Optical Wireless Communications for Beyond 5G Networks and IoT

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Lecture - 03
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Hello everyone. So, today we are going to discuss about optical sources in the last class we had discussed about lighting basics of lighting systems like radiometry, photometry and calorimetry. So, today now we are going to discuss about optical sources which are which will be used in optical wireless communication.

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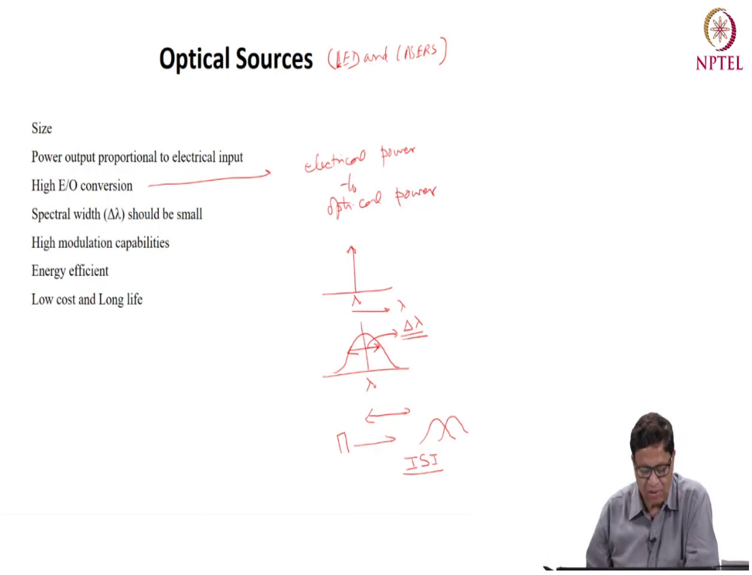

So, the typical optical sources which we will consider are LED and lasers. So, let us now understand the typical requirements of your optical source whether it is for optical fiber communication or it is for optical wireless communication. So, first that the size should be very small; it should be as small as possible. The second is you want that power output the optical power output which is coming from the source is proportional to electrical current because, ultimately I am going to modulate my electrical signal.

So, I want my power output to be proportional to electrical current or electrical input. It should have high electrode to optical conversion efficiency; that means, whatever my electrical power is it should give corresponding optical power. So, you should have that conversion rate between electrical power to optical power should be high, electrical power to optical power.

The spectral width that is delta lambda should be small. What I mean by spectral width? Spectral width is if the light is emitting at a single color then it will have a fixed lambda, suppose this is my lambda and this is a single wavelength source. So, this is a lambda 0. So, we will say that light is emitting at wavelength lambda naught, but in normal practice this lambda 0 is not a single wavelength.

So, it has some spread around lambda naught. So, this is spread is called as a spectral width. So, we want this delta lambda to be as small as possible because if the light has many colors in communication this could be a problem because, each wavelength will travel in the medium with different speeds.

And when they travel with different speeds they arrive at the receiver at different times and at different times meaning there will be a you know dispersion in the pulses or the pulses will spread. So, suppose if you launch a pulse like this if your delta lambda is high after say 20 kilometers or 30 kilometers in optical fiber for example, this pulse will become something like this.

So, if there is a dispersion in time then it will start interfering with next pulses. So, it will result into a limited data rate or it will result into something called which is called as inter symbol interference. So, we want this delta lambda should to be very small. We want high bandwidth capability which means I should be able to modulate the source at high speed it should not be limited I mean the wavelength the modulation bandwidth should not be kilo hertz or even megahertz I should be able to modulate the source at high data rate or it should have high modulation bandwidth of the order of few gigabits per second.

So, these sources should have you know high modulation capability. The sources should be energy efficient the kind of power which we apply to LED and laser should be small and it should give you it should give you adequate optical outputs. So, the sources are expected to be energy efficient and of course, it should be low cost and should have long life.

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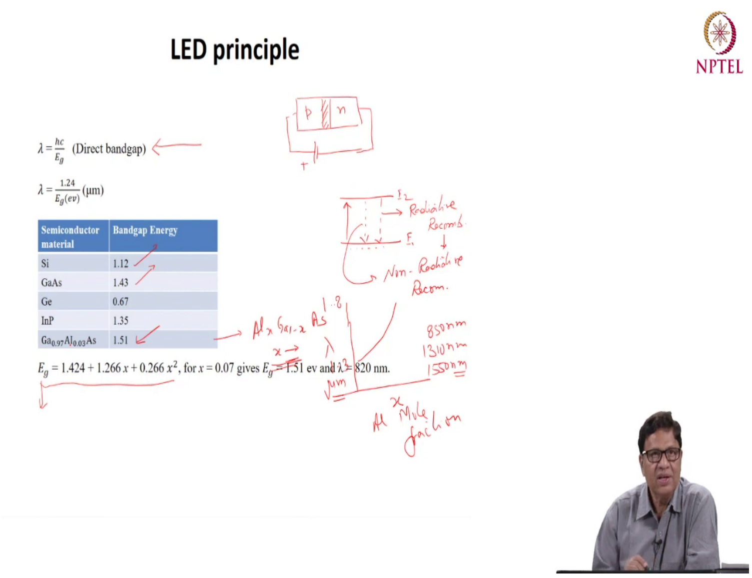

So, let us first understand the basic principle of a LED. So, LED is basically a pn junction diode which is forward biased. This is p this is n and this is the depletion region and this is forward biased. So, what happens in a LED when you forward bias it some of the electrons from the lower state they go to the higher state and from that state they fall onto the lower state and they release energy and this energy is in the form of photons. So, this is your lower energy level this is your high energy let say E 1 this is E 2.

So, some of the electrons which are here they will go up when the current is supplied to the device by giving this forward bias and these electrons come at the higher level and then they fall down. And so this may result into two types of radiations one is a radiative recombination and another is this will this result into light output and another could be a non-radiative, which may not result or which will not result into any light output non-radiative recombination.

So, this is the basic principle of LED and the photodiodes are of two types; direct band gap and direct band gap. So, for direct band gap the light which is emitted from a pn junction is given by h c h is Planck's constant c is velocity of light and E g is the band gap energy.

So, the lambda which is emitted is given by h c by E g and if I put the value of Planck's constant and now I also put the value of c here and then the lambda is actually 1.24 divided by E g and this E g is in electron volts. So, units are important here. So, you have to put the value of E g electron volts and then wavelength which you gets using this expression will be in micrometer.

So, the lambda which is emitted is equal to 1.24 divided by E g in electron volts and the wavelength is in terms of micrometer. So, if I take different material for example, if I take silicon the band gap energy is 1.12 it will give you a different wavelength. If I use gallium arsenide the band gap energy is 1.43 electron volts and for germanium it is 0.67 for indium phosphide it is 1.35 and then you can have a different combination of gallium and aluminum and then you can get you know different value of band gap energy.

So, basically you can change the doping. So, this is Gaa Ga x or rather it will be Al x because you are adding aluminum as a doping Al x Ga 1 minus x into As. So, you can change the value of this x and then you can get different band gap energy and when you change the band gap energy essentially you are changing the wavelength of deformation. So, for example, in this case G a is G a 0.97 aluminium 0.03 and As. So, this gives a band gap energy of 1.51.

So, similarly if you plot for example, have different levels of x this is say aluminum mode mole fraction and this is the wavelength of emission. So, this will be something like this. So, this is starting point 0.3 and this could be 0.8. So, by changing this value of x that is the doping concentration of aluminum in a material you can get different value of band gap energy and hence lambda.

So, you can make your lambda as per your choice because as we know there are certain wavelengths which are useful for communication for example, you know the wavelength which are around 850 nanometer or 1310 nanometer or 1550 nanometer they all good for communication using optical fiber where they have you know low loss. So, you can generate a wavelength of your choice by changing this value of x of course, this gives you this is 1.3 I am sorry about this is 1.3 and 1.8 micrometers.

So, you can basically get a wavelength ranging from 1.3 to 1.8 by changing the value of x. So, this is another example where you have E g actually is represented in terms of 1.4 plus 1.2 into x plus 0.2 into x square. So, this is a generic equation for E g and depending upon what value of x you choose you can find out this E g and corresponding to E g there will be a wavelength formation.

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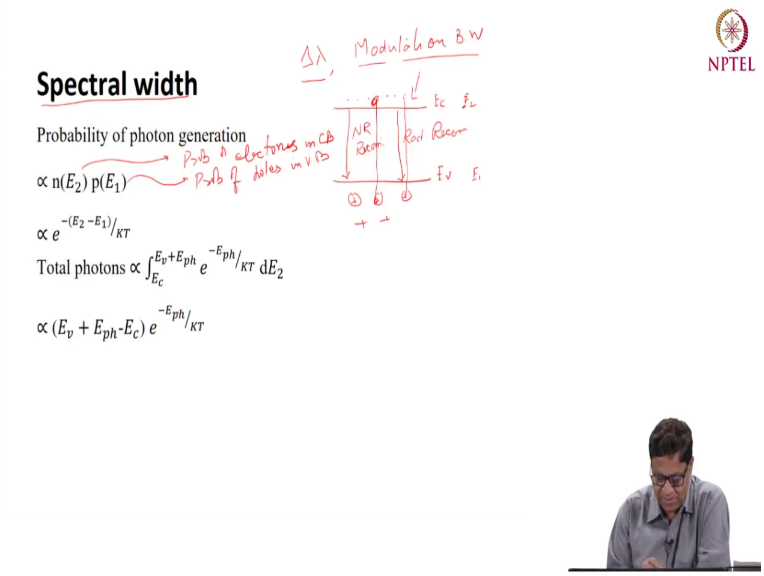

So, now we will study the two important things of source which one of them as I mentioned is the spectral width which we call as delta lambda and the other one is the modulation capability of the device modulation bandwidth of the device. So, these are the two important aspect of any optical source. So, first we will study the spectral width part. So, let us consider a pn junction of so.

So, this is for example, your valence band then this is your you know conduction band. So, there are electrons here, there will be some holes when you supply the current. So, there will be some holes and here there are different states. So, the electron is not limited to one energy line, but it has some distribution here.

Similarly, the holes are distributed here and this is the recombination radiative recombination part radiative recombination part and similarly you have the another part which is non radiative re combination. So, both are happening in the semiconductor and this is valence band. So, this will energy E 1 and this E 2 and E 2 is not a sharp line it can be you know is a broad line for these energy states.

So, let us find out what is the probability of photon generation. So, it is proportional to n E 2 into p E 1 n E 2 means the probability of electrons in the conduction band. So, this is probability of electrons in the conduction band and p E 1 is the probability of holes in the valence band. So, the probability of photon generation will be you should have you know electrons and holes when they combine they either give you radiative combination recombination or non radiative

So, for simplicity we will assume that all electron hole pairs they result into some photon generation. So, there is no non-radiative recombination. So, this probability of photon generation is given by this and this expression for n E 2 and p E 1 which takes into account the Fermi level also, but that Fermi level part is constant. So, I am absorbing that constant into that proportionality sign and this is proportional to e raised to power minus E 2 minus E 1 divided by KT K is the Boltzmann constant and T is the temperature.

So, this is the probability of photon generation and the total photons if I see here and I am assuming that all the electron hole pairs are combining radiatively they are emitting photons. So, basically this will be an integration of because you know this electron may combine with this hole for example, this electron may combine with the different hole similarly there are other holes also.

So, basically I need to integrate all possible you know combining of these electron and hole pairs. So, I will be integrating this from E c to E ph and E ph is the photon energy which is emitted which is given by between this point and this point. So, this is E ph and this E ph is actually varying for you know different pairs. So, this total photon and it is integrated from E c to E v plus E ph and if I simplify this integration this becomes E v plus E ph minus E c into e raised to power minus E p E ph by KT.

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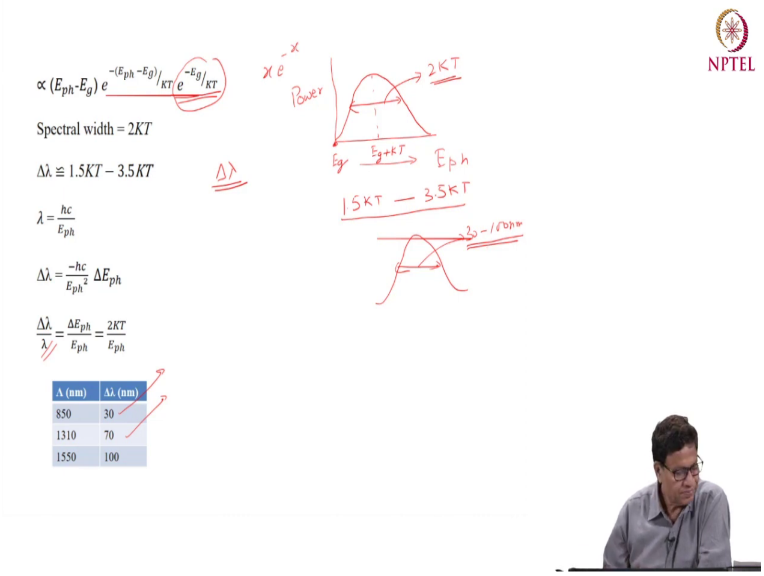

And if I multiply by e raised to power plus E g by KT and e minus E g by KT I somehow simplify this expression. So, this is the constant this part is a constant this part. So, if you see this part this is nothing but you know x into e minus x kind of form. So, if I plot this function then this will give me something like this. So, this is for example, E ph I am plotting this and this is the power because this is the photon generated.

So, this is a optical power this will give me something like this, this is the E g point where E p this power is 0. E ph is equal to E g is 0 and it has a maximum at E g plus KT and if I see this distance or this width this is nothing but 2 KT. So, this is actually the spectral width of the light emitting diode. So, I have taken so many approximations. So, that is why it is 2KT, but in actual practice this is 1.5 KT to 3.5KT.

So, the spectral width is 2KT as I mentioned here and delta lambda for typical you know experimental device experimentally it is found that this delta lambda is between 1.5KT and 3.5KT. So, now let us find out the value of delta lambda.

So, we know delta lambda is equal to hc by E ph this is the wavelength which is generated because of this E ph and if I sort of differentiate delta lambda with respect to delta E ph I get delta lambda is equal to minus hc E ph square delta E ph and if I replace you know write in a different fashion that is delta lambda by lambda is nothing but 2KT by E ph.

So, we can get some values or delta lambda for different wavelengths. So, if I put lambda is equal to 850 nanometers what I get delta lambda as 30 nanometers. And if I increase the wavelength to 1310 nanometers then I get 70 nanometers for 1550 it is about 100. So, typical LED gives you know 30 depending on the wavelength 30 to 100 nanometer.

So, it is quite high actually for communication from communication perspective in optical fiber particularly it is quite high. So, because it lead to lot of dispersion right.

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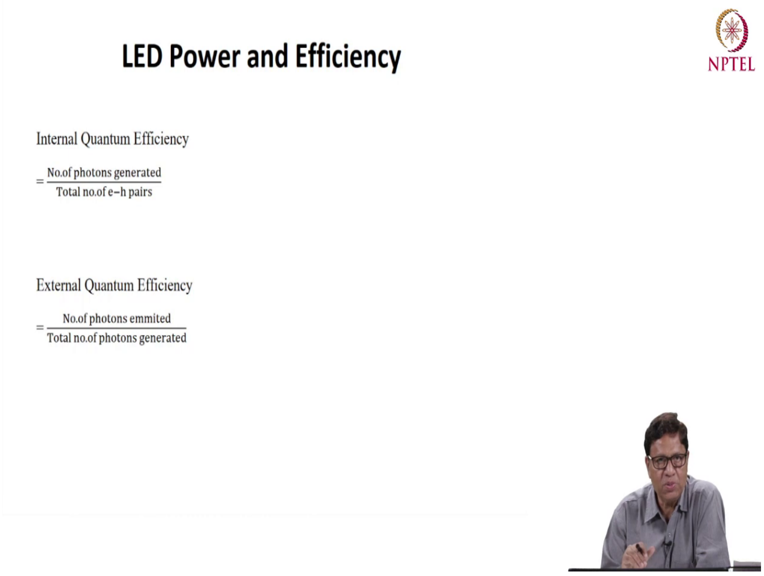

Now, we have understood about the spectral width, let us understand about the LED power how much power is emitted. And also we will try to understand the efficiency part. So, let us take the first the efficiency. So, there are two types of efficiency which is defined; one is internal quantum efficiency which is defined as number of photons which are generated inside the device divided by total number of electron hole pairs are which are generated inside the device.

So, if you know number of electron hole pairs are all converted into photons the efficiency is 1, but that is not the case most of the time. So, this is how internal quantum efficiency is defined external quantum efficiency is actually ratio of number of photons which are emitted out of the device and number of photons which are generated inside the device. So, this is called as the external to the external world or external quantum efficiency.

So, these are the two important parameters what is your internal quantum efficiency and what is your external because ultimately the photons which are generated they are going outside to either getting coupled to the fiber or traveling to a different destination at some point b. So, that is also important. So, these two quantities both are important for sources.

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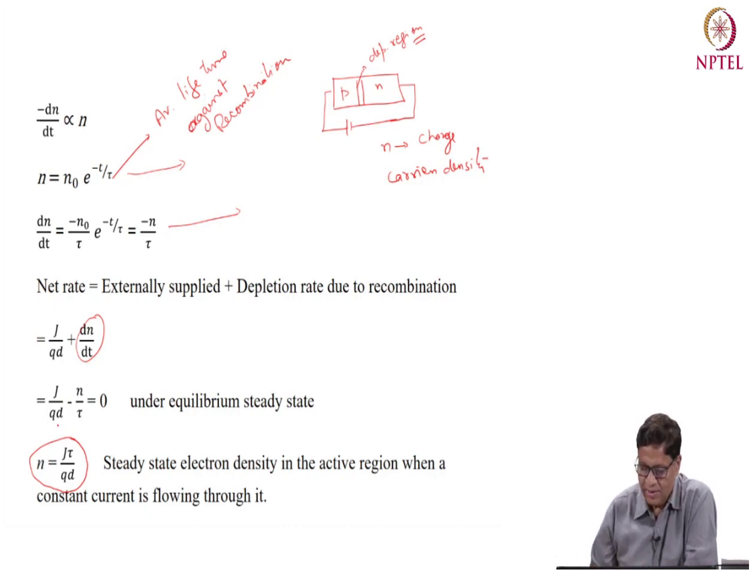

So, let us try to understand these efficiency parameter. So, as we know in a photodiode in a light emitting diode there is a p junction there is a n junction and there is a depletion region here. So, this rate minus dn by dt because the n is the carrier density charge carrier density it is getting depleted. So, minus dn by dt is actually proportional to n this is what is happening inside the LED.

And if I solve this so, this n is equal to n 0 e minus t by tau where tau is the average lifetime or against recombination. So, n is equal to n 0 n 0 becomes an initial charge carrier density is e raised to power minus t by tau and tau is the average lifetime against recombination and if I differentiate this expression this becomes dn by dt minus n 0 by tau e raised to power minus t by tau.

And I can replace this with n. So, this becomes dn by dt is equal to minus n by tau. So, what is a net rate you are externally supplying the current and there is a depletion happening because of the recombination. So, the net rate is externally supplied current plus depletion rate due to the recombination. So, externally supplied is J by qd, J is the current density and q is the charge and d is the width of the depletion region plus the depletion is happening at the rate of dn by dt that is a depletion rate due to recombination.

So, this becomes J plus qd plus dn by dt and under equilibrium state steady state this is 0 and I have replaced here this is dn by dt by n minus tau using this expression. So, this becomes J minus qd minus n by tau and net rate will be 0 under a steady state. So, this gives me the steady state electron density in the active region when the constant current is flowing across the device which is given by n is equal to J tau divided by qd.

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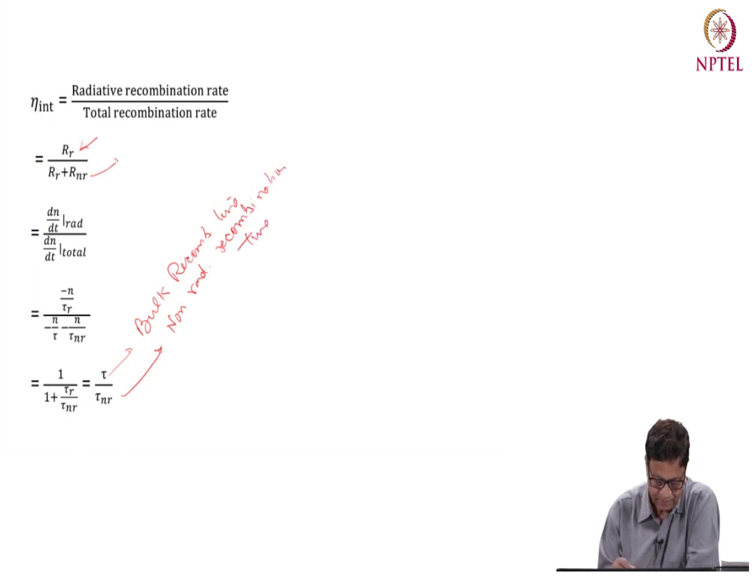

So, that was the n the current part current part. So, now, let us see the internal efficiency of the device the internal efficiency is defined by eta internal this is how I am designating is designating this. So, this is a ratio of radiative recombination rate divided by the total recombination rate. So, this is a useful light which is getting generated inside the device.

So, that is called the internal quantum efficiency and this can be represented as R r that is a radiative recombination rate and total combination which consist of radiative as well as non-radiative. So, it will be R r plus R nr and this is equal to d by dn by dt radiative this is the rate and divided by dn by dt total including both radiative as well as non-radiative. So, as from earlier expression dn by dt is equal to minus n by tau and for radiative it will be minus n by tau r.

So, this is the average career lifetime against radiative recombination and the dn by dt will be total. So, this will be minus n by tau minus n by tau nr. So, this can be little simplified here and gets canceled and what you get n internal eta internal that is efficiency internal as tau by tau nr. So, tau is the actually bulk recombination time this is the bulk recombination time and this is the non-radiative recombination time non-radiative time.

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$$\frac{dn}{dt}\Big|_{\text{total}} = \frac{dn}{dt}\Big|_{\text{rad}} + \frac{dn}{dt}\Big|_{\text{non rad}}$$

$$-\frac{n}{\tau} = -\frac{n}{\tau_r} - \frac{n}{\tau_{nr}}$$

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Generally $\tau_r = \tau_{nr}$

$\eta_{\text{int}} = 0.5$ or 50%.

Also we know dn by dt another expression which will connect tau and tau r and tau nr. So, dn by dt total is com is addition of dn by dt radiative plus dn by dt non-radiative. So, this we know minus n by tau is equal to minus n by tau r minus n by tau nr and this n will get canceled. So, we get a simple equation 1 by tau is equal to 1 by r tau r plus 1 by tau nr. So, generally what happens tau r is equal to tau nr these two times are same.

So, if I calculate the efficiency by putting these values tau r tau nr in the eta initial expression I get 0.5 or 50 percent; that means, 50 percent of the energy is only radiatively emitted the other part is there is no radiation it is absorbed or lost in the device. So, internal efficiency for a typical diode this is the order of 50 percent.

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$$\eta_{\text{int}} = \frac{R_r}{R_r + R_{nr}}$$

$$= \frac{R_r}{\frac{I}{q}}$$

$$= \frac{\frac{P_{int}}{h\nu}}{\frac{I}{q}} = \frac{P_{int} q}{I h\nu}$$

$$P_{int} = \frac{\eta_{\text{int}} I h\nu}{q}$$

$$= \eta_{\text{int}} \left(\frac{hc}{q\lambda}\right) I$$

Let us also try to understand the relationship between the internal efficiency and the power which is generated that is P int or p internal. So, this is n internal is defined as eta internal is defined as radiative recombination divided by total recombination and this is I I R r divided by total recombination will be I by q and R r that is a radiative is the P internal that is a power generated because of this radiative recombination divided by h nu, h nu is the photon energy divided by I by q.

So, the total becomes P internal into q divided by I into h into nu. And so, the P internal the power which is generated inside the device is eta internal into I into h nu divided by q. And it can be little written in a different form. So, this is the efficiency part, this is the Plank's constant this has units joule second.

So, while calculating you should be very careful with the units and c is in velocity of light meter per second, lambda is in meters and q is a charge in coulomb and I is the current in amps and you will get the power in terms of watts. So, if you are using mks system units these are the units you have to follow.

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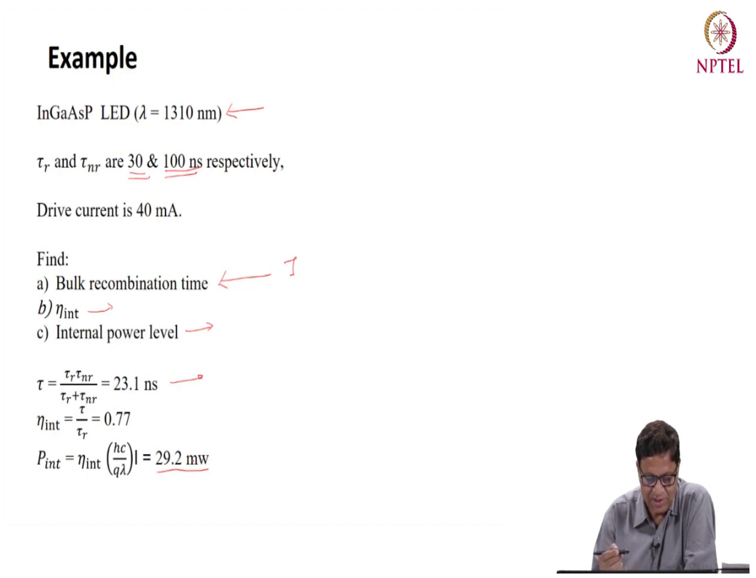

So, let us do an example and try to get some you know idea about the typical values. So, if I assume a in gas phosphide LED which is emitting at say lambda 1310 nanometer and it has radiative recombination time as 30. And tau nr non radiative as 100 millisecond here it is shown different, but normally these times are you know similar and the drive current which is the I is actually is 40 milli amperes and we will try to calculate what is the bulk recombination time which is nothing but tau and what is the internal efficiency of the device and how much power is generated inside the device.

So, if you put all these values in the expression which I have discussed what you get tau as 23 nanosecond what you get efficiency as 0.77 and the power which is generated inside the device is the order of 29.2 milliwatts. So, these are the typical values which are used in you know optical communication using optical fiber.

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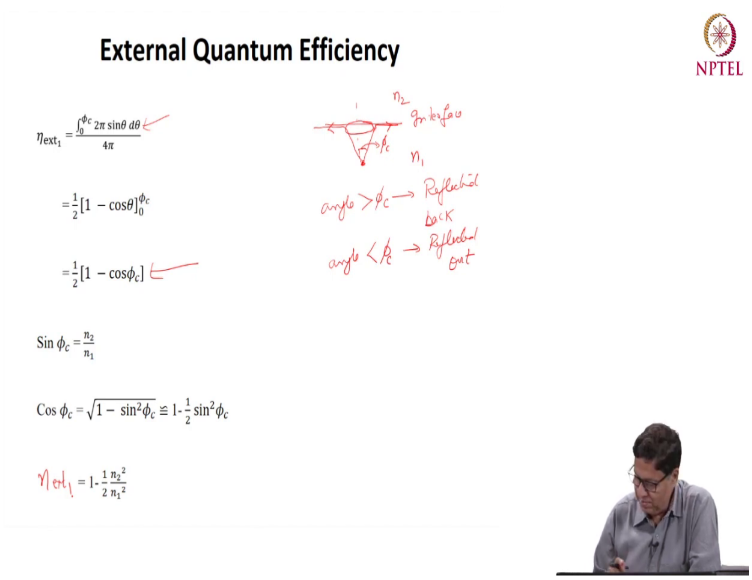

So, now let us try to understand the external quantum efficiency. So, for understanding the quantum efficiency external quantum efficiency suppose I have this interface I mean this is my device and this has some interface and this is air. So, this is a n 2 reflective index here is n

2 and inside the device it is n 1 this n 2 can be anything, but it if it is here then n 2 will be 1 actually. So, there is a interface and this is suppose the photon is generated here.

And then you know there is only certain cone here and let me put this as angle as phi c. So, if the your angle is greater than phi c then the light gets reflected back into the medium it gets reflected back into the medium which is not useful and if your angle is less than phi c the light is reflected out what I have shown here is a critical angle where the light is just grazing the interface.

So, reflected out right. So, all the light or all the photons which are in this cone only will come out the other will be reflected back and will be absorbed. So, if I you know put mathematically this is a solid angle where if the photon is confined to this solid angle only then it is reflected out. So, this can be expressed as this is this part is from the solid angle and the limits are from 0 to phi c and 4 pi is a total solid angle.

So, the external efficiency will be you know integral 0 to phi c 2 pi sin theta into d theta divided by the total solid angle which is 4 pi and I can write this sin theta I can you know solve this integral and limits from 0 to phi c and also. So, this gives me half into 1 minus cos phi c and we know from Snell's law that sin phi c is equal to n 2 by n 1 the other angle is sin 90 which is 1.

So, sin phi c can be converted into cos phi c and put in this expression by putting this expression using cos phi c is equal to root 1 minus n square phi c and doing some approximation here assuming that phi c is very small. So, this half can come here what we I get as n external efficiency as this. So, this is my n external 1 minus half n 2 square by n 1 square. So, as the outside medium is air. So, n 2 will be 1.

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$$\eta_{ext_1} = \frac{1}{2}\left[1 - \left\{1 - \frac{1}{2}\frac{n_2^2}{n_1^2}\right\}\right]$$

$$= \frac{1}{4}\frac{n_2^2}{n_1^2} \quad = \frac{1}{4n_1^2}, \quad [n_2 = 1]$$

$$= 0.0193 \text{ i.e. } \cong 2\% \text{ for } n_1 = 3.6.$$

And effectively I will get n external 1 as 1 by 4 and 1 square assuming n 2 is equal to 1 and n 1 for a typical semiconductor material is 3.6 and if I put this 3.6 value in here then n external 1 is 0.0193, which is roughly 2 percent. So, the external efficiency because of the light which is going back to the medium because of the total internal reflection and only part of the light is coming out of the device which is about 2 percent of the light which is generated inside. So, this part gives you 2 percent efficiency.

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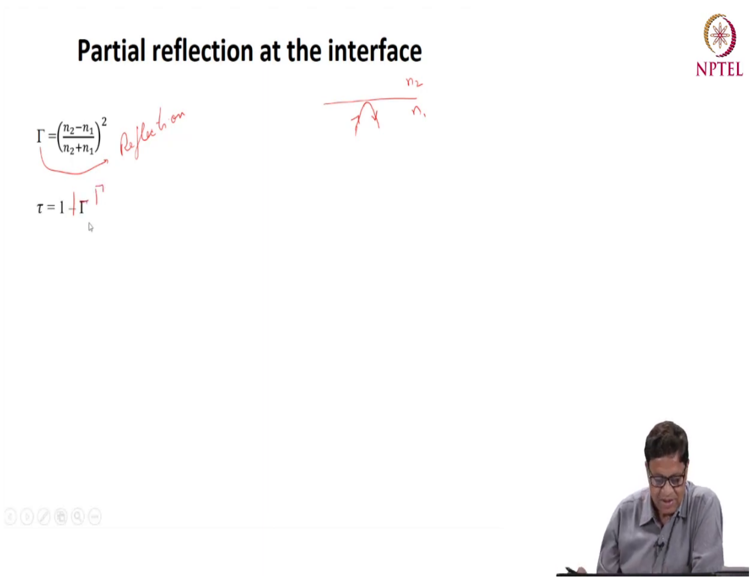

So, there is another thing which is happening here at the interface not everything which goes here and is inside the solid angle will go out of it some part will be reflected back right because the refractive index is changing at the boundary. So, even if the light is inside that cone, but when it is trying to come out of the device there is some part which will be reflected back.

So, we need to calculate this part also which will be reflected back. So, this is a reflection coefficient this tau is the reflection coefficient which is given by n 2 minus n 1 divided by n 2 plus n 1 whole square and we need to find out the transmission coefficient. So, transmission coefficient will be 1 minus tau the transmission coefficient will be 1 minus tau.

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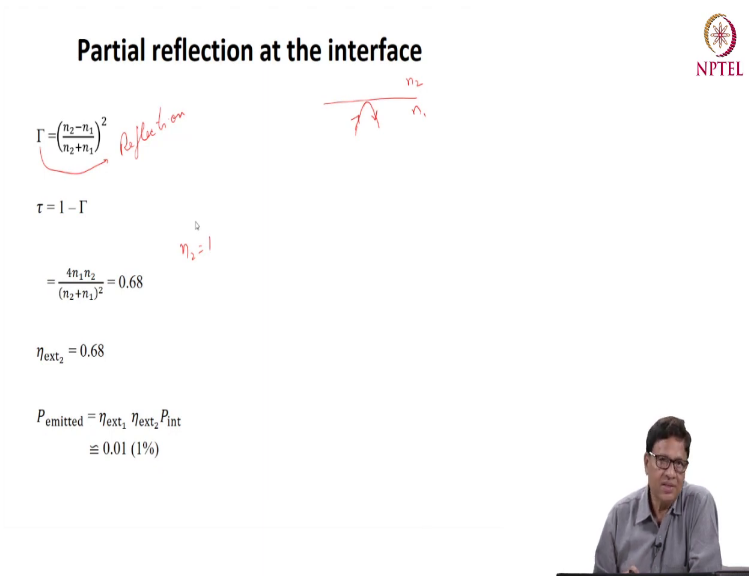

And if I put this value of tau here and do some calculation what I get is 4 n 1 and 2 n 1 plus n 2 square and again assuming n 2 is equal to 1 I get 0.68. So, this is a transmission coefficient I mean the light which is going out of the device. So, n external 2 earlier was n external 1 which we saw was 0.2 percent 0.02 rather and n external 2 is 0.68. So, the total power emitted will be multiplication of these two efficiencies into the power generated inside the device.

So, if I do this. So, basically it comes out to be 0.01 1 percent. So, only 1 percent of the light which is generated inside the device is able to come out.

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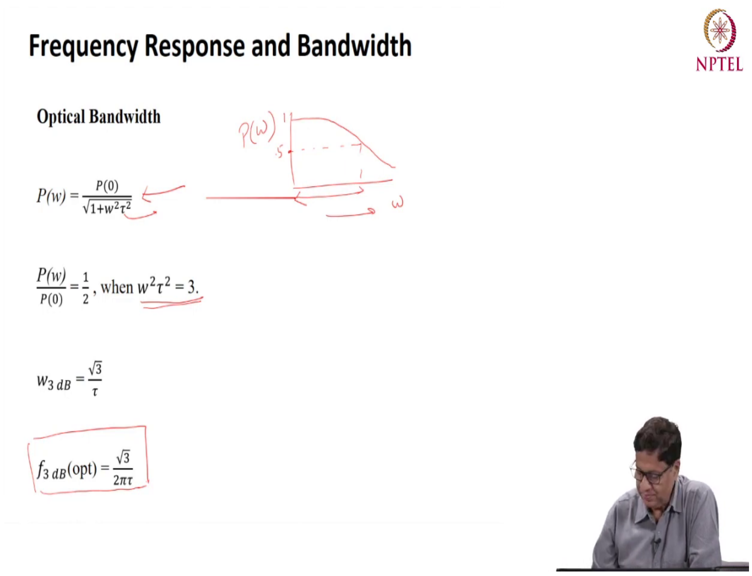

So, now, we will study about the frequency response and bandwidth of the device. So, the optical bandwidth let us first try to understand the optical bandwidth first and then there is other another concept of electrical bandwidth for the device. So, we will try to understand the relationship between the optical bandwidth and the electrical bandwidth.

So, as we know or you can find in some standard books of optical fiber communication when you are modulating your source with a light of frequency omega so, as you increase the omega the power output decreases. So, which is given by this expression P omega is equal to P naught P 0 is actually at dc power at dc divided by 1 plus omega square into tau square; tau square tau is the average lifetime of the photon.

So, P omega is the power at frequency omega. So, if we if I plot this. So, this is for example, the my frequency or omega and this is the power say P w. So, as the frequency decrease increases it follows this trend. So, this decreases with change in frequency. So, what is the tip the how do you define the bandwidth of the device so, where the power has fallen by a factor of half.

So, if somewhere here say this is 1 this is 0.5 corresponding to this whatever frequency you get that is the bandwidth of the device optical bandwidth of the device. So, this is how we define. So, this P omega is equal to P naught plus 1 by omega square tau square. So, as we know this bandwidth depends on this factor tau which is the bulk recombination time.

So, for this to happen P omega I am trying to calculate the optical bandwidth. So, P omega divided by P 0 will be half when this is you know 3 then 1 plus 3 is equal to 4 square root of 4 is 2. So, this will be half. So, at this point the we will have 3 dB bandwidth. So, this can be. So, w 3 dB will be root 3 by tau. And you can write in terms of frequency which is root 3 by 2 pi tau 2 pi tau. So, this is the 3 dB bandwidth optical bandwidth of the device root 3 by 2 pi by 2 pi tau.

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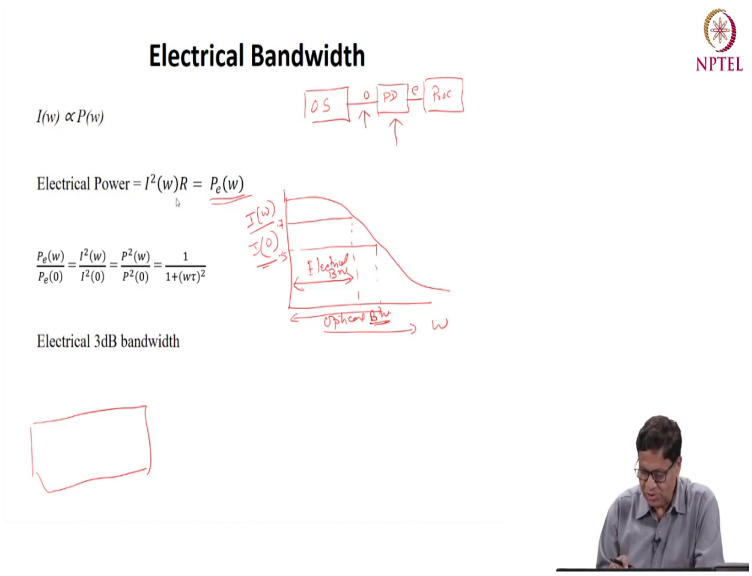

Now let us try to calculate the electrical bandwidth as we know the current which is produced in the device to calculate the electrical bandwidth actually see this is your optical source. And then you have the photodiode which actually converts this optical energy to electrical energy and then there is some processing. So, the current which is produced in this photodiode as a result of this optical input is proportional to the light falling onto it. So, there is a linear relationship.

So, I omega is proportional to P omega. And electrical power if I calculate will be I square R which is this is electrical power P omega I square omega R and if I take the ratio of P e omega divided by P e naught that is electrical power at omega and electrical power is 0 this will be ratio of I square omega by I square 0 and this can be related to optical power P square omega P square 0.

So, as you see the I and P they are directly proportional if it is optical bandwidth and for electrical power the this power is proportional to I square. So, this becomes equal to 1 by 1 plus omega tau square and this will be half when omega tau is equal to 1. So, the electrical 3 dB bandwidth is whenever this omega t is equal to half and by doing the calculation in similar way we find out that the 3 dB electrical bandwidth is nothing but 1 by 2 pi tau 1 by 2 tau.

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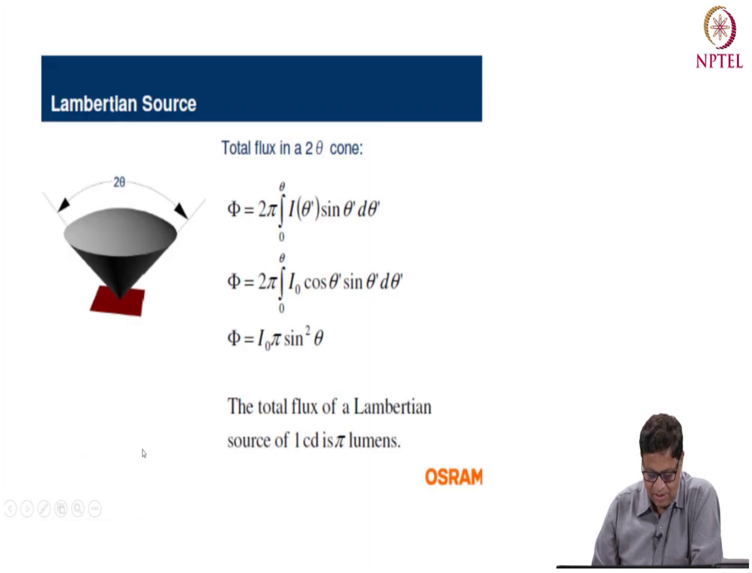

So, if I plot just to explain you. So, this is your omega and this is how the power is falling with rising omega. So, this is the power or let me now write in terms of current because that is a you know quantity which is common there. So, I let me plot this as I omega I 0.

So, from the expressions which I have mentioned here if you take there will be two points; one for the electrical bandwidth other will be for the optical bandwidth. The optical bandwidth will be somewhere 0.2 and this will be for the electrical bandwidth 0.7 because this becomes 1 by 1 by root 2.

So, this will be 0.7 points and the corresponding bandwidth is depicted here. So, this is the electrical bandwidth this is the electrical bandwidth and this is the optical bandwidth. So, there is a difference between the electrical bandwidth and the optical bandwidth and this is how they are related.

So, earlier I had shown you the expression for the earlier I had shown you the expression for electrical bandwidth and similarly for the optical bandwidth and this is how it is the difference is shown in this diagram. So, I will stop at this point and from next class we will work we will discuss about the laser and we will try to calculate similar quantities for the laser also.

So thank you very much.