Introduction to Semiconductor Devices
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Lecture - 78
Stimulated Emission and Lasting

Alright, let us get started. So, in today's lecture, I would like to talk about laser diodes. So, if you look at the history of semiconductors in the last 70 years, there have been two great inventions, or rather, in terms of broadly technology, there have been two great inventions. One of them is a MOSFET it has changed the electronics industry. And it has, you know, it has made computing possible.

The other invention was a Laser. This is also a nonlinear device, similar to a transistor. And essentially, instead of generating electrons, or you know, controlling the flow of electrons, you are actually generating light, you can turn it off, turn it on. So, in a laser, we build up on the concepts of LEDs to discuss lasers. But what laser has done is it has enabled communication revolution.

So, the olden days, there are a couple of wires connecting cities, and it used to take a, it was a lot of effort to actually make a phone call. Now, they used to call it trunk call, and it used to take a long time to actually make a connection, you have to fix a time and all that. But now you have you know, internet, within seconds, you can communicate anywhere in the world. And you know, you are able to download and you know, you are able to have so much information at your fingertips.

The reason this has been possible is information transfer revolution that has happened in the background, you do not see it in your homes. But you know, everywhere you have fibre optic connections, nowadays, almost the homes you have fibre optic connections nowadays. So, what is happening is you are transmitting information over fibre and that information is transmitted at a wavelength of 1.5 microns.

And the backbone of that is a semiconductor laser. So, without the corresponding increase in the technological development of lasers, it is not really exaggeration to say that current information technology revolution would not have been possible. You would have a supercomputer, but if you cannot access it, you cannot connect it to internet, there is no use of this supercomputer, only a few people would have access.

So, in essence, lasers have changed the world. And we would like to understand some aspects of it especially only the semiconductor lasers, we will not focus on the general lasers will only focus on the semiconductor lasers.

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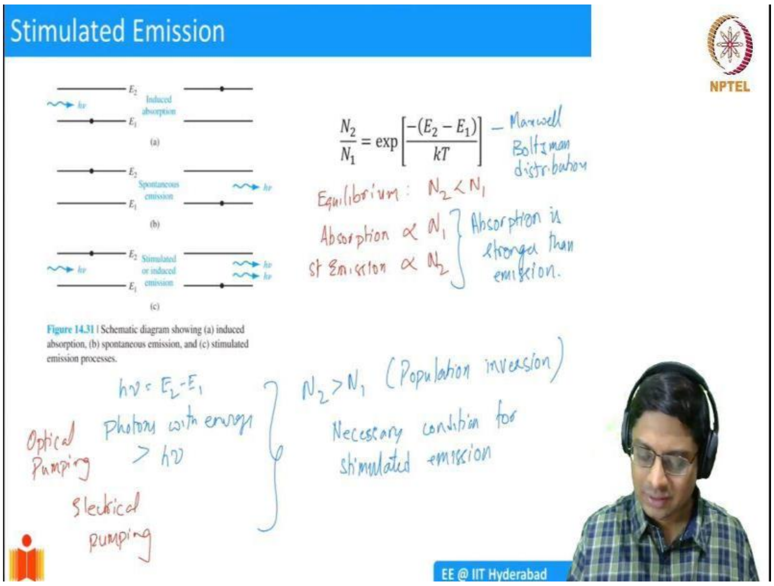

Stimulated Emission

Figure 14.31 | Schematic diagram showing (a) induced absorption, (b) spontaneous emission, and (c) stimulated emission processes.

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$ – Maxwell Boltzman distribution

Equilibrium : $N_2 < N_1$

Absorption $\propto N_1$
St Emission $\propto N_2$
} Absorption is stronger than emission.

$h\nu = E_2 - E_1$

Optical Pumping: Photons with energy $> h\nu$

Electrical pumping

} $N_2 > N_1$ (Population inversion)

Necessary condition for stimulated emission

So, I have already you know, introduced the concept of stimulated emission in the beginning of the discussion this week. So, what we said was, you have these three different processes absorption, spontaneous emission and stimulated emission. So, I do not want to repeat it all I just want to say that now, you can stimulated emission you are able to know if you have a single photon incident you can have two photons generated the same phase and frequency.

It is coherent processes what we said. So, this is a 2 level system and if you look at the population densities in a 2 level system, it turns out that you can write the ratio

$$\frac{N_2}{N_1} = exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$

N_2 by N_1 and it follows the famous Boltzmann kind of statistics were in the probability of occupational the higher level is proportional to the energy difference between the levels. So, what this essentially tells you is that if you have no thermal equilibrium.

Now, just consider equilibrium then the population density of the higher state is always lesser than the lower state. So, N_2 is the population of the highest state and thus will be lesser than N_1. And this is typical for all the systems you know, normal systems. So, we have already looked at absorption, absorption is proportional to the density of atoms in the lower state. If you have a lot of atoms in the lower state and there is vacant state of course in that higher state, then you can have absorption.

So, absorption is proportional to and one to lower state. Whereas, I can say emission, especially stimulated emission not normal emission is stimulated emission is proportional N_2. We want to have states that are available we wrote or the rate equations in the first lecture of this week. So, stimulated emission is proportional to N_2. That means, if you have higher number of electrons in the larger number of electrons in the higher state, then you can have stimulated emission possible.

So, from this, it seems that you know absorption is always stronger than emission. The conclusion seems to be that, because we have equilibrium N_2 is always smaller than N_1. So, we can say that absorption is stronger than emission. This seems to be the most difficult case. Well, it turns out that we can actually change this condition by what we call this pumping. We can pump a material with you know light.

Let us say if my energy difference I will call this as

$$h\nu = E_2 - E_1$$

just any 2 levels, it could be conduction band and valence band or it could be states in an atom and so, whatever. Energy difference, let us say is E 2 – E 1 I can pump I can supply photons with energy greater than $h\nu$. If I do that, higher energy photons apply, you will actually pump it and then you can create electron hole pairs and they will relax to the bandage and so on.

So, this is called as optical pumping. Likewise, we saw in the case of LEDs where you supply a blue photon to excite a phosphor. So, you are supplying a high energy photon that is an optical pumping process, you can also have electrical Pumping. By which may be mean that like in a laser LED rate we have seen you can supply minority carriers you can inject minority carriers and create a situation where you can have a higher population of electrons in the highest state.

So, we can create a situation where you can say N_2 is greater than N_1 and I call this a very important, and I call this population inversion. The regular way population is distributed is N_2 is less than N_1 that is a Maxwell Boltzmann distribution. We mentioned Maxwell Boltzmann distribution, this is the regular trend. But if I create pumping optically or electrically, I can create population inversion which leads to what we call a stimulated emission.

This is necessary for necessary condition for stimulate emission. So, there are essentially three conditions necessary. One is you need to have you know, stimulated emission process, you need to have you know gain and you need to have what is called as cavity. We will discuss that in this video. So, we will just qualitatively talk about them. So, this is population inversion. So, what happens if you have population inversion?

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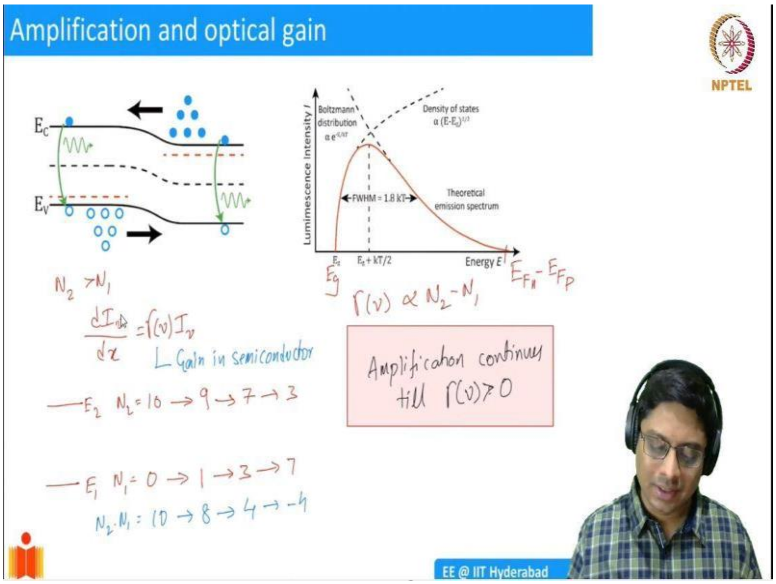

Amplification and optical gain

$N_2 > N_1$

$\frac{dI_\nu}{dz} = \Gamma(\nu) I_\nu$

└ Gain in semiconductor

E_2 $N_2 = 10 \rightarrow 9 \rightarrow 7 \rightarrow 3$

E_1 $N_1 = 0 \rightarrow 1 \rightarrow 3 \rightarrow 7$

$N_2 - N_1 = 10 \rightarrow 8 \rightarrow 4 \rightarrow -4$

$\Gamma(\nu) \propto N_2 - N_1$

Amplification continues till $\Gamma(\nu) > 0$

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Well, you can achieve amplification, how do we achieve amplification? Well, you know, you caused N_2 greater than N_1. Then let us say a photon is incident, we saw that it emits a second photon. So, let us say you created a situation where N_2 is greater than N_1. So, one photon is causing another photon, so you have 2 photons. Now, those 2 photons have to pass through the material with N_2 greater than N_1 then they cause 4 photons to be generated.

To more photons will be generated, and those 4 photons will call 8 photons to be generated. So, we are essentially amplifying the number of photons increasing the number of photons and so, this can be captured by you know, we can write rate equation for this we can say that dI_ν the intensity of photons at a particular wavelength by dx is going to be equal to of course, you know you have of this gain cycle you have this condition satisfied population inversion.

$$\frac{dI_\nu}{dx} = \gamma(\nu)I_\nu$$

When you have the condition satisfied, the number of the increase the rate of increase in the intensity is going to be proportional to the existing intensity. So, there is going to be Iν and then there is a coefficient that captures the amplification we call it gain and we say that is gamma is equal to this. So, basically, we have this which we are calling us gain in the material gain in semiconductor.

So, what how is this gain possible. So, this gain essentially is going to be proportional to gamma of nu is going to be proportional to $N_2 – N_1$, is it wavelength dependent? Well, of course it is wavelength dependent. The reason is we have seen that you know, the spectrum, emission spectrum of semiconductor, we said it is going to be on this shift. So, essentially what it means is that you have electrons in the higher energy level at this energy where these two these differences in energy.

So, if you talk in terms of you know, the range or which N_2 is greater than N_1 is going to be Eg on the lower side. And on the higher side it is going to be the difference in the Fermi energy $E_{Fn} – E_{Fn}$. So, that is the range or which you can have $N_2 – N_1$ satisfied. So, because of that, you are you know, wherever the extent of $N_2 – N_1$ is going to determine the gain.

And whenever you have photon emitted, it is going to reduce this population inversion. For example, if you take let us say, let us take a state higher state E_1 E_2, there are 2 states. And this has a population of $N_2 = 10$ and this has a population of 0, just as an example. Now, if a photon is incident, what happens? Well, it will cause another photon to be generated.

So, when a photon is generated, what happens to the N_2? Well, one electron is going to come down to the lowest state not only when it comes down to the lower state, it emits a photon. So, n to population reduces to 9. Whereas N_1 population goes to 1one electron has come into the lowest state. So, this has happened. So, now we have 2 photons and when these 2 photons go to the same material.

So, it can cause another 2 photons to be generated. So, if you have another photon two photons can be generated, the population of highest yet reduces to 7 and this guy increases to 3. Now, you have four photons, and these four photons can cause for more photons to be generated. So, quickly, this becomes 3 and this guy becomes 7. So, if you monitor $N_2 – N_1$ in this scenario, $N_2 - N_1$, this was initially 10 here, then it became 8, then it became 4, then it became actually negative.

So, it became less than 0. So, very quickly, the population inversion is destroyed. And we said that if you want to have amplification, we need to have $N_2 - N_1$ greater than 0. It has to be always greater than N_1. So, as long as you maintain this condition $N_2 - N_1$ greater than 0, amplification occurs, amplification continues till $\gamma(\nu) > 0$. The moment it becomes less than 0, it just will not amplify anymore.

It will simply observe photons, because now low state has lecture 7 and upper state has 3. It can easily the photon can easily excite as electron to go from lowest to highest, so it can get absorbed. These are completing processes. So, whenever you want a laser, we have to ensure that the amplitude of the $N_2 - N_1$ is greater than 0. The wave we do that is as I said, pumping.

So, it is not enough if you just simply supply a photon, we just have to continuously supply these photons. One moment, just let me pause this I will get back excuse this sorry, there was a small audio issue, so I had to check that. So, the necessary condition is that you have to keep pumping, pumping is necessary to create amplification. And if you want to create lasing, that is you know, very, very strong amplification.

We need to satisfy one more condition, which is basically to select a certain wavelength. Because gain can happen over a range of wavelengths, as you saw in this picture here, you have gain happening over a range of wherever the spontaneous emission happens you know, those ranges of frequencies can actually get support, you know, amplification. But it is not enough.

We need to make sure that there is a cavity that selects the photons which particular wavelength should be amplified.

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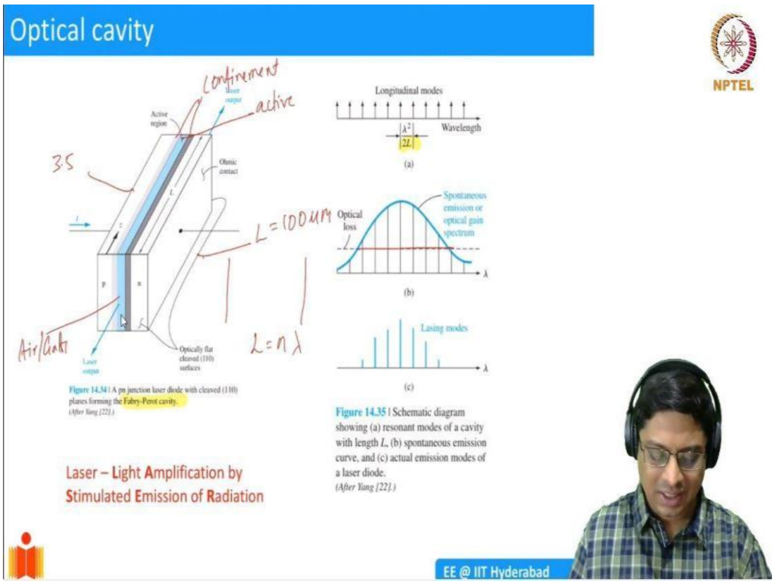

Optical cavity

Figure 14.34 | A pn junction laser diode with cleaved (110) planes forming the Fabry-Perot cavity. (After Yang [22].)

Figure 14.35 | Schematic diagram showing (a) resonant modes of a cavity with length L, (b) spontaneous emission curve, and (c) actual emission modes of a laser diode. (After Yang [22].)

Laser – Light Amplification by Stimulated Emission of Radiation

And this is known as basically a lazing cavity. For example, you know, we mentioned you know, you might have definitely encountered us, you know, system between 2 digit supports or even a quantum well, whatever you want to call it. So, you can have let us say two supports potential well maybe. What are the wavelengths that are supported by this? Well, the wavelengths are supported will be $L = n\pi$.

Whatever wavelengths for which you have integral multiple of wavelength = L those will be supported by this structure. Similarly, what we can do is we can make a hetero structure that we have discussed in the last couple of lectures. And you pack the faces of assets, take a piece cut edges of it, make them atomically smooth. So, that can be easily done, it is not that difficult to do.

So, when you do that, you have a piece of semiconductor. This case, you are actually seeing the 3 dimensional picture. So, this is your no contact one contact. So, actually you have the hetero structure in this direction. So, you have the confinement regions basically here these are the confinement regions and the blue one is an active region, where you have photos getting emitted.

So, and then physically you chop it and then you make it a certain size maybe this length can be length of 100 microns maybe. When you do that, you are essentially creating you know, this is a high index remember all the semiconductors have nearly same index 3.5 let us say outside is air. So, when the photon comes near the interface between know the outside here it is air, this is air let us say gallium arsenide interface.

Similar other side you have a gallium arsenide interface and we know that it primarily reflects. When it reflects you have this sort of a cavity formed essentially the reflection layer photons have to basically be confined between these two mirrors in some sense, this end will act like a mirror and we call this as Fabry Pero cavity you know, if you want to know more you can look up.

Essentially the idea is that the photons are confined to a region of space of certain length in the lateral direction. And these rights give rise to what are known as different modes. And we I mean qualitatively it is no or intutively, it is that makes sense wherever the wavelength is integral multiple of the integral length is integral multiple of a wavelength. Then those modes are supported, and you can have various modes, which are supported discrete modes.

That can we can compute what is the distance between the modes and so on. Now, you also have a gain region, where a certain range of wavelengths. Whenever you know, if the wavelength falls under the gain region here, it will get amplified. So, those photons will be amplified strongly. Whereas, photons of this mode will not be amplified strongly, they are weak. So, they will decay.

And here also they will decay; only those photons which fall into the centre region will get amplified. And so, the intensity increases. And then they will keep the one at you, for example, you have a cavity, your photons are going to get amplified, they will hit this part and then turn back they come back again they get amplified further again come back. So, the there is a circulation of energy in that.

So, this causes the energy to be building and building up in the cavity, which causes laser. Laser is very similar to a resonator. Now, you might have you know, saw resonator or oscillator, you might have studied oscillations oscillating some circuits like where in supplying energy from outside for using a power supply and then you are causing a build-up of oscillation.

When you satisfy certain feedback conditions, you are actually having a build-up of build-up of oscillation. And then you have large amplitude that is generated exact same thing happens in a laser. So, this cavity is essentially providing the feedback you have the game that is provided with a semiconductor material and the cavity is providing the feedback which is causing one single wavelength to be selected.

This is the principle of laser essentially. So, for basic to occur, you need to satisfy three conditions. One is you need to have stimulated emission; you need to have gain; you need to have a cavity. So, how do you get gain by pumping? How do you get a cavity? By mechanically you know, adjusting the size of your cavity. So, if you make the size of the cavity smaller, the distance between the modes increases.

So, it turns out that you can have lazing at a single mode or multimode and so on depending on how much is your gain bandwidth. Now, we call this width as again bandwidth. This particular guy has gained bandwidth depending on how much overlap is there between the gain bandwidth and the mode in the cavity. You can have amplification and laser.

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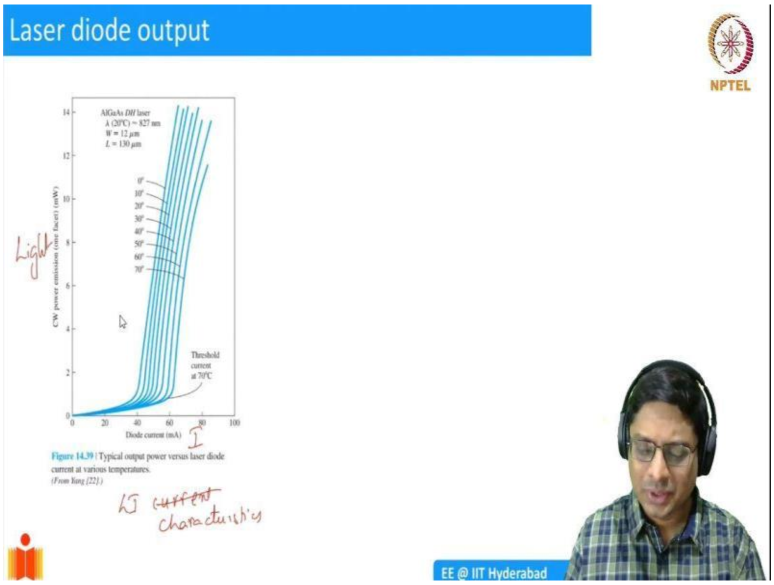

Laser diode output

Figure 14.39 | Typical output power versus laser diode current at various temperatures.
(From Yang [22].)

LI ~~current~~ characteristics

So, if you are looking at the IV characteristics of laser, they look not rather, no you should not call it IV characteristic we should call it a LI characteristic. So, you having the input is a light and the output is input is current and output is light. So, we call them LI characteristic light versus current LI characteristics. They look very similar to LI characteristics they look very similar to the typical IV characteristics.

So, there is a threshold. So, only when your gain increases beyond a certain threshold then you have amplification. So, you see that sort of a threshold like behaviour that is shown. And this

this threshold is very sensitive to temperature and so, on, I just wanted to show you how similar it is. So, whenever you have laser, you can you can talk about you know, you can plot it in a logarithmic scale and look at how it looks like and all that.

So, there is a lot of similar analysis that you can do. So, once you understand semiconductors very well you could also understand these lasers very well. So, I do not want to get into I do not want to get into all these details, I just wanted to show you how it looks like and I just also wanted to mention how LED is different from a laser.

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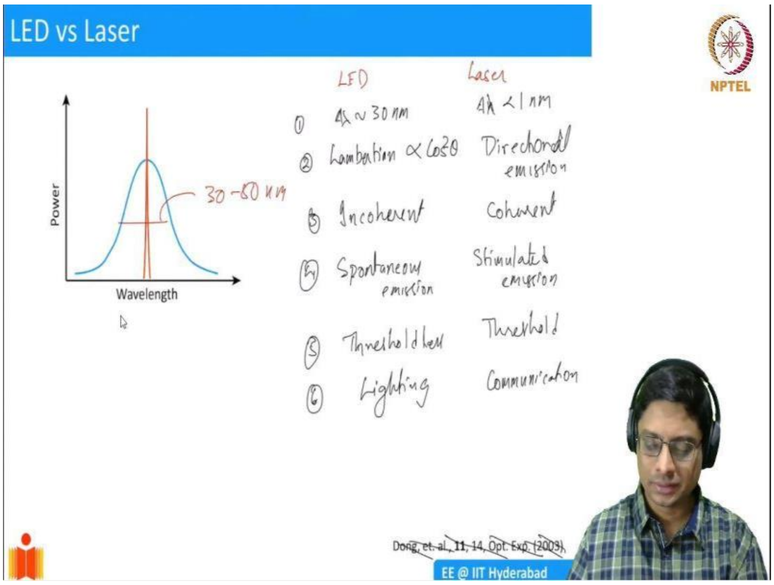

LED vs Laser

	LED	Laser
①	$\Delta\lambda \sim 30$ nm	$\Delta\lambda < 1$ nm
②	Lambertian $\propto \cos\theta$	Directional emission
③	Incoherent	Coherent
④	Spontaneous emission	Stimulated emission
⑤	Thresholdless	Threshold
⑥	Lighting	Communication

~~Dong, et. al., 11, 14, Opt. Exp. (2003).~~

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So, we saw that in LED you have emission over a range of wavelengths for example, we say theoretically that was a 1.8KT practically it will be about let us say 30 nanometres 30 to 50 nanometres maybe practically that will be the typical range of an LED. But laser, it turns out that because of the feedback, you have a very good oscillation at a single wavelength almost you know. So, there are a lot of differences between lasers and LEDs.

For example, you know, you take an oscillator, electronic oscillator maybe if you have said analog circuits. Initially you will start from noise variously frequencies are present, but over time only one particular frequency will be selected. The same thing happens in lasers, you have a particular wavelength that is generated. So, what are the differences between LEDs and lasers? So, we can list a few of them just for your knowledge.

The first one already mentioned is that LED has a delta lambda of let us say 30 nanometres whereas here delta lambda will be less than 1 nanometre ideally. So, it is very, very monochromatic and that is why this is useful, you know, the emission profile, if you look at it, the LED emission profile is what is called as Lambation basically it means we do not need to get into it, it is proportional to cosine squared theta.

So, LED emission will not be a straight line, but it has a certain angle spread over which it emits, it is not a directional emission whereas in a laser it is directional emission. Number 3 because again the same you know the delta lambda is small and in this case of LED, we have delta lambda large. So, we can say that leave LED is incoherent whereas, laser is a coherent source.

For example, if you take communications, you might have studied that you want to supply one single frequency you would like to be with ideal frequencies sinusoids. So, it is like you know, monochromatic sources, LEDs a monochromatic source where sorry, not LED laser is a monochromatic source whereas LED is not coherent. And you know, in LED you have spontaneous emission whereas, in a laser, you have stimulated emission.

That is again, the difference. And LED does not have anything like a threshold, it can simply keep emitting. Well, I mean, if you supply a certain current you, I mean, you will start seeing a generation of light. If it is an indirect direct bandgap semiconductor, you will have light right from the beginning. So, there is nothing intensity can be increased thresholds, I would say, you should have a threshold.

And lastly, you know, applications. LEDs are used for lighting mainly or you know, everywhere a lot of lighting even lighting. Lasers are useful for communications. So, whether this reference is wrong, I just, it is a leftover thing. These are the main differences between LEDs and lasers. So, how does the laser output look like I am sure all of you have seen a laser pointer.

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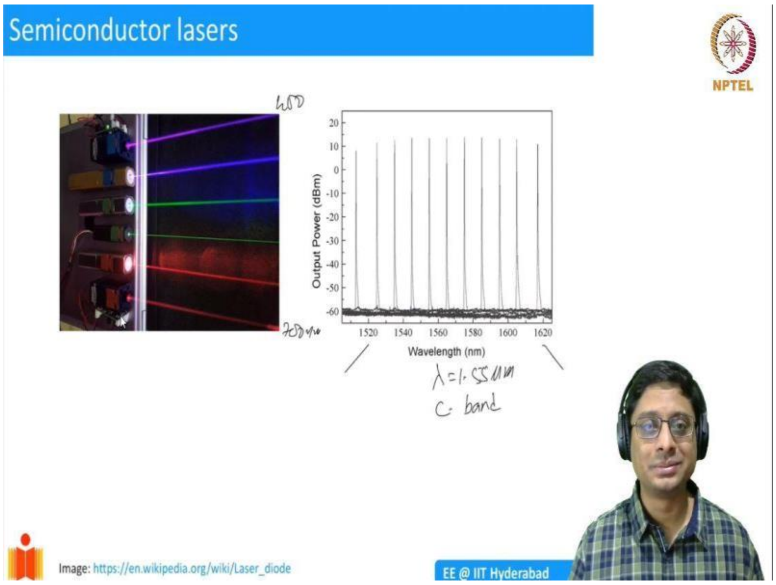

Semiconductor lasers

Image: https://en.wikipedia.org/wiki/Laser_diode

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You will see how you will have a single beam which is nicely traveling you can actually if you pour some dust or something, you know chock just hold the chalk and when you dust it. You will see that line nicely you know beam of lights that are propagating because of lasers and you can tune this laser from you know, 400 nanometres this will be nearly 400 nanometres. This is nearly 700 nanometres.

So, you can tune the wavelength of operation of a laser and they are very, very useful for research purposes, this is visible laser, you could also have IR lasers. In this case, I am just showing you how a laser is tuneable from, you know, 1520 to 1620 nanometres, this is, you know, centred around all important lambda = 1.55 microns, which is a telecommunications wavelength.

So, by tuning this, we are a telecommunication, we call it C band, communications band. In that if we are able to tune the laser, we can multiplex many, many channels. So, optical fibre is single fibre, you can send many different wavelengths, and we call it WDM wavelength division multiplexing. You can have WDM because of which you can have multiple channels very, very closely spaced channels.

And you can communicate a large amount of information, that is where the bandwidth of optical fibre is huge compared to electrical, you know wire. If you take a simple electrical wire, we are not able to we cannot really send very high bandwidth because at some point RC delays will come into picture. And you can multiplex different signals on the same wire, you can put two sources and drive it then there will be interference.

Because electrons by nature they interfere, whereas photons do not interfere. So, you can put multiple channels on the same waveguide and you can transmit and get huge bandwidth enhancements. So, one of the research frontiers is basically now to integrate this know, optical waveguides onto a chip, because we have seen that the processing speeds have saturated because of RC delays.

So, one of the research domains that is very you know, important nowadays is nano photonics wherein you try to integrate photonic ideas now, this lasers onto a chip. There are many, many challenges, but also it is a very exciting frontier. So, there is a lot of research that is going on. And this is completely open dimension right now. So, that concludes nearly my discussion on lasers.

It is very close to my heart, because I happen to be working on lasers and nano photonics for my research. And if you find some of this interesting, you can always write an email to me, and we can talk about some interesting opportunities and things like that, provided you have done well in the course of course. So, it is been my pleasure offering this course. And I hope that you know you have understood at least you know you have got a bird's eye view of various aspects of semiconductors and their applications.

And if you are interested, you could always pursue various subsequent courses that will take you in greater depth. With that, I will conclude my course. I had a great time. I hope you enjoyed it too. I will see you some other course. Thank you so much. Take care. Bye.