**Semiconductor Optoelectronics**
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**Lecture – 30**
**Light emitting diode-IV Modulation Bandwidth**

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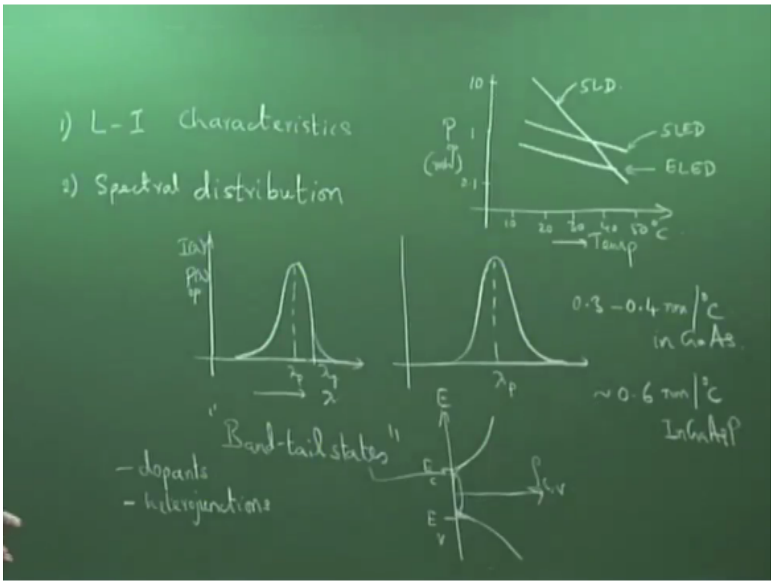


Okay, so we were discussing the characteristics; device characteristics or output characteristics of light emitting diode, so we have discussed first the LI characteristic; light current characteristics or IP characteristics and we have discussed this in detail, just one point here. If you have to plot temperature versus optical power; P optical, so this is 0.11 and 10 milli watt, P optical in milli watt, then for the 3 LEDs 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, 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 variation and if you look at the power variation for a super luminescent diode, then it would really start at high values.

But it is very sensitive to temperature, so this is for an SLD. The power output of a super luminescent diode is high but it 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 wavelength 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 and this started at lambda g, the band gap wavelength, you can always reverse it and see; Eg, so this is the variation.

But I had also shown you practical variations and they looked almost symmetric, practical graphs almost looked symmetric, centred around a line centre, here is the line centre, 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, as 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, v and this is versus energy, this point is Ec and this value here is Ev, the density of states. 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 reasons, 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 have a variation 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 to 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 nice curves, we have considered that it is a perfect crystal with the 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 2 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 reason and there are definitely, there are some defects you can minimize the defect density but there are also defects.

And 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 the hole here giving out a photon of energy less than Eg 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 had 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 based LEDs and typically of the order of 0.6 nanometer per degree centigrade in indium gallium arsenide phosphide LEDs that is in the IR.

Typical shift of the peak; typical shift of this peak with the temperature per degree centigrade is of this order. So, today we will discuss modulation bandwidth 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 the radiation pattern or the angular distribution refers to the angular dependence of the intensity of the source or output of the source.

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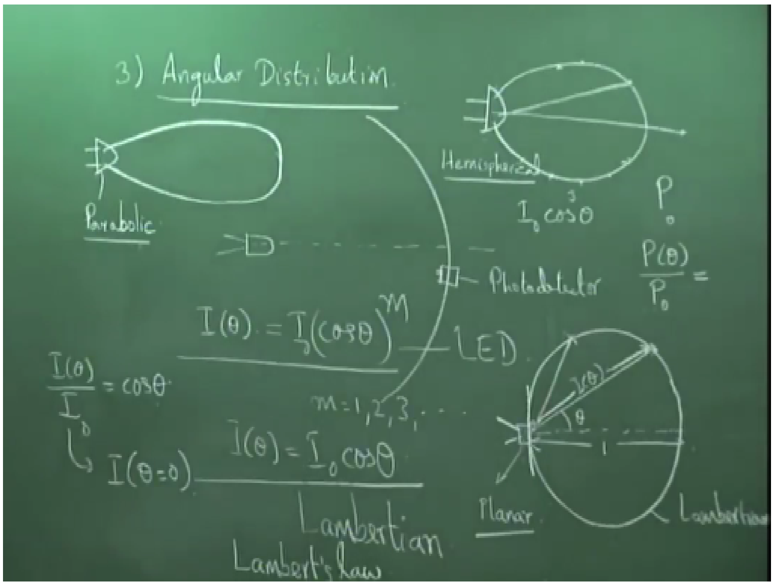


So, let us briefly see the radiation pattern, so the third characteristic angular distribution or radiation pattern. So, if a source is sitting here, let us say this an LED, if you measure the intensity distribution as a function of the angle, so you scan; let us say you take a photo detector, a P hole photo detector here, so this is a photo detector connected to a power meter and you scan 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 I0 * cos theta to the power m; with m = 1, 2, 3 not necessary they have to be integers but m can take numbers 1, 2 and 3 so on. What it means is; if you put m = 1, the dependence is I of theta is = I0 cos theta. In fact, this dependence is called lambertian, is a Lambert's law and the source is called lambertian.

Let us get the picture what it means is; okay, 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 the; how this is plotted? You see I of theta is = I0 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, whatever 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 chord 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 measure power or I can write this as I / I of theta/ I0 = cos theta.

I0 is nothing but I at 0 end that is here, this I0 is I of 0 theta = 0 at theta = 0, cos theta is 1 and therefore, I0 is nothing but I at theta = 0. So, right in front of the LED, we measure the power; let us say you get some power. I get P0 or intensity, I0 whatever, P0. At some other angle, I get power which is P of theta, then P theta/ P0, so I normalize this to 1; P / P0 will be < 1 and that is this length.

So, at different angles, you find out P of theta/ P0 and then corresponding to that length; length normalized to 1, this is 1. So, divided by this length, so the magnitude here of this chord 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 dome 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 LEDs, which have an encapsulation; directive encapsulation, which acts like a lens has a forward characteristic like this. Similarly, so how did we get this; is the same thing everywhere corresponding to theta, you measure what is the power.

Normalize it with respect to the power at theta = 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 LEDs, which have parabolic encapsulation, which has a better forward characteristic, so you get radiation patterns like this. This is circular and this is the lambertian source, this is lambertian distribution.

I hope you can understand this, this is cos theta, theta = 1 and at 90, theta = 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 I0 cos theta cos cube theta or cos 2 theta something like. Normal display LEDs have this m value about between 2 and 3. So, you have slightly bulging kind of a radiation pattern and this is with the parabolic; these are planar LEDs.

All are surface emitting LEDs; planar, the radiation pattern that I have shown. Planar LEDs, which do not have any encapsulation normally, have in nearly lambertian distribution, a near lambertian distribution. In planar LEDs, which do not have encapsulated or any micro lens in front, so, these are planar LEDs, this is parabolic, this is maybe hemispherical; hemispherical and parabolic refers to this the encapsulation, which gives a lensing action.

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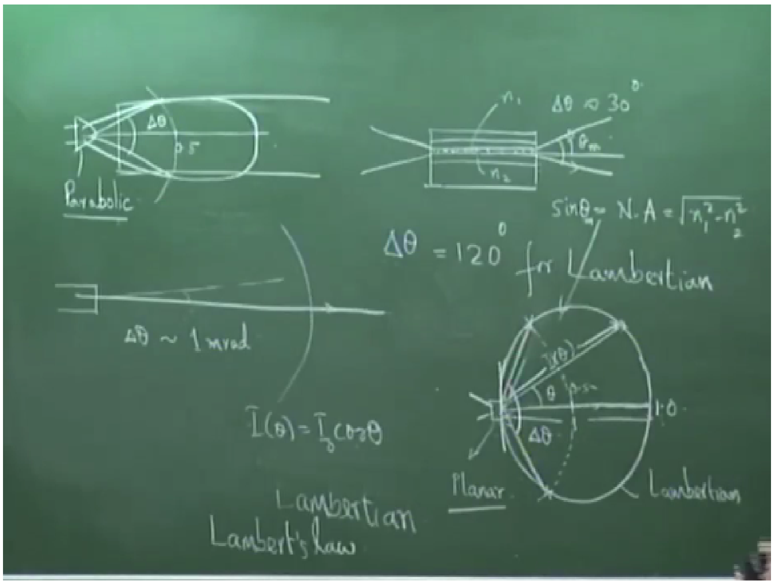


Here, there are none, just to appreciate this a little bit more, suppose I were to measure the radiation pattern of a helium neon laser, what do we expect a helium neon laser? A helium neon laser gives out an almost parallel beam, so you are measuring angular distribution, so what do we expect, what would be our radiation pattern? Even, if you move a little bit; even if angle theta is 1/2 degree, you will have 0 there because there is nothing coming out.

Because it is a highly collimated beam with very little divergence, the divergence is of the order of 1 or 2 milli radians and therefore, if you plot the radiation pattern, it will be almost like a straight line that is at theta = 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 angular distribution.

In display LEDs, 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 fibre you would like it to have a forward characteristic like this, so that you can place your optical fibre in front.

So, that there is maximum coupling that takes place. Normally, for optical fibres, one uses the edge emitting LED, all the 3 patterns, which I discussed are for surface emitting LEDs, display LEDs, surface emitting LEDs. For edge emitting LEDs, 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 n1, the refractive index of the cladding layers is n2, recall that this is the double hetero structure, the active region has a lower band gap and therefore it has the higher refractive index. The cladding regions have a higher band gap and has a lower refractive index, which led to optical confinement; confinement of the generated light, of course within the critical angle, rest of them is lost.

So, this is determined, so that it is characterized by a numerical aperture; numerical aperture is = square root of n1 square – n2 square. Those of you are doing a course on fibre optics or guided by 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 a mission here, then sin theta m is called the numerical aperture, which can be shown to be = square root of n1 square – n2 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 LEDs about 30 degrees is the divergence angle of the; of course they depends on n1 and n2 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 the angle where the intensity drops to half its maximum, so please see, this is 1 here at 1/ 2, 0.5, so this is 0, this is 1, at 0.5, I draw an arc of a radius, a circle of radius equal to 0.5. It intersects this here and it intersects this here.

So, the angle from 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 = I of theta is = I0 cos theta or I theta/I0 I is cos theta; cos theta is 1/2 when theta is 60 degree, so this theta is 60 degree half angle; theta is 60 degree, so the delta theta is = 130 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 + 60. Here, you can see it is smaller.

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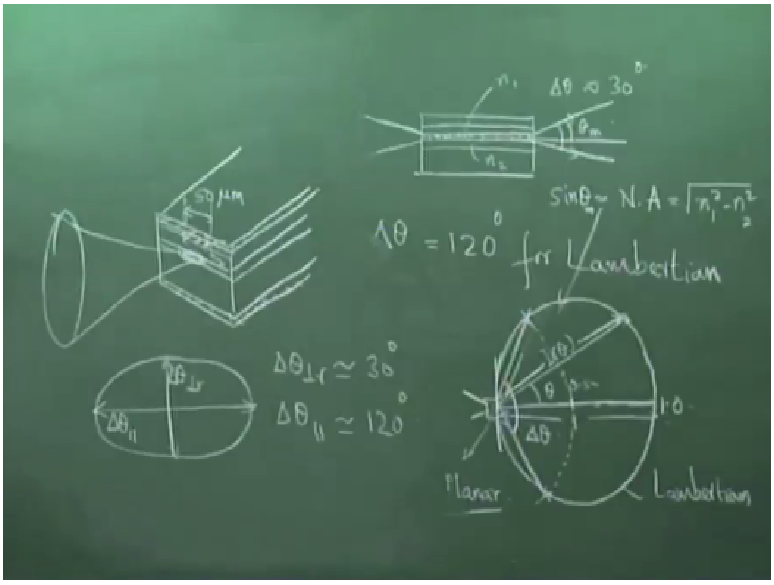


And for a laser beam, as I mentioned the delta theta is extremely small, delta theta is of the order of 1 million radians; extremely small, the divergence. So, in an edge emitting LED, this angle is typically about 30 but in the plane; so this is in this direction but in the plane, there is no confinement and the angle is quite large, it is almost lambertian distribution in the plane because if you see the 3D view of an edge emitting; if we see the 3D view of an edge emitting LED, so here is the face and this is the device.

And 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 n2 and n1.

And therefore, if the beam 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 the 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 a picture what I am showing, what we are 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 n1 and n2; numerical aperture.

Because it is determined by the slab waveguide, whereas in this plane, there is no confinement and 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 because there is no confinement, maybe a little less than that and what is the dimension here?

I hope I have given this dimension, the width here is typically about 50 micrometer for LEDs, you will see later that in laser diodes, this will be about 5 to 6 micrometer, so in LEDs, this is about 50 micron, the contact electrode; the contact point here width is about 50 micron. This width of the base total width is approximately 100 to 150, micron and this is a typical dimension of LED, all right.

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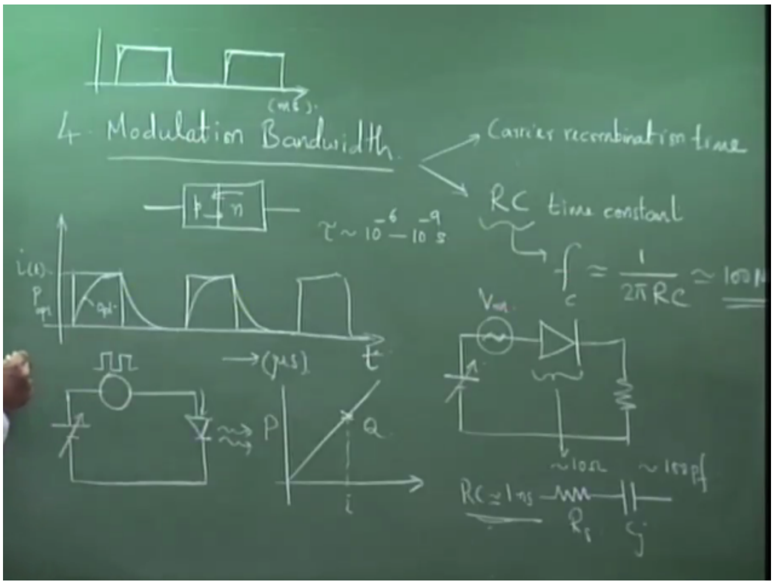


Let us quickly move on to the last characteristic that is the modulation bandwidth, we can go on discussing; there are so many interesting issues, we have to stop somewhere and let us go to the modulation bandwidth, which is the important characteristics from a communication point of view, all right. So, let us discuss modulation bandwidth, first what is this modulation bandwidth?

Modulation bandwidth of a device is determined normally by 2 aspects; one is; by that; it is limited by the carrier recombination time; carrier recombination time and the second one is by the RC time constant, almost in all circuits you have an RC time constant and which limits the bandwidth. But let us first look at this carrier recombination time because it is a diode, so it will have an R, it will have a junction capacitance, a series resistance.

So, there will always be an RC time constant associated with it, which could be quite small, we will see what is this R? So, this is; this gives a bandwidth typically, 1 over 2 pi RC, so it is determined by the RC time constant, so if you are using a forward biased LED and modulating it, so you are modulating with a Vm, this is for biasing and if you modulate it, then this diode itself has an RC time constant.

So, you can have an equivalent circuit of this, there is a series equivalent resistance and it is a current source and a junction capacitance, it is a current source with the series resistance and a junction capacitance, therefore this is the series resistance Rs and this is Cj. The series resistance in a forward biased diode is of the order of few ohms, maybe 10 ohm, a forward bias diode, the series resistance is very small; few ohms.

And the junction capacitance is typically of the order of 100 picofarad and therefore, you can see that this RC time constant, RC is approximately 1 nanosecond R * c. So, you can substitute here and the bandwidth is limited to about 100 megahertz. So, due to this you have a cut off approximately 100 mega hertz or it is also possible to make better diodes, which goes up to several 100 megahertz or maybe 1 Giga Hertz due to RC 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 okay mathematics is fine, what is physically what is happening? So, you have a diode, so you apply to this diode a square wave, so instead 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 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 ip; i verses p, which is almost linear, you would probably like to bias it at a Q point which is here corresponding to this I, there is a DC 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, this is time axis and this is current, i of t, a step function that is a square wave. When the current is suddenly current goes from 0 to a high value, 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 where is the bandwidth limitation coming or where is the modulation bandwidth coming due to the carrier recombination time?

It will become clear, as we go further series. So, this is the PN 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 dropped 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 optical; I 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 are still having light coming out after the current is switched down to 0. If you go further, again the current gets switched on, so it becomes maximum, it does this. So, those of you have done an experiment of modulation bandwidth, you will see this shape on the CRO, if you increase the frequency.

This is slightly at a 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 milliseconds, so I have come here now in microseconds. Here, you will see optical output also square output.

Because the times in (()) (35:30) are very small recombination time is 10 power -8 second, tau which of the order of; tau is of the order of typically, 10 power -6 to 10 power -9 second, very good communication grade LEDs have 1 nanosecond as the recombination time and normal display LEDs, will have 1 microsecond or less, you can measure the bandwidth easily of a display LEDs in a laboratory, they come out to be about 200 or 300 kilohertz.

But communication grade LEDs can go to 300, 400 megahertz easily, determined by the recombination time and recombination time whether it is small or large is also determined by the material properties and how many defects are there. If you can grow extremely good quality devices, then the carrier recombination extremely good quality, which means it takes longer time for the carriers.

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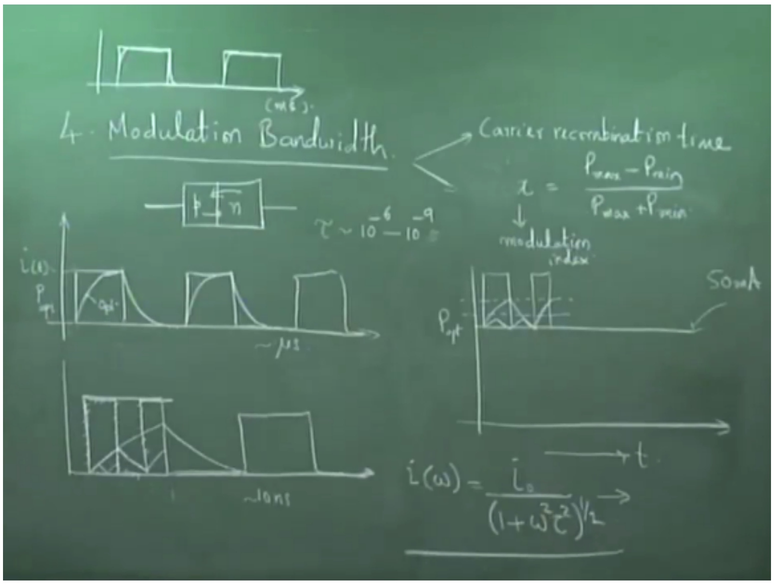


Now, let me come back here, if I increase the frequency more, which means these are coming closer, what would happen? I just increase the frequency and show you below the graph. So, this was at micro second rate. Now, I want to go to 10 nanosecond time scale, okay this time scale is 10 nanosecond. The 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 reached the saturation; even before it has reached a saturation like this, the current is switched off, so 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 light 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 decaying here. So, what has happened, 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 yeah; you see light could build up only up to this and now it has to start decaying 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 DC current, let us say you bias it at DC current 50 milliampere and this is the optical power; P optical. Over this, I am feeding it square wave or a sinusoidal wave whatever you want, you can feed a square. 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 AC variation in power originally, the average was somewhere here, now this is the DC level of power, the AC level variation of power was is somewhere here but 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 as I have shown here, you go for higher frequency it will build up only up to this.

Those of you are done the exponent 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 AC variation? AC level is only this; RMS level is only this, so this is the AC 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, AC 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 = I0 / 1+; this derivation we do not have to; you can see how the derivation comes but this is the AC current variation. Let me write a small i because capital I normally we use for intensity, so i of Omega is equal to i0; i0 is just DC.

When omega equal to 0, please see when omega = 0, this term is 0, so this is 1, so i of omega is i0. So, i0 is just the DC but i omega is = this, so the modulation bandwidth refers to the maxima to; is characterized by a modulation index ix is = P max - P min/ P max + P min or intensity 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.

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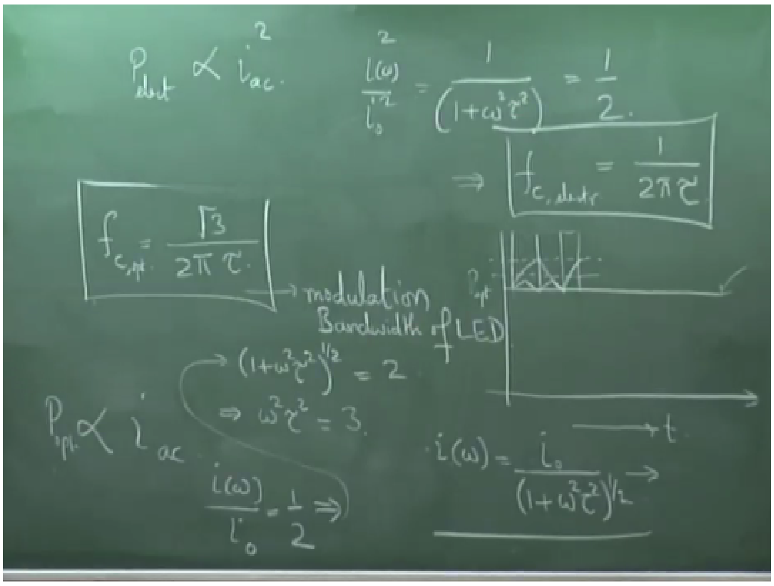


Now, it is going on reducing, so the modulation index goes on reducing as frequency increases. So, the optical power, so this is the AC current variation in the LED; this is AC current variation across the LED because of recombinations. The optical power; P optical is proportional to i ac, the optical power ac; optical power ac variation of optical power; AC variation of optical power is proportional to i ac because we know that power is proportional to the current.

And therefore, we want to determine modulation bandwidth, how do we define bandwidth? Bandwidth is defined where the power falls to half of its value, so P optical will fall to half of its value, when i ac will fall to half of its value, which means when i omega; I omega/ i0 = 1/2. When will i omega/ i0 1/2, this implies; let me write it here; this implies 1 + omega square / tau square to the power 1/2 = 2, this implies square both the sides, so this is 4; 4 -1, 3 omega square/ tau square = 3.

Or fc, the cut off frequency fc is = twice pi * tau. Please see, omega square / tau square, so square root of 3 = omega tau, this is 2pi into f and therefore 2pi tau goes to the denominator, so root 3/here, so this is the modulation bandwidth; optical bandwidth, modulation bandwidth of LED. Sometimes, in books, you will also see the electrical bandwidth; electrical bandwidth is proportional to i square; electrical power is proportional to i square.

Therefore, electrical bandwidth; if you let me just write down the electrical bandwidth and then come back to clear any doubts or repeat a little bit but let me first finish; P electrical is proportional to i square ac i square and therefore, this will become 1/2, when i ac square/; so I have to square this, by i0 square, this is i Omega, ac is Omega; i omega/i0 square is = 1/2 = 1/ 1

+ omega square tau square = 1/2, i omega/ i0, I square this, so this half goes, so it is 1/ 1+ omega square tau square, this is equal to 1/2.

The electrical power becomes 1/2 here, in the earlier derivation, the optical power becomes 1/2, optical power is proportional to i ac but the electrical power is proportional to square of the current so, 1/2. This gives you fc electrical =; Oh! That is okay; I thought I have written this is optical. So, we can see that the optical bandwidth is larger than the electrical bandwidth by a factor of root 3.

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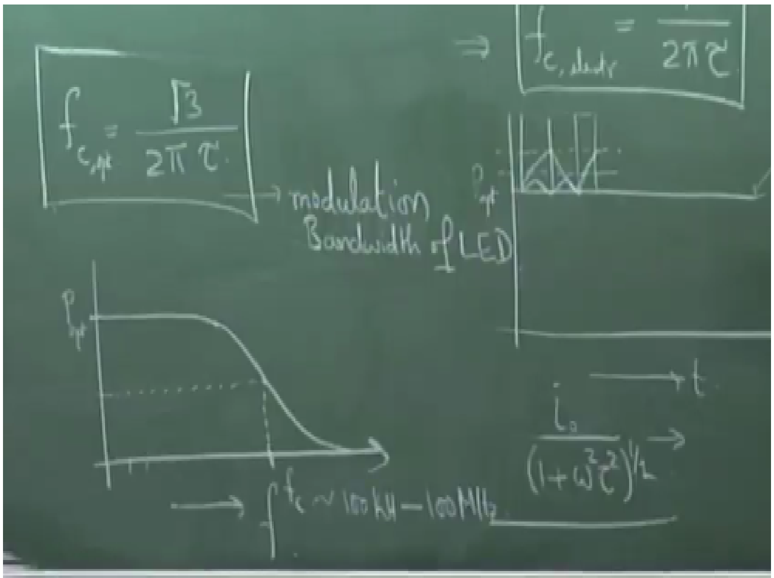


What bandwidth was I talking all the way, we come to more simpler level; practical level, what we have seen is; we were seeing optical; the ac power; P optical but ac. AC means varying optical power, one is there is a bias DC but what is the varying part of the optical power that is P ac, so that was initially remaining constant and as so this axis is frequency f, so as frequency increased that ac part dropped down to 0 and where this became 1/2 is your fc.

Do you follow? This is the frequency at which you are modulating the LED and the optical power came down to 1/2 its value at fc, which is 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 the purpose of the LED. Normal display LEDs have a few 100 kilo hertz as the cut off but good quality communication grade LEDs 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 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 bandwidth of the device.

This is true for all wherever, you have to find out bandwidth 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 bandwidths, is this clear?

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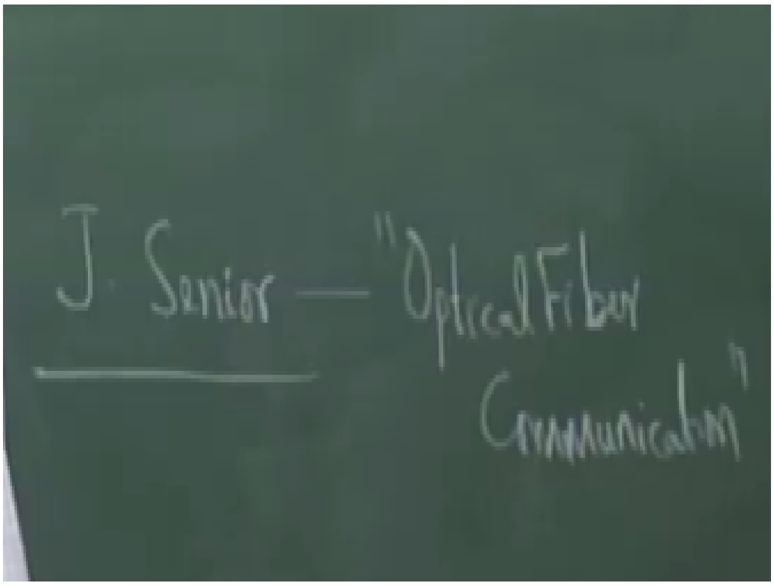


So, that brings us to the end of most of the device characteristics of LEDs and we will discuss the number of things which one can go on discussing but we have to draw a line here, you can see the references, which are given in the list, you can also see I do not know whether I have given the reference or not. There is a Senior; John m. Senior, optical fibre communication; optical fiber communication for LEDs and their characteristics given be in great details; John. M. Senior.

In the next class, we will come to the last topic on LEDs that is materials and applications. There are plenty of applications but we will discuss a few applications and materials; specific materials used for different range of wavelength emissions, is that okay, any specific question? Okay.