Introduction to Photonics
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Semiconductor light Source and detector Laser Characteristics

Okay, let us get started. So welcome back to introduction to photonics we have been talking about semiconductor light sources and in the last lecture we were talking about characteristics of semiconductor light emitting diodes and we were essentially looking at the emission characteristics, the output power as a function of injected current and then the modulation characteristics, as well as the spectral characteristics.

Today what I would like to do is extend this discussion to semiconductor lasers and semiconductor lasers are not very different it is not such a new topic because even while we are talking about semiconductor light emitting diodes we said if you had feedback from either ends of your this double hetero structure you will end up having a laser emission and you know so in some ways like I said semiconductor lasers are easier to do than LEDs, LEDs are going to have to go through this extra step of doing some surface treatment especially at the at either ends of the active region such that it frustrates total internal reflection and you could get light out of the structure.

So for the laser you do not have to do anything, you just have to take a double hetero structure and cleave on either side of it and you just based on that reflection you will build a laser.

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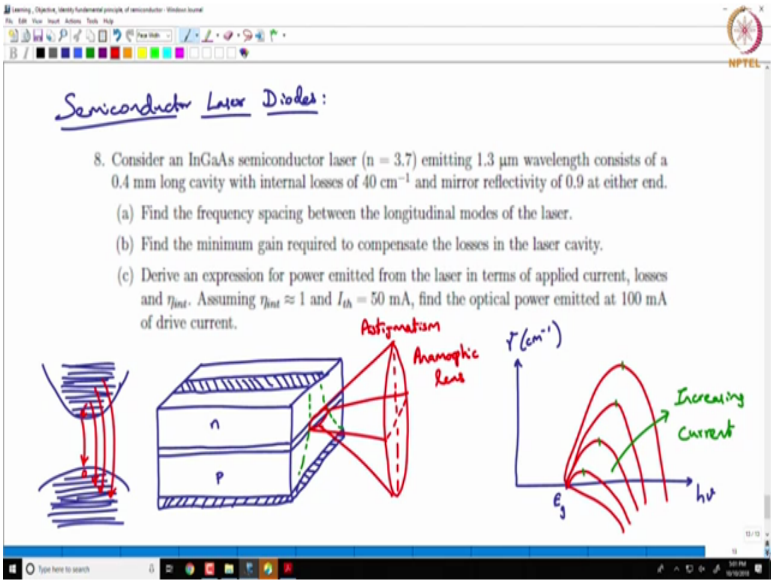

So what we will do today is consider some of the characteristics of semiconductor lasers and to help our discussion I just picked one of the problems that we have in the present tutorial, so this is asking you to consider a indium gallium arsenide semiconductor laser there are material refractive index is 3.7, so this is emitting at 1.3 micron wavelength, so you can imagine that the band gap energy for this material you know has is around is corresponds to a wavelength around 1.3 microns and so it consists of a 0.4 mm long cavity that is basically 400 micron long cavity with internal losses of 14 inverse centimetre and mirror reflectivity 0.9 at either end, so the mirrors also you know contribute to the losses the overall cavity losses.

So find the frequency spacing between the longitudinal modes of the laser so that should be relatively easy to do we know that it is corresponding to C over 2 n L, so n is given, L is given so it is just a direct substitution, find the maximum gain required to compensate the losses in the laser cavity so that part we will look into little more detail and finally derive an expression for power emitted from the laser in terms of applied current, applied current the losses and eta int okay so we will try to find such an expression as well okay.

So and then of course of course if you assume eta int is 1 and the threshold current is 50 milliamps, find the optical power emitted at 100 milliamps of drive current okay. So let us say this is what we want to achieve, so let us just go into the specific structure of a semiconductor diode laser. To understand that let us just first of all define the double hetero structure once again, so we said we are going to have a double hetero structure consisting of a p region and an n region right and an active layer in between which corresponds to material with lower band gap energy so that it accumulates all the carriers.

And if I were to just project this in 3 dimensions, so just give you a perspective of this it is going to be something like this and in order to have a current injected so what you normally do is you have layer here a contact layer right and then you define stripe in the top region as well, so that is basically a metallic contact to which you can connect an external source. So you can imagine that the current that is flowing through this structure is going to be something like this.

So all the carriers injected are going to be you know around the centre of this facet so when you look at the light that comes out of this laser you can say that it is going to come out of this region here okay and one characteristic that we can clearly see is it is limited by the thickness of the active region right in the vertical direction so that is basically how many layers you can deposit in epitaxially and in the transverse region or the horizontal direction there is not as much of a constraint so the vertical thickness could be in the order of a micron but in the horizontal sign there is not as much of a constraint.

So when you look at the light that is emitted from this structure what you tend to see is that the light that is emitted in the vertical direction since it is coming from a smaller aperture it tends to diverge much more. So whereas if you if you consider the light that is coming from the horizontal direction that does not diverge as much so because it is coming from a larger aperture, so larger the aperture less will be the divergence and aperture goes down to you know dimension comparable to the wavelength then you would have much more you know it is basically diffraction effects come into the picture so you will have much more divergence from that region.

So effectively your output beam is going to look something like this. So on the horizontal direction it will not have much divergence but the vertical direction it will have much more divergence. So this is actually something called astigmatism, if you go to an eye check-up so you know ophthalmologist (may say) tell you that you have some astigmatism so what does that mean? It means that your curvature of the lens you know in your eye is actually not the same in both directions, so you would have to have some special type of lens with different curvatures on either direction to correct for that.

So similarly we have a astigmatic beam and to correct for that what you need is actually what is called a anamorphic lens. So it needs to is it is basically a lens with two different you know focal distances for the two different directions and with an anamorphic lens you can essentially correct for this test astigmatism and possibly get it to circular beam. Why do we need a circular beam? Why is that we might need a circular beam? We talked about coupling into an optical fiber eventually so that you know it has basically got a circular cross-section, so you need to fit this beam into that optical fiber, so you may want to have a circular beam.

So that is one property of all edge emitting sources that you typically have astigmatic light output and you may need to correct for that astigmatism before coupling into the optical fiber. But anyway coming back to answering this question we first of all need to understand what is the gain that we are able to achieve as a function of the injection current.

So let us try to look into that and let us first try to look at the gain as a function of injection current for different energy of light that is emitted. So if you are looking at the gain coefficient which is expressed in inverse centimetre, so if you look at the gain coefficient as a function of H nu we can tell that there is nothing that is going to happen for energy less than band gap energy, why is that? No energy levels exist this all forbidden so you are not going to have any action happening to the left side of E g.

So initially if you are not injecting any current into this structure okay and if you are you know if you are sending light in basically it will act like an absorbing medium right because you have all your electrons in the valence band, no electrons in the conduction band. So now when you have light with energy greater than H nu what you are going to have is all absorption.

So higher energy higher frequency have more absorption because more density of states exist, so you can have you know higher absorption over there but the absorption starts at E g, right. So this is if you do not inject any current, now you start injecting some current then you can start having gain right and so you will start having this sort of a picture and so on and what you will see in general so this is as a function of increasing current injected and what you see is that the peak gain value is increasing and it is also shifting to higher frequency, why is that? Why do you have more gain when you have more injection current at higher frequency?

Because initially when you inject current you are filling the lower energy levels of the conduction band and so you start emitting from those levels. So the energy of those emitted photons are going to be lesser, so the just try to draw that over here. So this is my conduction band, this is my valence band and then you have much higher density of state so similarly lower density of states and then much higher density of states over here.

So initially when you inject some current you are having electrons over here and holes over here, so you have this recombination happening so that energy is low. But as you start injecting more and more electrons and you have more and more holes in this valence band, you start having deeper and deeper emission so you are emitting from a deeper level in the conduction band to the deeper level in the valence band and as a result of which the gain the peak gain happens at a higher energy level, do you understand that? Any questions about this before we move on?

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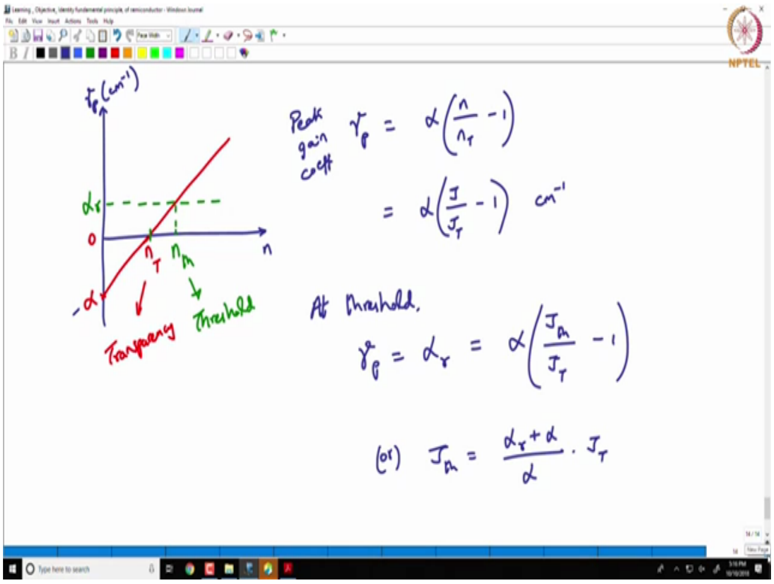

Okay, so now let us track here the peak gain in inverse centimetre just one second, as a function of the electron density that is a question there, that is right so the question is Fermi-Dirac distribution tells you that lower the energy level, more is the probability of finding an electron that is absolutely true, but there is also policy exclusion principle which says that if I fill my lower energy levels I need to keep going up, so I cannot have more and more electrons in the same state so extra injected electrons are going to start occupying higher energy levels.

So typically so with emission yes typically you are saying that you will have emission from the lowest energy level, so you have more emission near the band gap energy right that is what we typically say but as you populate more and more electrons the higher energy levels you start having this possibility of the peak shifting to longer or higher energy levels because you are starting to have more electrons in the deeper in the states and then then you would have these emission, yeah?

No, it can be I mean so that is the biggest difference between an atomic system and this semiconductor system, in atomic system you could have essentially different atoms in different places can have you know the electrons at the same energy level, so you could you could have that happening across the matrix.

But as semiconductor is concerned you are going to I mean you are excluded from having this is actually a combined system it is a coupled system so you are excluded from having more than one electron at any state, so you are actually having once you filled it you are having to go deeper you are filling the deeper states and then relatively you are saying (the peak is shifting to) the peak gain is shifting to longer wavelengths I mean higher energy transitions which correspond to shorter wavelengths actually because you have more states the density of states is more so more electron population there and because of that you could have more gain for higher energy levels.

It is a relative thing but you are right that it tends to stick closer to the band gap energy, but yeah as you pump harder you can go away from the band gap in it, any other questions? Okay, so let us track this part and what we was that initially you do not have much electrons in the conduction band, so your initial injection you know it does not really give you much of a gain.

So initially what you have is just absorption from the material so that is actually so you can say this gamma P is 0 over here so you have a negative gain which is corresponding to loss in the medium. And then as you increase you get to a point which corresponds to n T and this is actually called transparency, a transparency you have a net gain you have overcome the losses in the material okay you have overcome the losses in the material and you are starting to have a net gain beyond a certain level of electron density and beyond that you can increase like this okay.

So now comes this concept of when you make a laser you have extra losses in your cavity, you could have this background losses in the cavity as well as your mirror losses in the cavity. So that extra loss level may be somewhere over here alpha r and that means until you get to a value n T H which corresponds to a threshold only beyond that you are having I mean you are starting to have lasing happening.

So you are essentially having one point where you are overcoming the absorption in the material, you are starting to have a net positive gain, but you need to have more gain beyond that to overcome the losses in the cavity and then only you can have laser emission, yeah you have a question? Background losses, background losses since scattering type of losses you may have in the material or you can have impurities in the medium which are giving rise to some background some if you have some I mean in classes it is common to have some metallic impurities and some contamination and those could cause background losses so that is the extraneous losses that we are talking about.

So n is the electron density, so the electron density in the conduction band, so that effectively you are tracking that because those are the ones that are going to give you potentially this recombination and give you stimulated emission or gain. So you have two different quantities that you are having to track and let us say you are having alpha corresponding to the loss in the medium, then you can write your peak gain coefficient as gamma P is going to be equal to alpha multiplied by n over n T minus 1, so that represents this straight line over here.

Let us just quickly check when n equal to 0 gamma P is equal to minus alpha, so this is basically you are saying it is negative gain so which is corresponding to minus alpha and when n equal to n T that is the transparency density then gamma P equal to 0, so that is just a quick check to see that that is indeed correspond to the equation of that line. And we know that the electron density is going to be corresponding to the current that is injected or was the current density.

So you can write this as J over J T, J corresponds the injected current density, J T is a constant for a given material corresponding the current density required to achieve transparency that is a net gain of 0, so that is expression for your gamma P. Now what happens at threshold? At threshold we are saying that gamma P has to be equal to alpha the gain has to be equal to the loss and this loss we are saying but gamma P is also given by alpha J but we are considering a threshold condition, so we can write this as J threshold divided by J T minus 1, so gamma P from that expression at threshold J equal to J threshold so alpha into J threshold over J T minus 1 corresponds to gamma P.

Or you can write that if you are trying to find the threshold current density that threshold current density if you just rearrange these terms you are going to find that is going to equal to alpha r plus alpha divided by alpha multiplied by J T. So the threshold current density is greater than or equal to the transparency current density because you are needing to have extra current injected to overcome the losses in the cavity, so and then that how much extra is determined by this factor alpha r over alpha what is the resonator losses compared to the you know the loss in the material itself, the absorption in the material, okay any questions about this?

So we generally saying the threshold current density will be greater than the transparency current density, but you understand this picture? Any issues with that gain as a function of electron density? Okay let us move on, yes when the? Oh, yes so the question is whether there will be saturation of the gain? Yes I mean as you emit your electrons are you know getting depleted from this conduction you know energy levels and even if they deplete from the bottom they are actually going to trickle down to the lower most energy level that is what the other question was about and corresponding to that you will have lesser gain for the longer energy transitions, so for the shorter wavelengths you are going to have lesser gain and in general yes there is a gain saturation effect all those things that we talked about in terms of gain saturation is valid for this also.

Except that there we talked about some emission cross section you know and that saturation time, so those definitions change here. So there is still a saturation time here as well, yeah but the definition of the emission cross section all that changes.

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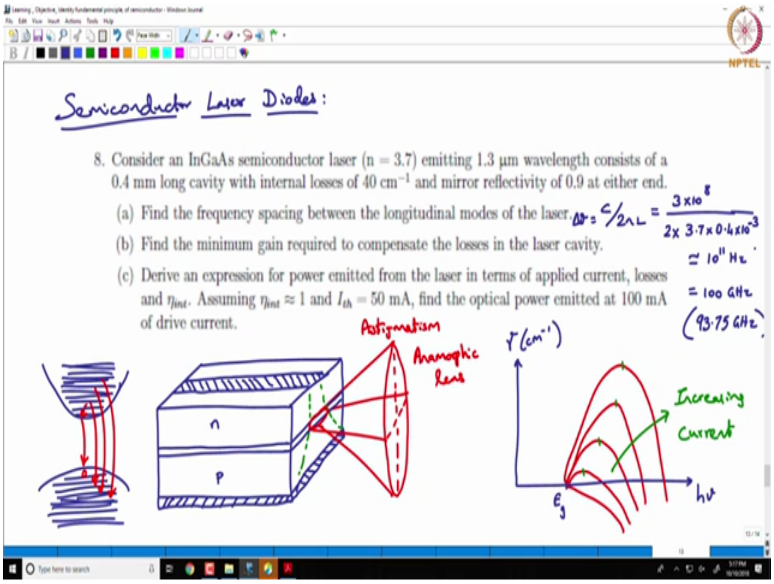

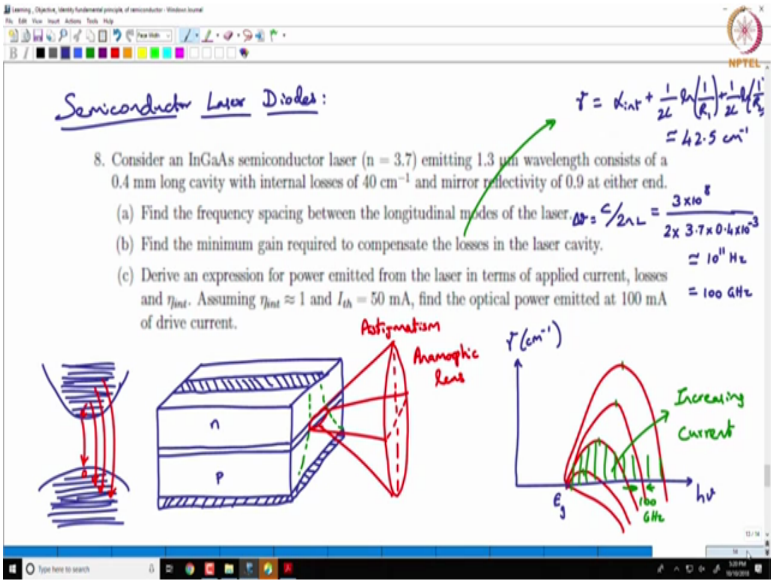

Okay, so let us move on now what we want to do is quantify these things now right here I can say that C over 2 n L, so delta Nu is going to be equal to C over 2 n L so C is given as 3 well C as we know is 3 into 10 power 8 divided by 2 multiplied by 3.7 multiplied by L which is 0.4 mm so 0.4 into 10 power minus 3 so what is that 0.8 that is about 3, 3 and 3 cancel so it is roughly about 10 power 11 hertz that points to 100 gigahertz, yes? (9.375) so 93.75 gigahertz is the accurate answer I was just giving some rough numbers but this is 93.75 gigahertz right that is, huh? It has to be in gigahertz 10 power 8 divided by 10 power minus 3, huh? What is the number you are giving? You are giving some other number, okay 1.01 that is more like it that yeah that is that is 10 power that is 100 gigahertz 101 gigahertz okay yes okay that is more like it I thought I could not be that wrong.

Anyway so that that is straightforward, so we are saying that we are going to have no one mode you know so if you were to represent that in the same picture over here you have the all these longitudinal modes here and those longitudinal modes correspond to 100 gigahertz and then the second part is what is the minimum gain required to compensate the losses in the laser cavity?

So that part if you were to write it out so the just like what we did before your gain has to be equal to alpha int plus 1 over 2 L (())(33:21) of 1 over R 1 plus 1 over 2 L (())(33:27) of 1 over R 2 and in this case R 1 equal to R 2 so I can actually say overall it is 1 over L into (())(33:37) of 1 over R that is reflectivity given as 0.9 so you can plug that in and you can find that answer, so this is 40 inverse centimetres and the other one is 1 over L corresponds to 2.5, so at be roughly about 42.5 inverse centimetres. So you can do the math and you can verify that okay.

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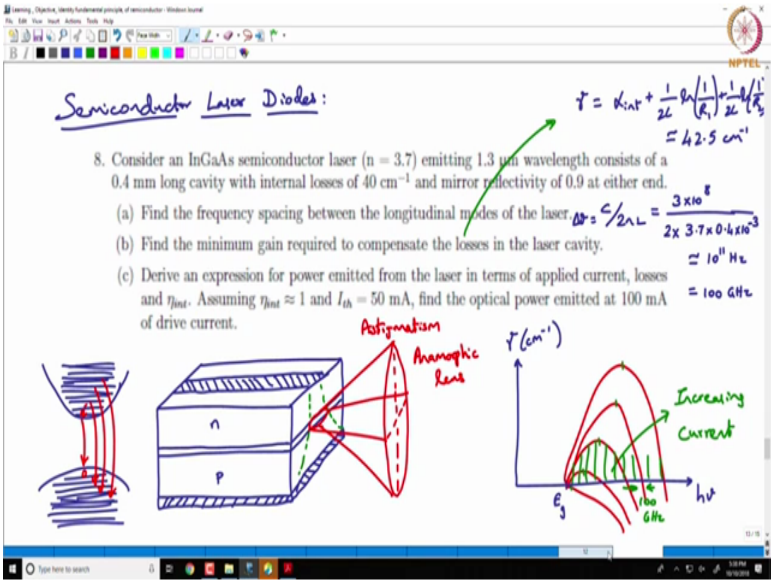

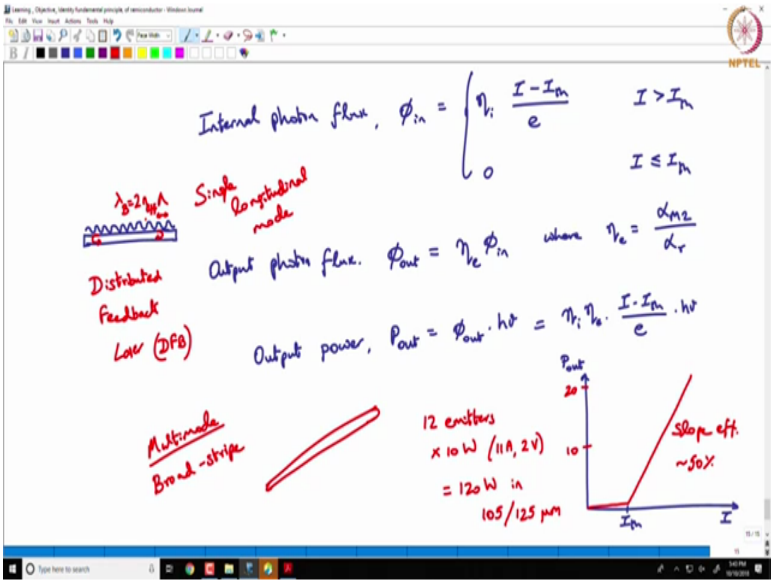

Now let us go ahead and try to derive an expression for the power emitted from the laser, okay. So let us try to do that part for calculating the power emitted we will have to look at first of all the internal photon flux, let us call it Phi in and that is going to be given by eta I just like we did for the LED case it is going to be given by the internal quantum efficiency which depends on the radiative rate over the total radiative plus non radiative rate and then you are going to have emission only for current beyond the threshold current, so I minus I threshold over e and that is what you have for I greater than a threshold it is approximately 0 it is not really 0 because there is still spontaneous emission but you can approximate that to be 0 for I less than equal to I threshold.

And if that is the case then you can say that the output photon flux Phi out that is got to be some factor of the input photon flux what is that factor? Recalling that eta e times Phi in, where eta e corresponds to if you are looking at the power coming out of mirror are mirror two then that is alpha M 2 divided by alpha r, so that that will be the that will be the fraction of power that you are extracting from the cavity.

And from photon flux hopefully by now you know how to write the expression for output power P out that just what? Phi out and then times H nu energy of the photon, so if you were to write it all out we would say this is equal to eta I eta e I minus I threshold divided by e multiplied by H nu. So he can track this right just like we did previously the only thing that has changed is with respect to the LED only this factor has changed before we were just saying I over e rate at which we were injecting current, so not all that injected current gives rise to laser emission you have to overcome threshold and beyond that whatever injected current you have gets converted into photons with energy H nu and the internal conversion efficiency and then the external photon you know photons that we get coming out of the cavity.

So typically just like what we have seen before output of a semiconductor laser as a function of the current injected you have something called I threshold up to that it is only spontaneous emission and then beyond that you could have stimulated emission and you could get output power. So you can so where all these lasers used for a variety of applications starting from UV lasers, UV lasers could be useful for lithography applications, shorter the wavelength less will be the spot size that you can get because the diffraction limit that scales as a function of wavelength, so shorter the wavelength you can get smaller feature sizes.

So if you want to do lithography with very small features you use ultraviolet light sources and lasers can be used for that, ultraviolet lasers are also packing a lot of energy each photon now has got you know several UV of energy right so ultraviolet lasers could also be used for ablating materials, so you can actually break bonds of several materials with UV radiation. So use UV lasers and then you go on to blue and green type of lasers, this blue lasers are what is used in your Blu-ray discs in your DVDs and Blu-ray discs and all that you use, shorter wavelengths specifically for that reason that you need to have very small features detected.

And then you go on to green lasers, you have these red lasers the red laser pointer is something that you have seen a lot, a green laser is also another thing that you have seen. Although when you talk about a green laser pointer we are talking about slightly different concept I think I touched upon briefly there is something called second harmonic generation going on, so that is that laser is actually a 1064 nanometer laser but then if you do a nonlinear conversion which we will talk about later in this course if you are able to do that nonlinear conversion you can convert 1064 to 532 nanometer photons which is used in the green pointer, okay.

So and then of course you go on to using 800 nanometer laser diodes 980 nanometer laser diodes where is 980 useful? Pump diodes for your amplifiers you know we saw with your erbium even ytterbium also has gained around 980 nanometers so you can use these lasers to pump other lasers okay and then so on then 1.3 micron, 1.5 micron these are all useful for communication applications.

And now people are looking at going into the mid infrared, so I was talking about sensing applications you need light sources in the 3 to 5 micron wavelength band and people are looking at making sources there. In all of this work what matters is you know if you want to get a particular energy photon you choose a material or engineer a material so that is the beauty of semiconductors, as supposed to these atomic systems where all your energy levels are all pre chosen by God so you cannot do anything about those energy levels, you just have to work with whatever you got with semiconductors by changing the material concentrations and mixing different material you can get band gap energies over a wide range. So you can achieve lasers over a wide range of wavelengths with semiconductors.

So you choose the corresponding band gap energy and then you achieve lasing at that particular in a wavelength. So let us see so that is one thing I wanted to mention and also these are fairly efficient because the slope efficiency of this you know can be in the order of 50 percent so and the threshold currents can be in the order of 10 milliamps or so. So effectively with no current with almost with negligible amount of current you are able to achieve threshold and beyond that you are converting your current into light energy.

So overall you can say that the wall plug efficiency of these lasers are in the order of 50 percent which is very very high because if you talk about this traditional gas lasers and dye lasers and all of that the all plug efficiency is fraction of a person even the solid state lasers that we have that bulk crystal based lasers the wall plug efficiency is only the order of 5 to 10 percent but this can give you much better wall plug efficiency.

Essentially for unit electrical power how much optical power are you generating? So this can give you some of the best numbers that you can see as far as wall plug efficiencies is concerned. But in terms of power that you get out these tend to be in the order of you know 10, 20 milli watts around tens of millions levels for single mode diode lasers because you know you cannot inject beyond a certain current level into it because once again like we talked about in the case of LED if you have very high current density then your coalition between the carriers and generates heat there is something called (())(45:57) recombination that happens and because of that the overall efficiency starts taking a dive, so you are limited in terms of the power levels.

On the other hand I should also mention that in our laboratory we have lasers that emit 120 watts is the highest power level that we have from a semiconductor laser. So here I am talking about tens of megawatts, there I am talking about tens of watts what is the difference? First of all the semiconductor lasers that we have in the lab they are all multimode lasers, so multimode what are called broad stripe lasers so you have a fairly large region over which this emission happens the stripe so it is a fairly broad aperture over which this emission happens.

So as you increase the gain volume as you increase the gain volume (you are able to generate) you are able to tolerate much more injected current and you are able to generate much higher power levels, but what gives in this can you guess? As you increase your aperture size it starts becoming much more than your size of your wavelength, so what do you have if you have much larger size? Well this is basically what I have written here these are a multimode so your spatial coherence reduces your multiple modes that are oscillating so you have a very low spatial coherence.

So the lasers that we use they are all multimode lasers they are actually coupled into a multimode fiber. So what I am getting is each laser is about giving about 10 watts of power and I have multiple lasers that are stacked on top of each other and overall the emission it starts looking like one large beam so you can use some optics to take shape the beam and then couple it into a multimode optical fiber. So (the fiber) the laser that I have has 12 emitters, each one of them emitting 10 watts of power and I should also mention that I am getting 10 watts of power with just a little bit over 10 amps of current okay and so this is basically roughly about 11 amps of current and you have basically 2 volts is the typical voltage draw across any of these diodes, so roughly about 22 watts so for 22 watts I am getting 10 watts of output power, 22 watts of electrical power I am getting 10 watts of output power so that that is pretty good it is close to 50 percent wall plug efficiency.

So all of this combined is giving me 120 watts in multimode fiber which is 105 microns in core diameter, 125 microns in cladding diameter. So I can have multiple emitters to scale up my output power but with a single emitter with a broad stripe emitter and all that you are not going to be able to go much beyond 10 watts of power. So right now people are stacking more and more elements the other day the record that we are seeing is about 350 watts of power from a very compact package I mean a package of size of your mobile phone you can get 350 watts of power.

And that of course you know when you say 50 percent slope efficiency, 50 percent wall plug efficiency where do you think the other 50 percent goes? It is generating heat, so if I am generating 120 watts of optical power I am generating 120 watts of heat also. So now I need to have these cooling plates and all that so these lasers are typically mounted on coal plates, we circulate cold water and all that so we can keep the temperature the operating temperature is still in the order of 25 to 30 degree centigrade.

So that is important so you scale with the higher power levels you need to have more and more efficient dissipation of heat that is required. So that eventually determines what is the size of your laser diode also, so you are not going to be able to keep it very compact because you need certain volume to dissipate your heat. So did I answer all these questions? Well the last part assuming eta int equal to 1, I threshold 50 milliamps, find the optical power emitted at 100 milliamps, I suppose that is once again just substituting into these corresponding values and then you get the output power. So the only thing you have to calculate is eta e, which you can calculate as alpha M 2 over alpha r then then you will get the output power.

So let me stop at that point so the spectral characteristics once again we talked about multiple longitudinal modes it is homogeneously broadened, so normally you expect only a single mode to be oscillating, but in reality there is actually because of spatial hole burning the you know the longitudinal modes where it oscillates it is jumping around so the average spectrum looks like a bunch of longitudinal modes oscillating together.

But one thing maybe I will mention is there is a specific class of laser known as DFB laser wherein if this is my active medium I am just this is my active layer, if I put some perturbation along this and let us say my perturbation is such that this capital lambda the period of that perturbation provides reflectivity at a particular wavelength called the Bragg wavelength, Bragg wavelength is given by 2 times ineffective times capital lambda, then that particular wavelength is going to be reflected all along the length of the cavity.

So this is called a distributed feedback laser or in short it is called a DFB laser, a DFB laser operates at a particular wavelength only at this wavelength just like the experiment you did you put an external grating, well external in the sense that it is not part of the gain medium it is outside the gain medium but it is all part of the cavity and you are able to show laser oscillation at a only at a particular wavelength.

So similarly if you have distributed feedback laser you can actually get single longitudinal mode operation. So with a distributed feedback laser you can actually have only one longitudinal mode oscillating so sometimes it is loosely called as a single frequency laser also, although there is no such thing as a single frequency laser, even this even if it is operating single longitudinal mode because of the phase noise associated it will actually have a finite spectral width, a spectral width in the order of megahertz.

But you can get some special properties with these type of lasers which is as an extension of a regular fabry perot cavity everything else is the same except that you have put this grating over that active region, so it provides feedback only for one wavelength, okay every other wavelength it is feeling loss, any questions before we close? Sorry? No it does, so in this case you do not need any mirrors because these provide all the feedback you want. So in fact you may want to frustrate other modes from oscillating, so you may want to actually put anti reflection coating on either ends, the feedback is provided just by the grating itself.

These are yeah these are the slope efficiencies, the numbers that I am quoting these are all typical laser diodes that you get, (so you would) this is not some exotic laser and this one like I said to get 10 watts you are pumping in only 11 amps that is something everybody can make these days, so the that is readily available so the efficiencies and I think the highest efficiency for a commercial device is about 65 percent efficiency.

So that just means that you have you start with a very good material you have very little background losses and so you are able to also give a structure where the conversion efficiency is very high.

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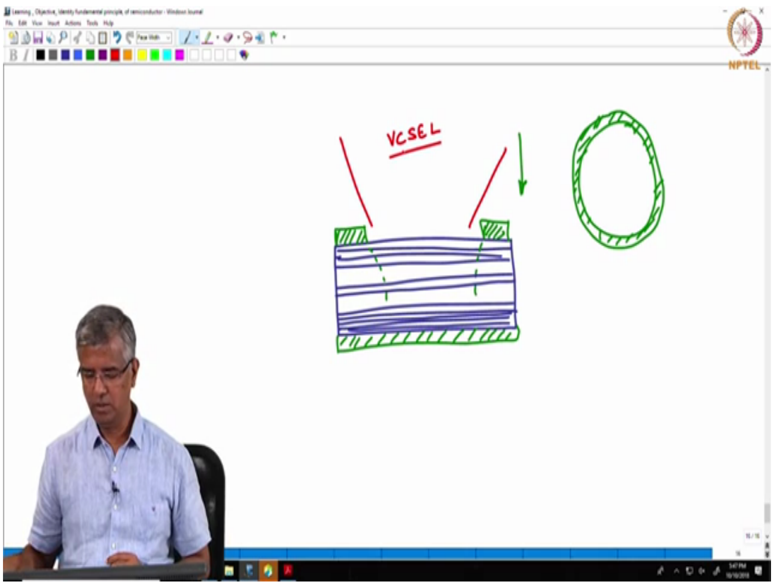

Yeah, so question is about VCSEL lasers so VCSELs are essentially what we talked about yesterday vertical cavity surface emitting lasers. So yesterday we were talking about surface emitting LEDs but in this case what you do is you can actually put sort of a periodic layer over here and periodic layers high and low refractive index layers over here so you are essentially having a Bragg grating here and a Bragg grating here and you define your electrodes in sort of a ring fashion, so the bottom electrode is like this, but if the top electrode if I am looking from here this will look like a ring electrode.

So your current injection is essentially happening across this entire region, so you once again have in this case you have an active layer here, where all the recombination is happening and then it is actually reflected by this top mirror and the bottom mirror, so the laser emission actually happens in this direction, so you have light emission happening over here. So this is called a vertical cavity surface emitting laser (VCSEL).

So VCSELs like I said yesterday the beam quality is defined by the ring structure, so you can actually get a nice circular beam as suppose to the astigmatic beam that you are getting from edge emitting lasers with VCSEL you get lights circular beams. So that actually means that you can couple it easily into an optical fiber, typically a multimode fiber because unless you define the ring structure to be very very small so that light emission can be a single moded but you get very nice circular beams out of these VCSELs so those are good for certain application, that is the electrode yeah that is the top electrode and then you have the bottom electrode which is totally planar, huh?

No the bottom electrode can be continuous, top electrode a ring only to define an aperture through which light can escape, yeah. So that is the important point, yes so you have to have a material that is not like a very good conductor it is still you have to have different refractive index and all that so you compromise that a little bit, but in general yes it should not give you a lot of loss to the it should not give a very high resistance to the current that is going through. So let us stop here and then we come back we will meet again tomorrow to discuss semiconductor light detectors.