Semiconductor Optoelectronics
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Lecture - 31
Light Emitting Diode - IV
Modulation Bandwidth

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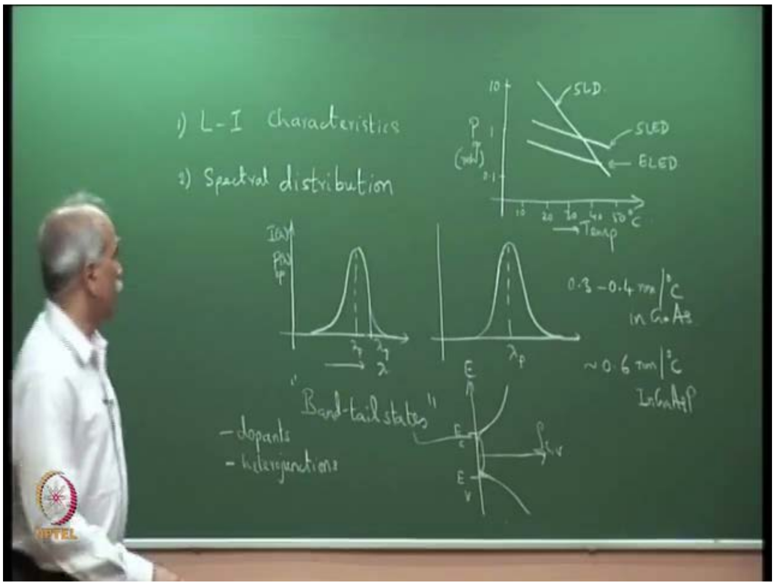

So, we were discussing the characteristics, device characteristics or output characteristics of a light emitting diode. So, we have discussed first the L I characteristics, light current characteristics or I P characteristics and we have discussed this in detail, just one point here, if you were to plot temperature versus optical power P optical. So, this is 0.11 and 10 milli watt, P optical in milli watt. Then for the three LED's it would approximately look like this, the variation. So, this is let us say… So, 10, 20, 30, 40, 50 degree centigrade. This is for an edge emitting LED - ELED. A surface emitting LED normally has more power, and therefore it would look almost parallel, the variation would almost look like this. This is for a surface emitting LED. So, qualitatively I am just showing that what kind of radiation. If you look at the power variation for a superluminescent diode, then it would really start at high values, but it very sensitive to temperature.

So, this is for an SLD SLD. The power output of a superluminescent diode is high, but is quite sensitive to temperature, because stimulated emission is the one which is contributing to it and normally it is much more temperature sensitive. The second characteristic which we discussed is the wavelength spectrum or spectral distribution, spectral distribution.

One, we have discussed this in detail, but still there was one point which I had not discussed and that is theoretically we got a graph, which is like this. So, this is wave length lambda versus the optical power or rate of spontaneous emission or P optical or intensity I of u, so I of lambda P optical of lambda or I of lambda. This started at lambda g, the bandgap wavelength you can always reverse it and see E g. So, this is the variation, but I had also shown you practical variations and they looked almost symmetric practical graphs, almost looked symmetric. Centered around a line center, here is the line center.

So, this is lambda P corresponding to peak value lambda P, but it does not show this sharp edge, this is because of the presence of band tail states. Is a matter of detail, but band tail states. So, band tail states refer to states which are present. If you see the density of states, we had shown the density of states like this. So, what I am plotting is rho of C comma V and this is versus energy. This point is EC and this value here is EV, the density of states. There is, there are no states in this forbidden gap, but in general in doped semiconductors you always have some states here. Similarly, there are some states here, close to the band edge. This is because of a variety of reason. It is a matter of details, I do not wish to go into those details at this point, but it is because of the band tail states. Actually this allowed the density of states has a variation which is which is not sharp at EC, but really there is a band gap narrowing.

Means this is the actual theoretical band gap, but you have some states close to EV and close EC there are a variety of reasons. One due to dopants, addition of dopants, the dopants are distributed randomly even though they could be substitutional impurities they are still distributed randomly. This leads to a random variation in the periodic potential. When you have got these mice curve, we have considered that it is a perfect crystal with periodic potential, but the period itself fluctuates in the presence of dopants and that fluctuations lead to some states here. This is one of the reasons due to dopants.

The second reason is because of the hetero structure, the hetero junctions that you have although we have taken care of lattice matching, at the hetero junctions there are two different types of atoms which form a bond and the corresponding electronic energy is close to this band edge. So, the states which come here are because of some of these reasons. There are there are definitely there are some defects. You can minimize the defect density, but there are also defects and these this tail like portion is called band tail states. So, what it means is the states do not start abruptly and therefore, it does not start abruptly here. You see an electron from here can combine with a hole here, giving out a photon of energy less than E g and therefore, this in practice this turns out to be like this. So, when you really measure, you get a spectrum which is smooth not symmetric, but smooth.

So, the explanation comes from band tail states. One last point in this, we have discussed that with temperature I would shown that with temperature the curve shifts to longer wavelengths, typical numbers are 0.3 to 0.4 nanometer per degree centigrade in gallium arsenide base LED’s and typically of the order of 0.6 nanometer per degree centigrade in indium gallium arsenide pass pate LED’s that is in the I R. Typical shift of this peak typical shift of this peak with temperature per degree centigrade is of this order. So, today we will discuss modulation band width, but before that I have just one more characteristic that is the angular distribution or the radiation pattern. The radiation pattern, indicates the directionality of a source. So, radiation pattern or the angular distribution refers to the angular dependent of the intensity of the source or output of the source. So, let us briefly see the radiation pattern.

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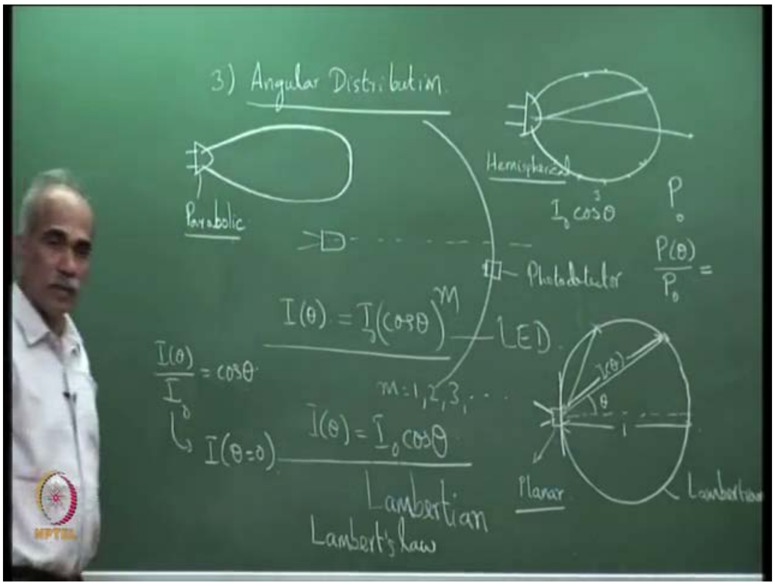

So, the third characteristic angular distribution or radiation pattern, so if a source is sitting here, let say this an LED, if you measure the intensity distribution as a function of the angle. So, you scan. Let say you take a photo detector a P hole photo detector here. So, this is a photo detector connected to a power meter. You stand as a function of angle and measure the intensity or the power detected by the photo detector. Then you plot I as a function of theta and what you get is the angular distribution. So, in general for led this I theta is approximately of the form I 0 into cos theta to the power m. With m equal to 1, 2, 3 not necessary they have to be integers, but m can take numbers 1, 2, 3 and so on.

What it means is, if you put m equal to 1, the dependence is I of theta is equal to I 0 cos theta. Infact this dependence is called Lambertian is a Lamber's law. The source is called Lambertian. Let us get the picture, what it means? Is let me so the LED is placed here, this is the LED. The LED is sitting here and you have measured as a function of angle. How this is plotted you see I of theta is equal to I 0 cos theta, this is called a Lambertian distribution or it is from Lambert's law. In this if it is Lambertian distribution, you will get this radiation pattern as a circle. What I have plotted I have plotted intensity as a function of theta. So, this is the theta the LED is sitting here, you are measuring the intensity as a function of theta and the point here that is the length of this cart is proportional to intensity.

This is I of theta so at every angle we measure the intensity and put a point where at in that angle, the length of this is proportional to the measured power or I can write this as I by I of theta by I 0 equal to cos theta. I 0 is nothing but I at 0 angle, that is here. This I 0 I 0 is I of 0 theta equal to 0 at theta equal to 0 cos theta is 1. Therefore, I 0 is nothing but I at theta equal to 0. So, right in front of the LED, we measure the power. Let us say you get some power I get P 0 P 0 or intensity I 0. Whatever, P 0 at some other angle I get power which is P of theta then P theta by P 0. So, I normalize this to 1 P by P 0 will be less than 1 and that is this length. So, at different angles you find out P of theta by P 0. Then corresponding to that length length normalize to one this is one so divide by this length to the magnitude here of this called here is proportional to the power at theta power measured at angle theta.

So, at different theta I measure the power and put the point this length is proportional to the power at that value. So, what you get is the radiation pattern. This is called the radiation pattern. Let me show you another radiation pattern. For example, if I have a do not shaped LED like this. Normally, this has radiation pattern which is in fact, those of you have done the experiment with the display LED, which already has an encapsulation here, you get a pattern like this. You do not get a circle the display LED’s which have an encapsulation directate. Encapsulation which acts like a lens has a forward characteristic like this. Similarly, so how did we get this? So, is the same thing everywhere corresponding to theta you measure what is the power. Normalize it with respect to the power at theta equal to 0 and plot it so plot everywhere and you get the radiation pattern.

So, this is a typical LED because of the lensing action it has a forward characteristic. There are certain LED’s which are, which have parabolic parabolic encapsulation which has a better forward characteristic. So you get a radiation patterns like this. This is circular and this is the Lambertian source, this is Lambertian distribution. I hope you understand this. This is cos theta theta equal to 1 and at 90 theta equal to 0. So, this is this forms a circle it is a Lambertian. Source for a Lambertian, source the radiation pattern looks like a circle for others this is probably I 0 cos theta cos Q theta or cos 2 theta, something like that. Normal display LED’s have this m value about between 2 and 3. So, you have slightly bulging kind of radiation pattern.

This is with the parabolic parabolic these are planar LED’s all are surface emitting LED’s planar. The radiation that I have shown planar LED’s which do not have any encapsulation. Normally have a nearly Lambertian distribution a near Lambertian distribution in planar LED’s which do not have encapsulation or any micro lens in front. So, these are planar LED’s, this is parabolic, this is may be hemi spherical. Hemi spherical and parabolic refers to this the encapsulation which gives a lensing action. Here there are none, just to appreciate this a little bit more. Suppose, I were to measure the radiation pattern of a helium neon laser, what do we expect? A helium neon laser, a helium neon laser gives out an almost parallel beam.

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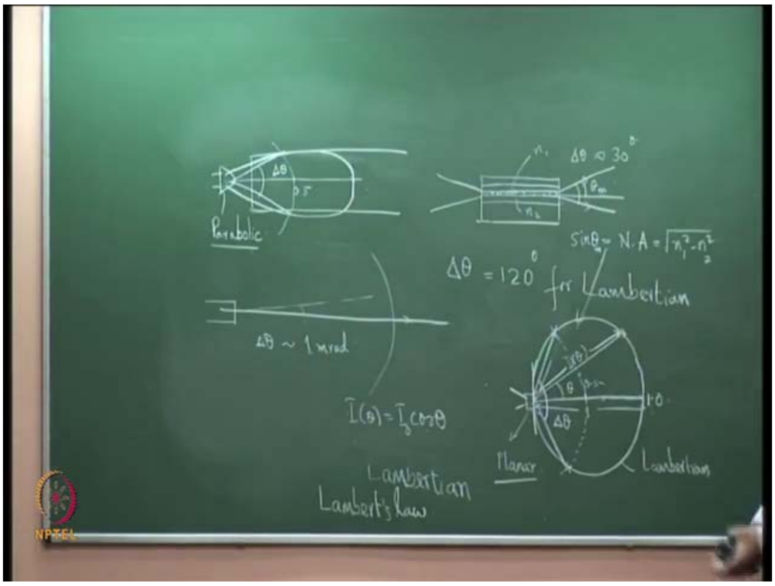

So, you are measuring angular distribution. So, what do you expect? What what would be our radiation pattern? Even if you move a little bit, even if angle theta is half degree you will have 0 there because there in nothing coming out, because it is highly collimated beam with very little divergions. The divergions is of the order of 1 or 2 milli radiants. Therefore, if you plot the radiation pattern, it will be almost like a straight line. That is at theta equal to 0, you have power, anywhere else you go there is no power. So, what does this indicate? It indicates the forward radiation pattern, the directionality of the beam. So, that is the importance of a angular distribution.

In display LED’s where you would like to see the display all around, one would prefer this kind of distribution, because so that you have maximum you can see this from different angles and still you can see the display. Whereas, if you want to use it as a directional beam or if you want to couple light into an optical fiber, you would like it to have a forward characteristic like this. So, that you can place your optical fiber in front so that there is maximum coupling that takes place. Normally, for optical fibers one uses the edge emitting LED. All the three patterns which I discussed are for surface emitting LED’s, display LED’s, surface emitting LED’s. For edge emitting LED’s you know that light comes so here is the active region and here is the cladding region and light comes out here in the form of a cone.

The cone the cone angle is determined by the numerical aperture. Please see if the refractive index here is n 1, the refractive index of the cladding layers is n 2. Recall that this is a double hetero structure, the active region has a lower band gap and therefore, it has a higher refractive index. The cladding regions have a higher band gap and has a lower refractive index, which let to optical confinement; confinement of the generated light of course, within the critical angle. Rest of them is loss. So, this is determined so there it is characterized by a numerical aperture. Numerical aperture is equal to square root of n 1 square minus n 2 square. Those of you are doing a course on fiber optics or guided wave optics you are familiar with this numerical aperture. So, numerical aperture is nothing but sin theta where theta. So, let me call this as theta m, theta m is the maximum acceptance angle.

So, theta m. If theta m is the maximum angle of the cone of emission here, then sin theta m is called the numerical aperture which can shown to you equal square root of n 1 square minus n 2 square. Typically the refractive indices are such that this cone angle here, the total cone angle delta theta here, is of the order of 30 degrees for edge emitting LED’s. About 30 degrees is the divergions angle after of course, the depends on n 1 and n 2 is typically about 30 degrees, but in the parallel plane. So, if I show you the 3D view. Before I erase this, what is delta theta? Delta theta is the angular width. Angular width is defined as where the intensity drops to at at the angle where the intensity drops to half its maximum. So, please see this is 1 here at half 0.5. So, this is 0, this is 1 at 0.5. I draw an arc of radius a circle of radius equal to 0.5 it intersects this here and it intersects this here.

So, the angle form here to here, this angle is called delta theta. That is angular width of the source delta theta is this. In this case for example, so this is 1 go to 0.5 0.5, and draw a radius a circle of radius 0.5. It intersects here so here and here so this is delta theta. As you can see this delta theta is smaller than this delta theta for a Lambertian. Can you guess what is delta theta? Where is this half I equal to I of theta is equal to I 0 cos theta or I theta by I 0 is cos theta; cos theta is half, when theta is 60 degree. So, this theta is 60 degree half angle theta is 60 degree. So, the delta theta is equal to 120 degree for Lambertian. I hope you followed half angle here that is theta from here. Theta is measured from here, whereas delta theta refers to the full width full angular width. So, delta theta is 60 plus 60.

Here you can see it is smaller and for a laser beam as I mentioned, the delta theta is extremely small. Delta theta is of the order of 1 milli radiants extremely small the divergence. So, in an edge emitting LED, this angle is typically about 30, but in the plane. So, this is in this direction, but in the plane there is no confinement and the angle is quite large. It is almost Lambertian distribution in the plane, because if you see the 3D view of, if if you see the 3D view of an edge emitting LED.

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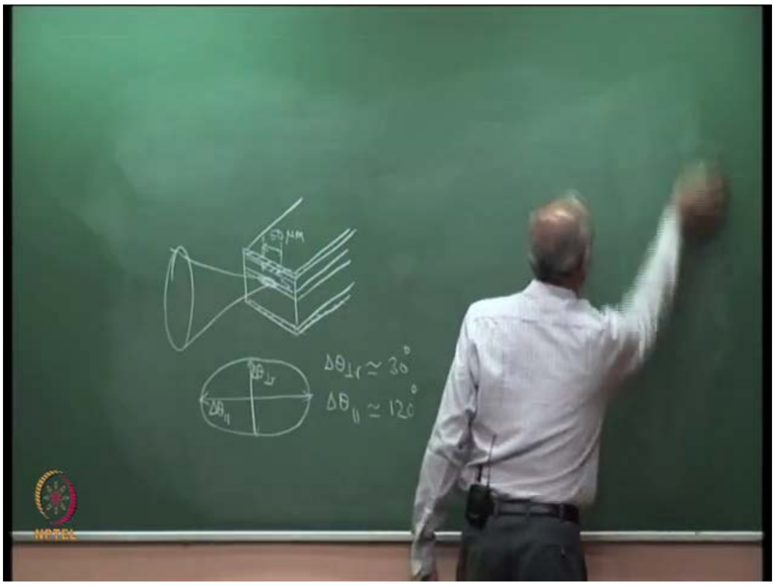

So, here is the face and this is the device. So, this is the metallic portion the contact electrode on top and contact electrode at the bottom. So, this is the metallic layer and this is our active layer and so on. So, this is the region where light is generated because the carriers are flowing here. These are blocking silica layers, blocking layer. So, carriers are flowing in this region and here is the beam which is generated. So, this beam in this plane it is guide it is confined by this layer n 2 and n 1. Therefore, if the beams comes out it would come out like this, with a certain angular distribution in this direction. In this direction in the plane of the layer, there is no confinement. So, it is free to come and therefore, if you see the distribution, if you see the transverse cross section of this beam which is coming out.

If I show transverse cross section this is perpendicular to the layer theta, perpendicular delta theta. Let me call delta theta perpendicular. Perpendicular refers to perpendicular to the layers in this direction and theta parallel parallel to the layers. So, this angle is theta parallel delta theta parallel this delta theta perpendicular. I suppose you have got the picture, what I am showing? What I have shown the cross section of the beam, which is coming out. So, in this direction this angular distribution is theta perpendicular, which is determined by n 1 and n 2 numerical aperture because it is determined by the slab wave guide whereas, in this plane there is no confinement. Therefore, in this plane it is relatively more spread, so literally Lambertian.

Therefore, this could be about 120 degrees in this delta. Theta perpendicular is about 30 degrees whereas, delta theta parallel is about 120 degree because there is no confinement, may be a little less than that. What is the dimension here? I hope I have given this dimension, the width. Here is typically about 50 micro meter for LED's you will see later that in laser diodes, this will be about 5 to 6 micro meter. So, in LED's this is about 50 micro meter. The contact electrode, the contact point here width is about 50 micro meter, this width of the base total width is approximately 100 100 to 150 micro meter. This is a typical dimension of LED. Let us quickly move on to the last characteristic that is the modulation band width.

We can go on discussing there are so many interesting issues we have to stop somewhere and let us go to the modulation band width, which is the important characteristic from a communication point of view. So, let us discuss modulation bandwidth first.

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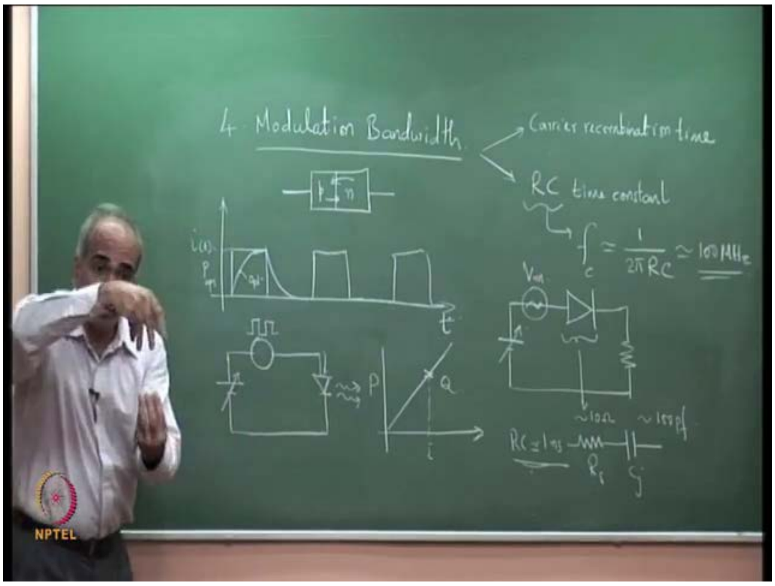

What is this modulation band width? Modulation bandwidth of a device is determined normally by two aspects. One is by that it is limited by the carrier recombination time carrier recombination time and the second one is by the R C time constant. Almost in all circuits you have an R C time constant and which limits the bandwidth, but let us first look at this carrier recombination time arcs because it is a diode. So, it will have a arc, it will have a junction capacitance, a series resistance. So, there will always be an R C time constant associated with it which could be a quite small we will see what is this arc? So, this is, this gives a bandwidth typically 1 over 2 by R C. So, it is determined by the R C time constant.

So, if we are using a forward biased led and modulating it. So, you are modulating width a V m. This is for biasing and if you modulate it, then this diode itself has an R C time constant. So, you can have the, have a equivalent circuit of this. That is a series equivalent resistance and it is a current source and a junction capacitance it is a current source with a series resistance and a junction capacitance. Therefore, this is the series resistance R s and this is C j. The series resistance in a forward biased diode is of the order of few ohms, may be 10 ohm. A forward biased diode the series resistance is very small, few ohms. The junction capacitance is typically of the order of 100 pico farad. Therefore, you can see that this R C time constant R C is approximately 1 nanosecond R into C.

So, you can substitute here and the bandwidth is limited to about 100 mega hertz. So, due to this you have a cut off approximately 100 mega hertz or is also possible to make better diodes, which goes up to several hundred mega hertz or may be 1 giga hertz due to R C time constant, but there is a carrier recombination time as well. So, what I would like to discuss is what is the bandwidth limitation due to carrier recombination time? So, how is this bandwidth coming into picture? This mathematics is fine. What is physically, what is happening? So, you have a diode. So, you apply to this diode a square wave. So, instant of this it is easy to easy to visualize. If I apply a square wave generator square wave pulses to this diode, there are resistances. So, this is what you get. This supply is to bias, the bias the led at the required operating point.

What I mean is if you have i p, i versus p which is almost linear you would purely like to bias it at a Q point, which is here corresponding to this i that is a d c bias and over that you superpose a ac signal. So, I am showing a square wave signal here. Now, to begin with this is not required. We can also directly give a square wave signal. So, what would happen is, if I give a square wave signal so this is the current signal I am showing. So, this is i and this time axis and this is i current i of t a step function that is the square wave. When the current is suddenly, current goes from 0 to a high value, in the in the diode carriers are injected in the diode. That is if you see the junction region, I want to my purpose is to show why, where is the bandwidth limitation coming or where is the modulation bandwidth coming, due to the due to the carrier recombination time. It will become clear as we go further series.

So, this is the p n junction and in the junction region you suddenly inject a current .When the current is injected into the junction region recombination takes place and light starts building up like this. So, in the same axis I am also showing optical power p optical. So, the second curve I am showing is p optical it is building up like this and it reaches its maximum value at this current value and at this time the current drop down to 0, means no more carrier injection into the junction region. Whatever carriers are there they are recombining at the rate of the recombination.

Depending on the recombination time and therefore, if you see the optical output it will drop like this. Do you follow? This is the optical I have applied a square current square pulse, but the optical variation is like this because of the finite recombination time. So, this has come down all the carriers have recombined and every carrier recombination is giving out a photon that is why we were still having light coming out after the current shifts down to 0.

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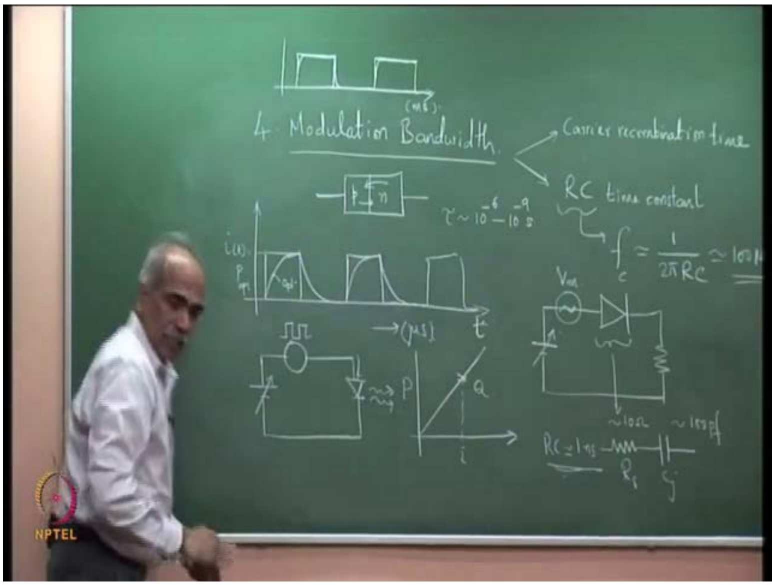

If you go further again the current get switched on. So, you it becomes maximum it does this. So, those of you have done an experiment modulation bandwidth, you will see this shape on the cro. If you increase the frequency this is slightly at higher frequency, I have shown because at low frequency. If I show at low frequencies, let us say this is a low frequency, then optical will also rise. So, fast there literally you will see the same square variation because the times involved here are very small. This axis is now in milli second. So, I have come here now in micro second, here you will see optical output also. Square output because the times involved are very small recombination time is 10 power minus 8 second tau is of the order of tau is of the order of typically 10 power minus 6 to 10 power minus 9 second.

Very good communication grade LED’s have 1 nanosecond as the recombination time and normal display LED’s will have 1 micro second or less. You can measure the bandwidth easily of display LED’s in a laboratory. They come out to be about 200 or 300 kilo hertz, but communication grade LED’s can go to 300, 400 mega hertz easily, determined by the recombination time and recombination time whether it is small or large is also determined the material properties. How many defects are there? You can grow extremely good quality devices. Then the carrier recombination extremely good quality, which means it takes longer time for the carriers. Now, let me come back here. If I increase the frequency more which means this are coming closer what would happen? I just increase the frequency and show you below the graph.

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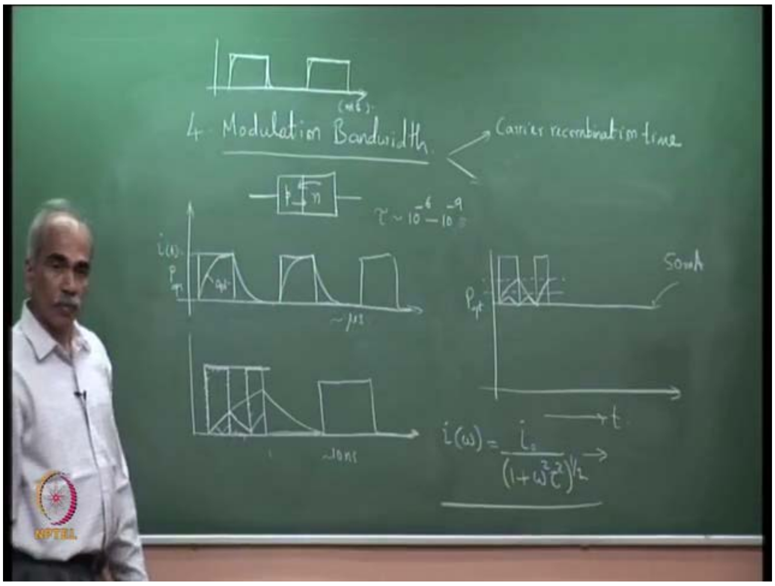

So, this was at micro second rate. Now, I want to go to 10 nanosecond time scale. This time scale is 10 nanoseconds. The square I am showing very large, but scale is extremely small in time light starts now. Slowly building up like this and even before it has reach the saturation even before it has reach the saturation like this, the current is switched off. Now, it is dropping. Do you follow? It is taking longer time, so what you see is if this was for a longer duration the height would have built up much more in other words. For the same amplitude the light variation is now smaller. Same amplitude variation of the current same amplitude here, amplitude variation of current is this and light variation is also this.

Here amplitude variation of current is this much that is 0 to this level and again this light also goes up to the maximum and comes down here. Current goes up to this but light has no time to become maximum, because before it became maximum the current has been switched off. So, it starts detain here. So, what has happen this has gone down if you increase the frequency further in the same scale, if I show you a higher frequency like this now, a higher frequency variation. So, let me differentiate in the same scale. So, this is at another higher frequency. Here you see light could build up only up to this and now, it has starts to detain and then again it is building up. So, what is the maximum variation is only this much current variation is the same, but the optical power has no time to build up. Now, let me show everything will become clear in just 1 minute you bias the led normally.

So, this is time scale, this is the optical power for a d c current. Let us say, you bias it at d c current 50 milli ampere and this is the optical power p, optical over this. I am feeding a square wave or a sinusoidal wave. Whatever you want you can feed a square wave. So, square wave if I feed the power then goes up over this and therefore, the power initially if the square wave was full. It was also varying like this optical power was varying like this. If the frequency became smaller then the optical wave could go up to this and could come up to this. Please see the a c variation in power originally the average was somewhere here. Now, the this is the d c level of power, the a c level variation of power was is somewhere here wet.

When the frequency was very small means light had all the time to build up fully and come down fully. Now, the frequency has increased. Has I shown here you go for higher frequency. It will build up only up to this. Those of you have done the experiment, you have seen the amplitude going down as you increase the frequency. So, this comes up to this and then is going up, so what is the a c variation? a c level is only, this r m s level is only this. So, this is the a c variation of power. If you increase the frequency, further that is if within this. If you increase this will build only up to this and go up to this, like this. So, a c variation of the optical power reduces with the frequency increase. In frequency and this dependence is given by an expression of the form i of omega is equal to i 0 divided by 1 plus.

This derivation we do not have to, you can see how the derivation comes, but this is the a c current variation. Let me write a small i, because capital I. Normally i we use for intensity. So, i of omega is equal to i 0. i 0 is just d c when omega equal to 0. Please see when omega equal to 0, this term is 0. So, this is 1. So, i of omega is i 0. So, i 0 is just the d c, but i omega is equal to this. So, the modulation band width refers to the maxima to is characterized by a modulation index ix is equal to P max minus P min divided by P max plus P min or intensity.

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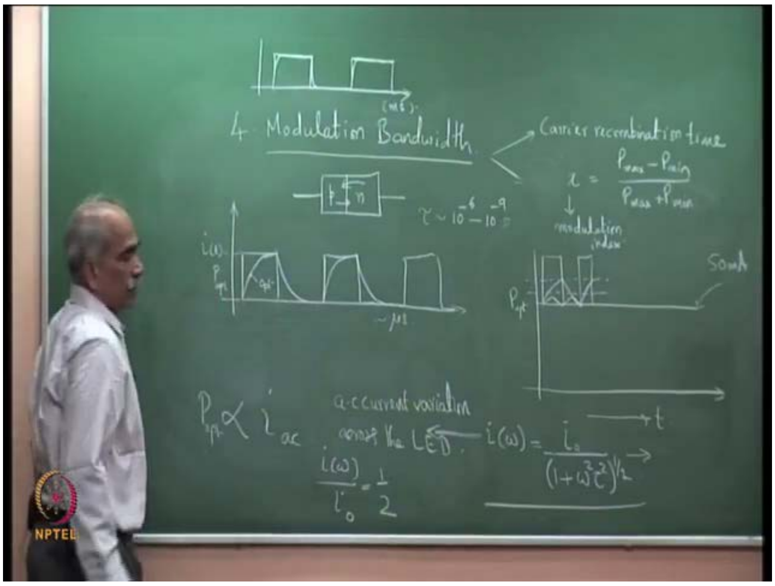

Whatever this is the modulation index. So, you can see the max to min variation is now, very small. Here, max to min was large full build up, max to min. Now, it is going on reducing. So, the modulation index goes on reducing as frequency increases. So, the optical power so this is the a c current variation in the LED, this is a c current variation across the LED because of recombinations. The optical power P optical is proportional to i a c. The optical power a c optical power a c variation of optical power a c variation of optical power is proportional to i a c, because we know that the power is proportion to current. Therefore, the we want to determine modulation bandwidth. How do we define band width? Band width is defined where the power falls to half of its value. So, P optical will fall to half of its value. Then i a c will fall to half of its value, which means when i omega i omega by i 0 equal to half. When will i omega by i 0 be half?

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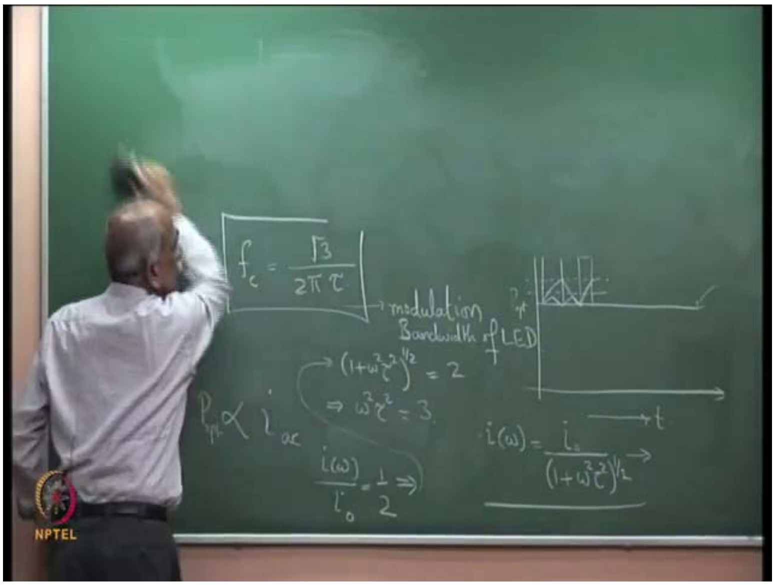

This implies let me let me write it here. This implies 1 plus omega square by tau square to the power half to the power half equal to 2. This implies square both the sides. So, this is 4. 4 minus 1, 3 omega square by tau square equal to 3 or or f c the cut off frequency. F c is equal to twice pi twice pi into tau. Please see omega square by tau square. So, square root of 3 equal to mega tau. This is 2 pi into f and therefore, 2 pi tau goes to the denominator. So, root 3 by so this is the modulation band width optical band width modulation band width of LED. Sometimes in books you will also see the electrical band width. Electrical bandwidth is proportional to i square, electrical power is proportional i square. Therefore, electrical bandwidth if you, let me just write down the electrical band width and then come back to clear any doubts or repeat a little bit.

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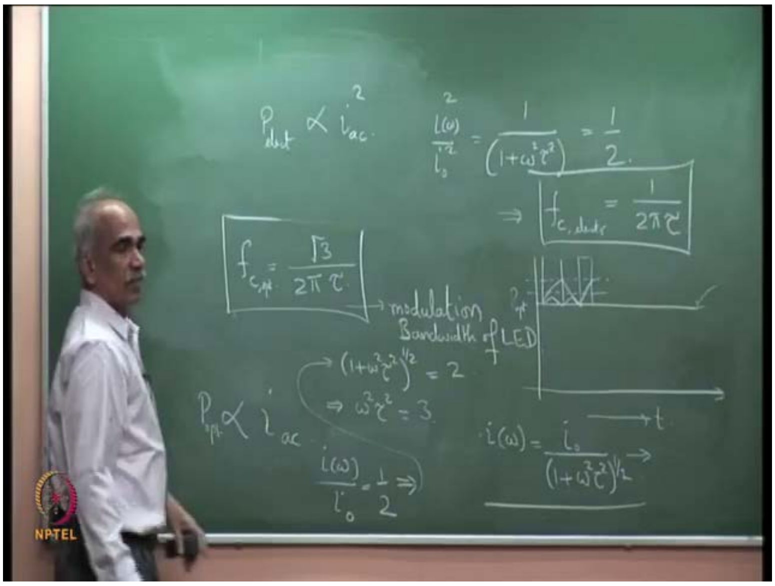

Let me first finish. P electrical is proportional to i square a c i square. Therefore, this will become half when i a c square by so I have to square these by i 0 square. This is i omega a c is omega i omega by i 0 square is equal to half is equal to 1 divided by 1 plus omega square tau square equal to half i omega by i 0 i square this. So, this half goes so it is 1 divided by 1 plus omega squareth of square, this is equal to half the electrical power becomes half here in the earlier derivation the optical power becomes half optical power is. Proportional to i a c, but the electrical power is proportional to square of the current. So, half this gives you f c electrical is equal to that is I thought I have written this is optical. So, you can see the optical bandwidth is larger than the electrical bandwidth by a factor of root 3. What bandwidth was I talking? All the wide we come to more simpler level, practical level what we have seen is.

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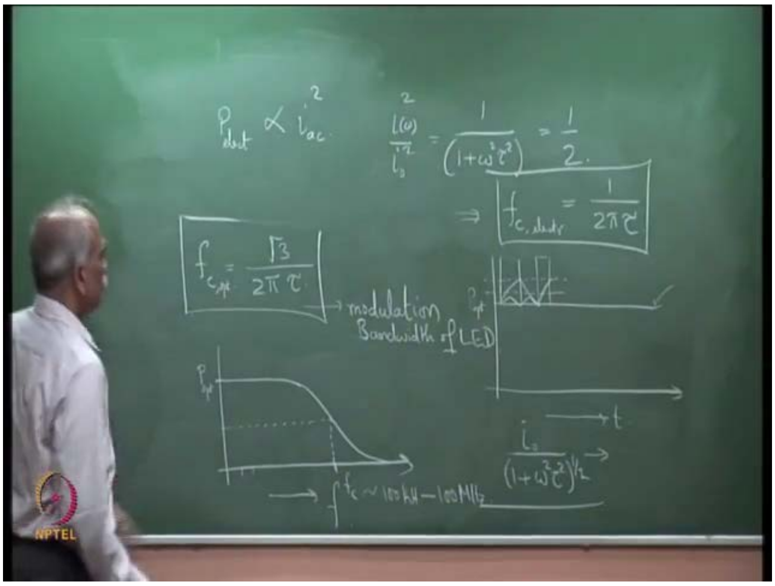

We were seeing optical the a c power P optical, but a c a c means varying optical power 1 is there is a biased d c, but what is the varying part of the optical power, that is P a c. So, that was initially remaining constant and has so this axis is frequency f as frequency increased that a c part drop down to 0 and where this became half is your f c. Do you follow? This is the frequency at which you are modulating the LED and the optical power came down to half its value at f c. Lambertianis given by this expression and this number is typically of the order of this is anywhere from 100 kilo hertz to 100 mega hertz depending on the quality or or the purpose of the LED.

Normal display LED’s have a few hundred kilo hertz as the cut off, but good quality communication grade LED’s can have hundreds of megahertz as the cut off frequency modulation bandwidth is this clear. First the origin of a finite modulation bandwidth is because the LED is not able to respond the current is varying rapidly, but the LED is not able to respond because the recombination time is more. It it requires more time to reach that maximum. That is why it is not able to respond as fast as the current variation and this is the primary reason for having a limited band width of the device. This is true for all, wherever you have to find out band width this is the reason.

That the device is not able to respond, current is varying very rapidly because frequency is increasing, but the device is not able to respond because of the small relatively larger times recombination times. If you make very good devices, then the recombination times can be much smaller and therefore, you can have much higher bandwidth is this clear. So, that brings us to the end of most of the device characteristics of LED's and we will discuss the number of things which one can go on discussing, but we have to draw a line here you can see the references which are given in the list. You can also see, I do not know whether I have given the reference or not?

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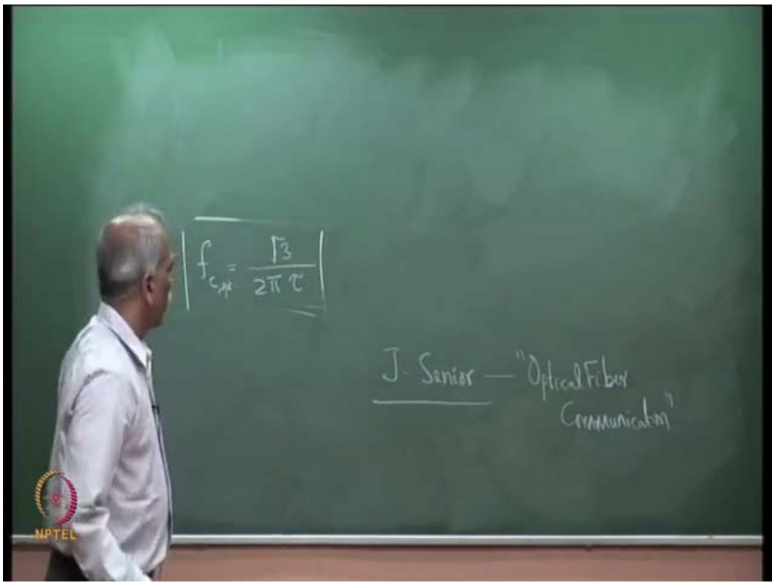

There is a Senior, John M Senior optical fiber communication optical fiber communication for LED's and their characteristics, given in a great details John M Senior. In the next class we will come to the last topic on LED's that is materials and applications. There are plenty of applications, but we will discuss a few applications and material specific materials used for different range of wavelength emissions. Is that okay? Any specific question?