diode, and we understood about the spectral width of LED and LASER diode, we also understood about the in coherency and coherency of these devices. We also understood what is the typical modulation bandwidth of LED and LASER diode.

So, this source is normally used in optical fiber communication as well as we will see the LED which are actually used for elimination will be used for you know communication as well. So, we are going to have extensive use of LED for communication along with elimination and the LASER diode will be used when we you know discuss about the outdoor optical wireless communication from point to point like free space optic links where generally LASER diodes are used.

So, we will see the application of these devices in you know future classes. So, this here we will end the discussion on Optical Sources, next we will take up discussion on the Photo Diode, what kind of different photo diodes, their frequency response that we are going to study in the next class.

Thank you.