Introduction to Photonics
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Semiconductor light Source and detector LED Characteristics

Ok, good morning welcome to introduction to photonics.

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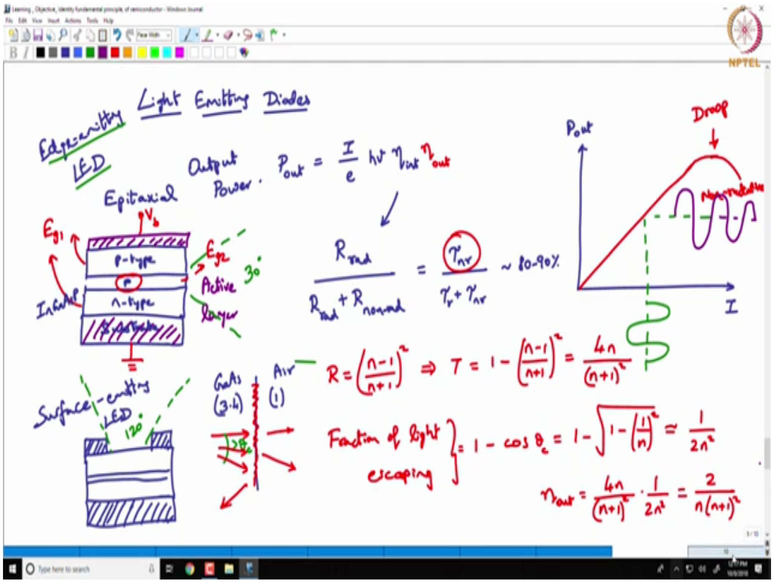

Light Emitting Diodes

Output Power. $P_{out} = \frac{I}{e} h\nu \eta_{int} \eta_{out}$

$\frac{R_{rad}}{R_{rad} + R_{nonrad}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} \sim 80\text{-}90\%$

$R = \left(\frac{n-1}{n+1}\right)^2 \Rightarrow T = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4n}{(n+1)^2}$

Fraction of light escaping $\Big\} = 1 - \cos\theta_c = 1 - \sqrt{1 - \left(\frac{1}{n}\right)^2} \approx \frac{1}{2n^2}$

$\eta_{out} = \frac{4n}{(n+1)^2} \cdot \frac{1}{2n^2} = \frac{2}{n(n+1)^2}$

In the last lecture we would been talking about semiconductor light Sources and we started looking at some of the characteristics of light emitting diodes, so when nature we are saying that this is going to be using spontaneous emission of radiation for this light emitting diodes and we talked about the typical structure being a double heterostructure where in inactive region is consist of material with lower band gap energy than the surrounding material will be used.

So we talked about a structure as shown in the left side of your screen where in the p type and n type are actually made of material with higher band gap energy compare to the p type at the centre or in the middle, so we can effectively see carrier confinement and we also said that choose a material correctly with lower band gap energy you made (accu) also have higher refractive index in that medium, the active medium.

So it ends up you know confining the photons also in the in that direction you know, so we will have photon confinement as well as carrier confinement happening in the active region and then your light emission will typically happen from one end of this region, so this sort of structure would be known as an edge emitting led, right. So in a edge emitting led your I make just sure we are not getting confused by this was actually explaining this from a different context for an led you do not have mirrors at the on either sides.

So the light emission is likely to happen like this, ok. So since is emitting from the edge of that structure we call this is as edge emitting led, ok this is actually slightly different from another type of led which is called the surface emitting led, in a surface emitting led you have the same heterostructure with the active region being like this and you may have the substrate also like this which may be highly conducting, so you can use it as an electrode but at the top what you would have is actually an electrode that is like a ring, ring type of electrode.

So from looking from the side it will look like this but looking from the top it will look like a ring and in this case the emission will happen like this, so it will emit from the surface of the led. So well what is the advantage? Advantage is that your how you define the your electrode at the top determines the aperture over which the emission happens, ok. In the other case in the edge emitting case you can say that light is actually confined within that active region, so the emission happens only from that active region and the active region the thickness of that is typically you know micron in the order of a micron, right.

So the emission essentially happens only from within that region whereas in a surface emitting led other than the electrode you know or any area within that electrode you going to have light emission and the light emission is tends to be distributed broader compare to what you have in the case of edge emitting led, so surface emitting led is typically they are able to support up to even 120 degree range of angles, ok whereas in edge emitting led typically supports about 30 degree range of angle, so this is about 30 degree is here and this could be all the way up to 120 degree is, ok.

So for lighting applications you would rather have a surface emitting led, right so where you can actually spread the light as widely as possible, ok and over a larger aperture because you do not care about the quality of the light when I mean quality of the light I should talk about what happens in a edge emitting led if you (meak) make your active region in the order of a micron what you can say about the special coherence of the light that comes out, so that is it is very small apertures comparable to the wavelength of light.

So the special coherence of the light that comes out can be quite good quite high, so in this case you can take optical fiber, right you can take an optical fiber and you can place it at the output of that edge emitting led and you can coupled lot of light efficiently in to the fiber because the special coherence is fairly good from this sources, ok. So edge emitting structures are more amenable to coupling into an optical fiber which may be useful for lot of applications like you know we are talking about led but we will go ahead and talk about a laser diode.

So in terms of semiconductor laser diodes those would tend to be the sources for optical communication application long distance optical communication application. In that case you need to take light from a (le) semiconductor structure and coupled that light into an optical fiber and you know from what you have done previously in the semester that if you want to couple efficiently in to a single mode optical fiber you need to have a highly specially coherence source, right.

So edge emitting led are very good for that if they are amenable to coupling into an optical fiber whereas if you want to just throw lots of light in to free spacing you do not worry about the mode quality and all that you just want to cover large area, you typically go for a surface emitting led, like this led is that are emitting light at these are typically surface emitting led is, you understand the difference, right.

So lighting application surface emitting led is for other application where you want to couple in to an optical fiber specially a single mode optical fiber you go for edge emitting led is. Now we talked about the output power as a function of injected current and we said ok we have a fairly linear dependence in terms of the output and of course we said we also said it cannot go forever because as you inject more and more carriers into the structure and they get confined and that active region you end up having such high density carrier density that you might actually have collisions between the carriers and that might generate heat, right and that will reduce the radiative efficiency what we have actually mentioned would this represented as eta int and the expression for the output power and so that may eventually limit the amount of output power are able to extract from the structure, ok.

So we will move further in to this, one of the interesting aspects that you see here is the output power closely follows the injected current, so that gives you some ideas right, so one of those ideas maybe that you know you can modulate the current that is fade in to the led and you can expect a corresponding modulation of the output power coming from that led, ok and that gives you some ideas because now we are using this led for just illumination purposes but nothing stop us from modulating the current give to led, right and if it is done at high enough speed if you modulate at 1 hertz 1 cycle per second you can probably given sense that the light is actually turning on and turning off we can see the blinking but if that is happening at 100 megahertz, right.

So the time period corresponding 100 megahertz is 10 nanoseconds your eyes is not going to able to make our that there is any change in the intensity, right it look like constant intensity to us but it is conveying information you can start conveying information through that, so pretty soon we going to see all this light panels over here replays by led panels, right and in fact you know a street just a big event in our street where I live, we had all the streets light converted to led panels.

The local mla came and there was a small function where he was inaugurating that thing and now we have led is lights over a streets but now that we have a led lights now we can actually convey information now we can modulate that light with some information and then you can maybe you know enable downloading of information through that led lamp which is primarily for illumination purposes but now we are enabling communication through that.

So you could have these led panels change to a I mean this light panels change to led panels and then you could have communication established between that led panel to your mobile phone, suppose mobile phone has some receiver which can pick up that modulated light then you can send information across that, ok so that is actually a new concept called Li-Fi just like Wi-Fi which is you know wireless fidelity, now we have Li-Fi which is based on light and that is a concept that is peaking up around the world, so people has starting to look at multiple functionality from your led panels.

So what we want to understand now is what is the maximum frequency I can support, you understand this, right now I am modulating the current and I am getting a modulation of the light that is coming out of my led, how fast can I modulate this, what is that limited by ok that is what we want to figure out.

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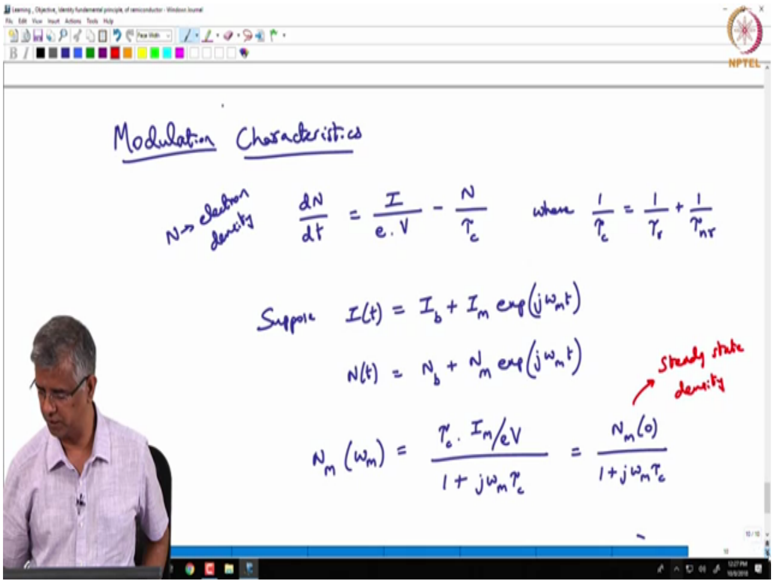

Modulation Characteristics

N → electron density

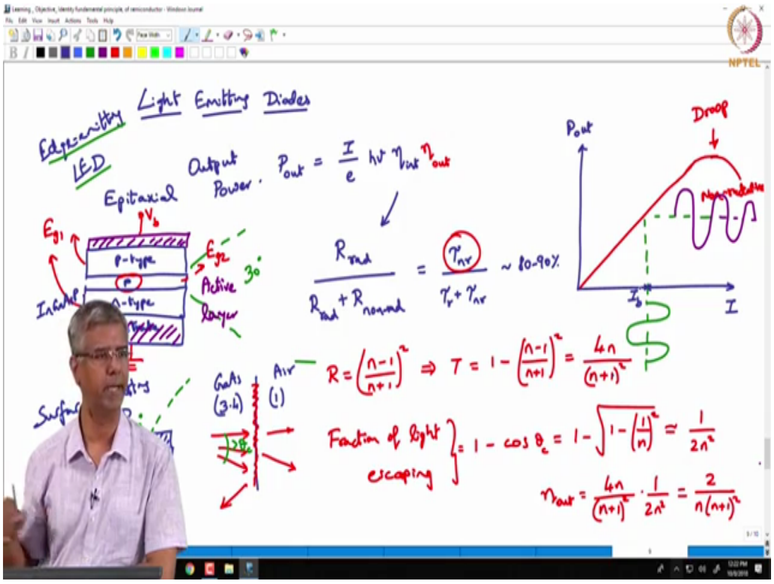
$$\frac{dN}{dt} = \frac{I}{e.V} - \frac{N}{\tau_c} \quad \text{where} \quad \frac{1}{\tau_c} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Suppose $I(t) = I_b + I_m \exp(j\omega_m t)$

$N(t) = N_b + N_m \exp(j\omega_m t)$

$$N_m(\omega_m) = \frac{\tau_c \cdot I_m/eV}{1 + j\omega_m\tau_c} = \frac{N_m(0)}{1 + j\omega_m\tau_c}$$

steady state density


Light Emitting Diodes

Edge-emitting LED

Output Power. $P_{out} = \frac{I}{e} h\nu\, \eta_{int}\, \eta_{out}$

$$\frac{R_{rad}}{R_{rad} + R_{nonrad}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} \sim 10\text{-}90\%$$

$$R = \left(\frac{n-1}{n+1}\right)^2 \Rightarrow T = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4n}{(n+1)^2}$$

$$\left.\begin{array}{l}\text{Fraction of light}\\ \text{escaping}\end{array}\right\} = 1 - \cos\theta_c = 1 - \sqrt{1 - \left(\frac{1}{n}\right)^2} \approx \frac{1}{2n^2}$$

$$\eta_{out} = \frac{4n}{(n+1)^2} \cdot \frac{1}{2n^2} = \frac{2}{n(n+1)^2}$$

So let us actually look in to this in little more detail, so we want to look at modulation characteristics of my led, ok to do that we need to start from the rate equations and the rate equations here it corresponds to in the previous rate equations we were tracking the atomic number densities, right in the case of rare it ions but here what is it dependent on? What number density is does not depend on this light emission? Electron and hole number densities, right.

So I can write rate equation with respect to that dN over dt where N corresponds to the electron density, right per unit volume just typically express in terms of centimeter cube, so this I can track I will say that, that is going to be dependent on the rate at which carriers are injected in to the structure, so what is the carrier rate.

Student is answering:

I upon q.

I upon q, very good well we decided to represent the charge as electronic charge as e, so I upon e and this is per unit volume, so I would put that V here where V corresponds to the volume over which the carriers are injected, so typically it is the active layer, the cross section of the active layer cross section area of them active layer multiplied by the length of that active layer, right.

So that is a rate at which the number density is increasing but it is also decreasing, the rate at which is decreasing would correspond to if N is my number density N over some carrier lifetime, right the carriers would end up either recombining you know the electrons recombining with holes or it could also be lost due to non radiative relaxation, non radiative process.

So we can say where 1 over tau c is going to be equal to 1 over tau r plus 1 over tau nr, nr corresponds to non radiative process, right we understand that, so there is a rate at which carriers are increasing and the rate at which carriers are getting depleted, ok. So if I were to drive suppose I drive t with drive the led with some sinusoidal you know current, so let us say I have bias current I b plus let us say the modulated current amplitude is I m and exponential of j omega m t correspond to the modulation, so it is basically sinusoidal modulation with some arbitrary face, ok.

So if I had to go back to this picture here what I am talking about I b is this value over there I am biasing at some value and then I am modulating around that value, right. So I have that is my driving signal then I have a corresponding change in the electron density, right. So once again corresponding to the bias point I am going to have some DC electron density plus this other component which is varying with respect to time, right it is a linear process you inject you know this carriers and this is that is going to correspond to the amount of current that is injected in to the structure, right.

So now I will substitute this expression in the above rate equation and then I will try to simplify, if I try to simplify I can get an expression for the modulation sorry I made a mistake here, this should be N m, right so what I want to get is N m as a function of omega m where what is omega m? Is angle a frequency corresponding to the (medal) modulation, so yeah we are tracking only the electron density but we are assuming that there is a corresponding number of holes that are available so the recombination obviously happens with respect to both the electrons and holes.

So whatever is happening to the electrons we are saying the as a corresponding picture for the holes as well.

Student is questioning:

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So yeah, so if your injecting a certain current I, right that is essentially (mul) physically it is just injecting a electrons but since the electrons are moving one way we say the holes are moving the other direction, right so we are not double counting that way it is essentially counting whatever is happening with respect to the electrons. So we want to get an expression for N m of omega m and if we do that and also the reason we have picked exponential of j omega m t to you know to represent the modulation is because when you do a d over dt of that you just get a j omega m, right so you can (repre) substitute d over dt by j omega m and then you can that simplifies the overall thing that we have.

So if we do that then what we get is this expression tau c multiplied by I m over e times V divided by 1 plus j omega m tau c, so I just all I did is I just substituted the expression for I of t and N of t in to the rate equation and replace d over dt by j omega m and then you know simplified it and you just one step from that you will get this expression, this I will write as N m over 1 plus j omega m tau c where N m or I can also say N m of 0 this represents the steady state density.

So how do I find the steady state density? What happens to dN over dt if I look at it is steady state that is that will equate to 0 then I would just basically have you know N m of 0 from that will correspond to I m over e V multiplied by tau c, right. So I can just write this as N m over this as numerator I can just represent the N m of 0, so what I want to know is what is called this modulation transfer function.

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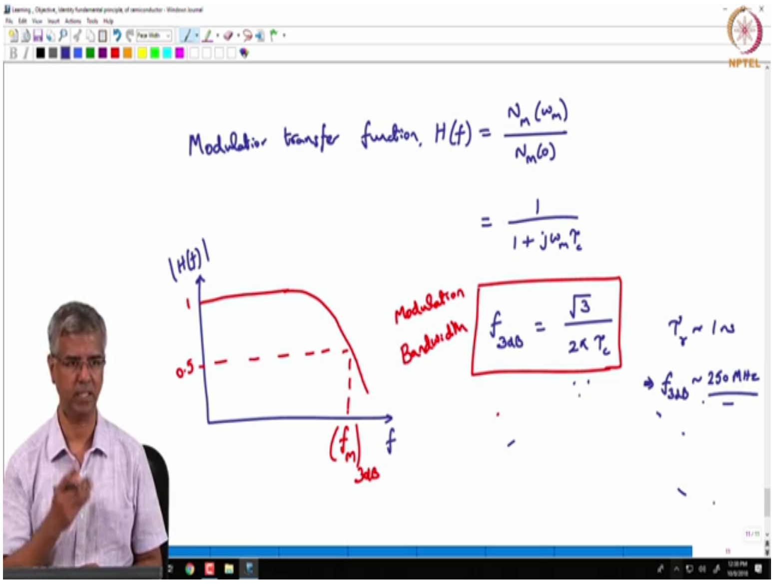

Modulation transfer function, $H(f) = \frac{N_m(\omega_m)}{N_m(0)}$

$= \frac{1}{1 + j\omega_m \tau_c}$

Modulation Bandwidth $\boxed{f_{3dB} = \frac{\sqrt{3}}{2\pi \tau_c}}$

$\tau_r \sim 1\,ns$

$\Rightarrow f_{3dB} \sim \underline{250\,MHz}$

So I can say that modulation transfer function H of f, H of f is going to be given by N m of omega m that is the modulation number density as a function of the modulation frequency over N m of 0 which is the steady state. So you can imagine what this thing represents at low frequency is steady state and I mean the DC and quasi steady state conditions you can basically say that N m of omega m is equal to N m of 0, right because you are if you are injecting some carriers slowly you can expect that there is a corresponding change in the output power.

Now I am injecting carriers at much faster rate, right I want to know whether the number density that I have in this is tracking that and you can probably physically or intuitively see that as I go faster and faster with my injection I may not actually be able to catch up because of two things one is either I can I will start my recombination process takes some time, so there is actually some phase slag with respect to the injection or my non radiative relaxation happens and that is also you know introduces a phase slag.

So as you go to higher frequencies you cannot expect the same number density as you would expect as you have in at lower frequencies but we have an expression for this and that expression is 1 over 1 plus j omega m tau c, right that is what we found out in the in a analysis, ok. So if you plot this if you plot this magnitude of this, so magnitude of H of f as a function of f what you will find is this represents a flat line and then it is going to start coming down.

So it is normalize is so this is corresponding to 1 but we are interested in the frequency at which the modulation transfer function falls of by 3 dB or half, ok, so this is f m at 3 dB, ok. So what you do is you find the magnitude of H of f, right and the that magnitude you equate to half, ok and once you equate to half you can actually find out what is f m of 3 dB, if you do that what you will find is this 3 dB frequency is going to be given by root 3 over 2 pi tau c in hertz, ok.

So that this is what you call as the modulation bandwidth of my led structure and forget about those numeric values, right basically it is says it is inversely proportional to tau c which is quite intuitive, right. So shorter the carrier recombination time, right shorter the carrier life time more will be the modulation bandwidth so it does not limited on the other hand if you have a longer carrier life time then that will correspond to shorter modulation bandwidth.

So if you are for example if you are a modulation is due to radiative processes, right and the that those radiative processes let us say the typical values for this thing is tau r is in the order of 1 nanosecond, ok that is typically the (radiati) radiative recombination lifetime in a semiconductor, if it is in the order of nanoseconds, so you can say that is going to be corresponding to fraction of gigahertz, right.

So it is root 3 is 1 point 7 divided by 2 pi that is probably f 3 dB for this is in the order of 250 megahertz, right something around at I do not have the exact number here but that just giving you ballpark idea. So typically 100 of megahertz modulation bandwidth is possible with these led is. Now I know there is one company which is actually communicating or trying to achieve 60 gigahertz communication, so they are trying to do this at 60 gigahertz, so you say if my modulation bandwidth is only 250 megahertz so how am I going to responds to 60 gigahertz?

Well you just follow this modulation transfer function curve and you say you go all the way up to 60 gigahertz you will find that H of f is very small but it is not 0, right it will probably be that modulation that strength of the your modulation that you are finally achieving is only in the order of 10 power minus 5 or something you know 10 power minus 5, 10 power minus 6 but still that constitutes have very small component that is modulated on a very large DC, right if it is not getting modulated which is represents a DC level, right.

So but that is ok as long as you have in your electronic circuit you have a filter which rejects all the short frequencies and picks up only the 60 gigahertz component, you can just beat with

60 local oscillator with 60 gigahertz and you can extract that complin with modulate to component and that is how they are planning to do communication. So when we say that the 3 dB bandwidth is 250 megahertz that just says that you know are 250 megahertz modulation transfer function is 50 percent, so only 50 percent of my light is actually modulated rest of it is actually a DC level, ok.

But still that modulated component you can pick up and you can do things with that or even if it is f 10 dB, f 20 dB corresponding to that you have higher modulation bandwidth, right so you can possibly if you can taller if you can pick up that modulated component precisely you can still do at higher frequencies, ok this is not like a hard set limit to the modulation that you can achieve just gives you an idea, you understand this.

Student is questioning:

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So the question is, is the phase nonlinear when you go to even higher frequencies? There is a phase delay? Yes it because is not responding quickly enough but there is nothing in this let us say is the phase is nonlinear, the phase will be nonlinear if your modulation transfer function starts actually having some other features in it, it is not a monotonic signature it is starts having some other nonlinearity in it, ok then you would have a phase distortion as well happening but according to the processes that we are tracking here there is no such nonlinear function come in to the picture but if there is some other physical effect it is giving you some nonlinearity here in the modulation transfer function then the phase will also get distorted.

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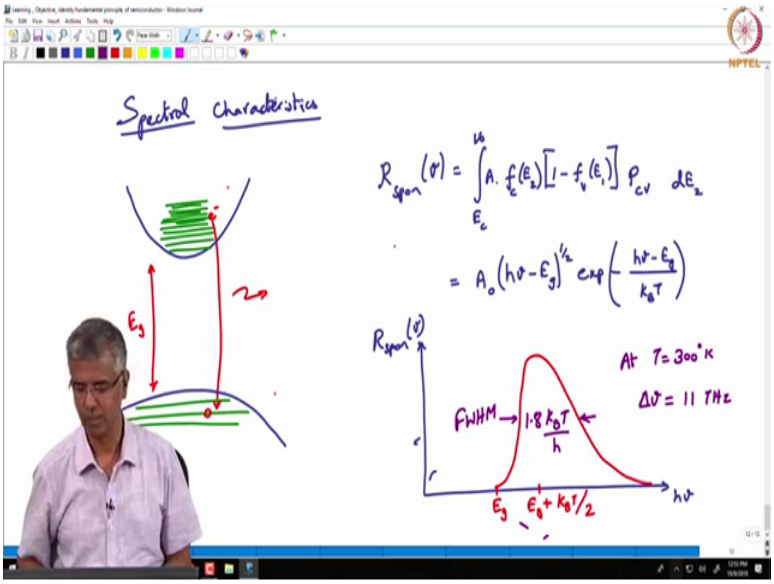

Spectral Characteristics

$$R_{spon}(\nu) = \int_{E_c}^{\infty} A \cdot f_c(E_2)\left[1 - f_v(E_1)\right] \rho_{cv} \, dE_2$$

$$= A_0 (h\nu - E_g)^{1/2} \exp\left(-\frac{h\nu - E_g}{k_B T}\right)$$

At $T = 300^{\circ}K$

$\Delta\nu = 11\ THz$

Let us look at the other characteristic that we have neglected so far which is actually the spectral characteristics, so what about the spectral characteristics of a led. So if I have recombination happening from an electron no from conduction band recombining with the hole in the valance band, right so what sort of spectral characteristics do I expect and of course the spectral characteristics are going to depend on where the electron is where the hole is and that corresponding energy is what is going to get you know emitted with respect spectral (corra) the spontaneous emission rate can be tracked as integral of E c to infinity over all these energy levels E 2 corresponds to the energy levels in the conduction band.

So some constant A f of E 2 that is corresponding to the probability that an electron is sitting in this energy level E 2, this is actually important to remember I did not talk about it explicitly before, in semiconductors this Pauli exclusion principle comes into effect, right which means that no to electrons can exist in the same state, ok. So when we are talking about f of E 2 we are talking about an electron occupying a particular energy level, right, and so you need that and you also need a hole in the valance band and that corresponds to, so this is actually the f c E 2 and this corresponds to 1 minus f E 1, right where E 1 corresponds to the energy level in the valance band and then you have the density of states also come in to the picture with which can be represented as a joint density of states corresponding to the conduction and valance band, ok.

So that will determine what is the you know emission characteristics in terms of the spectrum and if you evaluate that, that will correspond to some A naught multiplied by the joint density of states is going to be proportional to this factor H mu minus E g to the power of half, so remember the individual density of states in the conduction band or does it present corresponding to row c what it we say is equal to E minus E c to the power of half and row e we said was E v minus E to the power of half that is what define the individual density of states but the joint density of states can be expressed as H mu minus E g to the power of half and then the firmly probability when you look at for both of these electron and hole that will work out to be exponential of minus H mu minus E g divided by k B T.

So both of these essentially say that, ok the spontaneous emission is going to be dependent on this factor of h nu minus E g, right and ok so if I plot this is spontaneous emission as a function of H mu what I will see is that it is going to be something like this where in you have near the band edge, so you can say that the emission is going to be happening at a minimum energy corresponding to the band gap energy, right you cannot have any emission lesser than the band gap energy because you do not have any electrons and holes within that energy.

So between this is your band gap energy, right so you going to have emission for E g greater than for H mu greater than E g, right and then if you look at where the peak happens if you, you know differentiate this and with respect to H mu and equate to 0 you will find that the peak you can show that the peak happens at a point correspond to E g plus K B T over 2, right.

So it is just beyond the band edge that you going to have the maximums, so this emission cannot be less than E g, right and it will peak at a value correspond to E g plus K B T over 2, so on the lower energy side it is dominated it is decided by this H mu over E g to the power of half whereas on the higher energy side it is going to be limited by the fermy probabilities, ok so that is where the exponential comes in to the picture.

So you have a long exponential tale typically and on the shorter side it is going to be dependent on that square root function, ok and in this one of the important things one of the important things is what is this full width half maximum, right FWHM and that again we are not doing it you know rigorously but you can find out from that expression from plotting that expression and that you will see corresponds to a value which is given by 1 point 8 times K B T divided by h, ok that will be the full width half maximum of this led and interesting thing is you see that all of this are you know constants K bit well K B and h, h is the plans constant so there constant but T is the only variable.

So if you look at T equals to 300 degree kelvin if you substitute that into this expression you will find that this delta mu or corresponding to FWHM is about 11 terahertz, ok so at room temperature all led is have roughly a spectral with of 11 terahertz, right and there is 11 terahertz what it means in terms of delta lambda, in terms of the wavelength spread obviously depends on what wavelength you are operating at, so if you are operating at 1550 nanometers you will find that the wavelength spread correspond to about 100 nanometers.

If you are operating at 1 micron wavelength that wavelength spread will be more like 40 nanometers and so, ok and of course if you are around visible region that may be even smaller, ok in terms of delta lambda but delta mu you know you can say that it is will correspond to 11 terahertz if you are operating at 300 degree kelvin, ok. So that is another interesting aspect, so we say that all these led is what is the primary emission wavelength? We said it is gallium nitride base led is what you can say about their emission, no these are actually UV led is ultraviolet led is, ok.

And we can actually show this to you the t s can remember can you just bring ours spectrometer, we have that maya spectrometer or some spectrometer visible spectrometer is there, so let us bring that and let us examine this led is what you will find is this is actually emitting in UV radiation, right it is emitting UV radiation and you can say if it is ultraviolet less than 400 nanometers the spectral width there correspond to only a few nanometers, ok.

Only few nanometers and how we are getting white light which is spanning 400 to 700 nanometers it is because each of those led elements there is actually a phosphor coating on it, that phosphor coating gets eliminated by UV light just very much like your old fluorescent lamps you know you allow a phosphor coating in the inside, so you will emit white light, so similar case it is excited by UV radiation but it is emit white light.

Now while be interested in knowing how much UV light is not getting converted, how much UV light is coming through this and how much UV light am I getting expose to I would want to know, so let us actually bring that spectrometer and checks this light seriously. So yeah there is a conversion efficiency involves so there are some photons that could be scattered and not really going through that conversion.

So there is a conversion efficiency involve but I believe the conversion efficiency is greater than 50 percent but depending upon the thickness of the phosphor coating you may or may not absorbed all the UV radiation, so I am fairly sure I am going to see a UV component coming out of this and I am actually curious as you are to find out how much of that UV component is coming through, ok.

So let us stop at this point, what we will do you know next is actually look at similar characteristics for semiconductor diode lasers but knowing all the laser characteristics that we already have discussed in rare it systems I am not expecting to spend a lot of time on that and then we will go on to semiconductor light detectors, ok thank you.