Photonic Integrated Circuit
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Lecture No. 42
Semiconductor Light Emitting Diodes cont.

Hello everyone, so we have been looking at light emission in a semiconductor, in particular we have done discussion on the light emitting diode. So, we looked at homojunction and heterojunction, the advantages of heterojunction. Let us continue our discussion on the heterojunction and continue with assessing the characteristics of this light emitting diode based on the structure and how do we confine light and how we can extract light in particular. So, let us look into the ways of assessing the characteristics of LED.

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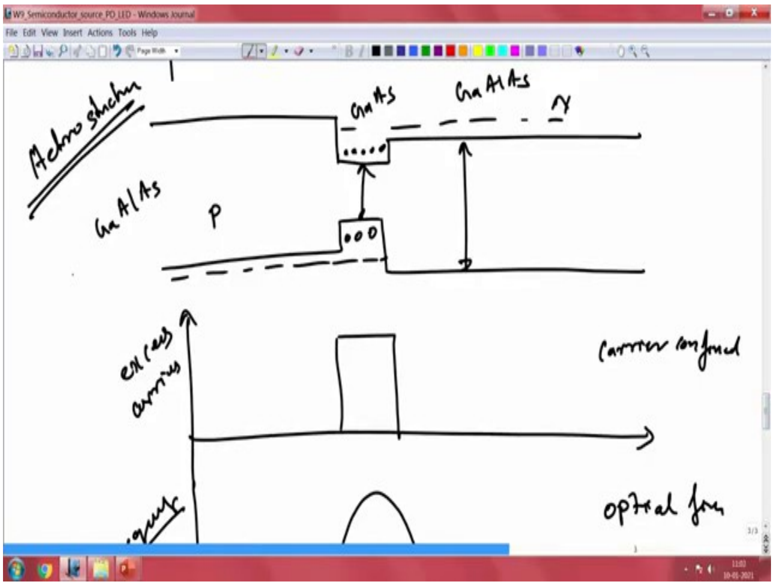

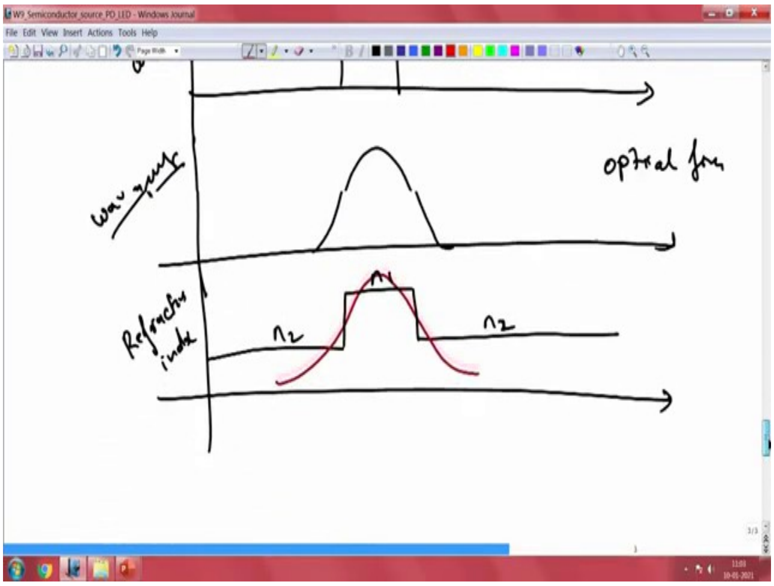

So, this is where we left in the last class where we looked at the heterojunction here as you can see where we have difference in the band gap between two different materials so low band gap material sandwiched between two wider band gap material, so because of the confinement that we have in the charges we do get emission only in the region where you have, and we can also extend this for refractive index as well.

So, the refractive index in this case will also follow the band gap here so you will have low index and then we have high refractive index like this so this could be n_2, n_2 and this is n_1. So, as we all know that when there is an index contrast you will have optical confinement in this region, and this is how we keep the light in this active region where you could efficiently generate light.

So, the other thing to look at is how are we going to feed the charges here, how are we going to inject the charges. So, there are two ways to look at it. So, let us look at the two configuration that we can have when we have a simple semiconductor emitter.

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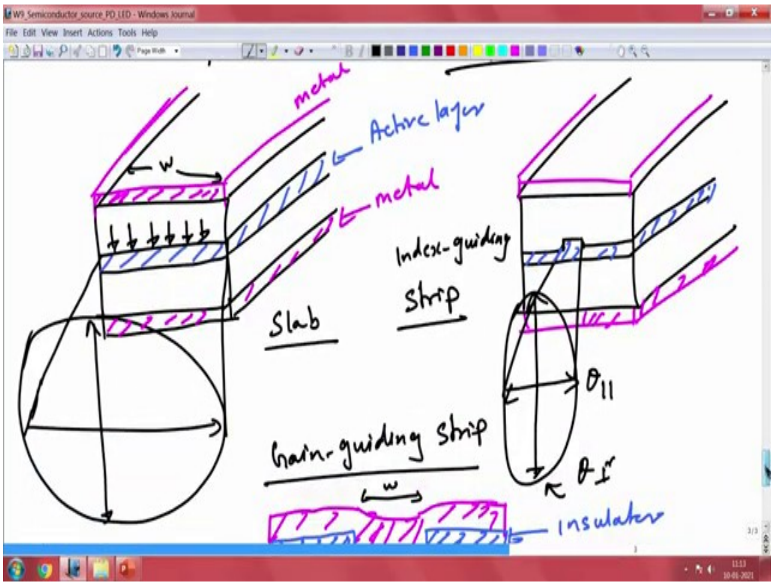

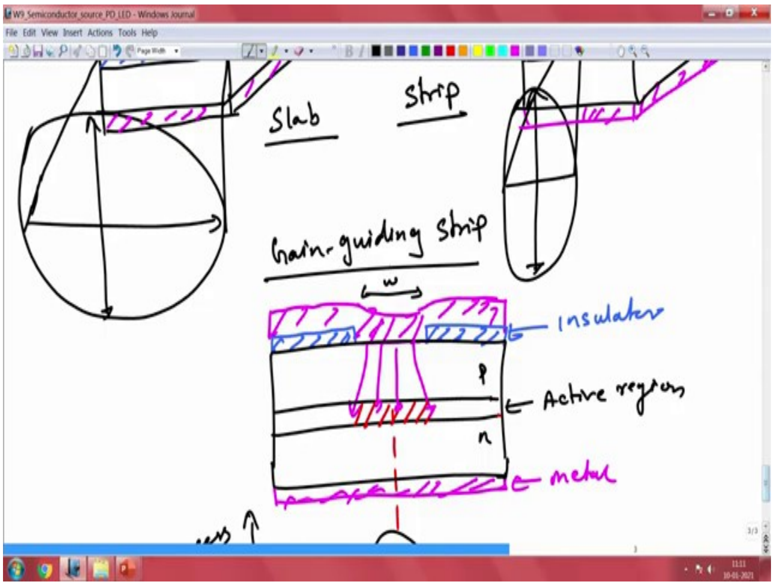

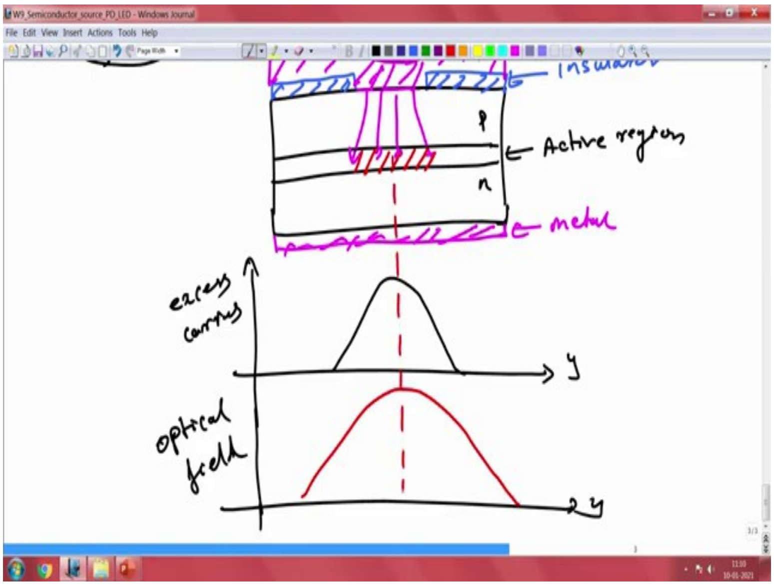

So, when we take a block of semiconductor here, so we are going to make an active layer. So, the active layer is here so the junction is here, so this is the active layer and then we need to supply current through this, so we need to add metallization here. So, we will, let us add metal here and also on top, we need to add metal, so here again this metal. So, we are going to inject carriers from vertical section here.

And the light emission in this case is going to be from the edge so it will come out from this edge like this and this will have a reasonably large cross section, so this is our injection that we have and this is our active layer and what you would get is a very large emission of this cross section and let us say if w is the width that you have for this particular structure and this is what your edge emitting structure is going to be, so this is edge emitting structure, that is pretty broad.

We can also have edge emitting by confining this active region so instead of having light emission from everywhere we could confine this emission within a very small region, so we call a strip geometry, so this is a slab geometry, so this is slab geometry. So, we could have a similar kind of patch but instead of having your emitters all over we could have a guided strip here.

So, we could make a very simple waveguide like this where this is our active region now. So, if you have a structure like this then your emission is primarily from this region and what you will have is a asymmetric structure is what you are going to have. So, you are going to have an asymmetric emission out of this particular, so we will have something like this coming from this. So, you will have emission in divergence that are asymmetric. So again, the thickness and everything is all the same but then the structure is little different, so this is called strip geometry based emission.

So, by doing this kind of injection we could make the output a profile as you like. So, another way of doing this is in this case what we are doing is again a uniform injection, so we have a uniform injection from both top and bottom. So, what we could do is instead of patterning this particular active region we could have a very specific current injection scheme. So, let us look at that cross section so this you can call this is, this works similar to a strip, so we have the p type and then we have the n type, this is the active region and now we have the metallization at the bottom as usual, we have the metal here at the bottom.

But on the top instead of having a uniform metal so if you have a uniform metal you are going to have uniform injection so all (the) you will be energizing your active region with the carriers that are uniformly distributed that means your light emission is going to be everywhere here, so this is something that you do not want, so you want to confine this. So, how do we confine this?

So, instead of having this full slab injection we can create an insulator here, so we can create an insulating region, so this is an insulator. So, we put an insulator and top of the insulator we can put a metal here so now since we have metal here on top of the insulator, we are not going to have any current going through this because you have an insulator here, in this junction we have a perfect contact, so your charge is going to move this way. So, by doing this you are only energizing this region that means you are injecting only in this region so your emission will be only in this particular region.

So, let us draw how your, as a function of distance, so here the excess carriers are important, so the excess carriers are only confined in this particular place and then again, our optical field, your optical field will be also confined only in this region, it will be slightly larger than your carrier, but this is how you can confine your charges and your light just by changing your injection strategy.

So, in this case we used a strip. So, we instead of having a thin slab we created a guiding region so we created an index contrast in this case but then instead of having the process this material we can just start with a slab which is much easier to do but then on the top we are going to create a location specific injection. So, once we have this kind of excitation then we do not need to have the strip so it can be generated along the length. So, this is a gain guiding strip, so this is called gain guiding strip.

So, the strip is a physical change in the waveguide or the active region we had but then in a gain guiding you are just modifying your injection, so when you modify your injection, we can nicely make this happen. So, we can control this width as you like so that we can have very high confinement. So, that is one thing and this, this strip is index guiding, so this is strip or index guiding.

So, we can, we can make various forms of index guiding, in fact we can completely remove this the shoulder regions here that is also possible, various configurations one can think of but as a simple structure your ridge could be used as an index guiding. So, another important thing to notice here is the output, the edge emitting output so there are two angles associated with this. So, there is a parallel angle and then a perpendicular angle.

So, in this case, this one is the parallel to your thin film, so this is $\theta_{\parallel}$ and then this one is $\theta_{\perp}$. So, these two are the divergence angles that we have, and we should know how this divergent angles could be controlled particularly when it is index guided and this, this particular divergence, this case this just Δ here, the divergence here the Gaussian beam divergence in a guided system.

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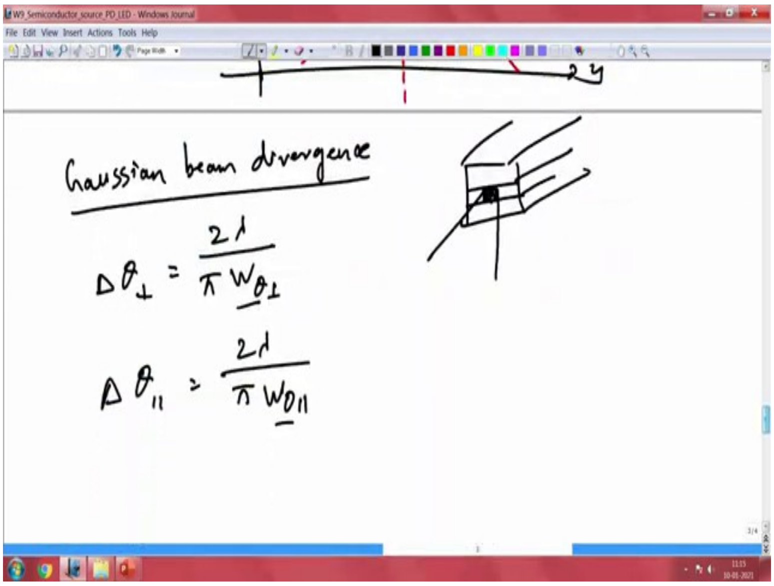

So, Gaussian beam divergence particularly happens when you have edge emitting structures. So, when you have a waveguide here the light is going to come out in a asymmetric fashion. So, what is that asymmetry that you have, so that angle? So, the width or rather the angle here the perpendicular angle is nothing but $\frac{2\lambda}{\pi w_{\theta_\perp}}$ that you have in the (particular) perpendicular direction.

And similarly, the parallel one is $\frac{2\lambda}{\pi w_{\theta_\parallel}}$ that you have or width parallel. So, what is the width that you have and what is the height you have based on that we should be able to calculate your divergence, so how much is the divergence of this spot size. So, that is about the beam divergence that we have between the two different axises that we have; one is the parallel axis, the other one is the perpendicular axis.

So, one can control this, so as you can see here when you go for very small widths or very thin waveguides, you will have larger divergence that is very apparent from this, so which is something that you should also note it down here. So, that is all about the physical phenomenas here that we see but let us look at the characteristics or figure of merits of this light emitting diodes, so the first thing to note is the power conversion efficiency.

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LED performance metric

Power conversion eff. $V \rightarrow \phi$

electrical $\rightarrow$ optical

$$\eta_c = \frac{P_{out}}{P_p}$$

$P_{out} \rightarrow$ optical power out

$P_p \rightarrow$ electric pump

$P_p \rightarrow$ electric pump

external Quantum eff

$$\eta_e = \frac{\phi_{out}}{\phi_p}$$

$$\eta_c = \eta_e \cdot \frac{h\nu}{eV}$$

$$\eta_c = \eta_e \cdot \frac{h\nu}{eV}$$

η_e depends on the construction of the LED/Source

In a led we want to understand the performance matrics, so what is the performance metrics to start with? The first thing is power conversion efficiency. So, what is power conversion efficiency? Basically, you are giving an electrical input that results in some flux or optical output. So, electrical gives you optical output so basically your, if the efficiency is given by power out divided by the electrical power. So, this is optical power out divided by the electrical pump, electric pump that you have.

So, since you do not have threshold for an LED because it works in the forward bias, your quantum efficiency is something that we should know, so which is something that we already saw earlier but let us revisit that because it is, it is necessary here to come up with our quantum efficiency here. So, our external quantum efficiency is given by the flux that is coming out divided by the pump flux and we already know that this, the efficiency that we have, this is external efficiency.

So, now we can convert this conversion efficiency is now a function of external efficiency times $\frac{h\nu}{eV}$ So, this is our power conversion efficiency, so as you can see your power conversion efficiency depends on the external quantum efficiency. So, we should understand the external quantum efficiency in order to calculate our total conversion efficiency.

So, what is that external efficiency is basically how much flux is coming out out of the electrical flux that you put in? So, it is not straight forward to calculate this external efficiency because the external efficiency depends on how you build your diode so how do you construct your diode. So, let us look at a very simple cross section that we saw earlier. So, external quantum efficiency depends on the construction of the LED. So, in principle any source for that matter, this also applies for lasers as well.

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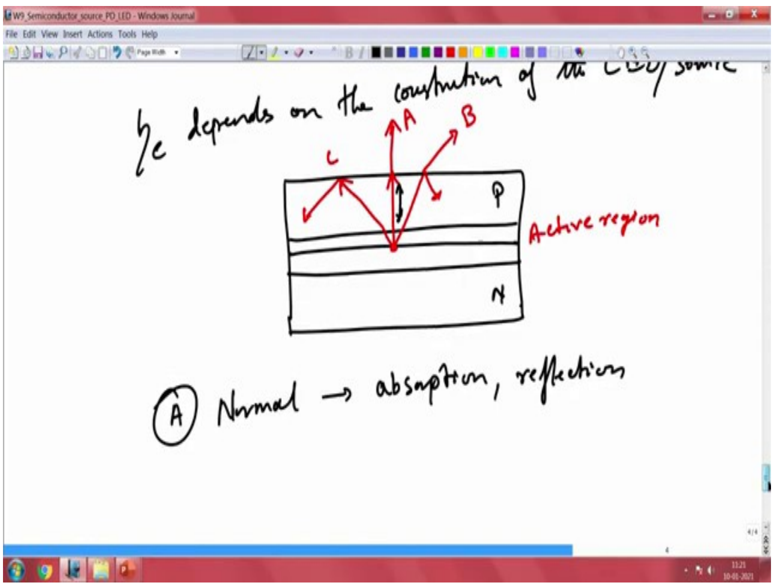

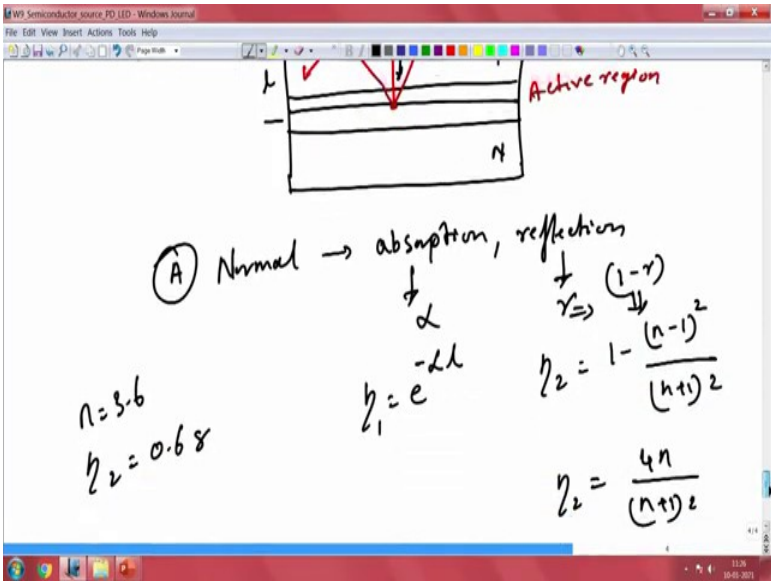

So, how we construct this, why this is, is important is when you are taking a very simple laser diode, sorry the LED stack here we will have p and n, so this is our active region, so this is p and this is n region and now the light is going to be generated in this junction so this is our active region. So, in active region, so you can generate your light. So, there are different ways that you could extract this light.

So, let us look at how this light is generated here, it is isotropic generation in nature so isotropically you generate so that is how light is generated in a simple LED in a spontaneous process it is isotropic in nature. So, let us take three simple scenarios. One is scenario A, where the light is normal and then one more scenario where you have light going through so that is let us say A and let us say this is B and then scenario C where light has another angle.

So, if you look at these three cases it will be very clear that an isotropic generation could result in light that is going through straight A or B or in C direction, these are all possible cases. So, when you look at case A, case A is normal, so light goes through this at a normal to the surface so there are two phenomenas that could happen when the light is propagating through this medium.

So, one is absorption, so in the medium it is travelling a certain distance here so it will have some absorption associated with this and the next thing is reflection so these are all the two things that could happen when you have light propagating through this system particularly along A.

So, absorption is characterized by α, so when there is a absorption this is what happens, there is absorption there and the reflection give it as a function of r so you would either have absorption α or you would have reflection, so both will be present in this case of A so let us say it is travelling at distance of l so let us say this is l to come out of the active region and out into air so let us say n equals to 1.

So, in A, so the internal quantum efficiency depends on these two factors. So let us look at the absorption, effect of absorption, so the absorption, that the attenuating factor depends on the α so there is -αl is the attenuating factor but let us look at reflection. So, your reflection is going to be given by $1-(1-n)^2$, basically this is the transmission that you have so because of reflection what is the effect. So, this is the transmission of this, the efficiency the attenuation because of absorption is given by this so this is what you will get out.

And because of reflection, η_2 is your efficiency that would result because of reflection. So, now you can modify this into $\frac{4n}{(n+1)^2}$, so that is η_2. So, now what is the total η here so it is nothing but $\eta_1\eta_2$. So, this is your internal or total transmission for A so just to give you an example here let us take a material for example a III-V material with refractive index n of 3.6 let us say.

So, in this case η_2 will be 0.68. So, you can imagine that the higher refractive index will create higher reflection. So, your η_2 will be higher. So, you want to make sure that your transmission here should be better so this is 1-r so that is what we have here that is your transmission. So, that if you, the reflection is something that we should try to reduce and by doing that we should be able to improve our light extraction. So, that is the case with A.

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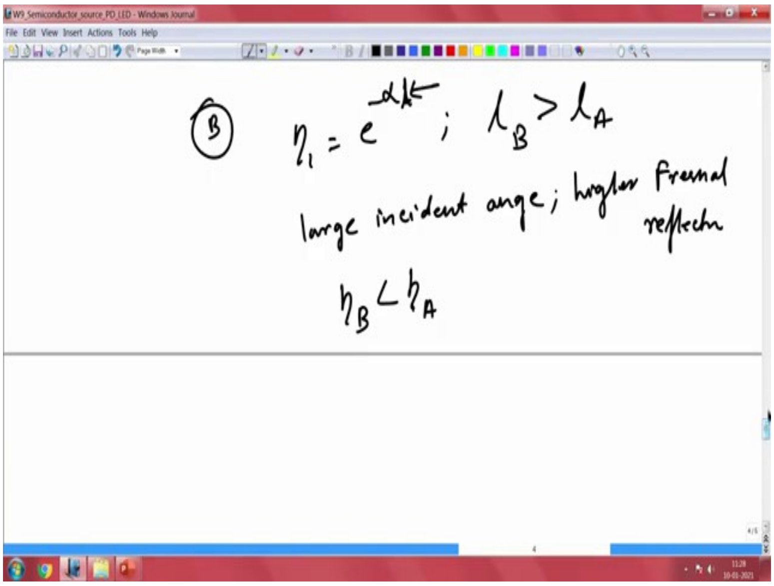

So, let us look at B, so in B we have two scenarios again, one is light that is refracted the other one is reflected but you still suffer from the absorption here you see the absorption is still there, you still have absorption but then there is a refraction and then reflection. So, the same argument applies there as well the only thing is the reflection is at an angle. So, your η_2 here $e^{-\alpha l}$ so this l that is travel l_B is greater than l_A.

So, the length that a travels is the actual length or the distance between the active region and the surface but look at B, so B is travelling longer. So, because of this η_1 is going to be larger compared to η_A so overall efficiency of, extraction efficiency of angle with B is going to be less than A so this is because of the reflection loss as well because it is incident at a large angle. So, η_2 is taken care here but then because of the length and the next reason is the large incident angle.

Because of large incident angle you have higher Fresnel reflection. So, that means η_2 is also going to be larger so as a result η_B will be less than η_A. So, it is better to have a vertical emission while the rays that are going in the direction of B is going to suffer higher loss because of both reflection and absorption.

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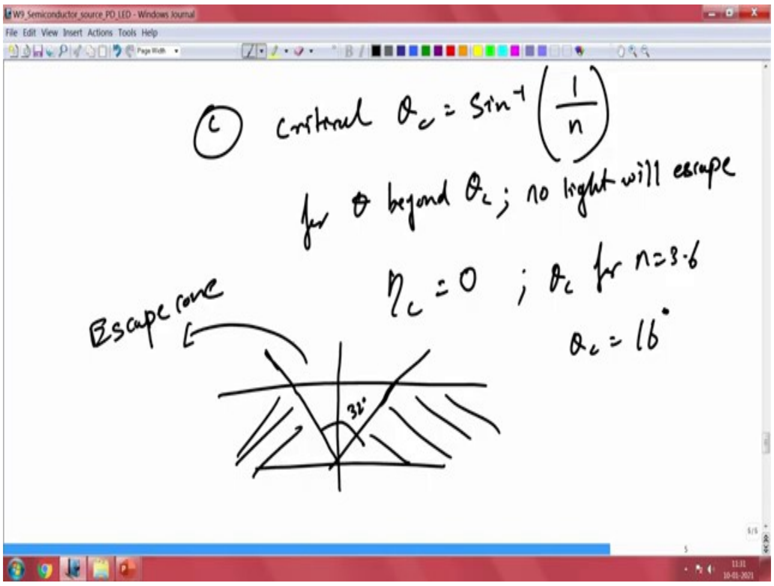

So, let us look at the other scenario that is C, so C as you can see here has a total reflection, total internal reflection so then let us calculate that critical angle. So, critical angle is given by $\sin^{-1}\left(\frac{1}{n}\right)$ so this is our critical angle because the refractive index of the medium is 1.

So, now if you have a total internal reflection for θ beyond θ_C, no light will escape, look at this when there is a total internal reflection you will not get any light out. So, what does that mean? That means the efficiency that you have is 0 and again for the θ_C here for n 3.6 for example is about 16^0. So, we need to make sure that this light escapes within that 16^0. So, what we mean by that is your cone, the light cone that you have so this is 16^0 that means this is 2θ that means 32^0 is what we have to collect the light.

So, this is all you can collect out so look at how much light we are actually wasting so we would not be able to collect all of this, and this is what we call, this whole cone, is called escape cone. So, the rays inside this particular angle can only escape out, so beyond this you would not be able to have any light through.

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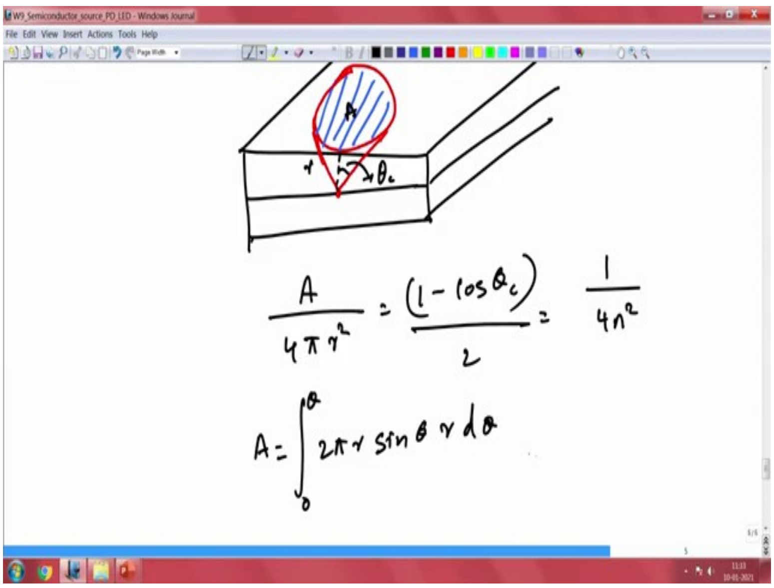

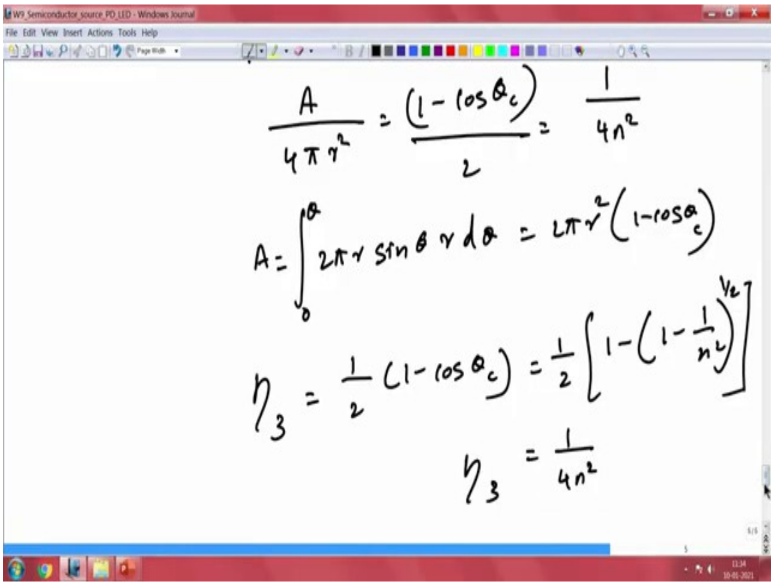

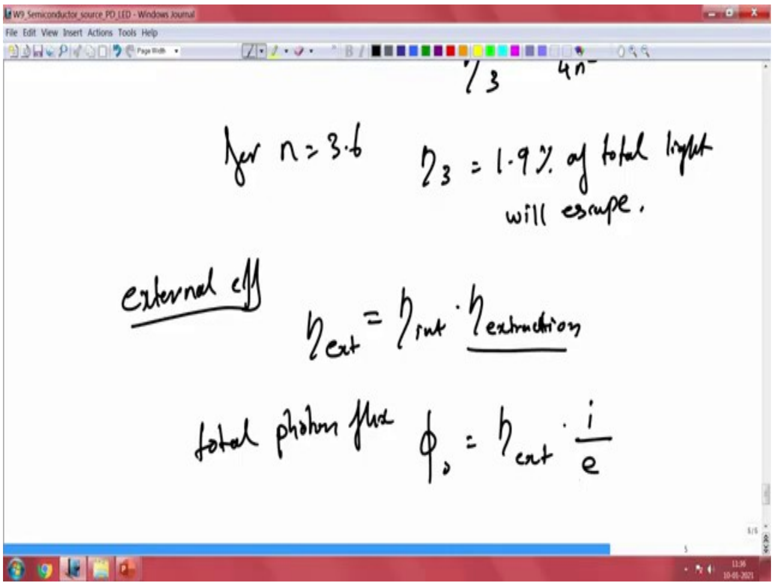

So, let us just look at that escape cone in a three-dimensional fashion, so we have this very nice slab and then we have this region and we have emission from here so we have emission and this emission will have a nice angle to this and this is going to result in a cone and it will have a certain r and θ, this is θ_C and it has area A. So, now for a point source like this this is our cone that we have and that is given by the fraction of light lies within this escape cone from a point source is given by $\frac{A}{4\pi r^2}$.

So, that is the radius that we have which is equal to $\frac{1-\cos(\theta_C)}{2}$, in other words $\frac{1}{4n^2}$ is how we could calculate this. So, what is the fraction of total generated photons that lies within this cone is what we are interested, what is the total fraction that means you can just integrate, it is the area of this circular disc that we have is where we are collecting the photons, so this is the region from where we are collecting this photon.

And we can get that by integrating it over that angle θ, so $2\pi r \sin(\theta) r d\theta$ in other words $2\pi r^2 (1-\cos(\theta_C))$, that is the critical angle. So, now we can look at the efficiency of this escape. So, what is that particular efficiency when it comes to escaping from this, it is given by this particular function or we already know what this is, it is nothing but $\frac{1}{2}\left(1-\left(1-\frac{1}{n^2}\right)^{\frac{1}{2}}\right)$ or in other words $\frac{1}{4n^2}$, so this is the escape cone and this is how much you can get out so that is your η_3.

So, here again the refractive index plays against you. For example, again for n is equal to 3.6 your η_3 is only 1.9%, so this only 1.9% of total light will escape, so this is rather poor and this combining all of this is what we call the extraction efficiency. So, the light that is going out based on all these consideration coming from your escape cone is what we call the external efficiency. So, the photon, the external efficiency that $\eta_{external}$ is equal to internal efficiency times extraction efficiency or η.

So, the extraction efficiency is what we just saw, so the internal quantum efficiency we already saw it is just based on the injection but then the extraction efficiency depends on your structure and the refractive index and so on. So, the total photon flux, the total photon flux that is φ_0 is given by the external efficiency that we have times $\frac{i}{e}$. So, this is our total output photon flux, so this is total photon flux that is coming out.

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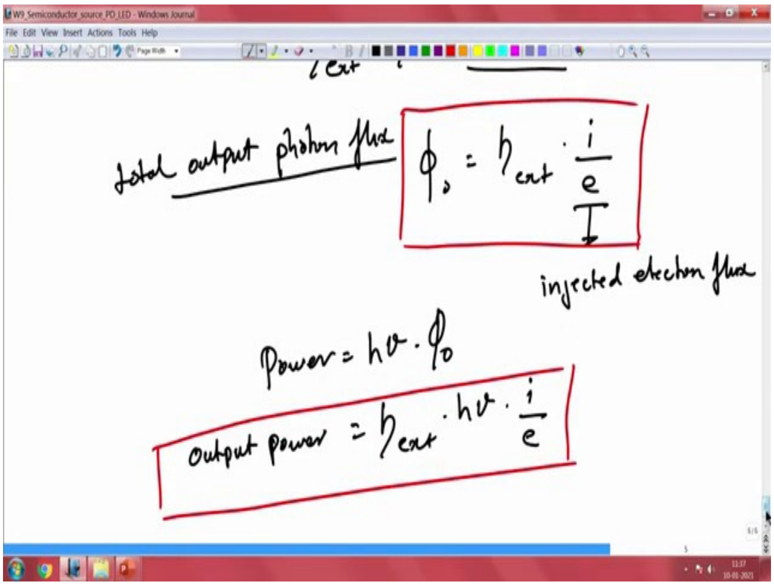

So, you can also call this total output photon flux, and this is related to our injection flux, so this is nothing but what we have here is injected electron flux. So, this will give us how much flux that we can get out but then the power, the output power is given as $h\nu\phi_0$ or in other words external times $h\nu\frac{i}{e}$. So, this is our output power, so these are all important relations that you would use when you are calculating your efficiency for a given structure and what is the output power for a given efficiency and for a given injection and so on. So, just make sure that we revise all of this for the assignments and tests and so on.

Your external efficiency as we saw is rather low, the internal efficiencies can be 0.5, 0.6 easily but then you look at the internal efficiency so it is rather low we are talking about 1% or so your generation could be 50% efficient or 60% efficient in some of the systems you can have nearly 80, 90% generation that is internal quantum efficiency, you are converting electric to photons, but then how much can you take out so that extraction efficiency can be very low.

Because of that extraction efficiency low your external quantum efficiency, so external quantum efficiency will also be going to be rather low. So, this can be very high but then the extraction efficiency will be low, 1, 2% or 3% as the max. So, that is something we should keep in mind that it is not just the generation it is also about extracting the power out of the system all. So, with that I think we have a understanding of how the power and conversion efficiencies could be understand.

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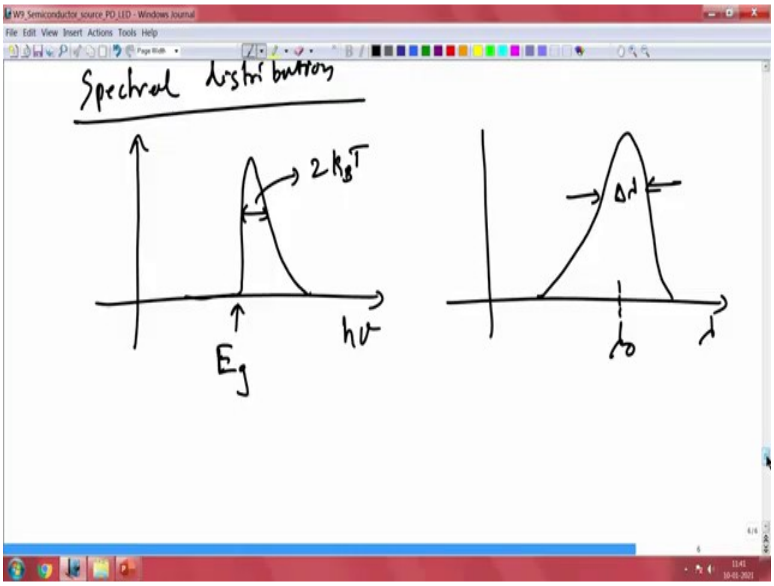

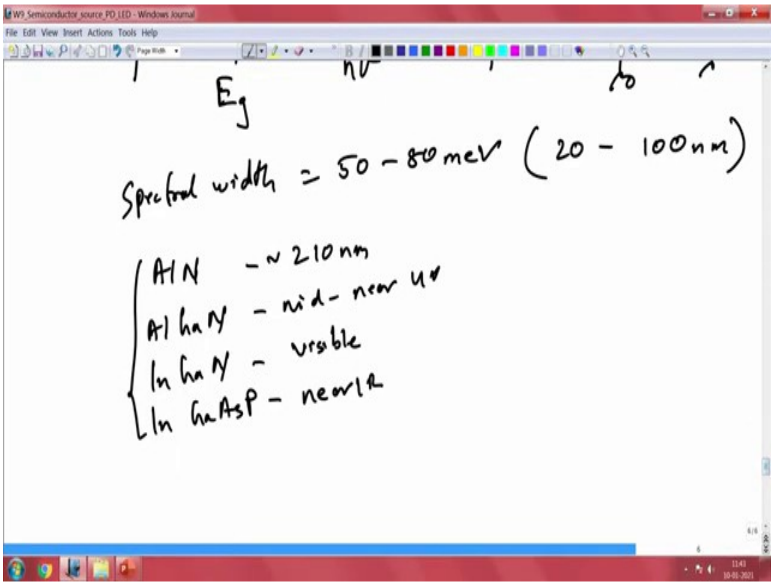

The next thing is the spectral characteristics. So, how is the spectrum going to look like, so what do we mean by spectrum, how the energy is distributed with respect to frequency. So, ideally what we need is a single wavelength source, but we all know that LED is a spontaneous source and there is a limitation to that, and that limitation is coming from our the spectral line width. So, over a spontaneous emitter, you are limited by the band-to-band transition so that is going to dictate our line width.

So, if you look at the frequency here the energy that we have here so you will have a very sharp increase and then going down. So, what we see here is nothing but your band gap and the emission here the line width is dictated by $2k_BT$. So, this is a classic spectrum from a light emitting diode source. In wavelength domain you could have something like which is going to be asymmetric, that asymmetry and this is your λ_0 and this asymmetry is coming from our density of states that is distributed in here so in the band edge you will have the density of states that this determines how your transitions are.

So, when you, when you are drawing your states so it is going to be sparsely (())(39:25), so you will have going like this, so this distribution will show up in your spectrum as well, this is your fundamental solid state physics. So, what should be the width? So, width can be, depend on the material system itself, but in in conventional sense the spectral width could be anywhere between 50 to 80 milli electron volts.

So, let us say the spectral width, this could be between 50 to 80 meV which is a real possibility. So, this is at all a room temperature, in terms of spectral, in terms of λ, this is in terms of energy, in terms of λ you can have anywhere between 20 to about 100 nanometres, so this is all possible, for example an LED like indium gallium nitride LEDs would have a narrower spectral emission while indium gallium arsenide phosphide kind of material will have much broader emissions.

So, it is possible to have this whole range of spectral emission based on your material system that you have and the composition that you have, so that is on this spectral side so you can have various material system for different emission for example, aluminium nitride you could have for aluminium gallium nitride, indium gallium nitride or indium gallium arsenide phosphide, so these are all different material system that will be from different wavelength regions of your interest.

So, this could be really deep ultraviolet, so you can have mid to near UV, this is all visible and then this is near IR. So, this is all a possible generation of light sources from different material system, it is up to us to choose the light system that we would like to have for corresponding wavelengths.

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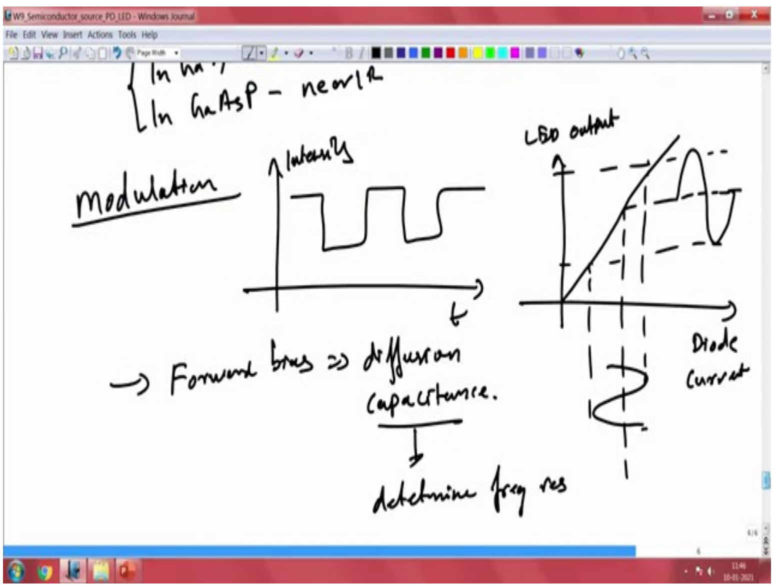

So, the next item is, is it possible to control the emission, so what we call modulation. For example, you want to control the intensity of light as a function of time, so I want to control the intensity of light as a function of time, why would I want to do that? Even for visible light there is a recent advancement where you want to communicate using visible light for indoor applications for example or you want to do communication for optical fibres through optical fibre.

So, you want to change the intensity of light that is coming out, so all you are trying to look at is a change in the current should result in change in the output intensity which is something that you can easily do because of our LED characteristics. So, when you have the L-I curve that means the diode current versus LED output that is our intensity, so it is rather linear in nature. So, because of this when you change your the diode current that we have, so this should result in change in our intensity as well.

So, that is what you are looking for, so you want to make sure that the LED output changes with input current, is it possible to do that, of course it is possible the only problem here is the capacitance, the diffusion capacitance that you have so you can do it in forward bias of course the light is in, the LED is in forward bias, but then this would result in diffusion capacitance and this diffusion capacitance is going to determine frequency response. So, how quickly can you change this current so that your output is still the replica of the intensity that you have.

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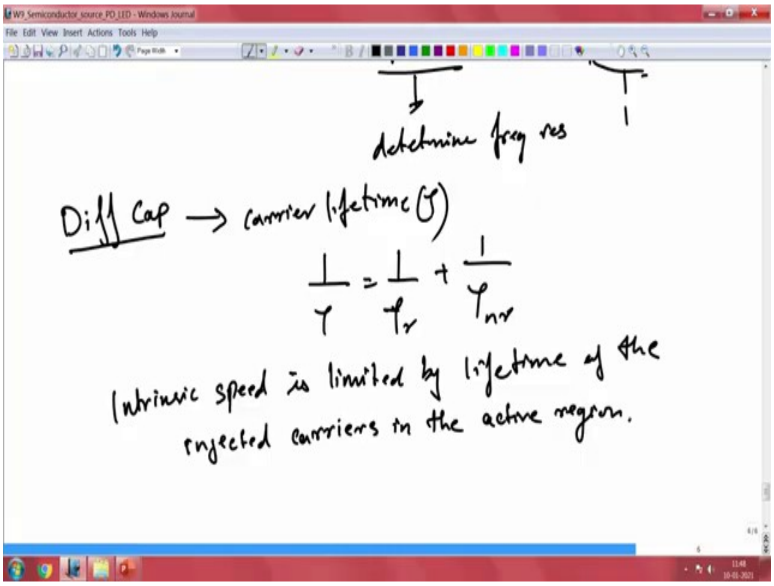

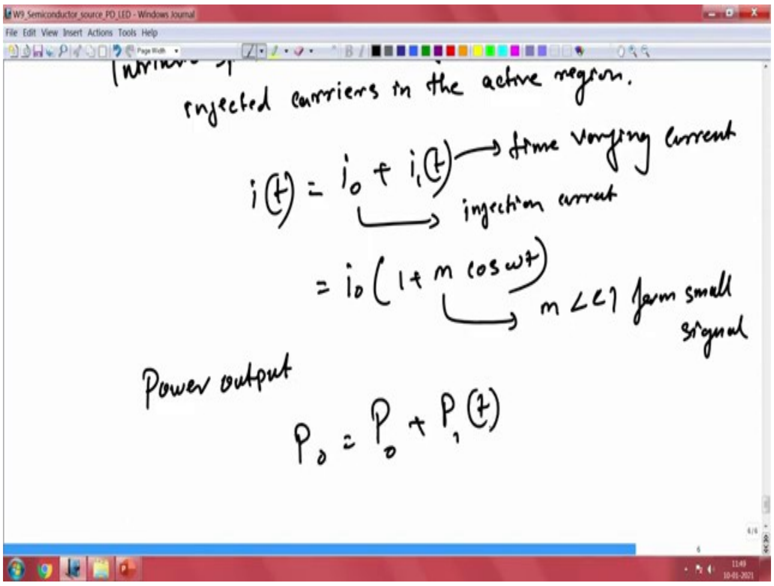

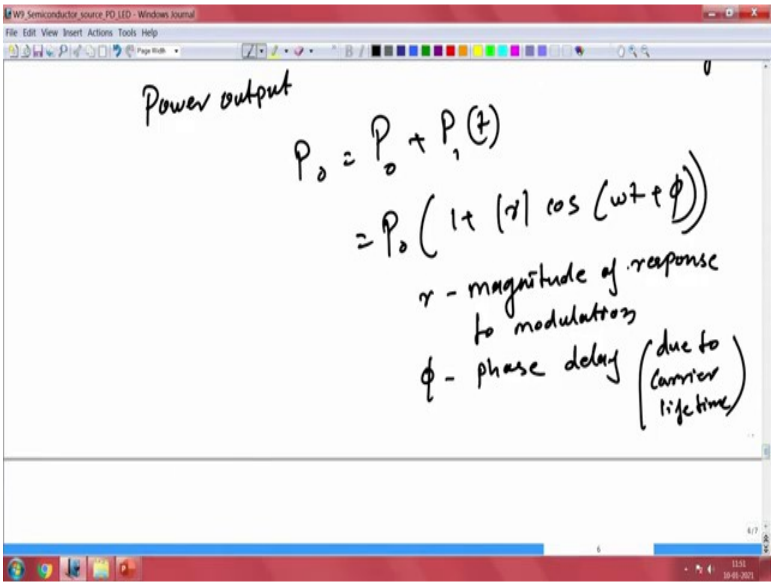

And the diffusion capacitance that we have here as a limitation, so diffusion capacitance depends on the carrier lifetime. So, the carrier lifetime plays an important role here for the diffusion capacitance and we all know the carrier lifetime relation because we saw that in our transition rates so there your lifetime depends on your radiative and non-radiative recombination process here.

So, because it is strongly dependent on the injection of this and the radiation sorry, radiative and non-radiative recombination process, your speed, the speed is limited by the lifetime of the injected carriers in the system. So, the intrinsic speed is limited by lifetime of the injector carriers in the active region and that is given by a simple relation i(t) is the current that I want at the output. So, i_0 is our base current, so this is our injection current plus some $i_1(t)$ so this is the change, the time varying current that we have and this is our injection current that we have that is the base injection current, where you have forward.

So, this $i_1(t)$ could be written as $i_0(1+m)\cos(\omega t)$ let us say so ω is the frequency and m is what we call an in integral factor or integer factor here that characterizes whether it is small signal or large signal, so this is normally much less than 1 for small signal. So, we can take that out of the system, so now the there is a linear response for the change in your input to our change in our output.

So, let us look at how the power is going to look like here. So, the power output is nothing but the base power output plus some input that we have as of that results in this power change and which is given by $P_0(1+|r|\cos(\omega t+\phi))$, so what is this r? So, r is our frequency response or magnitude of response to modulation and φ is the phase change or phase delay that you have. And this phase delay (of) is primarily due to carrier lifetime.

So, these are all the factors that determine your output power. So, we could go on further and then characterize this frequency response r. So, frequency response r that you have here, so modulation frequency response.

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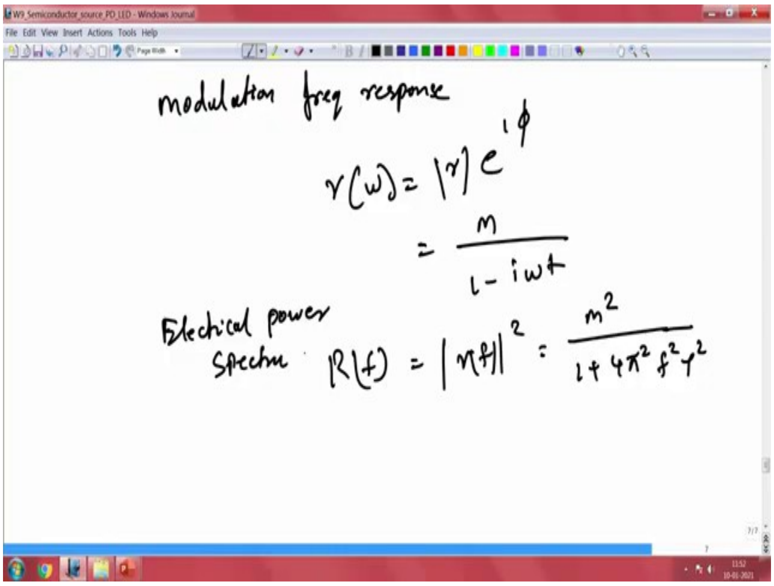

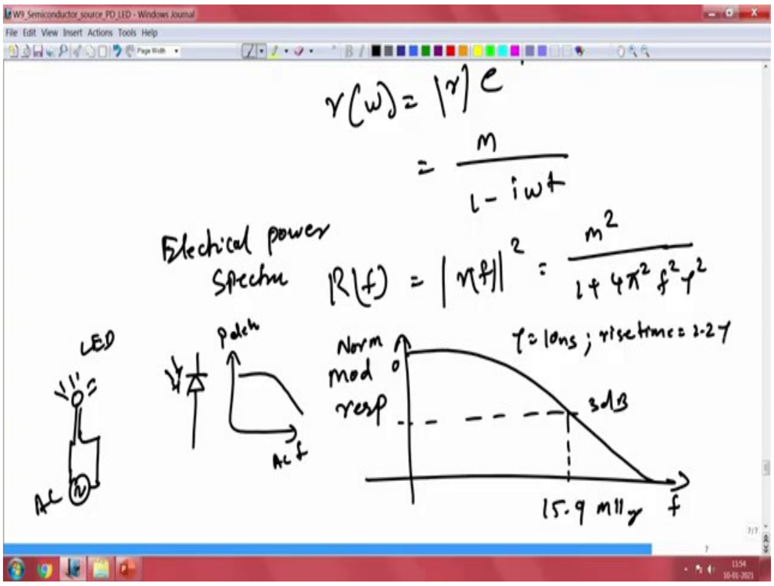

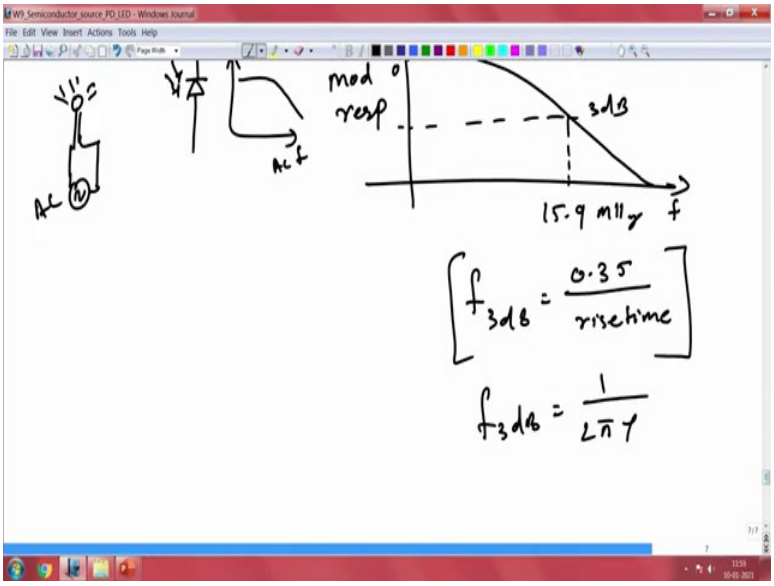

So, modulation frequency response, r, as a function of ω depends on φ as simply like this or you could write it, so this is something that we know from our control theory but what is the actual transfer function, a solution to this? R(f) is nothing but $r(f)^2$ which is nothing but $\frac{m^2}{1+4\pi^2 f^2 \tau^2}$. So, this is the relation for the electrical power spectrum.

So, the way that we do this measurement is by taking an LED and then running it through an AC with various frequency, so you will have a time varying field and then you put a detector, so you measure the electrical response of this. So, whatever AC frequency that we have and what is the response of this so or the power that you get, the electrical power that you get, so this is $P_{electrical}$ and as a function of frequency you see how your response looks like.

And that response as a function of frequency and this is our (modulate) modulation response normalized modulation response would look something like this. So, for, let us say in this particular phase are, about 10 nanosecond you will have 3 dB bandwidth so if this is 0 and this is 3 dB is about 15.9 megahertz when you have a rise time this is τ is equal to 10 and rise time of 2.2 τ. So, let me write it here, so here τ is 10 nanoseconds and rise time is 2.2 τ.

So, that means your, we already saw this f_{3dB} is 0.35 divided by the raised time, so this is something that you can use in order to calculate your f (())(53:00), this is coming from the electrical 3 dB. So, based on this you could calculate your 3 dB bandwidth, the other way to do that is f_{3dB} could be calculated by $\frac{1}{2\pi\tau}$, this is, this is exactly the same. By doing this we could calculate your 3 dB bandwidth.

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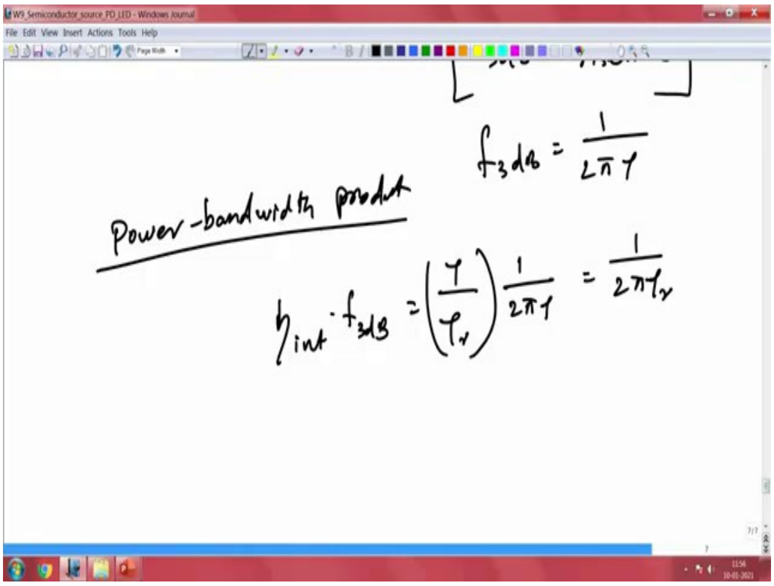

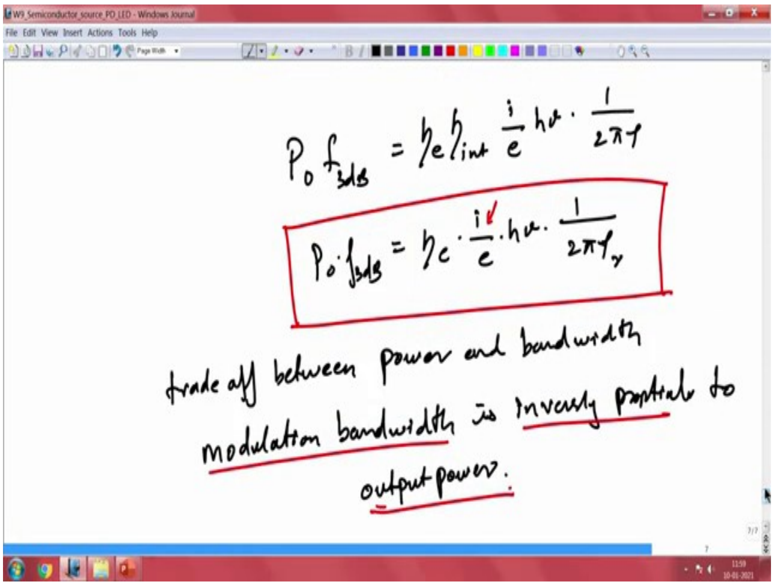

So, now we need to look at the power bandwidth product, so power bandwidth product, so what is that power bandwidth product? So, you need to get high output power, so that is what we saw here, let me go here, yes so we want to get more power out of the device that is what we all try to do, so for the same injection that you do, you want to have higher conversion efficiency, a lot of the injection current should be converted to your photons. So, ideally you want it to be 1.

So, one electron hole pair will create one photon that you can extract but we saw that that efficiency is going to be rather low because of your extraction efficiency, we try to do that. But, the another parameter we have is how quickly I can push and pull the carrier so this is the modulation front how easily I can change the intensity. So, the question here is can we still do this intensity change with, without affecting the bandwidth so we need to understand that and that is given by η internal in this case let us say times f_{3dB} and that efficiency is given by $\frac{\tau}{\tau_r}\frac{1}{2\pi\tau}$ that is given by $\frac{1}{2\pi\tau_r}$.

So, now you can see that gain bandwidth is primarily depend on the radiative recombination factor only. So, now the you can even further expand this, look at the power bandwidth $P_0 f_{3dB}$

which is nothing but external efficiency, internal efficiency, $\frac{i}{e} h v \frac{1}{2\pi\tau}$ so that we saw and if you can move things around, so what you see is your power bandwidth product depends on your external efficiency and our radiative recombination.

So, your power bandwidth product depends on the injection, directly (depend) proportional to the injection here so if you increase the injection, you will get high power but then it is going to reduce your speed, the reason for that is your radiative recombination rate so there is a trade-off.

There is a trade-off between power and bandwidth. So, high power will give you, high injection will give you high power but then it is going to reduce your rate. So, the modulation bandwidth is inversely proportional to the output power. So, in this case modulation bandwidth is inversely proportional to output power, so this is again an important relation that we should all remember.

So, with that we can conclude our whole understanding of light emitting diodes here, so we started off with the structure and now we understand what is the parameters, the functional parameters you should look at in order to qualify any light emitting diode, so in terms of power, the spectral distribution and also the bandwidth. Thank you very much for listening.