Fiber Optics
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Lecture – 35
Optical Sources and Detectors- III

In the previous lecture we were discussing about the LED, and we were talking about the internal quantum efficiency of LED. Now let us look at how much internally generated power, what fraction of internally generated power comes out of the device. So, what is external quantum efficiency, and some other characteristics of a light emitting diode.

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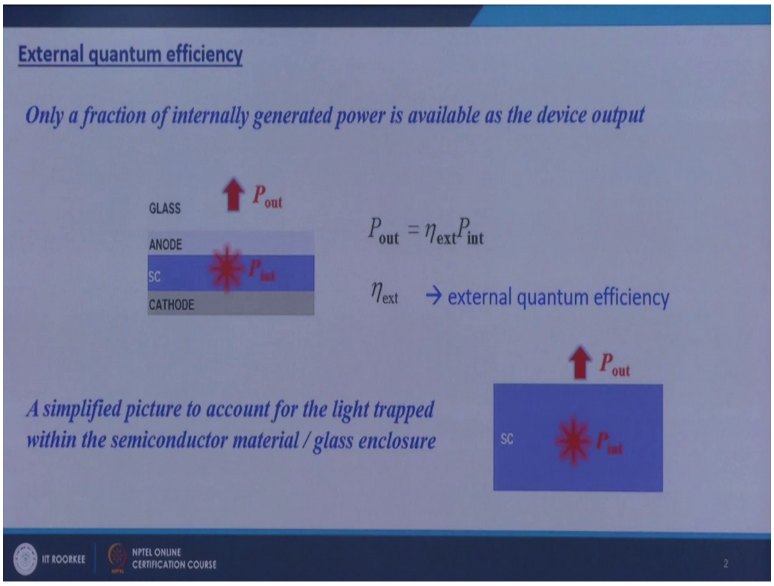

External quantum efficiency

Only a fraction of internally generated power is available as the device output

$P_{out} = \eta_{ext} P_{int}$

η_{ext} → external quantum efficiency

A simplified picture to account for the light trapped within the semiconductor material / glass enclosure

So, as we had seen that in an LED certain fraction of electric power is converted into optical power and the optical power which is generated inside the device is P int. But, because of the structure of the LED index contrast between different layers only a fraction of this internally generated power comes out. And therefore, there is a finite external quantum efficiency of a light emitting diode.

So, in a simplified picture what we can do; we can just put a light source with power P int inside a semiconductor material. And just let us have a look how much power comes out of this block of semiconductor.

So, let us look at this picture now.

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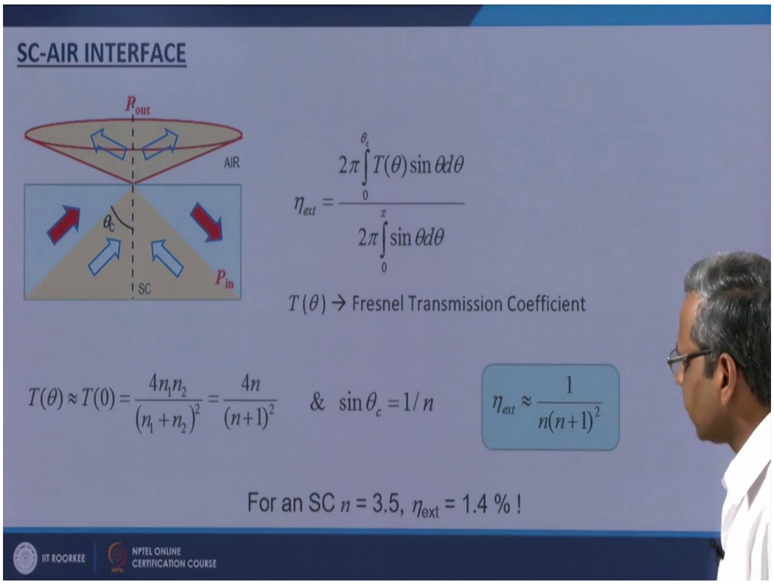

SC-AIR INTERFACE

$$\eta_{ext} = \frac{2\pi \int_0^{\theta_c} T(\theta)\sin\theta d\theta}{2\pi \int_0^{\pi} \sin\theta d\theta}$$

$T(\theta)$ → Fresnel Transmission Coefficient

$$T(\theta) \approx T(0) = \frac{4n_1 n_2}{(n_1+n_2)^2} = \frac{4n}{(n+1)^2} \quad \& \quad \sin\theta_c = 1/n$$

$$\boxed{\eta_{ext} \approx \frac{1}{n(n+1)^2}}$$

For an SC $n = 3.5$, $\eta_{ext} = 1.4$ % !

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This is the medium of semiconductor and where the light sources kept in a point source which sends light in all the directions. So, you have all the possible angles of incidence here at semiconductor air interface. And we know that the angles which are greater than the critical angle at the semiconductor air interface they are reflected back via the process of total internal reflection.

So, if all the angles are going, if light at all the angles is incident at this interface then light only in this cone which has semi vertical angle theta C, where theta C is the critical angle then light only in this cone will be reflected will come out of this block. Rest of the light will be totally internally reflected and will come back into the semiconductor material. And this contributes towards finite quantum, internal finite external quantum efficiency of an LED.

So, let us work out what fraction of P int will come out. This fraction external can be calculated like this; it is if I have a transmission coefficient from semiconductor to air for refracted light S T theta then the light in this cone from 0 to theta C will come out. So, I have this integral 0 to theta C T theta sin theta d theta and this 2 pi accounts for all the angles in phi direction from 0 to 2 pi. So, this is the fraction of light that comes out, and this is the total light which is incident.

So, where I integrated from 0 2 pi where I take into account the incidence at the lower interface also. So, this T theta is Fresnel transmission coefficient, and for simplicity and mathematical convenience let me approximate it by Fresnel transmission coefficient at normal incidence when theta is equal to 0. I know that at normal incidence if you have an interface between two media of refractive index n 1 and n 2. Then this fraction of power is transmitted, which is given by 4 times n 1 n 2 over n 1 plus n 2 square.

Here if the semiconductor has refractive index n and here you have air which has refractive index 1. So, you can put n 1 is equal to n and n 2 is equal to 1 then you simply get the Fresnel transmission coefficient as 4 n over n plus 1 square. So, you can put it here and integrate it. Also, I use the fact that sin theta C is 1 over n which is n 2 over n 1 n 2 is 1 n 1 is n. So, sin theta C is 1 over n. So, if I use this also and simplify this then eta external can be approximated by 1 over n times n plus 1 square.

So, this fraction is purely due to index contrast between the semiconductor material and air. How much it is? Of course, it depends upon what is the refractive index of the semiconductor material. If I take typical value of say- refractive index of a semiconductor let us say silicon then n is equal to 3.5, then eta external would come out to be just 1.4 percent. So, you imagine that only 1.4 percent of internally generated power will come out.

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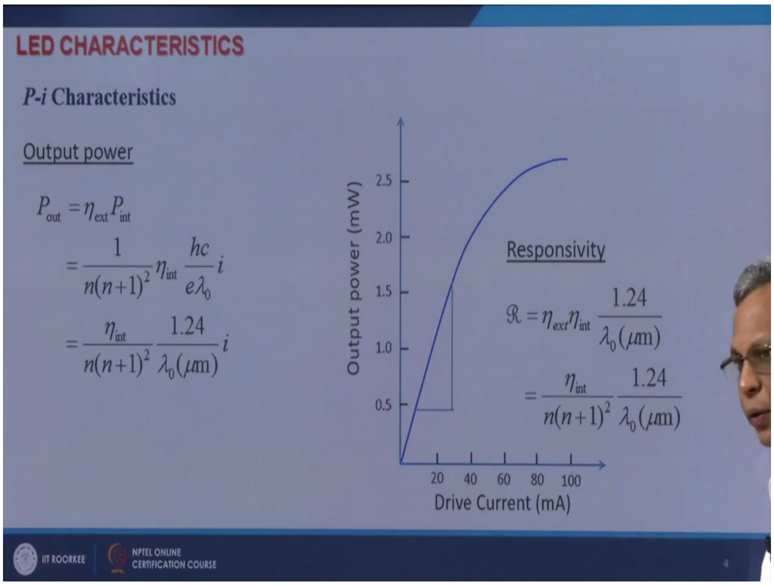

LED CHARACTERISTICS

***P-i* Characteristics**

Output power

$$P_{out} = \eta_{ext} P_{int}$$
$$= \frac{1}{n(n+1)^2}\eta_{int}\frac{hc}{e\lambda_0} i$$
$$= \frac{\eta_{int}}{n(n+1)^2}\frac{1.24}{\lambda_0(\mu m)} i$$

Responsivity

$$\mathcal{R} = \eta_{ext}\eta_{int}\frac{1.24}{\lambda_0(\mu m)}$$
$$= \frac{\eta_{int}}{n(n+1)^2}\frac{1.24}{\lambda_0(\mu m)}$$

Let us look at some other characteristics of a light emitting diode. And an important one is P-i characteristic. What it is? If you supply some drive current i to forward bias current i to an LED then how much power would be generated. So, to calculate that what is the output power? I know output power is eta external times T internal and eta external is 1 over n times n plus 1 square, P internal is eta internal times h c over e lambda naught i; this we had calculated in the last lecture.

Then I can write it down in the form eta internal divided by n times n plus 1 square and h c over e I can calculate and write it as 1.24 and a factor of 10 to the power minus 6 is there which is absorbed in micrometer here times i. So, this is the output power I can see that this output power depends upon i; you increase that drive current you will increase the output power.

So, this how it goes. If I look at this region then I can define the responsivity of an LED by this; what is responsivity? Responsivity is simply the slope of this. Responsivity of a device is basically response of the device for a given input. Here the response is output power and the input is injection current.

So, in this LED I am injecting current and I am getting optical output power. So, this T out over injection current will give me the responsivity. So, from here I can immediately see that this out over i would be simply eta external times eta internal times 1.24 divided by lambda naught in micrometer. Or simply this factor. Let us work out an example.

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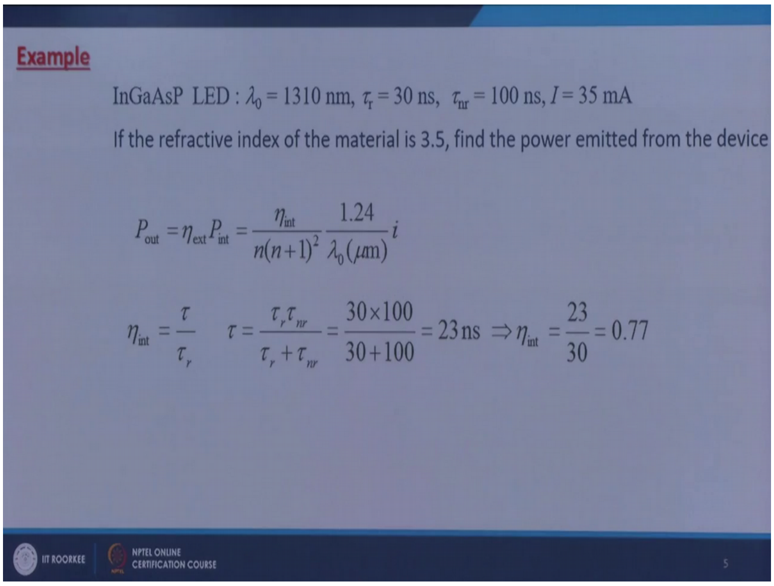

Example

InGaAsP LED : $\lambda_0 = 1310$ nm, $\tau_r = 30$ ns, $\tau_{nr} = 100$ ns, $I = 35$ mA

If the refractive index of the material is 3.5, find the power emitted from the device

$$P_{out} = \eta_{ext} P_{int} = \frac{\eta_{int}}{n(n+1)^2} \frac{1.24}{\lambda_0(\mu m)} i$$

$$\eta_{int} = \frac{\tau}{\tau_r} \qquad \tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{30 \times 100}{30 + 100} = 23\,\text{ns} \Rightarrow \eta_{int} = \frac{23}{30} = 0.77$$

If I have indium, gallium, arsenide, phosphide, LED which gives me a wavelength 1310 nanometer; the light of wavelength 1310 nanometer. For this material the radiative lifetime is 30 nanoseconds and non-radiative lifetime is 100 nanoseconds. And I operate this LED at 35 milliamps current, then if the refractive index of the material is about 3.5 then what would be the output power.

I know that output power is eta external times P int which is eta internal divided by n n plus 1 square times 1.24 divided by lambda naught in micrometer times i then, what I need to now calculate is that eta internal: eta internal is given by tau over tau r and I know 1 over tau is equal to.

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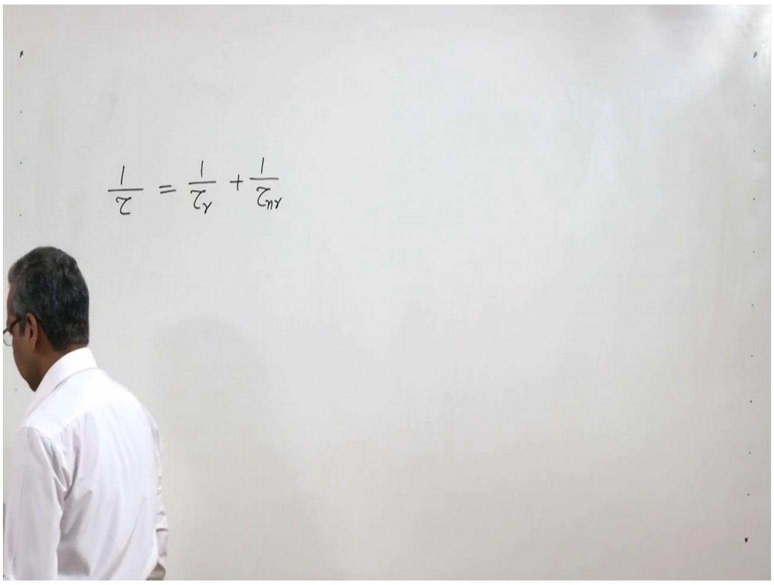

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

If you remember 1 over tau is equal to 1 over tau r plus 1 over tau n r. So, this gives me tau is equal to this. And if I calculate it, it comes out to be 23 nanoseconds. So, from here I can get eta internal as 0.77. Now eta internal I have got rest everything I already have. So, if I plug in these numbers then I will find that P out would be 0.36 milli watt.

What happens if I change the temperature of an LED?

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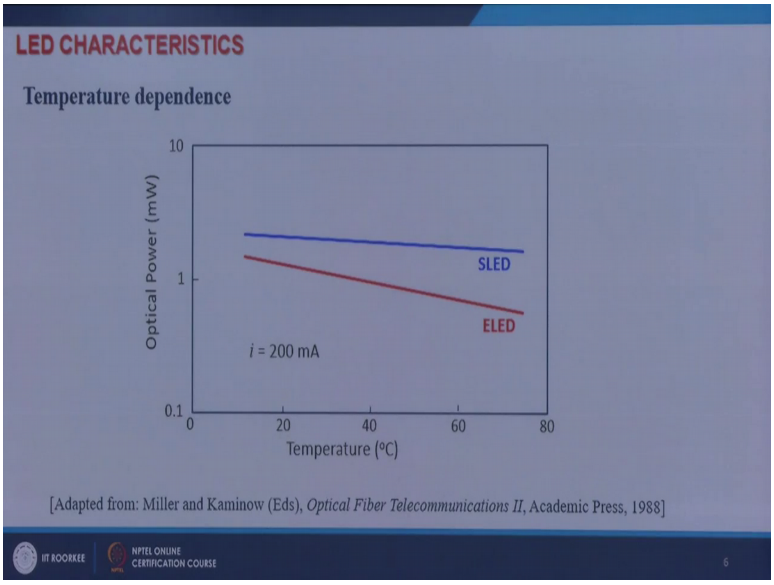

LED CHARACTERISTICS

Temperature dependence

[Adapted from: Miller and Kaminow (Eds), *Optical Fiber Telecommunications II*, Academic Press, 1988]

If I change the temperature then I see that the output power will slightly decrease. And this decrease is more prominent in h emitting light emitting diodes as compared to surface emitting light emitting diodes.

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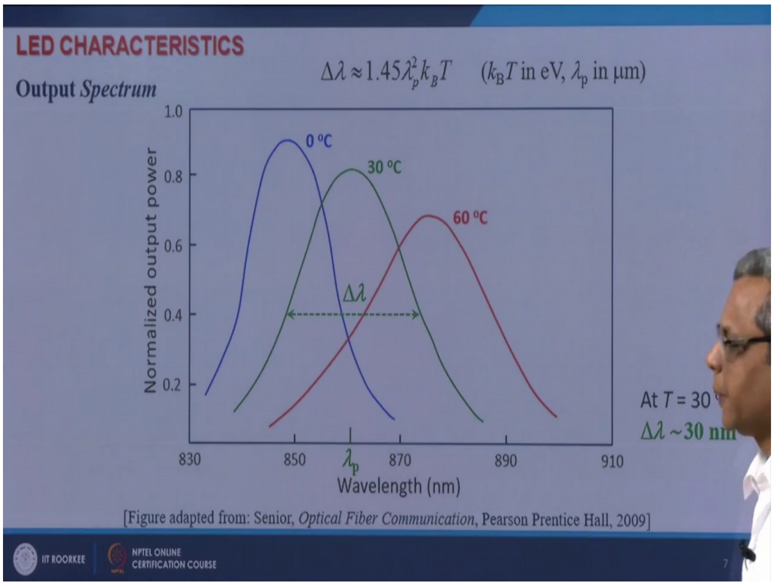

LED CHARACTERISTICS

Output *Spectrum*

$\Delta\lambda \approx 1.45\lambda_p^2 k_B T$ ($k_B T$ in eV, λ_p in μm)

At T = 30

$\Delta\lambda \sim$ 30 nm

[Figure adapted from: Senior, *Optical Fiber Communication*, Pearson Prentice Hall, 2009]

If I look at the output spectrum of an LED then, I find that it occupies a certain spectral range. Although, I say that it is an LED at 860 nanometer wavelength, but it is not strictly an LED at 860 nanometers, it extends beyond this on either side. So, we quantify this spectral extend of this light output from an LED in terms of the line width. This line width is full width at half maximum.

So, you half the peak power, you come here and then you measure this width then this is delta lambda which is known as a spectral width. This spectral width is typically given by 1.45 times lambda P square times k B T; where lambda P is the peak wavelength, where the peak occurs k, B is Boltzmann constant and T is the absolute temperature. And this formula is valid when k B T is used in electron volts and lambda P is in micrometer.

So, what I find that at room temperature about 30 degree centigrade this delta lambda is about 30 nanometer. So, an LED has a spectral width of about 30 to 40 nanometers.

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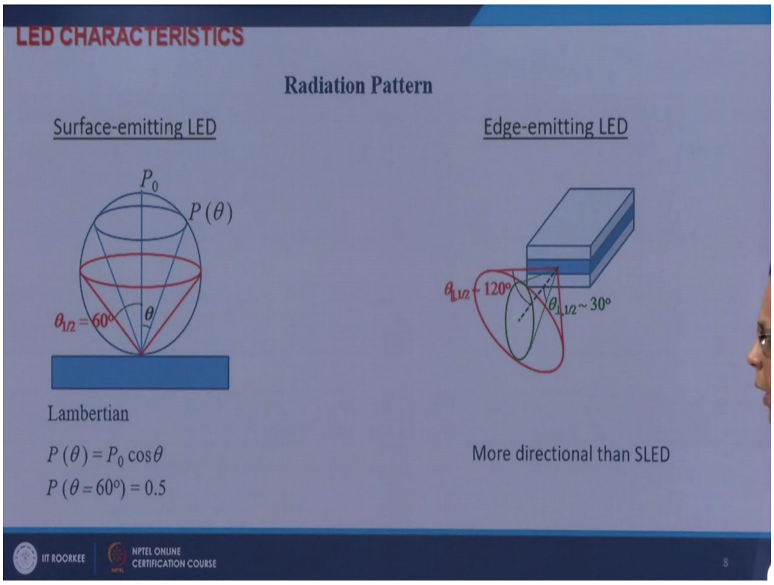

LED CHARACTERISTICS

Radiation Pattern

Surface-emitting LED

Edge-emitting LED

Lambertian

$P(\theta) = P_0 \cos\theta$

$P(\theta = 60°) = 0.5$

More directional than SLED

What is the radiation pattern, how directional it is? If I look at surface emitting LED, then it emits in all the directions like this and the pattern is Lambertian it is similar to that of an Lambertian source. For a Lambertian source the power varies with angle theta as P 0 cos theta where theta is the angle from the vertical. So, in this direction if you have maximum power at theta is equal to 0 and if you go away from this direction then power decreases. And I can see from here that at theta is equal to 60 degree the power will become half.

If I look at edge emitting LED then edge emitting LED is a bit more directional as compared to surface emitting LED, because the light is coming out from this edge, so where you have certain confinement in one direction. So, here in one direction I have this theta half about 30 degrees and other direction I have theta half which is about 120 degrees similar to this. Theta half is the whole angle, however this is half so this is the complete angle, it is not the semi vertical angle here it is semi vertical angle of the cone.

So, what I see that edge emitting LED is a bit more directional as compared to surface emitting LED.

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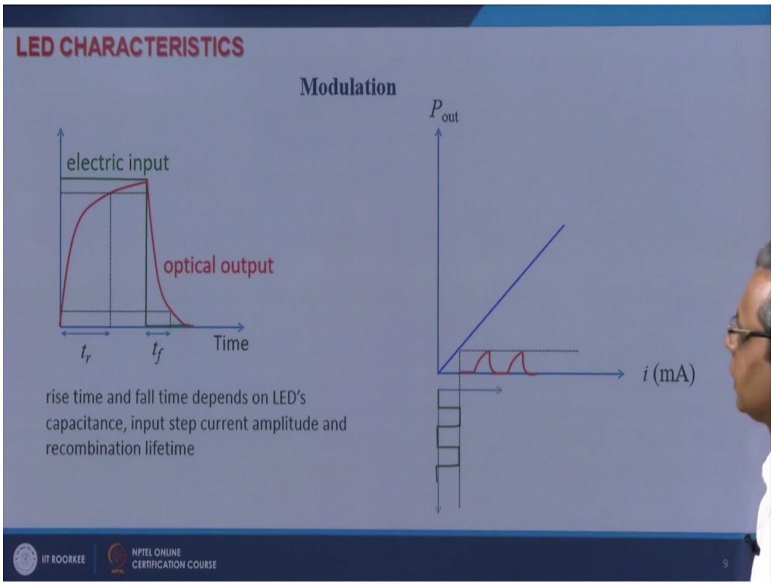

LED CHARACTERISTICS

Modulation

rise time and fall time depends on LED's capacitance, input step current amplitude and recombination lifetime

Another very important characteristic of an LED is modulation, after all I would like to use this LED for optical communication then I need to modulate the light source. If I look at how does this LED respond to the electric input, then I see that if I apply an electric pulse like this then it takes certain time because of its inherent capacitance, it will take some time to reach to this high value. And this is 90 percent level so the time in which this optical power will rise to 90 percent of the maximum then it is called rise time t r. And then when the electric input drops down then again due to the capacitance of an LED it will not immediately fall down, but it will take certain time to go to the 0 go to the value 0. And if again this is 90 percent then this time is called fall time t f.

Now what happens if I modulate it, how do I modulate it? Well, I apply injection current to an LED and I modulate the current, ok. So, if the current has this kind of variation this axis is i, this is I in milliamps and this is time. So, if i varies with time like this then correspondingly the optical power will vary like this, because this is P out versus i. So, if I modulate injection current I will modulate optical output from an LED.

What is the modulation bandwidth?

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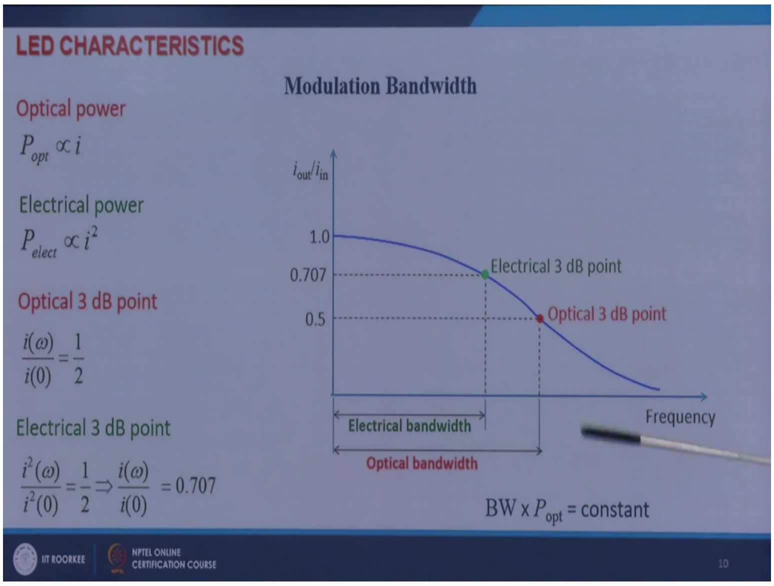

LED CHARACTERISTICS

Optical power

$P_{opt} \propto i$

Electrical power

$P_{elect} \propto i^2$

Optical 3 dB point

$\frac{i(\omega)}{i(0)} = \frac{1}{2}$

Electrical 3 dB point

$\frac{i^2(\omega)}{i^2(0)} = \frac{1}{2} \Rightarrow \frac{i(\omega)}{i(0)} = 0.707$

Modulation Bandwidth

BW x P_{opt} = constant

I know that optical power I have seen that P out of an LED is proportional to i injection current, while the electric power is proportional to i square; electric power is basically i square r. So, I can define optical 3 dB point and electrical 3 dB point.

What do I mean to say- what is the modulation bandwidth essentially you are supplying electric current to an LED and then you increase frequency. When you increase frequency then the power drops down. The point at which, the frequency at which the power drops down by 50 percent is known as 3 dB point. And since optical power is proportional to i, so optical 3 dB point would be i omega over i 0 is equal to half. And if I look at it here then here I have i omega over i 0 which is nothing but I out over i in i out is at frequency omega i in is DC. So, this is optical 3 dB point, where this ratio is 50 percent.

Electrical 3 dB point would be defined as i square omega over i square 0 is equal to half which means i omega i 0 would be 0.707. So, electrical 3 dB point would be somewhere here. An important point here is that the bandwidth times P optical is always constant. So, if this is the optical bandwidth then bandwidth times P out would be constant.

So, after having discussed the light source LED now it is time that we discuss laser diode which is more widely used in optical telecommunication. Why laser? Well, it is obvious that because laser has as we will see here; laser has much stronger output power, it is highly directional, it is more monochromatic, and it is coherent also. So, because of all these characteristics wonderful characteristics of a laser, a laser is used in optical communication.

Why in the form of diode? Because it is compact; so let us look at laser diode, and how does it work, what are the requirements for lasing.

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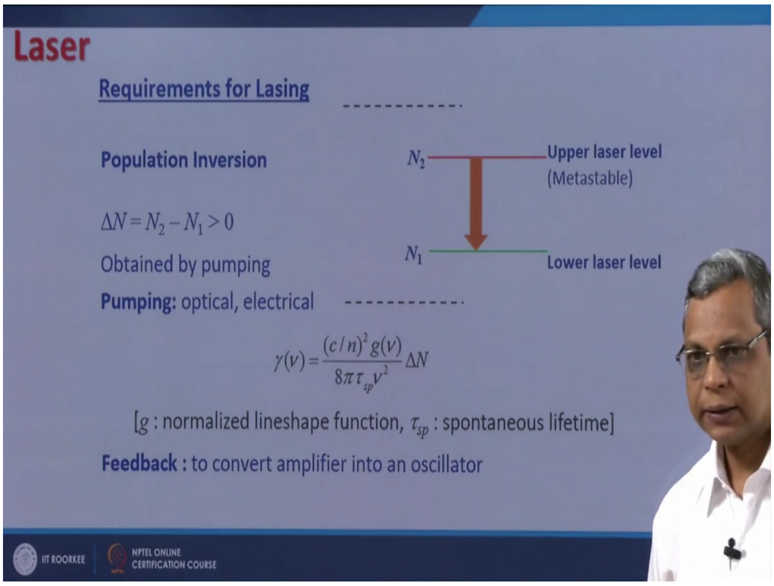

Laser

Requirements for Lasing

Population Inversion

$\Delta N = N_2 - N_1 > 0$

Obtained by pumping

Pumping: optical, electrical

$$\gamma(\nu) = \frac{(c/n)^2 g(\nu)}{8\pi\tau_{sp}\nu^2}\Delta N$$

[g : normalized lineshape function, τ_{sp} : spontaneous lifetime]

Feedback : to convert amplifier into an oscillator

For that let me consider a system a material system out of which I am making the laser. And in this system I consider the laser levels. This is the lower laser level this is the upper laser level, there might be some other levels also I am not much interested in those levels. I am only interested in lower laser level and upper laser level.

Upper laser level is meta stable level so that I can have a stimulated emission. If n 1 is the number of atoms per unit volume in lower laser level and n 2 is the number of atoms per unit volume in the upper laser level, then the requirement for the very first requirement for lasing is population inversion. That is, delta N which is n 2 minus n 1 should be greater than 0; that is I should have more number of atoms in this state as compared to in this state so that there would be downward transitions and I have optical output- radiative output.

And this is obtained by pumping. This pumping can be optical or electrical. So, you will have to basically lift atoms from here to here using a pump. In diode lasers it is electric pumping, it is by injection current. Then the gain of this system is given by gamma nu is equal to c by n square g nu divided by 8 pi tau sp nu square times delta N. Because, what does it mean that if I have such kind of system and I have achieved population inversion here, in that case now if I input a signal then it will be amplified via the process of stimulated emission.

The gain of that amplification is given by this expression. So obviously, it depends upon how much inverted my system is, how much is the population inversion. And this is frequency dependent, because these are not just single very fine levels but there are bands first of all. And another thing is that even if they are discrete levels then they have certain width they have to have certain width, they have broadening; this line is always broadened. So, this g nu is normalized line shape function. And tau S P is the spontaneous lifetime.

So, by this process I will have an amplifier, but laser is a self sustained device. So, I am not inputting any signal into this and amplifying, I am just giving injection current here and it is producing light. So, that can be done if I convert this amplifier into an oscillator. For that I need to make a resonator cavity. I will have to include this material between two mirrors so that I can provide feedback and make it a resonator cavity.

Then the lasing would start when the round trip gain, because now light is going back and forth between the two mirrors and in one round trip if the net gain is greater than 1 then I will have lasing, great. What do I mean by net gain? Because there is gain and also there are losses. So, this gain should be able to compensate for losses to have oscillations or lasing.

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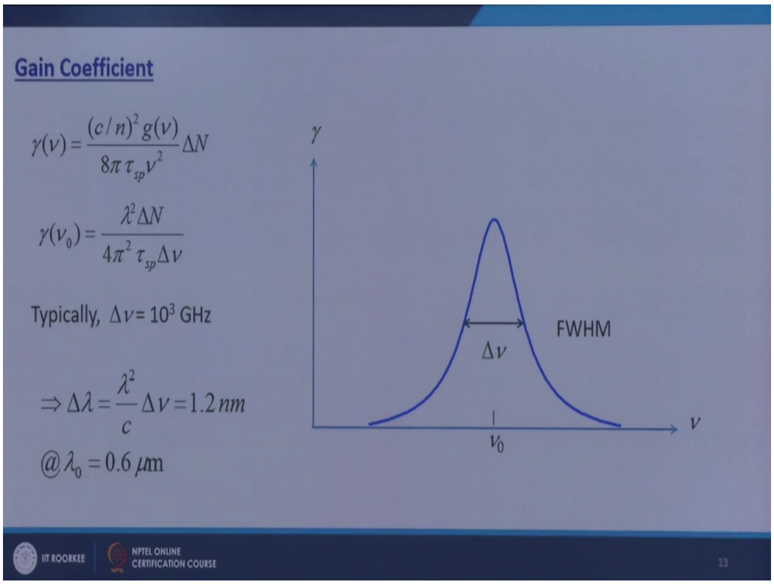

Gain Coefficient

$$\gamma(\nu) = \frac{(c/n)^2 g(\nu)}{8\pi \tau_{sp} \nu^2} \Delta N$$

$$\gamma(\nu_0) = \frac{\lambda^2 \Delta N}{4\pi^2 \tau_{sp} \Delta\nu}$$

Typically, $\Delta\nu = 10^3$ GHz

$$\Rightarrow \Delta\lambda = \frac{\lambda^2}{c} \Delta\nu = 1.2\,nm$$

$@\lambda_0 = 0.6\,\mu\text{m}$

If I look at this gain coefficient then it looks like this. It is variation with frequency looks like this, so it has a peak at nu is equal to nu 0 and the peak gain is given by this lambda square delta N divided by 4 pi square tau S P times delta nu. And this delta nu is full width at half maximum which is typically 10 to the power 3 gigahertz and if you convert it into nanometers in wavelength then it would be about 1.2 nanometer at 0.6 micrometer wavelength.

In the next lecture, I would look into the condition for lasing, what is the threshold value of gain, and then what are the various characteristics of a laser diode.

Thank you.