Photonic Integrated Circuit
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Lecture No. 43
Semiconductor Lasers

Hello everyone, let us look at another kind of light emitters in this case, lasers. So, we have had a very detailed look at LEDs which is a spontaneous emission process driven device. So, light emitting diodes are, understanding of light emitting diodes are, basic for understanding any light emitters. In this case of lasers, they are amplifiers right within where you have oscillations in between. So, it is oscillator or in other words amplifier put inside a cavity, so that is all about laser so very simple construction.

You must have had detailed understanding of this lasing process and so on which we are not going to deal today but what we are going to look at is when you try to create a laser in an integrated platform or in a guided wave system what are all the implications and how one can construct and realize this kind of device. So, let us start from looking at a very simple amplifier for example and then we can create this cavity to create a stimulated emission. So, let us look at that.

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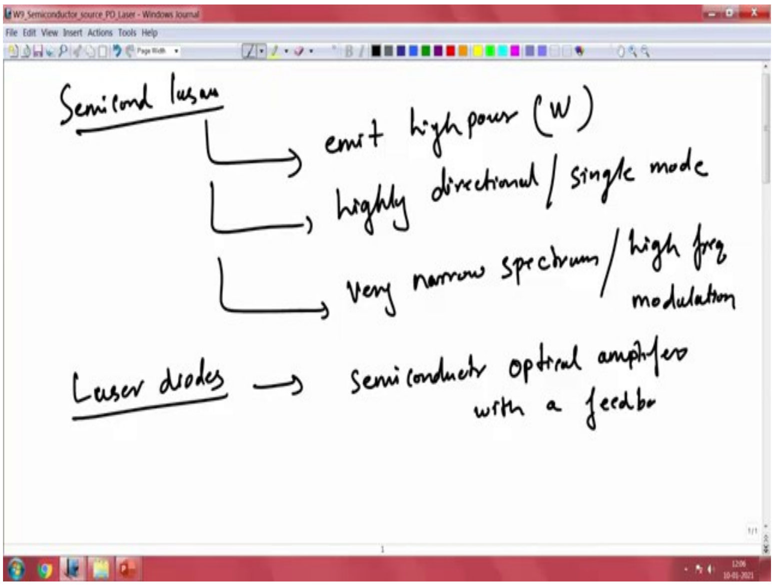

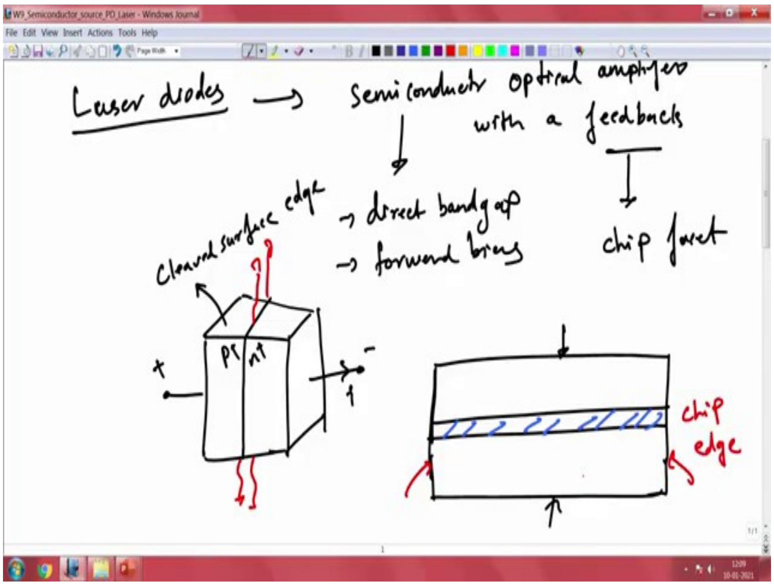

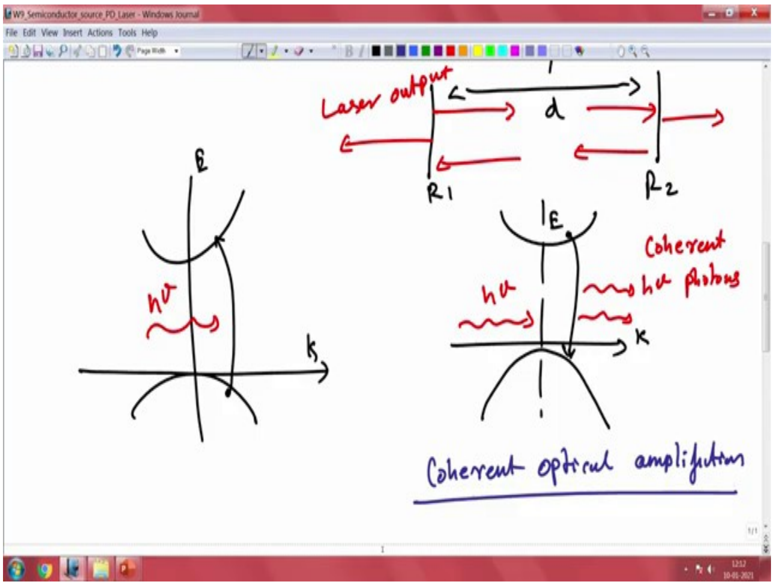

So, the semiconductor lasers are naturally an interesting device as light emitters say semiconductor lasers, we primarily use them because it could emit high power, it can be in the range of watts, it is possible to get and we get highly directional highly directional output beams and we could have single mode operation here. So, light could be, and then very narrow spectrum and this allows us to do high frequency modulation.

So, these are all important characteristics of semiconductor lasers, not very different from conventional laser but this laser diodes are, laser diodes are the ones that we are interested in which is nothing but optical amplifier, so this is nothing but semiconductor optical amplifier, amplifiers with a feedback and this is what laser diode is. So, similar to our LEDs or any light emitters we are going to have a forward biased heavily doped pn junction here and we are going to make this with a direct band gap material and we are going to have it in forward bias, because of the injection that we have and that should give us the required necessary condition to realize a light emitter.

But what about the feedback? So, we need to have a feedback, so the feedback is, can be given through a very simple facets, so we can have chip facet. Chip facet could act as a feedback here so let us look at a simple diode cartoon here. So, we can have a diode like this and we have p+ and n+ so we are going to inject the current through this you will have current flowing through and this should result in light emission from the edges and that is enabled by this facet, so this is the cleaved surface.

So, when you take a very hard material and then break it, it creates a very smooth surface as an edge. So, this cleaved surface edge provides the cavity here. So, this oscillation that we are looking for is given by this very simple reflection from the edges that we have. So, if this is from the top down, so this is the active region where we have your junction and we can inject it from left to right, so this all the two edges that we have, very smooth chip edge, so this is the edge we have.

And this edge is going to help us in reflection, and the current injection is given like this. So now when you take the same structure as a cartoon you can look at this as a reflector R_1 and the reflector R_2 and now we have the light bouncing back and forth between this and then you can take the laser out from this. So it has a certain cavity, so, it has a certain cavity length of let us say some d. So, the basics we all know because we need to get population inversion in order to generate the carriers.

So, that means you need to provide enough injection into the structure here so that you create the population inversion and once you have population inversion, then you have a recombination starting to happen and then you have stimulated emission process coming from your population instability that you have. So, when you talk about a very simple, so this is your E, so you can take one electron from the ground state and put it up by putting injecting a photon.

So, when you inject a photon inside the system you have absorption, at the same time when you want to create a photon or stimulate photon coming out so you will again put a the same energy level here so you have your electron sitting on top will come down and this will result in emission of two coherent photons. And these two photons are coherent in nature and this process is called coherent optical amplification. So, this coherent optical amplification is the fundamental process that you use in order to enable lasing.

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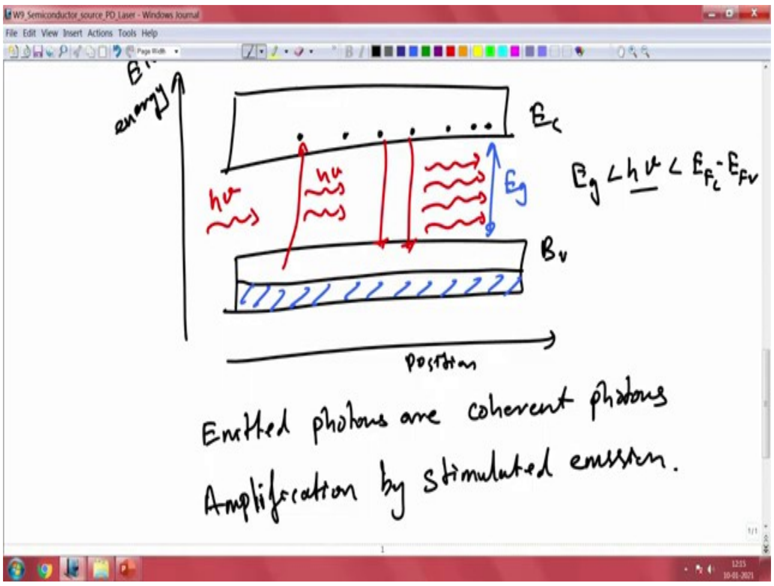

So, let us take a piece of semiconductor and this is position and this is our energy and now this is our conduction band and this is our valence band. So now we have a filled state here so when there is no input. So, this is filled and once we give energy that is required in order to increase the population, so now there is a transition that happens so there is a hν that we give and this energy hν, the condition for that is something that we know.

So, hν should be that less than E_{FC} - E_{FV}. So, this is the range of photon energy that you want. So, when you have this transition happen you put the charges in the excited state and when you continue to do this the photon is going to go through this and when it is going through you will have excited electrons sitting here but then as it progresses you will also have recombination.

So, when they are coming back, they are going to emit coherent photons here. So, this is something that, that happens along the length of the device that you have. So, the emitted photons that you have, so this emitted photons are coherent photons. So, the frequency and your phase are identical in nature, so this is called amplification by stimulated emission, so this is whatever you have here is nothing but amplification by stimulated emission.

So, I do not want to go into the junction discussion again because we have already done those discussion earlier but this generation something that we have not discussed in this particular sense is this particular energy gap that we have. So, what is the spectrum of the photons that we get out, so how will they look like? So, we said they there is an energy spread here right that we have so what is the frequency of that?

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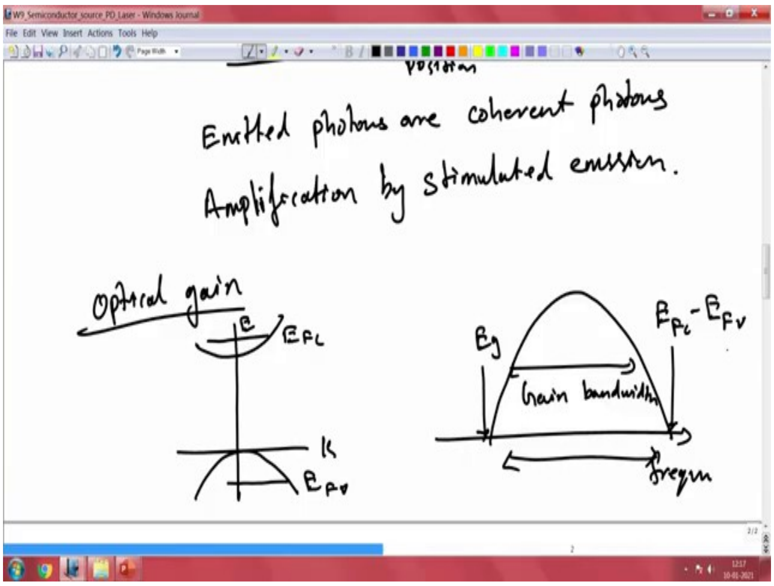

So, what is the bandwidth, the optical gain, what is the optical gain that you have, what is the gain spectrum. So, when you have, let us start with our E-k representation, so you have energy and you have your k and here is our E_{FC} and here is our E_{FV}. So, the generated electrons could be anywhere between these two, so that would result in the frequency spectrum, the gain spectrum starting from E_g to E_{FC} - E_{FV}. So, this is our gain bandwidth, so this is our gain bandwidth.

So, whatever we have, so this is rather broad so we can any photons within this frequency range should get amplified within the system so that is what it means. So, this gain spectrum is important, we will, we will bring this discussion later on when we talk about how we are going to control the gain here, so the gain spectrum is given by this. So, once we have this gain we can now look at how this gain spectrum is going to help us understand stimulated emission within the material system that we have.

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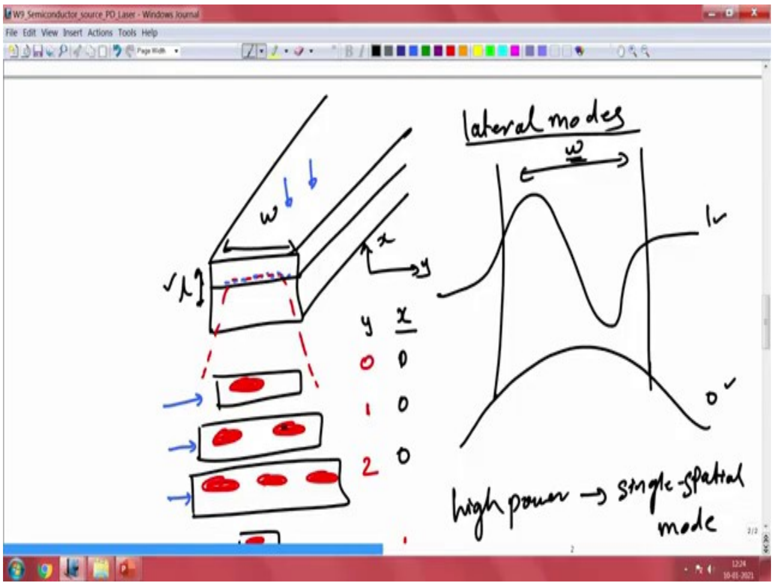

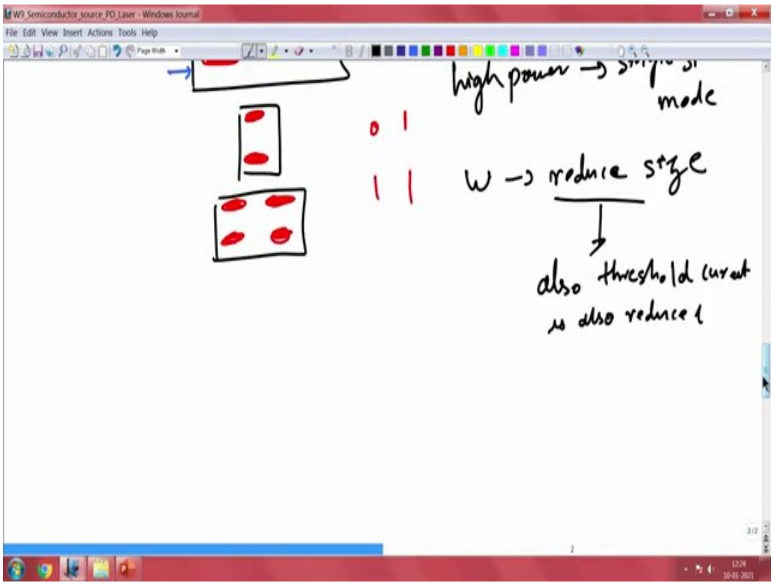

So, let us look at the spatial characteristic of this particular device. So, I can take a block of semiconductor here it is a thin guided system let us say that I have, so p-type, n-type we have and this will have a certain width and also certain length or height of the system. So, we all know from our wave guide principles and the understanding of the solutions we can have different spatial modes. So, there are what we call the lateral modes.

So, if this is the width that we have, so the lateral, what are all the lateral modes we can, we could have this mode or we could have this mode, these are all the possibilities or we could have higher order mode, so this is mode 0 and this is mode 1 to start with. So, spatially, you could have a single point like this, or we could have spots like this, or we could have spots like this, so this is mode 0 mode 1 mode 2 so this is spatially located in this region. So, that is what we are trying to understand.

So, they are going to be distributed along this so that means when you have larger width, then you have more number of modes allocated. So that is from w, we already know that, so the V number tells you that. So, you should now revise your, the waveguide principles, so waveguide design part to understand on what we are talking here.

So, when you change the increase the waveguide width you allow more number of solutions in this, so I am just drawn 0 and 1 here but as you increase width you will get higher order modes here so they will have spatial modes starting to appear here. So, this is 0 1 2 3 mode but then we have we have to represent it as x and y so this is in x direction so this is y let us say and you could have x where it is all 0 0 0 1 but you could also have x is also changing here, so when you have y to x.

So, you can also have higher order modes when l is larger, so when l is larger you could have higher order mode starting like, like this. So, you could have a y in y direction it is 0 but x direction it is 1 so you could have 1, 2, 3,4. So, in this case 1 1 so these are all modes that you will have propagating through the system based on the dimension, as the dimension increases you are going to have higher order modes.

So, the higher order modes are not necessarily a good thing for us, the reason for this is the following. So, when these modes are laterally present, they are going to also absorb the injection carriers. So, when you are injecting the carriers into the system here, that means you have carriers distributed along this, so they are all, all these modes are going to fight for those charge carriers, so they want to pull these charge carriers in order to phase match with this second order mode or the fundamental mode.

They are all going to fight for that energy or the excited electrons that are sitting into the system, so if you want to achieve really high power, it is better to choose a single spatial mode, it is preferable to have a single spatial mode to have high power. So, the high-power requirement, it is better to go for single spatial mode, this is highly preferable. So that means you will not have these other higher order modes that are scavenging the charges that you have in the system.

So, this is similar to, there is a limited availability of food, but then if there are more number of people then you have to distribute it to 'n' number of people there but they may or may not completely fill their stomach let us say if that is what you want to do. So, by reducing the number for the available amount of food you could feed one with full stomach let us say it may not be really one to one example here, but you can imagine in that way.

So, you want only one mode to win here, so that means you want only one spatial mode to survive and take all the energy, so but we do not want to lose it to the other. So, other modes are going to take their energy and the total power is going to be distributed among this other modes which is undesirable. So, this is, this is something that you want to do and how do we achieve this is by working with a dimension. So, you can always narrow the dimension reduce the size of the device that you do that will help you in getting rid of this higher order modes.

And what is the other advantage of reducing, so, your width reduce size, so you can do this. The other advantage of doing this reduction in size, so, the advantage here is also threshold will be reduced, so the threshold current is also reduced because of the reduced size you do not need to pump too much of power into the or rather current into the laser here. So, we need to look at the size effect on the output as well.

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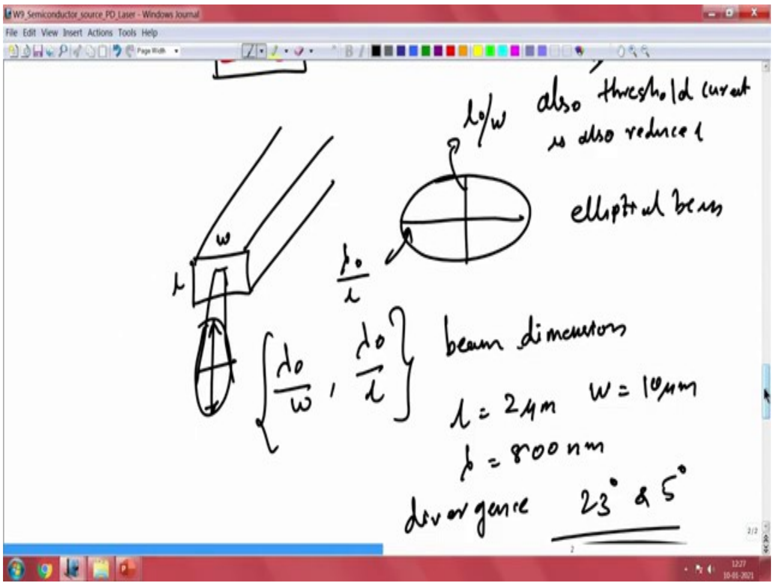

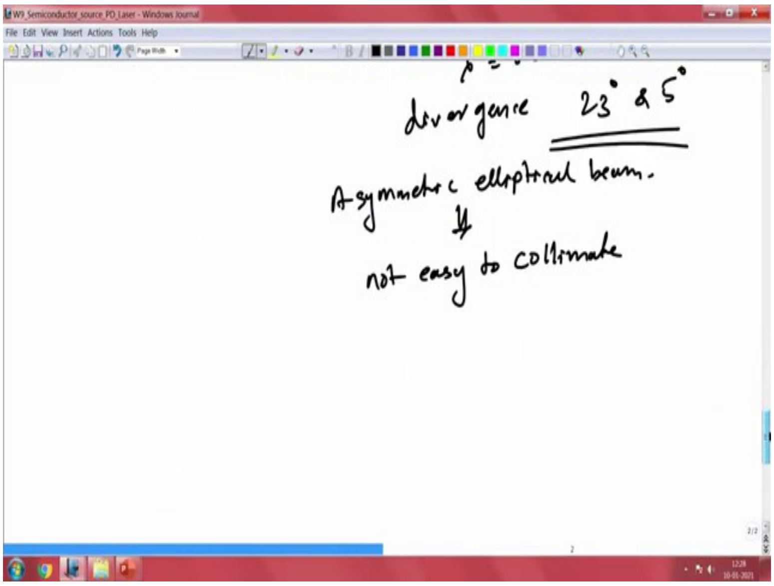

So, let us look at what is the implication of the size on the output. So, we have a certain width here and certain length here, so because of this asymmetry, the size of your beam that you are going to get out will also be asymmetric in nature and that depends on the wavelength and your width that you have. So, $\frac{\lambda_0}{w}$ and $\frac{\lambda_0}{l}$, so this is our beam dimension, depending on whether w is large, or l is large this is going to be an elliptical beam.

So, you could have this as $\frac{\lambda_0}{l}$, so when you have larger you will have larger, so it should be the other way around let me draw that, like this, and this is our $\frac{\lambda_0}{w}$, and this is the emission from our active region and we need to choose it appropriately for example if l is 2 micrometres and w is 10 micrometres and let us say lambda is 800 nanometre light then the divergence is going to be 23^0 and 5^0.

So, this is going to be an asymmetric beam, so this results in asymmetric elliptical beam but what is the implication of this? It becomes not easy to collimate the light, so you want to put a a lens in front of this diode in order to collect the light, because of this asymmetry it becomes difficult to put a very simple collimator lens. So, the lens is going to be again symmetric, so it is not going to be easy to collect this light when it is asymmetric in nature. So, that is about the light coupling that we have, the power and everything is already fundamental discussion was already done when we had this LED discussion.

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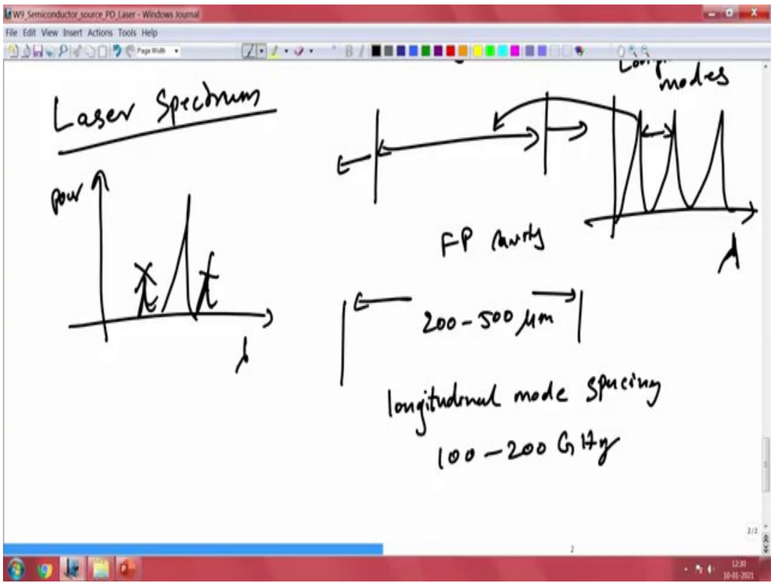

So, let us look at the light spectrum, so there is an important property here, so what about the laser spectrum, how the spectrum of the laser is going to look like. So, you want to have a narrow spectrum, do, that means as a function of wavelength you want it to be very narrow, so this is what you want to do and you want to?

You do not want any other modes coming in, the reason for that is when you take a cavity, so this is something that we already know, when you take a Fabry-Perot cavity when the light is between, reflected between the two mirrors here, your output spectrum is periodic in nature and this is nothing but your longitudinal modes, what we saw earlier was on the transverse or lateral modes, but then as a function of length you also have a length associated.

As a function of length, we will have longitudinal modes and this is as a function of wavelength you are going to have this, so this longitudinal modes are going to result in a spectrum where you will have the other modes are present. So, this is the reason why we have to understand about this longitudinal modes and the gain spectrum that we discussed, so we talked about the gain spectrum.

So, there is an overlap between the longitudinal modes we have and the gain spectrum. For example, if the cavity length is let us say 200 to 500 micrometre, if the length of the cavity is between 200 to 500 micron, then your longitudinal mode, so your, so longitudinal mode spacing that you have, like here, will be around 100 to 200 gigahertz. So, this is rather important, so you have 100 to 200 gigahertz of spacing that you have, between the different longitudinal modes.

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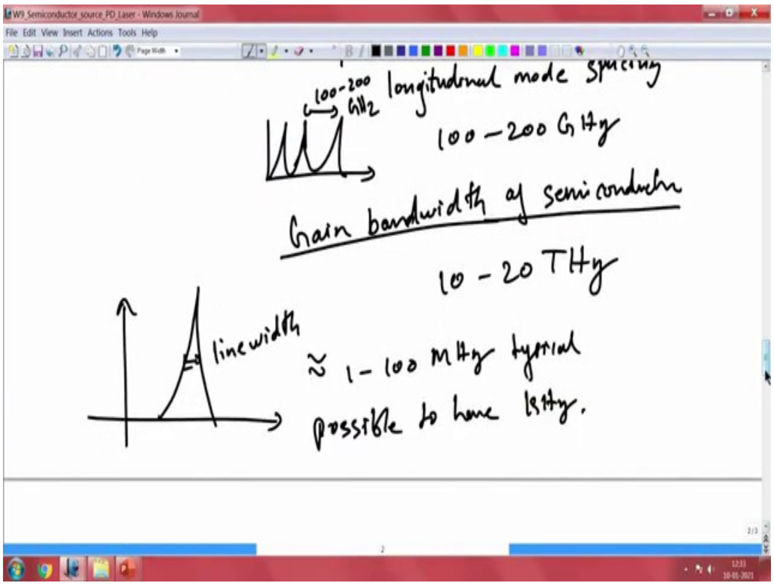

This is nothing but, we are talking about this difference. But then earlier we saw that the gain bandwidth, so your gain bandwidth of a, gain bandwidth, so gain bandwidth of semiconductor depends on the energy gap. So, let me just go back and show you that, yeah, so we have this gain bandwidth optical gain, we can say bandwidth here, so this gain bandwidth is this whole region, so this for a semiconductor will be in terahertz, so it will be about 10 to 20 terahertz.

So, gain bandwidth will be 10 to 20 terahertz, so you can now see that your longitudinal modes are in gigahertz, hundreds of gigahertz but your gain bandwidth is in terahertz, so definitely you have a larger gain region compared to the number of spatial modes that you have. So, this is definitely a challenge to just make sure only one longitudinal mode wins that means your spectrum can be narrow or only one mode survives, so you want to have a single mode or even in the transverse direction right.

So, in terms of line width, so that is the number of modes, the line width is how sharp this could be like. So, the laser line width will be around 10, to it can be anywhere between I would say 1 to 100 megahertz right, so this is very typical. So, it is also possible to have kilohertz class line width as well, so once you can try to make sure that this cavity finesse is high enough. So, let us look at the implication of this longitudinal modes so with a with a very small example I am going to show you.

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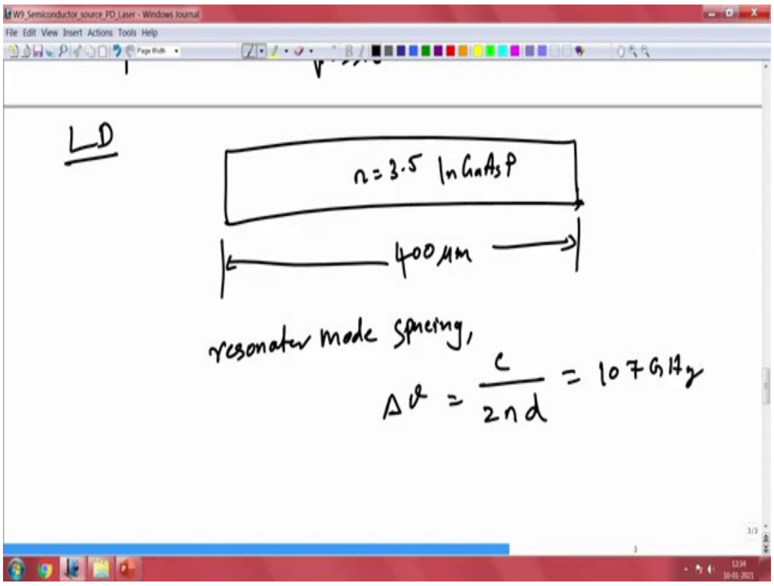

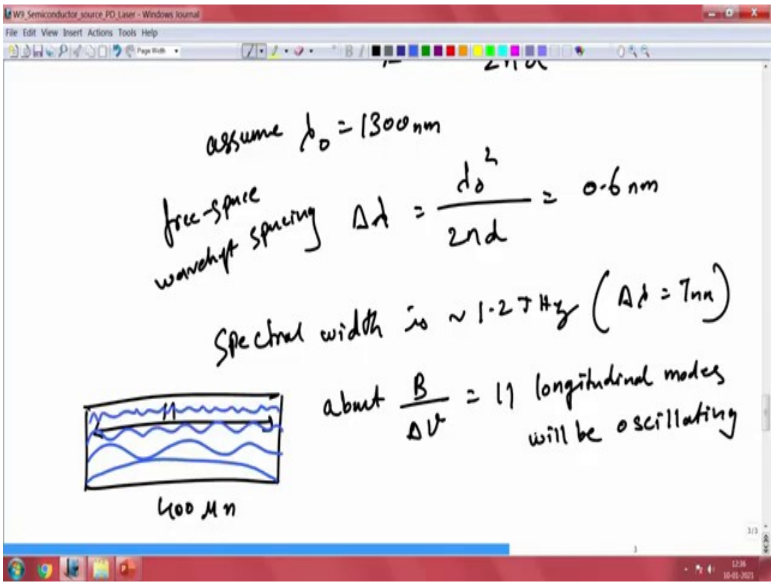

Let us take a piece of laser here, so this is a laser diode, so this is laser diode of length 400 micrometre, so this is 400 micrometres in length. The refractive index here is 3.5 let us say and this material is indium gallium arsenide phosphide let us say and we created this cavity and there is a reflection coming out. So let us look at what is the longitudinal modes that you could have. So, (how) what should be the frequency spacing, resonance, this is a resonator mode spacing, again these things are from Fabry-Perot cavity so what is that spacing?

That is Δν which is given by $\frac{c}{2nd}$, so this is what we add which is nothing but 107 gigahertz for this particular geometry. So, let us say our central wavelength, assume the lambda is 1300 nanometres. So, then Δλ or wavelength spacing, free space wavelength spacing is given by $\frac{\lambda_0^2}{2nd}$ and that is 0.6 nanometres.

So, now if the spectral bandwidth, the spectral width, this is B, the spectral width is about 1.2 terahertz let us say or in other words Δλ of 7 nanometres, so you will have about 11 modes, so this is $\frac{B}{\Delta\nu}$ and that is 11 longitudinal modes will be oscillating. So, what I mean by that is you have this cavity that has 400 micrometre long, within this cavity there are 11 modes that can be going back and forth so what are all those modes?

So, you could have the fundamental mode here, you could have this, this very high frequency here. So, you could have large number of spatial modes so they are standing waves.

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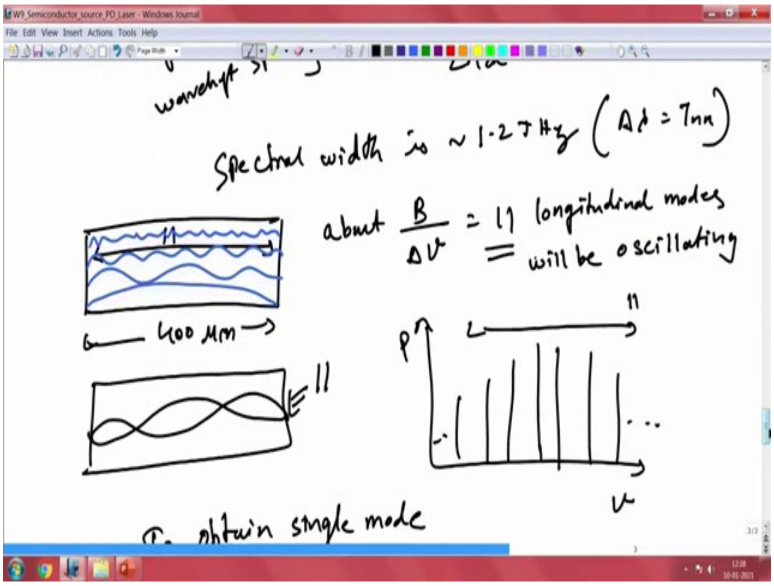

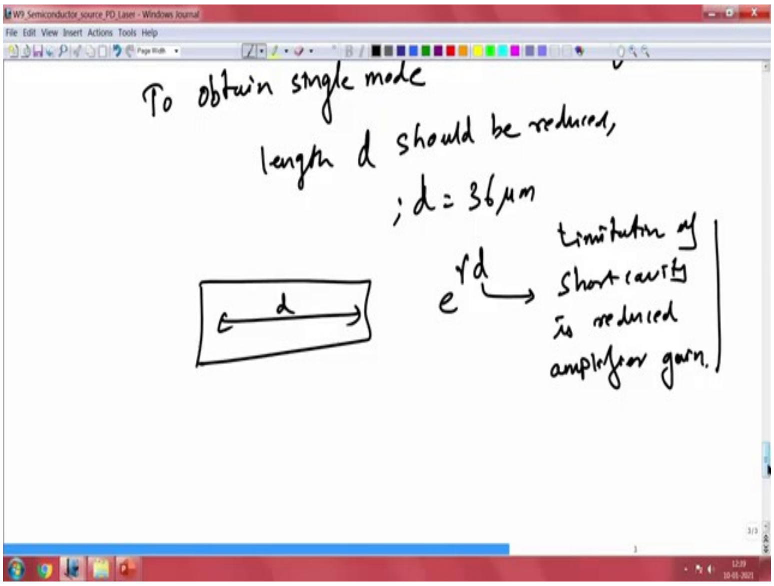

So, the proper way to understand is they are standing waves, so they go like this and then they come back so these are all the standing modes so you could have these standing modes inside this cavity and how many such modes we have? There are 11 possible modes. So, that means you will have all these modes getting amplified. So as a function of frequency you will have all these 11 modes, there are 11 modes that are getting amplified as a function of, so this is the power let us say, because of your large spectral width that you have.

For example, if you want this to be a single mode, what about single mode, what you need to be single mode, to obtain single mode the length d, this 400 micrometre we had, that should be, that d, length d should be reduced, so that is what we want to do, so let us go here. So, we want to reduce this length d in order to make this much larger so when you make this length d go down this is going to be much larger so that is what you are trying to do.

So, the length that we need in this case, should be about 36 micrometres, is what you want to do. So, when you reduce the length, so when you reduce the length of this interaction or the cavity you can have only a single mode that is oscillating so the other modes are all taken out. So, what is the implication on the (amp) laser itself. The problem is the laser gain, the laser gain depends on your length here, in this case d.

So, when you reduce d your laser gain is also going to reduce so that is the problem with the, having a very short line. So, let us say the limitation of short cavity is reduced amplifier gain, so this is something that should be kept in mind when you are trying to make very small cavities. So, let us look at the oscillations that are happening inside and how one could create a single mode operation in a homogeneously broadened medium.

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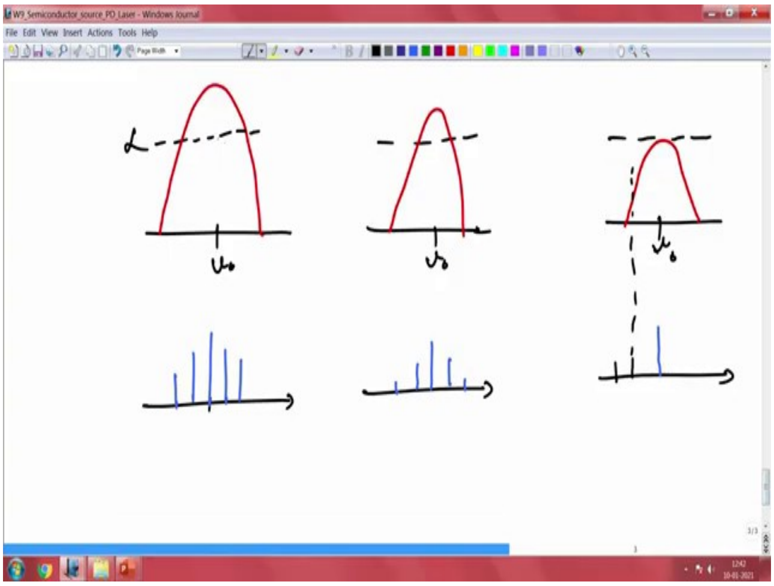

There are different scenarios I would like to take three scenarios here based on the gain that we have, so central frequency here and this is our loss line let us say, so this is our loss that we have α, so the gain could be, the gain spectrum could be like this or a little bit of gain or just compensating the loss. So, in these three scenarios how our longitudinal modes are the frequencies are going to look like?

So, when there is a gain to all the modes here so all the oscillating modes are going to get amplified, there is an amplification for all of it but in this case the oscillations that are below this threshold are going to get very low amplification or low gain and they would die out but then when you have the right amount of gain here you will have only single mode, there is no oscillations that are supported outside the gain region here.

So, this is very important to understand how you should make this gain choose the number of longitudinal modes that we have here. So, by having the saturation here right so this is the gain saturation that we have to a level that you compensate for the losses in the cavity we should be able to just make sure that only the one overlapping mode that you have wins while the other modes that are sitting outside you see here the gain is much lower than the loss that we have.

So, that means these modes that we have outside this cavity will not get amplified so they will all die out. So, this is how your homogeneous broadening will help you, your gain saturation will help you in achieving single mode and in this case, this is a homogeneous broadening. So, your gain spectrum is moving up without having any distortion at all so that is a good thing and the second thing is about the spatial distribution.

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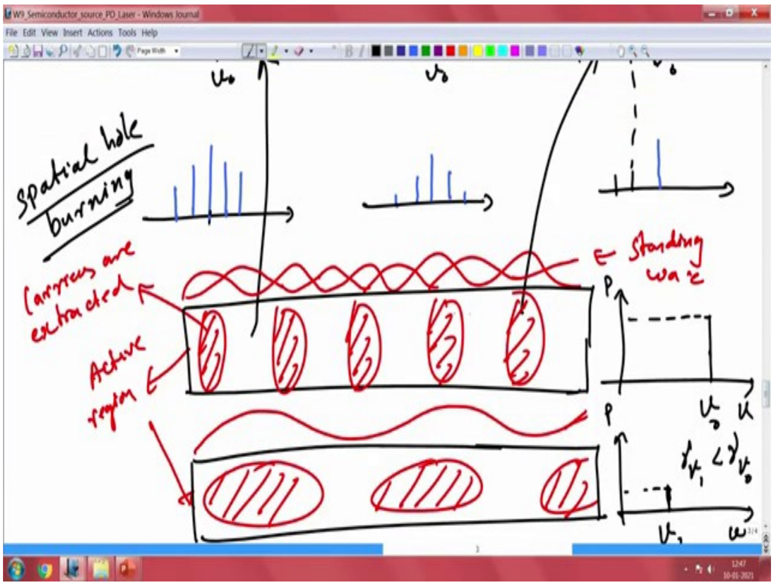

So, when you take a piece of semiconductor in this case the laser here, so there are two possible modes we will look at those two modes. So, one mode has a oscillation with a higher frequency, so in that case the mode is having high frequency mode. So, your spatial distribution is like this and another mode as a low frequency. So, in this case, so in the frequency domain you have a mode here and then a mode here, so this is ν_0 and this is ν_1.

So, when you have this injection, so we are having injection here, so this is actually the active region. So, in the active region the mode is present in such a spatial distribution, this is the longitudinal mode, this is the standing wave that we have, so this is basically the standing wave that we have. So, then the wave is going back and forth this is the electric field profile that you get.

So, now you can see here there are certain places where the mode is actively interacting with the material and there are places that there is no interaction at all. So, this shaded region is where carriers are extracted. So, this is the active region that you have. So, in these regions is where we have the regions where there is no overlap here are the regions like this. The active region, the active overlap regions that you have are the regions where you have just the right amount of saturation.

So, the regions that are shaded here is the saturation region while the unshaded region is where you have the higher gain. So, you can look at these two modes right and when you look at these two modes which mode efficiently extracts the charges, that is our mode ν_0 so that is a high frequency mode, and this mode will have higher gain compared to ν_1 with low frequency.

So, the gain that you have, so this is actually the power that you have, so the gain that you have for ν_1 is less than the gain that you have for ν_1. So, this is something that you should keep in mind that when you are having a spatial distribution of this mode in the semiconductor, the more the overlap, the more the longitudinal mode is having with the material the higher the gain will be and this process of collecting all the charges is called spatial hole burning.

So, this phenomena of this spatial hole burning allows the modes to win over the other by efficiently extracting the carriers and then generating your necessary mode to survive in the mode. So, in a shorter cavity this also exists but it only exists for few standing waves, few modes, but then in a large cavity you will have large number of such modes. So, one should create this standing wave patterns of course that those are all the ones that are surviving but understand where to pump these injection current in order to enable this.

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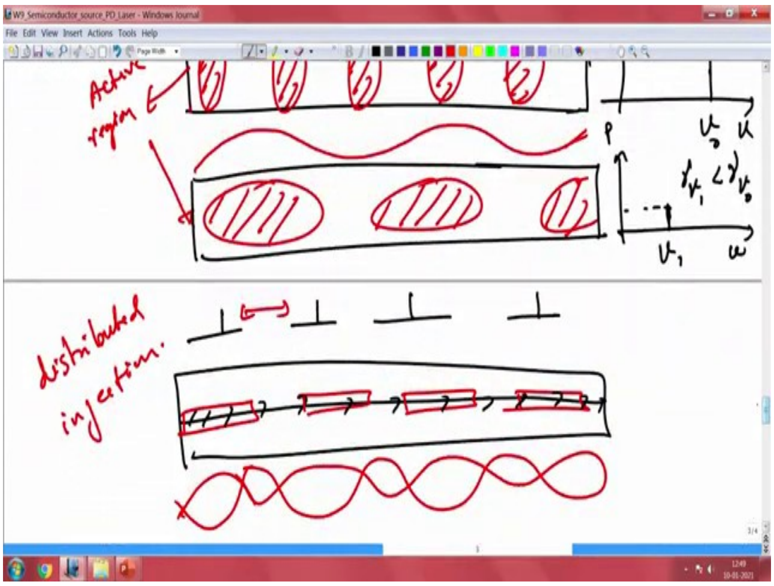

So, what one could look at is distributed injection. So, when you have distributed injection, you are not going to energize the active region across the active region here, so there is only particular regions here that could be energized while the others would not. So, this will allow a mode of certain spatial distribution to get amplified while the other modes will die down. So, distributed injection. So, this particularly works with the higher order modes where the frequencies are much larger but then it would not work for high frequency modes the reason for that is it is going to be very challenging to put these electrodes very close to each other because there is a technology limitation associated with this.

So, with this we have understood some of the important criterias in achieving (())(46:04) lasing in a semiconductor. So, the basics are all covered in fundamental courses but what we understood here is something that you might not covered in any of the basic courses about the whole burning concept and how do you select the longitudinal modes and what is the effect of the cavity, the longitudinal modes that we have and the gain itself. So, by making all these relations we have fairly good understanding in designing a semiconductor guided wave amplifier and also a laser. Thank you very much for listening.