Advanced Optical Communications

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Lecture No. # 14

Light Emitting Diodes – II

We are discussing LED as an optical source for high speed communication. In the last lecture, we investigated the specter characteristics of an LED, and we found that the spectral characteristic depends upon the band gap of the material, and the temperature at which a devices operating to the band gap of the material essentially decides the peak wave length of emission, whereas the spectral width is purely decided by the temperature of the device, and we saw that LED has a fairly large spectral width.

So, if you go to about 15 15 nanometer the spectral width of an LED would be typically of the order of one hundred nanometer, the second aspect which we are discussing about LED is the efficiency of electrical to optical energy conversion.

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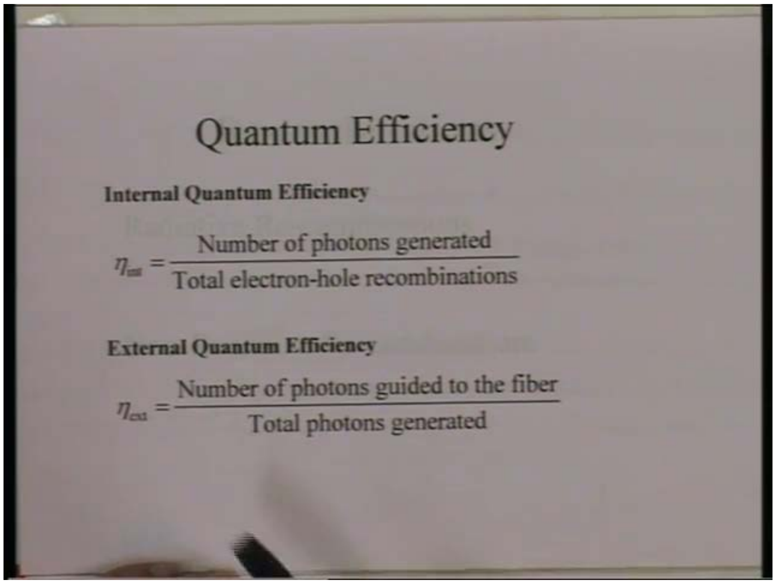

Quantum Efficiency

Internal Quantum Efficiency

$$\eta_{int} = \frac{\text{Number of photons generated}}{\text{Total electron-hole recombinations}}$$

External Quantum Efficiency

$$\eta_{ext} = \frac{\text{Number of photons guided to the fiber}}{\text{Total photons generated}}$$

Internal Quantum Efficiency & External Quantum Efficiency:

And in that contest we essentially define a parameter, what is call the quantum efficiency and then we saw that there are two types of quantum efficiency is one can have one is, what is called the internal quantum efficiency and otherwise the external quantum efficiency the internal quantum efficiency essentially is the related to the photon generation process that means, if so many electron hole pairs are recombined, how many of this can give you a photon out the ratio of that gives you. What is call the internal quantum efficiency, whereas the after the photon is generated while capturing the photon, whatever loss takes place that is captured by this parameter. What is calling the external quantum efficiency?

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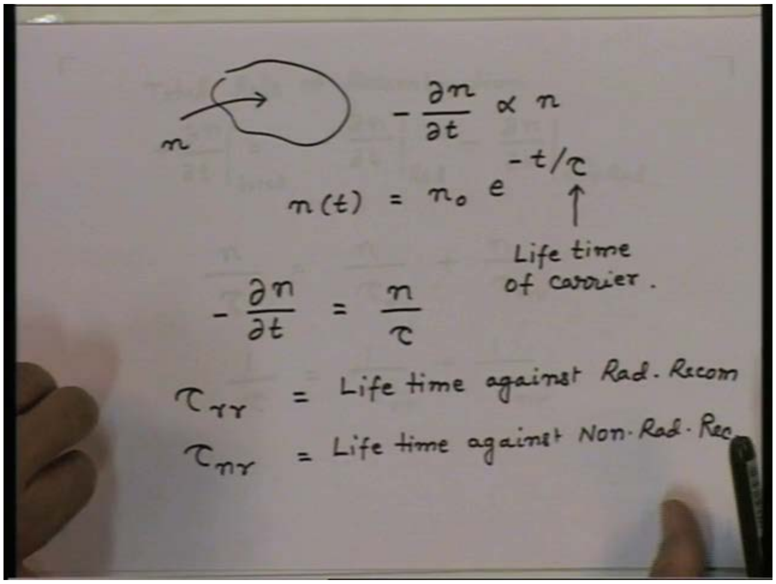

$$-\frac{\partial n}{\partial t} \propto n$$

$$n(t) = n_0 e^{-t/\tau}$$

↑ Life time of carrier.

$$-\frac{\partial n}{\partial t} = \frac{n}{\tau}$$

τ_{rr} = Life time against Rad. Recom

τ_{nr} = Life time against Non-Rad. Rec

Internal Quantum Efficiency & External Quantum Efficiency:

Then we define the important parameters for the photon generation process, which are- what I called the carrier life time ,and we saw that the carrier life time can be against radioactive recombination process or against non-radioactive recombination process.

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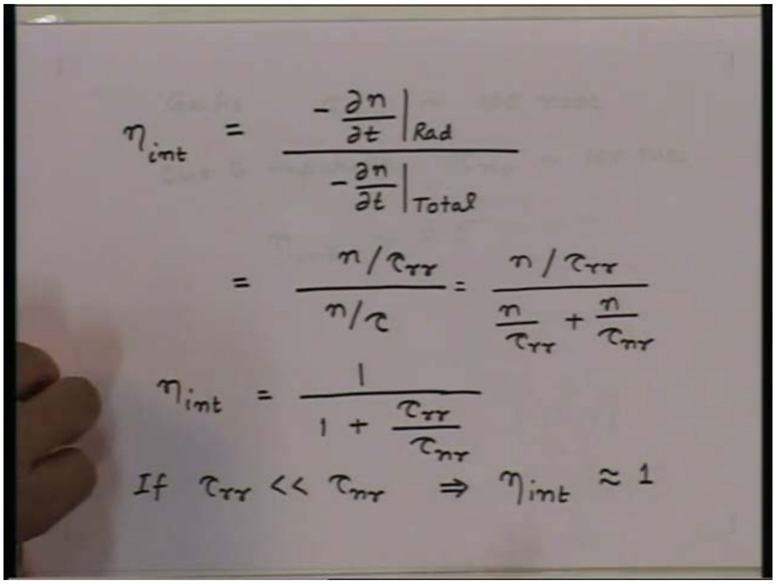

$$\eta_{int} = \frac{-\frac{\partial n}{\partial t}\Big|_{Rad}}{-\frac{\partial n}{\partial t}\Big|_{Total}}$$

$$= \frac{n/\tau_{rr}}{n/\tau} = \frac{n/\tau_{rr}}{\frac{n}{\tau_{rr}} + \frac{n}{\tau_{nr}}}$$

$$\eta_{int} = \frac{1}{1 + \frac{\tau_{rr}}{\tau_{nr}}}$$

If $\tau_{rr} << \tau_{nr} \Rightarrow \eta_{int} \approx 1$

Radioactive recombination process or against non-radioactive recombination process:

And them by simple analysis we got the internal quantum efficiency of this device, which is given by one upon one plus tau r r upon tau n r, where tau r r is the radioactive recombination life time, whereas tau n r is non-radioactive recombination life time, so we find that if tau r r is much less ten tau n r then the internal quantum efficiency of the devices very large.

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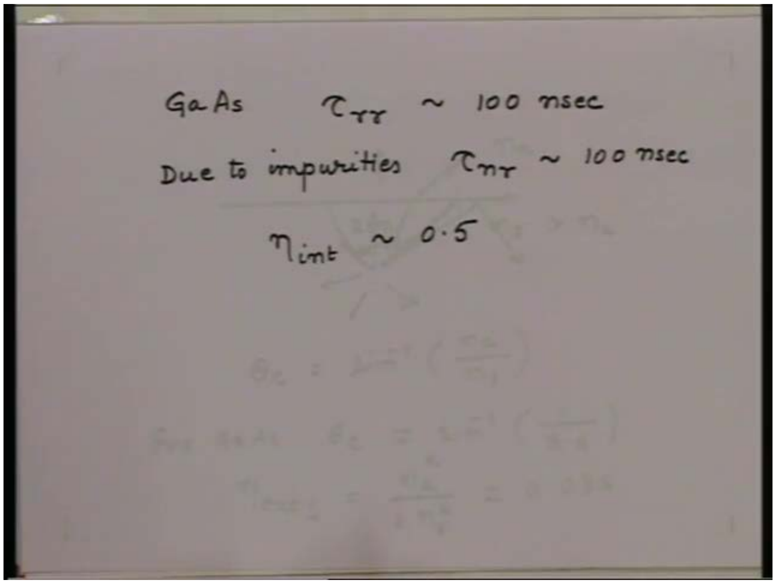

GaAs $\tau_{rr} \sim 100$ nsec

Due to impurities $\tau_{nr} \sim 100$ nsec

$\eta_{int} \sim 0.5$

And we found for typical parameters for gallium arsenide the tau r r and tau n r or more or less comparable. So, we get a internal quantum efficiency which is about fifty percent and we said that this number is quite large, because typically when we talk about energy conversion process a quantum efficiency or and efficiency of energy conversion which is more than about two zero three zero percent is consider to good efficiency.

So, what we conclude that electrical to optical energy conversion process is the fairly efficient process, because we have a efficiency typically of the order of fifty percent then we started investigating the external quantum efficiency, and that is after the photon is bourn through which process the photon goals till it reaches to the finally the optical fiber. And what are the losses with the photon incurves while having this journey from the generation point to the optical fiber.

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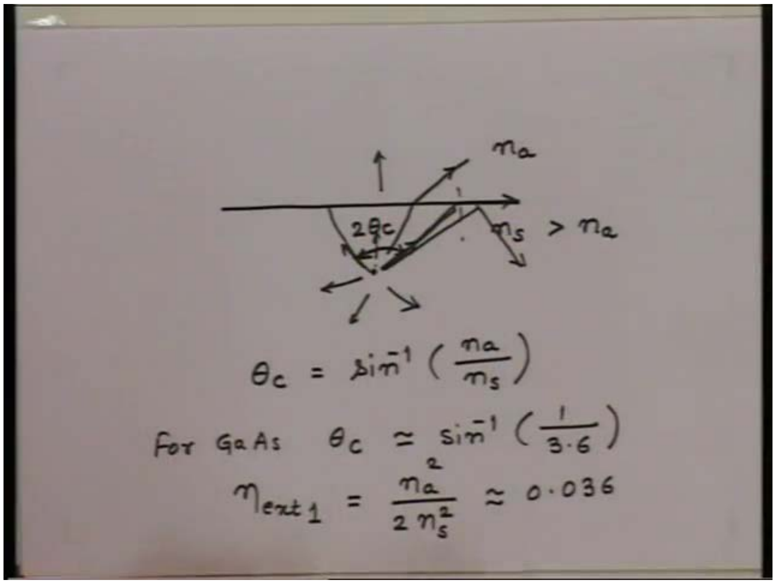

$$\theta_c = \sin^{-1}\left(\frac{n_a}{n_s}\right)$$

For GaAs $\theta_c \simeq \sin^{-1}\left(\frac{1}{3.6}\right)$

$$\eta_{ext\,1} = \frac{n_a^2}{2\,n_s^2} \simeq 0.036$$

And we found that if we take a very simple model, and if you assume that the photon was bon somewhere d inside the material here that yesterday the photon is bon. It is scattered so with equal to probably the photon can move in all directions.

So, essentially the emission the photon from the location where it is boned is isotropic and then we found that essentially those photons which are lying within the critical angle. They can escape from this device and all the photon, which are boned; therefore, cannot come out of the device a large number of these photons get buried back inside the junction and thus what contributes to the external quantum efficiency.

So, first photometer which we saw, because of the critical angle till let us is doing that analysis little more correctly.

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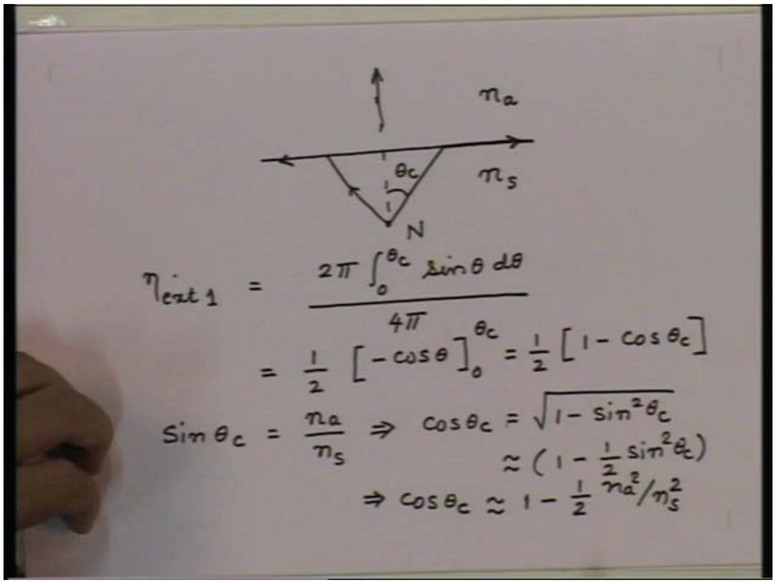

$$\eta_{ext\,1} = \frac{2\pi \int_0^{\theta_c} \sin\theta \, d\theta}{4\pi}$$

$$= \frac{1}{2} \left[-\cos\theta\right]_0^{\theta_c} = \frac{1}{2}\left[1 - \cos\theta_c\right]$$

$$\sin\theta_c = \frac{n_a}{n_s} \Rightarrow \cos\theta_c = \sqrt{1 - \sin^2\theta_c}$$

$$\approx \left(1 - \frac{1}{2}\sin^2\theta_c\right)$$

$$\Rightarrow \cos\theta_c \approx 1 - \frac{1}{2} n_a^2/n_s^2$$

External quantum efficiency:

So, let us say we have a semi-conducting material here and the photon is bon that this point. So, we saw that those photon which lie within the critical angle cone which is this, so this angle is that a c. So the photon which comes normal to this will escape in the direction, but the photon which goes along this path essentially will go tangential to the surface, and the photon which are travelling in between angles the essentially go in different directions.

So now, one can ask a question if and photons where boned at this location then how many photons would finally come out through this solid angle, which have this half cone angle of that a c so one can do a simple calculation?

So, let us say then photon are boned at this location and they are going a is tropically whereas the photon which are collected are through this solid angle, therefore the external quantum eta external. And let us call the it is external one that will be equal to the solid angle of this cone divided by the total solid angle (( )) the photons are going that is four pi.

So, this one is circular spot, which are going to get on the surface of the device so the solid angle for this can be return as two pi zero two that a c sign that a d that a divided by the total solid angle over with the photons are travelling that is equal to four pi. We can write this so this pi will cancel with this, so you have one upon two you can integrate this quantity so that is minus cos of that a with limits zero to that a c, which is equal to half to one minus cos that a c now if the refractive index of this material as we said is n s and the refractive index of this material is n a then the critical angle that a c is given as sin inverse of n a by n s.

So, we have sin of that a c which is equal to n a by n s this gives cos that a c will be equal to squawroot of one minus sin square that a c now since the that a c angle is small sin square that a c is the small quantity so we can make a small approximation, so we say this is a approximately equal to one minus one upon two sin square that a c, which gives cos of that a c approximately equal to one minus one upon two into this quantity here sin square that a c, which is n a upon n square, so you have n a square upon n s square we can take this quantity and substituted to this expression here.

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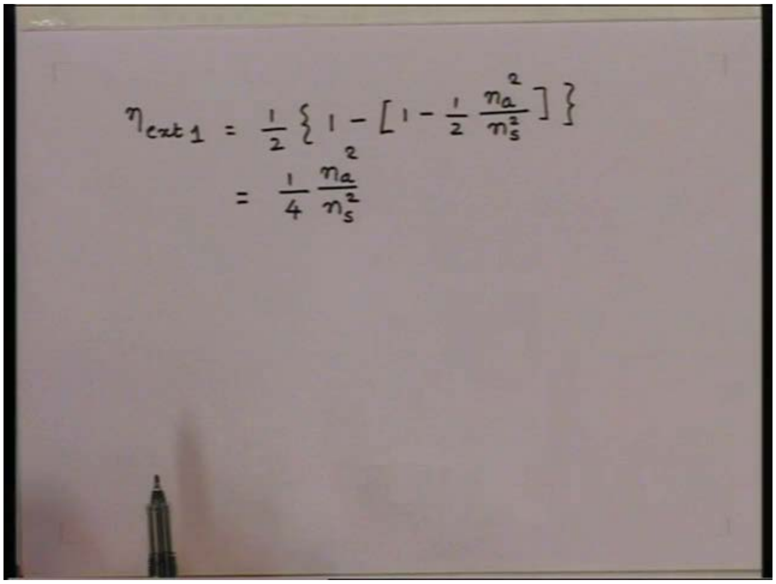

$$\eta_{ext1} = \frac{1}{2}\left\{1 - \left[1 - \frac{1}{2}\frac{n_a^2}{n_s^2}\right]\right\}$$

$$= \frac{1}{4}\frac{n_a^2}{n_s^2}$$

External quantum efficiency:

And then we get the external quantum efficiency eta e x tone that is half to one minus this quantity here cos of the a c, which is this so one minus one minus one upon two n a square upon n a square so you get the external quantum efficiency, because of the total internal reflection of the photon inside the device that is one upon four to n a square divide by n a square.

Now if you substitute the numbers for a gallium arsenide, so n s for gallium arsenide is about three point six and let us say the photons are coming out in air so n a is equal to one.

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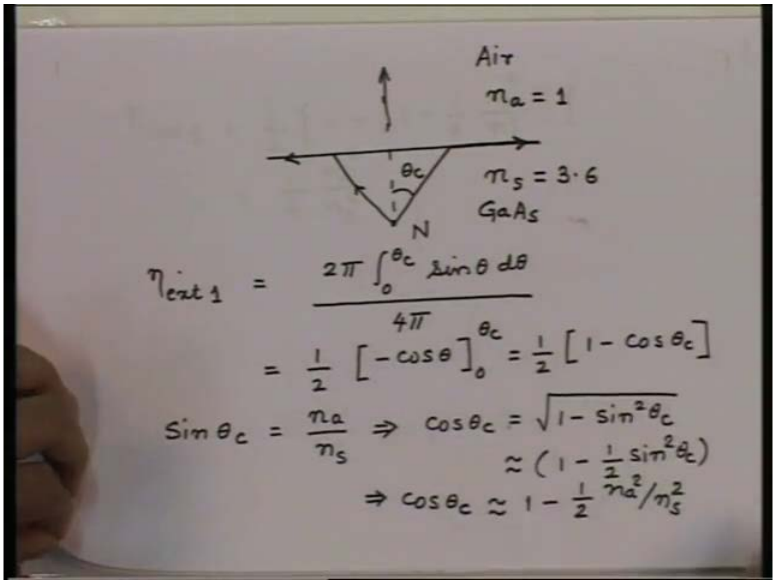

$$\eta_{ext\,1} = \frac{2\pi \int_0^{\theta_c} \sin\theta \, d\theta}{4\pi}$$

$$= \frac{1}{2}\left[-\cos\theta\right]_0^{\theta_c} = \frac{1}{2}\left[1 - \cos\theta_c\right]$$

$$\sin\theta_c = \frac{n_a}{n_s} \Rightarrow \cos\theta_c = \sqrt{1 - \sin^2\theta_c}$$

$$\simeq \left(1 - \frac{1}{2}\sin^2\theta_c\right)$$

$$\Rightarrow \cos\theta_c \simeq 1 - \frac{1}{2} n_a^2/n_s^2$$

So, let us say in this device, here we have material which gallium arsenide so n s is equal three point six and here is air, so n a is equal to one.

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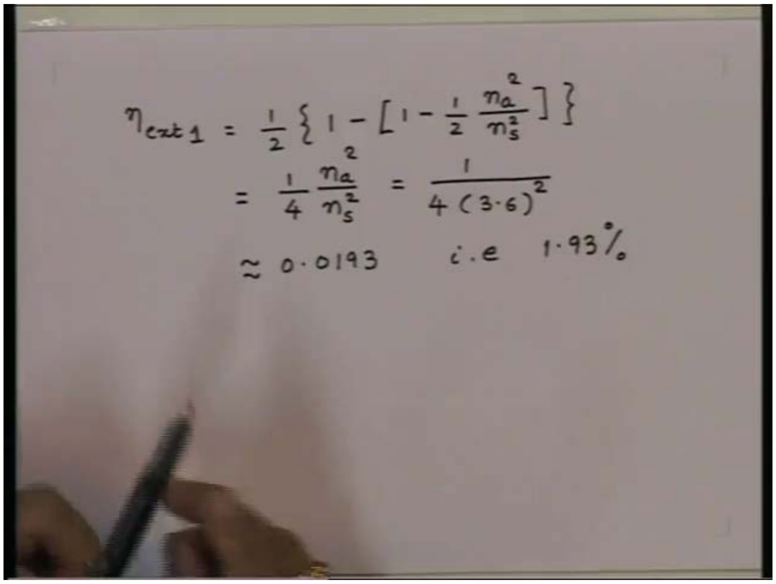

$$\eta_{ext1} = \frac{1}{2}\left\{1 - \left[1 - \frac{1}{2}\frac{n_a^2}{n_s^2}\right]\right\}$$

$$= \frac{1}{4}\frac{n_a^2}{n_s^2} = \frac{1}{4(3\cdot6)^2}$$

$$\approx 0\cdot0193 \quad i.e \quad 1\cdot93\%$$

External quantum efficiency:

So, if I substitute is numbers inside this expression here we get that is equal to one upon four into three into six whole square which is approximately zero point zero one nine three or that is about one. Nine three percent, so as be saw yesterday we mention that when the photon twice to come out a large number of photon essentially get buried back inside the device and now with this accurate calculation. We see that about two percent of the photon essentially can escape from this device that be ninety eight percent of the photons which are bon are buried back inside the device itself so you see there is a substantial loss of photon we stage place right at the location where there boned.

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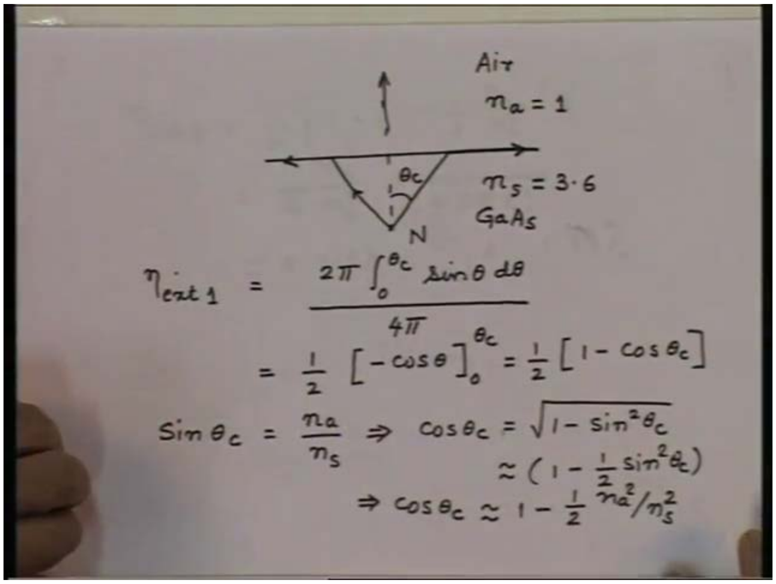

$$\eta_{ext\,1} = \frac{2\pi \int_0^{\theta_c} \sin\theta \, d\theta}{4\pi}$$

$$= \frac{1}{2}\left[-\cos\theta\right]_0^{\theta_c} = \frac{1}{2}\left[1 - \cos\theta_c\right]$$

$$\sin\theta_c = \frac{n_a}{n_s} \Rightarrow \cos\theta_c = \sqrt{1 - \sin^2\theta_c}$$

$$\approx \left(1 - \frac{1}{2}\sin^2\theta_c\right)$$

$$\Rightarrow \cos\theta_c \approx 1 - \frac{1}{2} n_a^2/n_s^2$$

Now the photon which are travelling inside this cone of critical angle would all the photon is coming out of this junction. Now we can use the photon as a packet of light or we say that now the photon is a wave, so there is an electromagnetic wave which is trying to an escape this region and there is a chain is refractive index from this medium to this medium.

So, this is going to be a partial reflection of the electromagnetic wave so we say that even those photons which are within this angle or within the cone of this critical angle canon escape there be partial reflections of the photon, and the reflection coefficient will depend upon the refractive index of this material and refractive index of this material.

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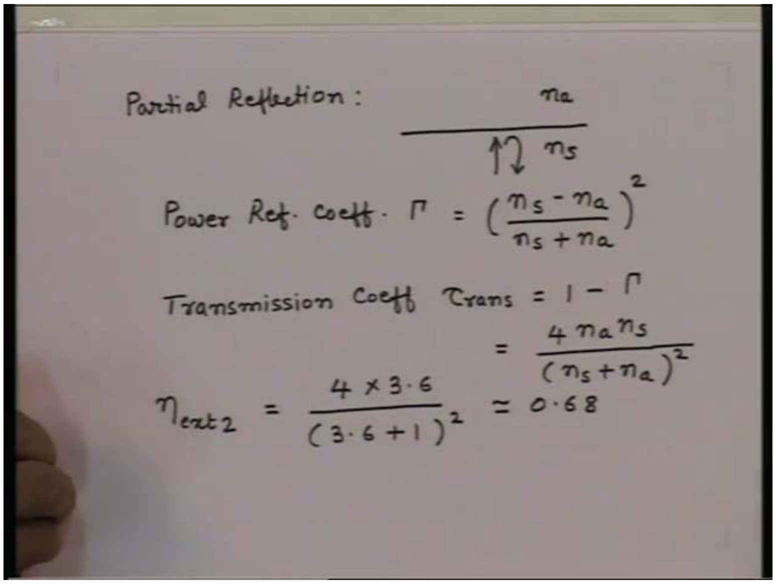

Partial Reflection :

n_a

$\uparrow\downarrow$ n_s

Power Ref. coeff. $\Gamma = \left(\frac{n_s - n_a}{n_s + n_a}\right)^2$

Transmission Coeff $\tau_{Trans} = 1 - \Gamma$

$= \frac{4 n_a n_s}{(n_s + n_a)^2}$

$\eta_{ext2} = \frac{4 \times 3.6}{(3.6+1)^2} \simeq 0.68$

Refractive index of this material:

So, we say that because of partial reflection of the photons or photons, which are even lying within the critical angle cone canon, escape the junction. So, just what simplicity let us assume that the photon which are now coming out they are travelling almost normal to this interface.

So, we say that this is my junction and the photon essentially are travelling in this direction here we have refractive index n s and the here the refractive index is n a, then the reflection coefficient for this power reflection coefficient can be return as n s minus n a divided by n s plus n a whole square. And therefore the transmission coefficient will be one minus this quantity. So, we get the transmission coefficient let us called tau Trans that is equal to one minus gamma.

So, that is equal to four into n a into n s divided by n s plus n a whole square, Now this quantity is nothing but again the external quantum efficiency against this process of partial reflection so let us called to this quantum efficiency as eta external two. So, that will be equal to this quantity here and now if I substitute the numbers again for the gallium arsenide you get here this is four into three point six divided by three point six plus one whole square and that will be approximately zero point six eight.

Now while travelling from this location to this location again there would be absorption of the photon, because of the photon make a three absorb inside the material.

So, you may have some loss of photons even during the propagation over this distance so addition to this loss and this loss there would be some loss due to the intrinsic absorption into the material. So, we have some efficiency factor associated with the absorption that is call it eta external three that is due to absorption in the material.

So, if you are talking only about the efficiency external quantum efficiency from the generation of the photon to the escape of the photon then external quantum efficiency essentially would be the product of eta e x t one tell to eta externally two and eta external three, however if you saying that the quantum efficiency is defined by the availability of the photon inside the optical fiber for communication then we have to add one more factor that is the photon, which are coming out how many photons of that will get guided inside the optical fiber when a fiber is put inside or in front of this device.

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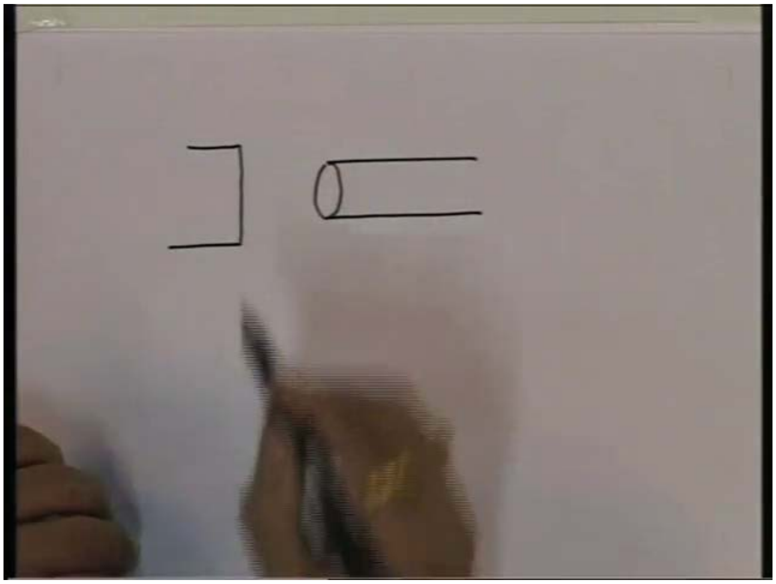

Quantum efficiency:

So, the question we are asking is that if this was the optical source from is photons are coming and if i take an optical fiber, and put in front of it how many photons finally will get guided from the two device two the optical fiber. Now without varying about the area incomparability let us say the area is match with the device. So, it is just the matter of angle through which the photons are coming. So, we are asking so total photon which are emitting from this device how many of dim would finally we guided in side optical fiber and as we seen only those light rays get guided inside optical fiber which lie within the cone of a numerical aperture.

So, what is saying now is what we have a cone of numerical aperture for optical fiber only if the photon is incident within this cone then only it finally get guided inside the fiber those photon, which are coming at an angle greater than this they will be again loosed, because they will not be guided inside the optical fiber now let us point out again here that when we talking about the critical angle inside this junction only those photon which are lying within this that a c are escaping, but let us not have a wrong impression that when the photons are coming out they will have a cone which is that a c. Because as I mention the photon which is travelling perpendicular to this will go in this direction whereas photon which is travelling in this direction will be along the surface that means, if I see externally the cone over with the photons are a emitted it essentially one eight zero degrees cone.

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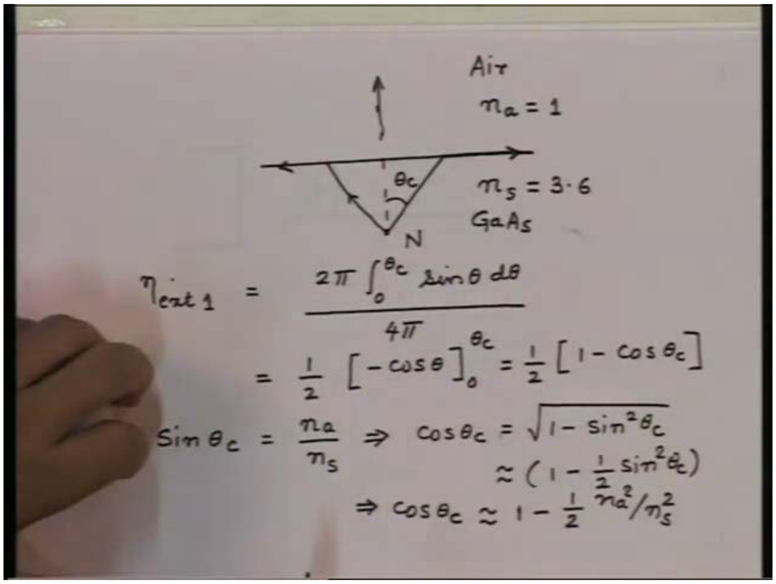

$$\eta_{ext\,1} = \frac{2\pi \int_0^{\theta_c} \sin\theta \, d\theta}{4\pi}$$

$$= \frac{1}{2}\left[-\cos\theta\right]_0^{\theta_c} = \frac{1}{2}\left[1 - \cos\theta_c\right]$$

$$\sin\theta_c = \frac{n_a}{n_s} \Rightarrow \cos\theta_c = \sqrt{1 - \sin^2\theta_c}$$

$$\simeq \left(1 - \frac{1}{2}\sin^2\theta_c\right)$$

$$\Rightarrow \cos\theta_c \simeq 1 - \frac{1}{2} n_a^2/n_s^2$$

So, you having a complete have a spherical emission, which is coming from LED so LED is not a directional device so do whatever the photons are an emitted into this cone when they come out essentially they come out over this two pi solid angle.

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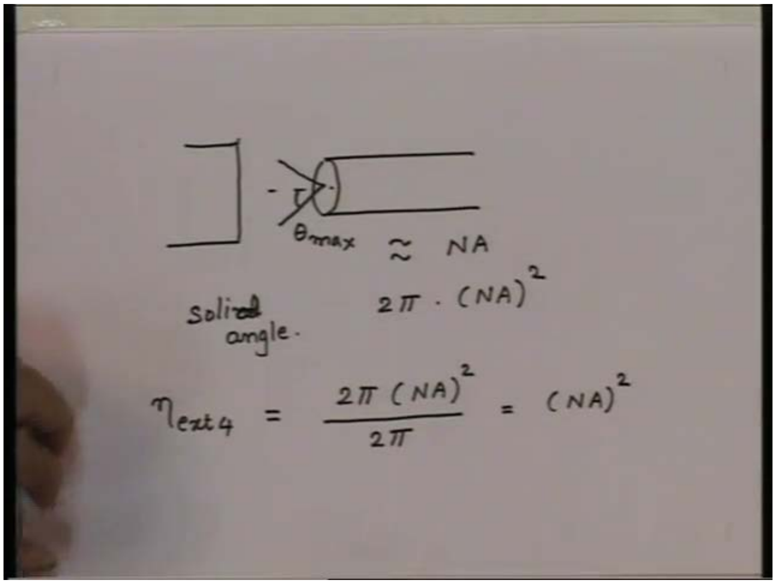

$\theta_{max} \approx NA$

solid angle. $2\pi \cdot (NA)^2$

$$\eta_{ext4} = \frac{2\pi (NA)^2}{2\pi} = (NA)^2$$

So, we are having the emission of the photon which is isotropic as for as this half is concerned and only from that isotropic incoming radiation that radiation, which is incident within this cone of numerical aperture will get guided inside the optical fiber. So as we know that maximum angle which the fiber can except that a max that is approximately given as the numerical aperture so we have that a max which is approximately the numerical aperture again assuming circular symmetric, here the solid angle of this numerical aperture would be two pi into n a square solid angle.

So, the efficiency of photon reception by the optical fiber is this solid angle divided by the solid angle of the variated photon, which is equal to two pi so we can have now eta external four, which is equal to two pi into numerical aperture square divided by two pi there is a solid angle of the radiating photon so that is equal to n a square.

Now, if we take a typical fiber the numerical aperture lies between zero two to zero point three, so a typical range of numerical aperture is zero point two to zero point three that means this quantity here eta external four that would lie somewhere between zero point zero four to about zero point zero nine.

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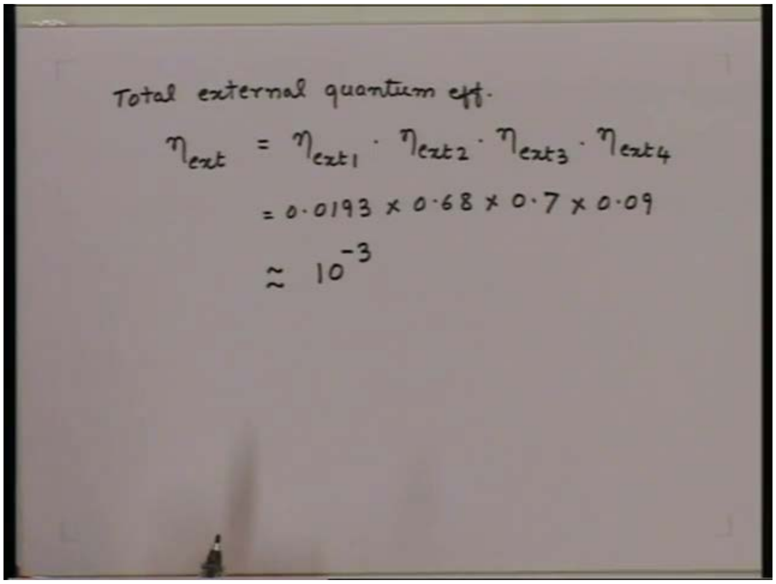

Total external quantum eff.

$$\eta_{ext} = \eta_{ext1} \cdot \eta_{ext2} \cdot \eta_{ext3} \cdot \eta_{ext4}$$

$$= 0.0193 \times 0.68 \times 0.7 \times 0.09$$

$$\simeq 10^{-3}$$

Total External Quantum:

So, now if I put all the things together and then ask what is the total efficiency, which I have got from the photon generation to the photon guidance inside the optical fiber we get total external quantum efficiency eta external; that is equal to eta external one into eta external two into eta external three into eta external four.

So, if I put all this factors this is zero point zero one nine three into zero point six eight eta external three, which is because of the absorption let us take some number for that let us say zero pint seven or zero point eight and this quantity here which we have got which is n s square. So, let us take the best possible value for that which is zero point zero nine, if you to this multiplication this quantity will be approximately one zero to the power minus three what that means is that if one zerio zero zero photons. Where bon effectively one photon becomes available finally for communication and they if you, so on if you put the internal quantum efficiency on top of this which is about fifty percent it is about two thousand electrons, whole pairs when the recombine one photon becomes available for optical communication inside the optical fiber.

So, we see that this process is extremely in efficient process, because we are seen that the electron whole pair essentially is proportional to the current which is injected into device, so we have to inject so many carriers to get a very little light coming out of this.

So, one important conclusion which we have got about the light emitting diode and that is. It is extremely in a efficient device, because all the photon generation process is very efficient the photon collection max it difficult to make a photon available for optical communication. So now we see that the LED essentially has to problems one is it has very large spectral width.

That means it cannot support high data rates and secondly it has extremely low efficiency, that means it cannot give you a very high power another words the LED cannot be used for a long distance communication, because the long distance communication requires both it requires low spectral width so that dispersion is low and the same time the power should be high so there is signal can travel over long distance.

So, at this point essentially we conclude that LED is a good device for short distance communication and it has problem of the device to be use for long distances communication. However we will see that the LED has very nice feature and that is LED is fairly linear device what that means is just follows that if I take the LED for every recombination which takes place you get a photon out again after putting all this efficiency factors there is a reduction number of photons but still the final number of photon.

Which are going to come out of which are going to will become available for communication that is proportional to the number of carriers injected inside the p junction or another words we are having the number of photons emitted by LED proportional to the current, which is injected in the p n junction now the current which is going inside the junction is the rate of injection of the carriers.

So, the photon which are going to come out will be the photon per unit time by the rate of emission, if I multiply by the energy of the photon we get the energy per unit time which is nothing but power optical power so what do you find is that for a LED we are having a proportionality between the optical power and the injected current in the LED.

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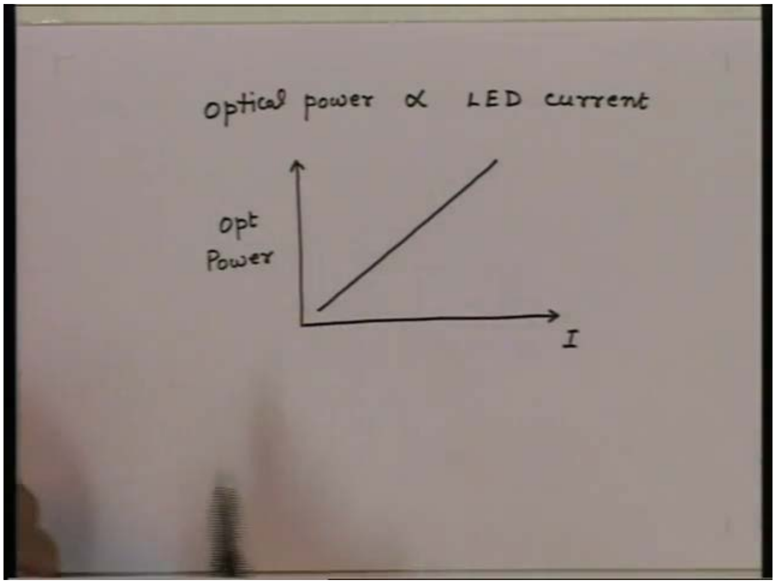

So, we get a proportionality which is optical power is proportional to the LED current, so if I plot what is call the output characteristic of this device this is the current is injected inside the p n junction, and this is the optical power we get a linear characteristic the slope of this will depend upon here efficiency an all the constants in so on.

But the important thing is that the output which is optical power here to the input which is the current there is a linear relationship, and therefore this device can be use for analog kind of modulation because it analog modulation we require a device which is linear. And then one can get a very simple circuit we are having now this LED here you can bio this LED with some this voltage, and then you can put a small a c signal you can get light here which will be emitted by LED since this is proportional to the current which is flowing into this you will get the a c light out here which will proportional to this voltage which is applied.

So, essentially just by changing the current inside the LED we can generate the light output, and since there is proportional between these two essentially all the characteristics of the current temporal characteristics are transfer to the optical flats, so optical light also will fluctuate exactly same way as the current is going to fluctuate.

So, that essentially say now that using LED just by changing the voltage is applied across this or current which is injected inside the device we can change the optical power or essentially. The light can be modulated by modulating the current, so the modulation process now is very state forward process that you put a c source in series with the biasing source for the LED, and whatever modulation is there on this a c source essentially. It will get transferred to the optical signal however one can do little dipper investigation to find out that what rate the modulation can be carried out or fridge in the question in different way if I increase the frequency of modulation. What will happen to the fluctuation of light would by LED, we respond we able to respond to the fast fluctuation which are there in there in the current.

Now this can be answered in two different ways one is from the circuit point of view the since LED is a junction you are having a junction capacitors. There it has a resistance so you are having r c constant associate with a device, so once we are having a r c time constant approximately one upon the time constant is the highest rate at which the device can operate.

There is the band width of the device other way of looking at this is that was the carry injected inside the depletion region the carriers are going to remain their till they are recombine and as we saw there is a characteristic time. What is call the recombination life time was the carriers that means one the carriers are rejected on average the carriers are going to remain in that region over that life time. So, even if the current is switched of the carriers are not going to disappearing instantaneously in the region.

But they will disappear only after a time which is the recombination life time, so one can now ask a question that even if I fluctuate the current, which is faster than the recombination life time or the device respond to this kind of fluctuation and the answer is no it will not because even if you fluctuate the current i injection of the carriers the carrier which we are injected earlier, that are still there they not disappeared. So, the light which is emitted will not fluctuate at the same rate so essentially the bandwidth of the device now will depend upon the recombination life time does the were simple analysis that what is the spit of the modulation of LED and can be change the spit or can be it is the speed of the this device.

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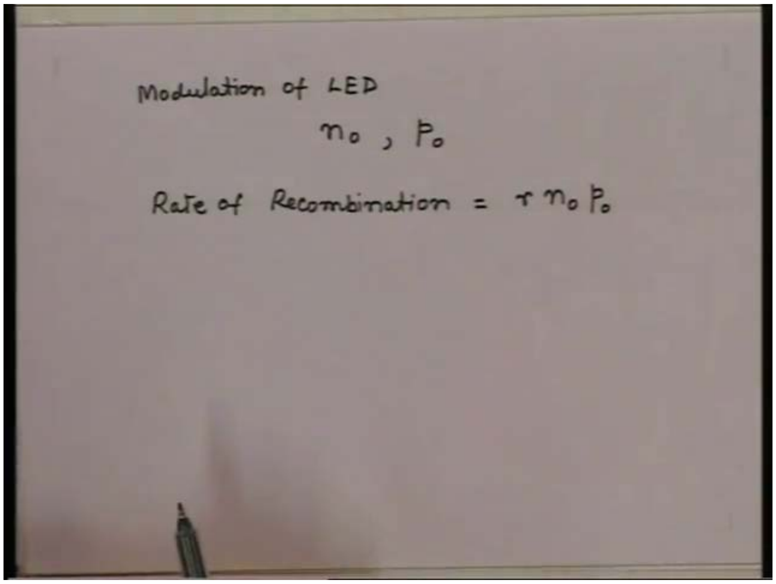

Modulation of LED

n_0 , p_0

Rate of Recombination = $r n_0 p_0$

The modulation of LED:

So, we are essentially saying if I go for modulation of LED then how can be manipulate the recombination life time of the carriers inside the junction, so let us say we have a p n junction and the recombination taking place there are intrinsically, there are carriers which are having density n zero and p zero let us say the recombination constant, which is arc so rate of recombination inside the junction will be equal to this arc which is proportionality constant which depends upon the mater into n zero and p zero into p c now, because of thermal excitation the carriers are getting generated also.

So, if the devices not injected with an additional current you are having a ambient electron density which is n zero ambient whole density, which is p zero and the recombination rate which is given by this completely balance by the thermal emission rate the carriers are getting generated because of thermal excitation, so this rate is also the thermal generation rate because this number is not changing as a function of time in equilibrium so this is also equal to the thermal generation rate.

Now let us say we inject certain electrons and whole inside the p n junction, so the electron density is now change from n zero to delta n and the whole density is change p zero to delta p again the rate of recombination will be proportional to the product of the electronic density, and the whole density but now you are having a thermal generation rate of… So, some recombination taking place but because of the thermal excitation some electron hole pairs are getting generated. So, then we have a net recombination rate.

Which is the net recombination rate, which is equal to proportionality constant r into n zero plus delta n into p zero plus delta p minus the thermal generation rate which is r into n zero p zero, which is equal to r into n zero plus p zero, and if I assume that the injected electrons and holes are equal in number the delta n equal to delta p we can say the deices delta n into delta n where we have taken delta n is equal to delta p.

So, now I have gotten net recombination rate and that we can write now if I write for a electrons that is minus d delta n by d t, that is equal r into n zero plus p zero plus delta n into delta n. Now we can consider two cases one is when you having a low injection that means the currents are low inside the p n junction, and in that situation this quantity delta n will be much-much smaller compare to the ambient density of electrons.

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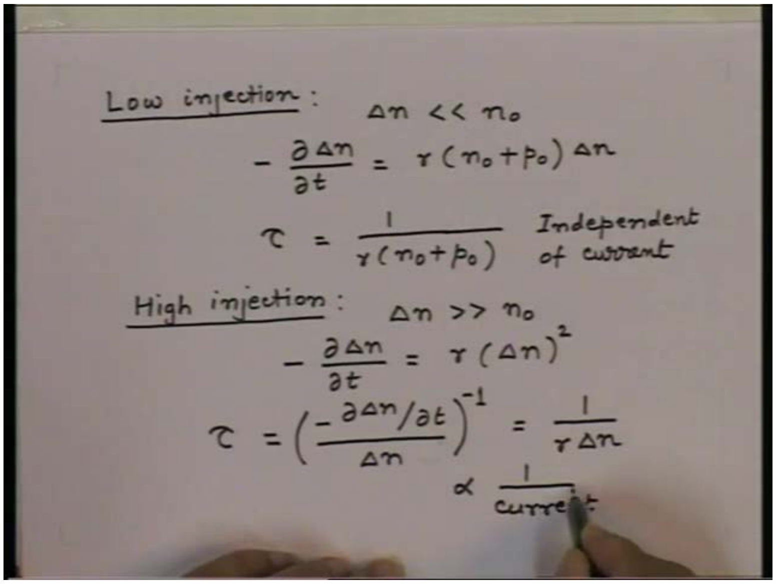

Low injection : $\Delta n << n_0$

$$-\frac{\partial \Delta n}{\partial t} = r(n_0+p_0)\Delta n$$

$$\tau = \frac{1}{r(n_0+p_0)}$$ Independent of current

High injection : $\Delta n >> n_0$

$$-\frac{\partial \Delta n}{\partial t} = r(\Delta n)^2$$

$$\tau = \left(\frac{-\partial \Delta n/\partial t}{\Delta n}\right)^{-1} = \frac{1}{r\Delta n}$$

$$\propto \frac{1}{\text{current}}$$

The ambient density of electrons:

So, we have two cases now two consider one is what is called the low injection case and in this case we have delta n which is much smaller compare to n zero, so we can approximate this expression here so we say minus delta d delta n by d t that will be equal to r into n zero plus p zero into delta n.

So, we have minus d delta n by d t that is equal to r into n zero plus p zero into delta n and as we seen earlier this has exponential variation as a function of time and one upon this quantity will be the life time of the carriers, so it is a recombination life time.

So, we have at now here the tau which will be equal to one upon r into n zero plus p zero this is independent of the current, because this current is proportional to this quantity which is delta n and there is no delta n appearing in this, so essentially the recombination life time. Now is purely decided by the intensity of electrons an holes in this and the constant here are which depends upon the material, whereas on the other hand, if I take the high injection that means the current is high.

So, I take delta n is much greater compare to n zero and in this case then one can make an approximation that this quantity minus d delta n by d t that will be equal to r into this quantities negligible. Now, so you have delta n hole square so you get in this case minus d delta n by d t that is equal r into delta n square now as you have seen earlier. We have the recombination time define tau which is minus d delta n by d t divided by delta n was one upon this minus one.

So, if I take from here this quantity will be equal to one upon r into delta n and since the current injected inside the junction is proportional to delta n essentially. We are what defined is now that recombination time is inversely proportional to the injection current so as the current increase the recombination times becomes smaller and smaller that means the device can be switched on or off at much faster rate, so we have here this is proportional to one upon current. So, what is simple analysis tells us is that if your operating the LED at low currents then the speed of the LED is practically independent of the current whereas if you increase the current inside the LED then the speed of the LED can be increased, because the recombination life time will reduce.

So, the fluctuation in the light now could be faster if you are injected the LED with the high current. So that means if you want to operate the device for a high speed modulation the LED can be use with high injection current, but when you and that the current more current inside the device essentially the current density large inside the junction. And because of that the heat generation is more so the life of the device essentially comes down so what we find here is as that if you can scarify some parameters like life the device so on then the LED can be operated at high speed whereas if you operate the LED with low powers it can operate over much longer time but is speed will be very limited.

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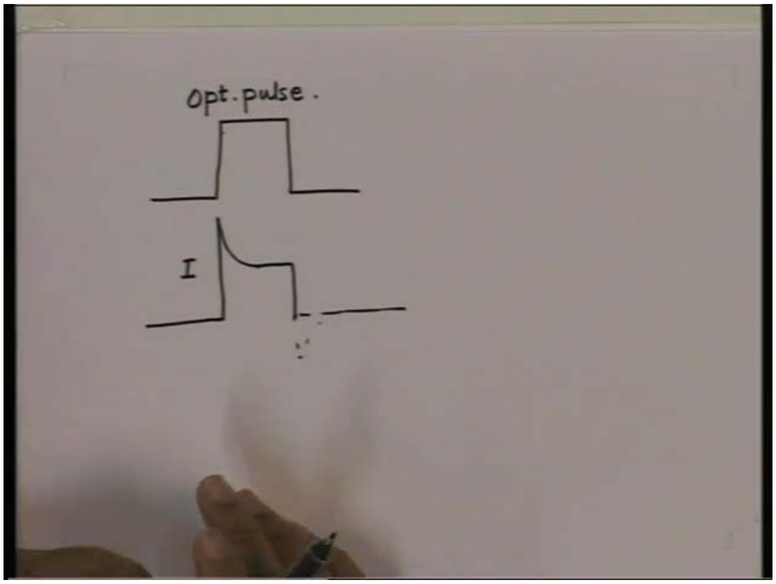

So, let us now say that suppose I wanted to modulate the LED let us say which digital kind of data is. So, I wanted to give a data which is like this which is a pulse. So, I want that when the light is emitted, it would a emit a pulse which would look something like this what one notice here that you require a very high pitching speed in this region.

So, essentially current has to be change in such a way the device is switched on at first speed but once the optical level is listed here then even if the speed is low then you don’t have vary about it, because now the optical intensity to this two these two two level so essentially what we are looking for is when we are considering LED as a digital modulation device we want that is speed should be much faster somewhere here. And even if the speed reduces over this region it is not affect the performance so what one can do is one can inject high current inside the LED for short duration.

So, red can switch fast because if inject more current the recombination time will reduce so device can be switched on much faster once we reach to this level, then essentially the current can be switched off or can be reduced and the optical intensity will be stabilize, so to generate this optical pulse essentially one can put a current which is much higher then what is required then switch off the current. So, current dies down and then is stabilize that is point same thing what can do here switch off the thing one can down like this.

So, to generate an optical pulse which is off rectangular nature here and if the speed of this is large then the appropriate current which should be pumped into the LED, would we something of this nature so on this age the current will be having a over shoot, which will essentially reduce the recombination time and other words switch on the device very rapidly once you reach to this optical intensity then you can reduce the current and then optical intensity will be constant like this so for this current incident on the LED this will be the optical pulse.

So, let us summarize the now what we have seen about the LED starting from the semi-conducting material and this properties essentially we made a very simple device which is nothing but a p n junction where we jet the electrons an wholes and they electrons are wholes recombine part of this recombination give photons out. And part of the recombination essentially produce some thermal energy which goes in heating of the junction the photon which are generated, because of the recombination when they try to come out many of them get buried again inside the junction.

So, a very small fraction of the photons come out of LED so LED gives a very less efficiency at the same time because of the intrinsic nature of the semi-conductor the spectral width of a LED is very large. So, if we look at LED as a source from of optical communication point of view the LED essentially has two deficiency one is it has very low efficiency. And that is reason cannot give you high power which can travel or long distance on optical fiber it also has very large spectral width, which is bad for dispersion, because it cannot support high data rate so LED then is a good device for small area networks is essentially good for local area networks also since the emission which comes from LED is more or less isotropic you require an optical fiber which is large numerical aperture otherwise again the efficiency, because very small.

So, LED suited essentially for multimode fiber but good point of LED is diode it has a linear relationship between the optical power, and the current. And therefore this device is quite suitable for the annual up kind of modulations, so what we conclude that LED is a good device for analog modulation but because of this other limitation the LED can be use only over short distances and that’s why this device can be use for local area networks with multimode fibers whereas when we go for long distance communication the LED is not suitable device. And therefore, we look for other device which is the injection laser diode which essentially removes all the deficiency of LED. So, next when we discuss the laser diodes or injection laser diodes essentially, we have to are the questions what way this new device is better compare to LED.

So, will discuss in the following lectures the development of injection laser diode and every time will compare this with the performance of the LED, and then will see that the injection laser diode is superior compare to LED in both count it is more efficient, and also it has spectral width which is much smaller compare to LED noise.