Optical Fiber Sensors
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture 5
Optical Sources

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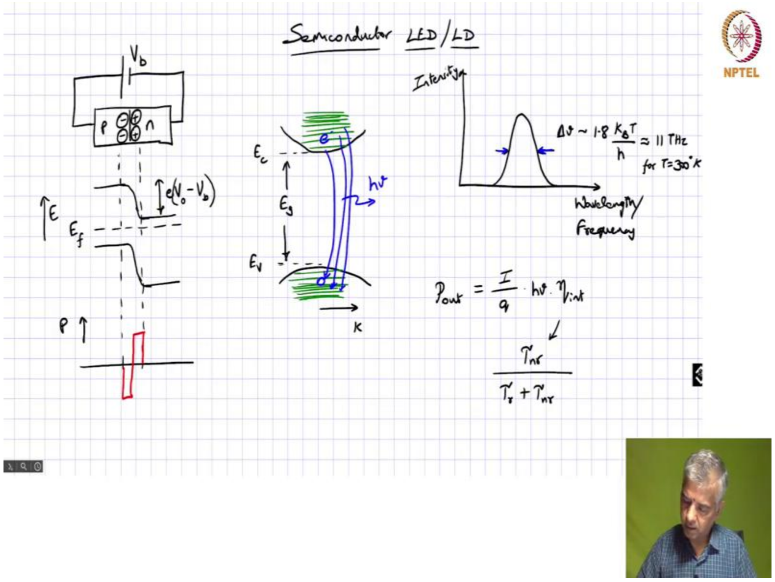

So far, we had looked at what constitutes an optical sensor, namely your optical source, then whatever perturbation it goes through, the light from the optical source goes through, and then what we pick up, the optical receiver. And then we also said what are the typical characteristics involved.

Now, let us go into a little more detail. And, let us actually start with semiconductor LEDs and laser diodes. And like I said, I am just going to go through a very quick sort of refresher on these things. I do expect that most of you have this background, if you do not have the background, I suggest that you go to a text like Saleh and Teich or lectures on Introduction to Photonics and pick up the necessary background. So, let us just go and see what semiconductor, so light sources all about?

Light emitting diode or laser diode. So, what is that? What is that based on? Well, we know that semiconductor light sources are essentially forward biased PN junctions. So, you take a P type semiconductor and you put that together with an N type semiconductor. Then you are going to have certain charges move from the P side to the N side. The majority carriers on the P side are holes, and they are going to, go to the N side and similarly, from the N side the majority carriers, electrons are going to diffuse into the P side.

So, you will essentially on the N side, you leave behind positively charged, positive charges, and on the P side you leave behind negative charges. Now, how do you represent this in energy level diagram? Well, you draw this across and you say that is your Fermi energy. The Fermi energy is equal for both the P side and the N side.

And, we know that the conduction, sorry, the valence band is going to be very close to the Fermi energy for the P type semiconductor. And, it is going to be very close to the, conduction band is going to be very close to the Fermi energy for as far as the N type semiconductor goes. So, you have something like this, where this transition region which corresponds to essentially the depletion region is somewhere over here. It can be defined like this and what is happening in the depletion region?

Well, if you look at the charge density, we have essentially negative charges on the P side and then some positive charges on the N side. And so, there is a sudden difference in the charges and we know that difference in the charges is going to cause a barrier here. That is the barrier that we are seeing here that corresponds to e times let us say V naught. Well, that that is the barrier. So, that barrier essentially stops. Further, transport of these, exchange of these carriers electrons from the N side going into the P side, or holes from the P side going into the N side.

But things change when you apply a positive bias, forward bias. So, when you apply a forward bias that bias is now acting against this potential. So, if this is your, let me call it as Vb, then your effective barrier height is reduced now by this V naught minus Vb. So, when that is reduced, then you have these carriers injected, the electrons that are injected from the N side into the P side and similarly holes injected from the P side on to the N side.

And, and then, that actually allows the recombination of these carriers. So, how do you, how do you represent that? Well, you can, essentially this your energy level diagram. So, this energy you can now plot it as a function of your momentum in what is called the EK diagram.

So, if you draw the EK diagram, it would look something like this. And so, the bottom of this is what you have as your conduction level and the top of this is your valence level. And, this is drawn as a function of k. If the top of the valence band is aligned to the bottom of the conduction band in terms of for the same k, then what do you call that? That is actually called a direct bandgap semiconductor.

And of course, you could have a case where this bottom most energy in the conduction band can be happening at a different k value. And those sort of cases, it is called an indirect bandgap semiconductor. So, we know that direct bandgap semiconductors have much higher radiation efficiency compared to indirect bandgap semiconductor.

Example of indirect bandgap semiconductors is silicon. So, we know that the radiation efficiency for silicon is very poor, but if you are looking at direct bandgap semiconductor like gallium arsenide, indium gallium arsenide and so on, they are many, gallium arsenide phosphide and so on. Those cases, the radiant, radiation efficiency is much much better.

Nevertheless, what we are trying to track here is actually the transitions, the recombination of your electron with a hole. So, let us actually look at this in little more detail. To look at that we need to now look at the specific energy levels within this band. And, we know that the energy levels are closer to the band edge. They are relatively wider space, but as you go deeper into the band, then they will, they will all be much, they will have much higher density of states.

And similarly, on the valence band around the band edge, we have relatively low density of states, but as you go away, you start having high density of states. So, what we are talking about is now, when we do the forward bias, you have this electron sitting in one of the energy levels in the conduction band recombining with a hole in the valence band.

And, that recombination event now is producing a photon. That is generating a photon provided that this bandgap energy which we are calling here as Eg, that bandgap energy is much larger compared to the thermal energy. Thermal energy defined by kBT. Then, you have a good probability of having a photon emitted from this, from this process, from this recombination process. The question then is, so how does the spectrum look like for emission like this?

So, you can, you can go ahead and draw the spectrum as far as the LED is concerned. So, this is intensity as a function of, say, wavelength. And what we see, so, you can, you can write it as in terms of wavelength or in terms of frequency and what we see is that it will typically look like this.

So, the intensity will peak at a value, at a particular wavelength value or a particular frequency value, it will peak such that h times nu which is the energy of the photon that is emitted, h times nu is just little larger than the bandgap energy. So, of course, there is very little emission, photons lesser than the bandgap energy but beyond the bandgap energy you start having emission. And, the peak of the emission will typically happen somewhere closer to the bandgap energy.

So, Eg plus kBT by 2 typically is where the peak of the emission happens. But what we are interested in is the spectral width. So, what is the width of the spectrum? And, the width of the spectrum is typically given by delta nu that is change, is this spread in frequency. The spread in frequency is approximately 1.8 times kBT, where kB corresponds to the Boltzmann constant divided by h, where h is the Planck's constant. So, this for example, if you talk about room temperature T equals to 300 degrees centigrade, let us say, this will be approximately 11 terahertz for T equal to 300 degree Kelvin.

So, it is an order of 10; 11 terahertz when, when T equal to 300 degree Kelvin. So, 11 terahertz, what does that mean? If you are doing this at 1550 nanometers 100 gigahertz corresponds to about 0.8 nanometers. So, 1 terahertz will be 8 nanometers. So, 10 terahertz or 11 terahertz, let us say, it is corresponding to the roughly about 80 to 90 nanometers.

So, that will be the width of the emission, which actually corresponds to the picture here of transitions happening from different levels. All these different levels are what is causing this emission, this wide spectrum over here. Like I said, the emission will start in terms of, if you are looking at from perspective of frequency, h nu greater than Eg is where the emission will be. And the width of the emission will be roughly about 11 terahertz. Now, that is actually explaining what happens with the spectrum, but we are also interested in what is the kind of output power we get.

So, what, how would we define the output power from LED? If you say the output power is P out. P out is going to be given by the rate at which the carriers are injected. So, if you say that the injection current here corresponds to Ie, you say, I over q, where q is the charge of the, is the electric charge.

So I over q corresponds to the rate at which carriers are injected into this PN structure and those carriers that are converted into photons which have an energy h nu and that is actually through recombination process. So, which is actually determined by Eta int. So, what is Eta int? Eta int corresponds to the, what is called the internal quantum efficiency. So, Eta int, for example, is going to be given by the ratio of the radiative rate versus the total rate which is corresponding to radiative rate plus the non radiative rate.

If you do that you say that this will correspond to Tau nr that is the lifetime corresponding to the non radiative recombination divided by Tau r plus Tau nr. So, if Tau r is relatively fast, which means that Tau r is relatively small compared to Tau nr that means the radiation is happening faster than compared to the non radiative recombination. In that case E int will be close to 1. So, so, we are essentially looking at materials and structures where Tau r is typically much faster or much smaller, Tau r is much smaller compared to Tau nr.

So, that is one part and that actually explains what is happening as far as the generation of photons are concerned, but when you talk about LED structure, a PN diode structure, that will correspond to certain a structure like this.

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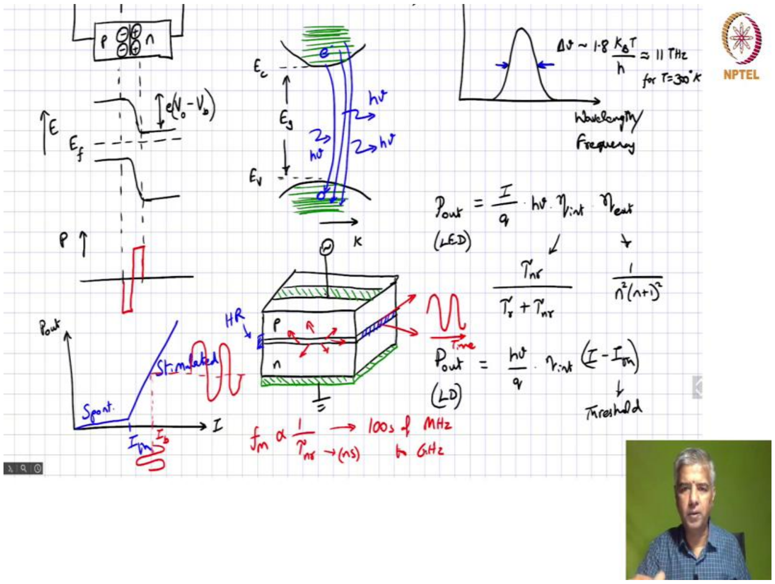

Let me just try to draw this here. So, you have what is called an epitaxial structure. So, you have a layer by layer growth of the P and N material. So, you have P over here and N over here. And, I have drawn a thin slice over here that typically corresponds to what is called an active region. An active region is one where these structures tend to be what is called a double heterostructure.

So, that means, the material in this region, in this thin slice over here has got a lower bandgap compared to the P and N type material. And, that allows for confinement of the carriers and also confinement of the photons. So, that is what we call us an active region.

And, if you extend it to the third dimension, it is going to look something like this. And, then you can define your electrodes like this. So, you can put one electrode there and then you could have another electrode in the bottom. And so, the current actually flows across this and then that, that is when these, these carriers are injected and they recombine within this active region. And, then they generate light, certain output.

But not all the photons that are generated from this, the photons that come off of this are going to be going in all sorts of directions, some of which is going to go straight down, some others that are going in other directions and so on.

So, only part of the light is actually going to be escaping this entire structure and then only that part of the light is going to come out of this structure. So, that actually is a very small fraction. And that fraction is given by what is called Eta external, is the external, what is called the external quantum efficiency. And, like I said it defines what is the fraction of photons that are escaping from the structure.

And, that is typically given by 1 over N multiplied by N plus 1, the whole square, something like that. So, that is actually, if you say N is for gallium arsenide, N is greater than 3. So, we are looking at a fairly small number. I think this is N square, N square into N plus 1, the whole square. That is what it comes down to. So, we are typically looking at only a fraction of the light that is going through 1 to 2 percent and so, on.

In fact, some other commercial LEDs, if you want to get a lot of light out, what you need to do is to frustrate reflection at this surface. Especially total internal reflection at this surface by making that surface a little corrugated. So that there is not a whole lot of total internal reflection happens.

And with that, you could potentially extract a higher level of light from the structure. But nevertheless, that sort of explains what happens as far as semiconductor light emitting diode is concerned.

So, now, how do we essentially look at laser diode? Well, the laser diode, it could be a very similar structure, the double heterostructure and all that with the same P-N material and the active region and so on.

The only big difference here is that as far as the laser diode is concerned, you also have basically a mirror in these regions. So, you have a mirror coating on this side, maybe a high reflection coating. You call it HR, high reflective, highly reflection coating over here, and here this could be a partially reflecting coating. In which case you have what is called stimulated emission happening. So, what is stimulated emission?

We are saying this photon here, if you have an incoming photon, then that incoming photon can stimulate this recombination event. And then in that case, you get 2 photons out. For every photon you have another clone of that photon generated. When you say clone, what we are talking about is, it is having the same frequency, the same direction, the same face, that is generated.

And so, you once you have stimulated emission happening within the structure and that is what is actually this mirror is doing. This mirror coatings on either side is actually allowing some of the light to bounce back and traverse along this active region. And in that case, it can undergo, it can simulate further transitions and through that stimulated emission, now, you could generate laser radiation.

So, if we were to look at the output power, so, what we defined here is the output for LED, but if you look at the output power for a laser diode. So, that will be given by h nu over q Eta int, that is the same as before. But now, instead of all that the current directly giving you the stimulated emission, the stimulated emission for that to happen it has to overcome certain loss inside this structure. Only when you have a cert, beyond a certain number of photons that are within that structure, then only you can achieve stimulated emission. So, your output becomes significant only beyond this value, this threshold value. So, this is actually your threshold.

So, the threshold condition corresponds to where the gain in the semiconductor material, which is actually a function of the injected current, the gain in the semiconductor material overcomes the loss inside this cavity. And, this is actually what is called a Fabry Perot cavity. So, once you overcome the loss, then only you can sustain oscillation, and then you can have laser emission. So, if you are looking at the output power.

P out as a function of current, then what you have is, at lower current levels, all you have is this spontaneous emission. You do not have enough photons to stimulate this recombination process, but with the help of the mirror, it is building up more and more photons. So, beyond a certain current level, the output goes like this.

So, what is happening here? Here, it is spontaneous emission and here it is dominated by stimulated emission. So, you can say that a semiconductor light source acts like LED for current levels below the threshold current. And, once it achieves threshold, beyond that, it is actually working as a laser diode?

So, that is all I think we want to learn about LEDs and lasers, or maybe, maybe there is one more thing that I want to mention. That is actually corresponds to the modulation of your light source. So, semiconductor light sources give us this ability to directly modulate the light coming out of this.

So, what do I mean by that? Now, if I have a current source over here, and if I actually have alternating current source. So, I am injecting current in a sinusoidal manner, then correspondingly the output, when you look at it, the output is now going to be increasing and decreasing as a function of time.

So, you can actually modulate the output. So, what are we talking about here? So, maybe I can bias as my this current level, operating current level at somewhere over here. So, I would say this is my Ib. And, if I apply some change in the current level around that, my output will correspondingly show that change.

So, you can modulate the output power by modulating the injection current as far as the semiconductor light source is concerned. Of course, you can do that with the LED also, but in

LED, you would operate below threshold and you would basically be modulating around this. The question is, what is the maximum frequency with which you can modulate?

That frequency that is what is called the modulation frequency Fm. Fm tends to be limited by the non radiative lifetime. The non radiative recombination processes. So, it is inversely proportional to Tau nr. So, it is inversely proportional to the carrier lifetime. But carrier lifetime at the lowest level, if you say the radiative lifetime, you have done all the thing to increase the radiative lifetime. It is eventually limited by the non radiative lifetime. And, the non radiative lifetime could be in the order of few nanoseconds.

So, if this is in the order of nanoseconds, Fm now is in the order of hundreds of megahertz to a gigahertz, that type of frequency. So, that is one of the advantages of using a semiconductor light source. Your modulation frequencies through this direct modulation process can achieve up to hundreds of megahertz to gigahertz.

So, that is actually a very big advantage which we will of course, during the later part, when we are actually designing a sensor, we will see how this modulation capability is very beneficial, So, I think that is good for now. We will continue with talking about optical receivers as we move from here.