Introduction to Photonics
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Lasers Part 2

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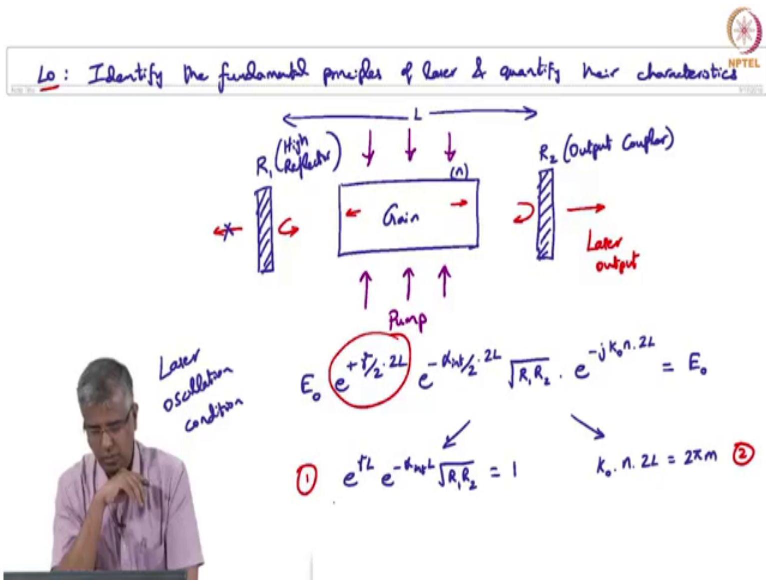

So welcome back to Introduction to Photonics, the last lecture we started discussing about lasers so we said ok laser is nothing is but an amplifier with feedback and we consider this simple case of gain medium on either side of the gain medium we have the mirrors providing the feedback and we said ok once you pump a gain medium an external energy source then you excite this atoms in the gain medium which can provide spontaneous emission and those spontaneously emitted photons when they get bounced by the mirror reflected by the mirror they come around and stimulate the transition inside the gain medium and then you have build up of stimulated emission photons and then we said ok it is not like all this stimulated photons survive within the cavity we basically said that first of all you get laser action when you are able to overcome the loss in the cavity with the cavity gain.

So that was one condition and then the other was that we said you know for this waves to be consistent inside the cavity you have to essentially satisfy the constructive interference condition and you know that essentially meant up only certain frequencies and survive inside the cavity so even though you may have other frequencies that are positive because of the cavity that maybe supported by the cavity only certain frequencies whose gain is equal to or greater than the loss inside the cavity will survive in the cavity right. So we talked about that concept then we said ok its probably better that we look at the saturation of the signal photons saturation of the gain inside the cavity.

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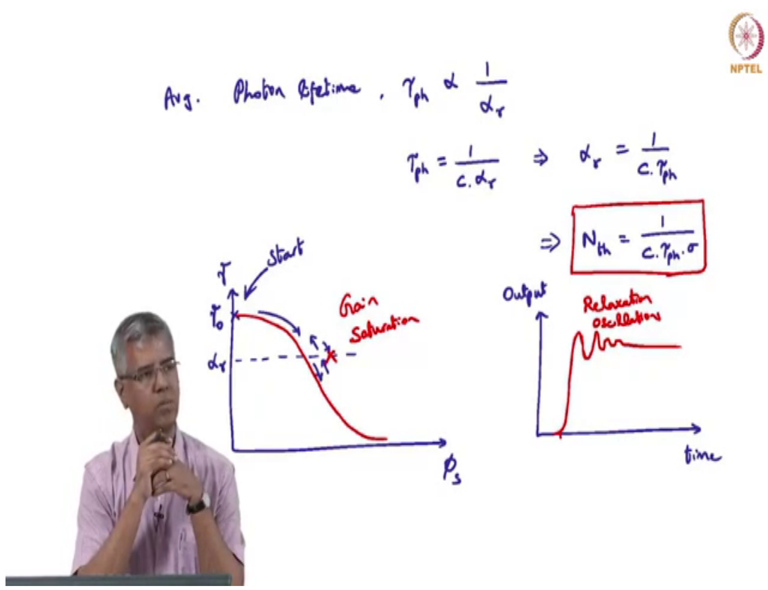

So we said ok we may start at relatively high inversion right which corresponds to a relatively high small signal gain so that small signal gain here is given by gamma knot you may start from that point but the moment you start you know having stimulated emission of photons you start building up those photons you start saturating the gain this is our concept that we already disclosed when we were looking at optical amplifiers so that gain saturation reduces the gain available to the to this photons inside the cavity and correspondingly what we see is initially the output is you know it shoots up the moment pump energy is turned on and then it gain saturates so the number of photons inside the cavity reduces and then when the photons reduced the gain recovers right.

Gain is not saturated as much so the gain recovers and so it goes through this oscillations what we call as relaxation oscillations and then it achieves steady state and at the steady state what we saying is you whatever excess pump photons you need a certain pump photons to provide the inversion necessary or the gain necessary to overcome the loss but any excess pump photons are now contributing to the signal photons and that is the output that we are seeing in the steady state. Ok so what we are essentially saying is although you maybe pumping at a relatively high level ok as far as a gain is concern the gain of the medium is concern the gain gets clamped at the level of the loss inside the cavity ok.

So and like I said any excess pump photons are contributing to the signal photons that are escaping the cavity, is that clear? So question is what are the typical times scales at which this relaxation oscillations happen? So this relaxation oscillations happens a few cycles few pumping cycles ok so what are the pumping cycle? You take a photon from ground state to an excited state and you stay in the excited state until the stimulated emission happens and you come back to the ground state and then your pumping again right.

So it is in the order of and that is determined by typically on one end very few photons it corresponds to the spontaneous lifetime (spontaneous emission lifetime) and on the other hand if you have a lot of photons already in the cavity then your stimulated emission then it is fraction of spontaneous lifetime. So this relaxation oscillations time period correspond to a fraction of the spontaneous lifetime so it will be in the order of few tens of micro seconds typically if you are talking about a system like erbium system that we are now familiar with (you know) our discussion on optical amplifiers. So it is a few 10's of micro seconds is what it takes to achieve steady state and that for all practical purposes is not is a problem right so we can hardly perceive that sort of oscillations but there may be some applications where this may be you know some may be important to track ok.

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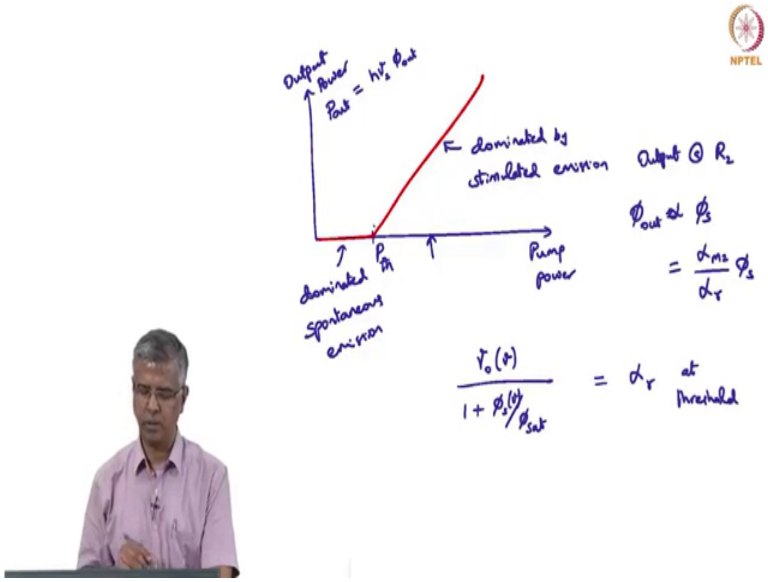

Then we went on to look at this picture little more detail with respect to we pump our if you are looking at the output power or the output flux right. The output power by the way is denoted is dependent on the output flux why what, you have the energy of the photon that is the signal photon that we are getting out multiplied by the rate at which the photons are escaping and the rate at which the photons are escaping is not the same as the signal photons within the cavity right. The photons that they get out is only a fraction of the photons that we have build up in the cavity for example if it is a (())(08:18) cavity with very high reflectivity mirrors then you build up a lot of photons in the cavity and you are actually leaking out only a few photons from the cavity ok. So that is phi when we talk about phi out as the signal photon flux that is coming out of the laser it is actually a fraction of the signal photon flux that is present within the cavity, that signal photon flux is what we are tracking as phi s here right so I can write maybe I will just go to the next page I will just come back to that well I think I can write here itself phi out is a fraction of phi s and that fraction is determine by the loss of the mirror right.

So if you are taking output at R2 so what is R2? If I just go back and look at this picture this R2 this mirror which we would normally call as the output coupler right so that laser output ok is if you are looking at that output that is the it is proportional to phi s right phi s corresponds to the signal flux that is inside the inside that cavity and that proportionality constant is dependent on let us say the mirror loss with respect to the overall resonator loss you understand that? So we are tracking only the fraction of photons that are coming through mirror 2 which is having a reflectivity R2 right so a fraction of that loss compared to the overall loss in the cavity is what we see coming out of that laser ok. Normally what we try to do is you know if you go back and look at this picture you make this as high reflector right.

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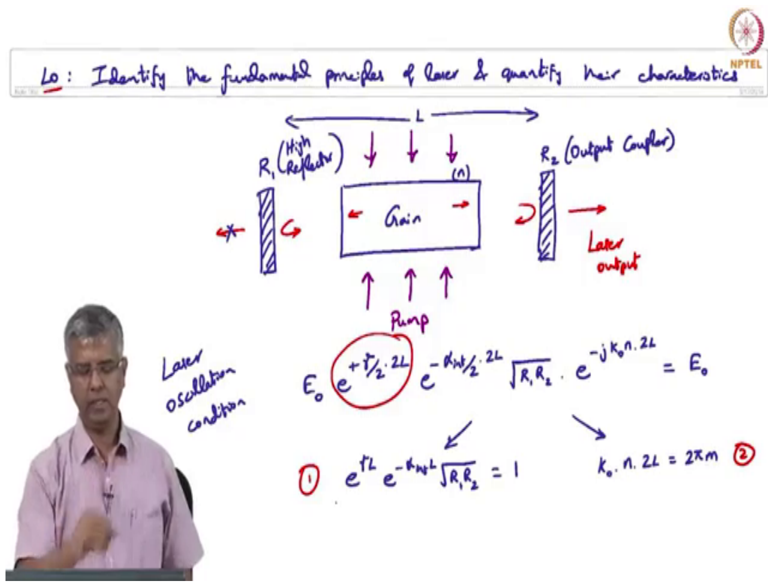

Make one of the mirrors the high reflector so you have very little light going out this way you direct all the light to come out and towards the right side ok. So that is what we do we stop at the point where we were looking at you know from the threshold condition for saturated amplifier right. We basically were trying to get an expression phi s and phi s we say it is given by phi sat this is a saturation flux multiplied by m knot m t h.

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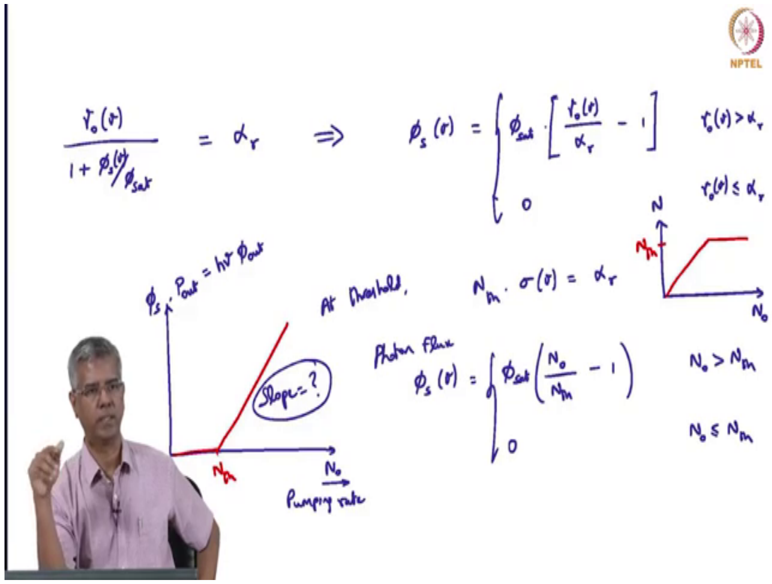

So how much is the small signal gain over the that was sure gain right because any small signal gain that you have beyond the threshold gain is actually contributing to the extra signal photon that we have having in the cavity right minus 1and that is something is happening for n knot greater than n th.

Now I can represent that using another graph just to help you visualize this so when you are tracking n as a function of n knot right or n knot is the inversion that is available to you without any signal photons right that is the small signal inversion that you have right and that just is proportional to the rate at which you are pumping or the pump power right. So on the X axis you are increasing the pump power and correspondingly the Y axis what you get to see is there will be a corresponding increase in the inversion that you have inside the gain medium but that inversion gets clamped at a value n th ok so that inversion will get clamped at that n th value because any further pumping is the inversion which is basically n2 and relative levels of n 2 and n1 are clamped and any further n photons are essentially continuously giving signal photons out right.

So that is essentially what is happening as far as this cavity is concerned. So just to illustrate that we have a question there

Student: (())(14:32)

So it is a good question so the question is do you have only the signal photons coming out or can you actually have pump photons also come out? Right, so any unutilized pump photons can also come out of the laser and if you are designed your laser cavity y you would have absorbed all your pump photons but if the design is not so good then you have the possibility of this pump photons also coming out and then you would have to have a filter at the output external filter to cut off the (pump photons).

Normally when you design this mirrors in this picture when you design this mirrors you design them to be highly reflective well when we talk about high reflection and output coupling those reflectivity's we are considering for the signal photons so this is our actually the reflectivity that we are defining at the signal wavelength but you could possibly you know if you want to conserve all your pump photons you could probably put you know you can make them highly reflecting both the mirrors highly reflecting at pump wavelength.

So the pump photons do not escape the cavity they are all just reflected between the cavity itself right. We know that we have gone through this design of a dielectric thin film filter right you can make this stack of phi and lower refraction index regions and you can actually put coatings such that it behaves or it provides a certain reflectivity at certain wavelength and certain other reflectivity at certain other wavelength. You can basically stack this dielectric thin film layers such that you know one stack can give you let us say 50% reflectivity at 1 micron wavelength ok let us say 1 micron is your signal wavelength and let us say 0.8 micron is your pump wavelength.

You can put another stack on top of that which will reflect all the pump photons ok so you can make your mirrors to be so this mirrors are typically dielectric thin film filters and you can make the mirrors such that they provide different reflectivity's at different wavelengths ok. So just to get all of this together let us just go through a very simple animation ok which is showing how the this laser works right and once again we are looking at a fabric (())(17:45) cavity with a gain medium between the mirrors.

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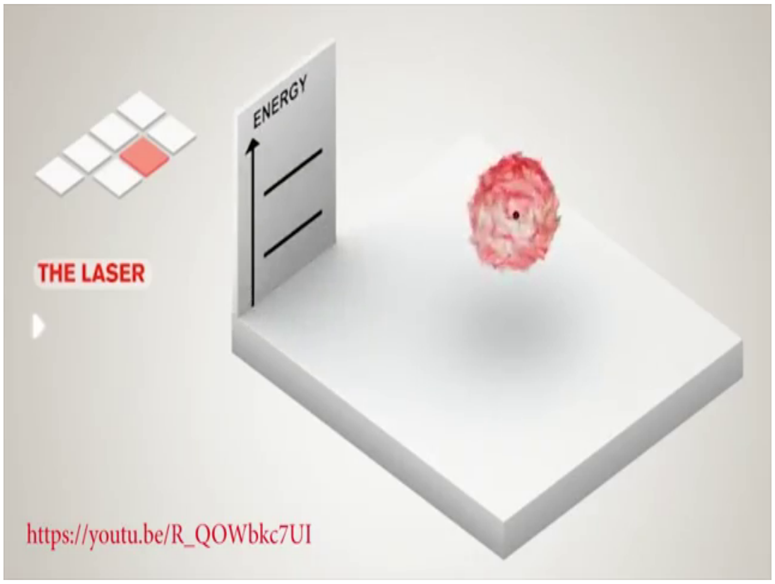

So one is actually atomic picture and you know that red color thing around that atom is actually showing the excitation level of the atom and towards the left side of your screen you actually see the energy level diagram ok. So you are tracking simultaneously what is happening in the energy level diagram as we are exciting this atom.

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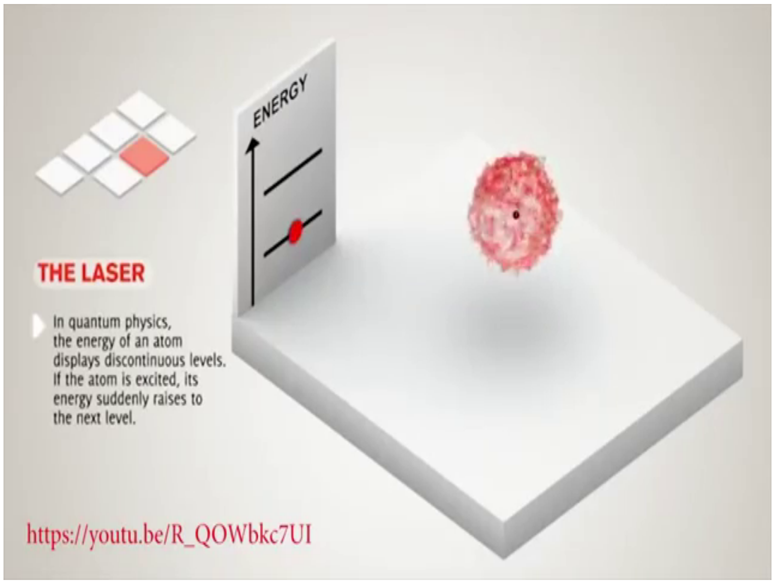

So now it is actually going to a excited state so you can assume that some pump energy has been provided to this atom and it is taken to that excited state.

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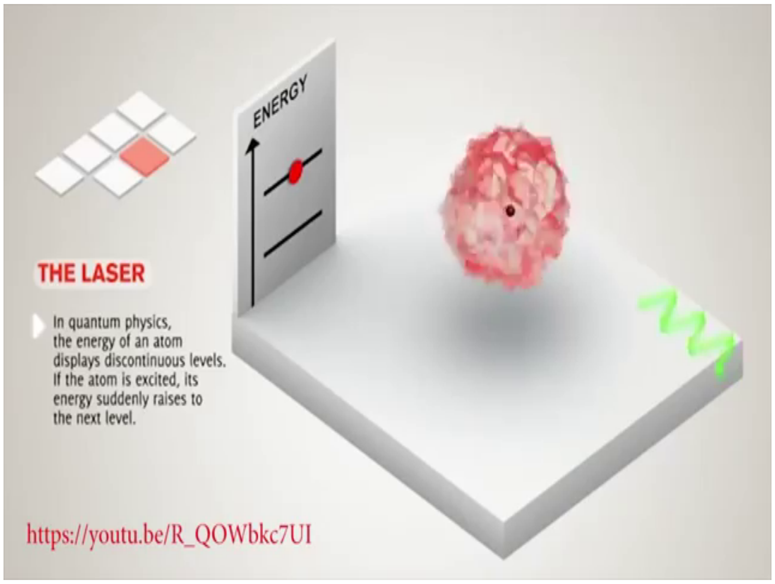

And this is actually denoting a spontaneously emitted photon right this spontaneous emission may actually come from another excited atom in between that gain medium. So when that stimulation happens you see correspondingly the atom is actually de-excited back to the ground state ok now we are starting to build up stimulated emitted photons. So now we go to a picture where you have multiple atoms you know this is a realistic picture where you have multiple atoms each of them could be excited and what we have now is we have put mirrors on either side so this photons are reflected within the cavity and you want to pay attention to the green (()) (19:56) because initially spontaneously emitted photons so they were the periodicity is not very well defined but what happens when you go through a bounces.

So what happens to the things is actually gaining coherence because initially you may have spontaneous emission corresponding to several different frequencies but as you go through this reflections only those photons which are at specific frequencies that correspond to the round trip you know the that interference condition that we talked about only those photons will survive. So this actually becomes more periodic so you can see that now you have not only so many photons but there all quite synchronous with respect to each other.

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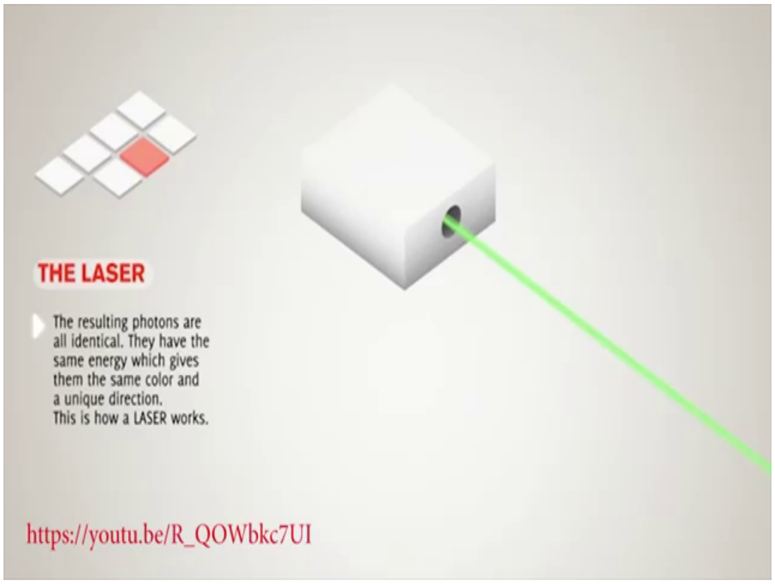

And that is the oscillation that we have and then you have output coupler which is partially reflecting so it is actually leaking out so this is actually showing as a the build up is happening and then you suddenly turn the tap and you get the beam out that is not what is happening really right. So you do have that was just for illustration purpose but we have continuous streaming of output that you know just to show the different processes it is been put in a chronological order right so let just quickly see that again.

And towards the later part of that you actually saw the way that you had is actually a standing wave right so that is what happens in a real cavity it is actually a standing wave you know in the photon picture initially you can think of this photons bouncing around but the wave picture that actually corresponds to a constructive interference criteria and it actually sets up a standing wave pattern inside the cavity ok and so that you can whatever oscillation that you are seeing of the light it is coming out that oscillation you can imagine is actually happening within the cavity itself ok, any questions about this before we move on? Yeah.

Student: (())(23:33)

Professor: so the question is what happens to those other frequencies which are not coherent within that? They actually they just die away they not getting any gain but they are experiencing loss they just die away right. So when we go to multiple round trips they are discriminated against they keep using their energy right only the this particular frequencies are building up (energy) building up in terms of number and the total power as well, any other question before we move on? Ok so let just get back to the so the question is we showed that the atom is de-excited to the ground state upon you know the stimulated emission, how much time does it take for the atom to go up to the excited state again?

It just depend on the pumping rate so the number of pump turns you have the pump photons you have and the probability of the transition which is determine by the transition cross section that determines you know how many of this atoms go back to the excited state again? You have to remember that the numbers that we are talking about are large you know the that numbers that we discussed the number density of ions you know 10 power 24 and the number of photons is in the order of 10 power 19, 10 power 20 so you are looking at that many photons this many ions so there is you know depending upon the relative quantities and the probability of the transition (()) (25:33) any other questions?

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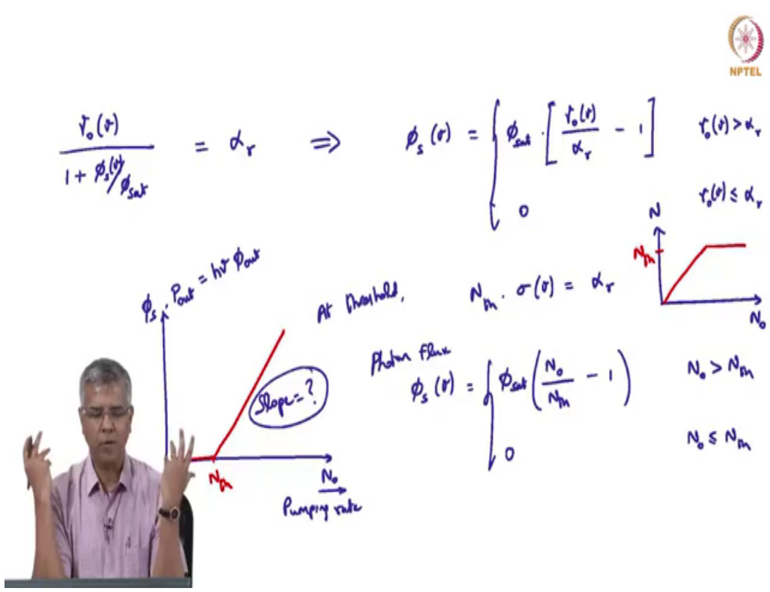

Ok so let us just get back to this discussion so let us continue from where we left off yesterday so the question is what is this slope? Right, so what is that slope and tat is typically what we call a slope efficiency of the laser so slope efficiency clearly determines what is the efficiency with which you are converting pump photons to signal photons, you want as large as slope efficiency is possible ok, that slope efficiency I should mention is related to one more common terminology that is used which is called the wall plug efficiency. As a user of a laser you do not want to worry about how much I am pumping, how much I am (())(26:42) signal photons I am getting and all of that.

You are you know when you look at a eagles eye view of this entire thing you are wondering how much electrical energy that I am spending, how much optical energy am I getting right so in this case you can think of it in terms of power so how much electrical power I am consuming and how much optical power I am getting so that optical power over the electrical power is called the wall plug efficiency.

So you want lasers to have a very high wall plug efficiency to give you an idea the wall plug efficiency of semiconductor lasers can be as much as 50% ok whereas we think about gas laser just some of the earlier gas lasers like argon ion laser the wall plug efficiency is fraction of a percent because there you are trying to setup a discharge and so your putting a lot of electrical energy in setting up the discharge and that discharge is effective and creating an inversion only a fraction of that power is getting converted to stimulated emission and finally the optical power that is coming out.

So nowadays it is become very important because initially whichever way you can get a laser you got it right you just went about I want a laser at this particular wavelength and you did not bother about this wall plug efficiencies and all that. Nowadays you cannot do that everything is you know driven by how much energy use in the process so the wall plug efficiency becomes very-very important number and what supports the wall plug efficiency is the slope efficiency how well do you convert the pump photons into signal photons. So see I have run out of time even before I started my lecture that is the way it is ok let us just stop right there and we will continue after 10 days ok. Hopefully you remember all of this until that time I do want to mention one thing though which is important for the lab session that you are going to have.

What you will do in the lab session is not a Fabry Perot cavity so here I have a made a laser out of a Fabry Perot cavity but as per the laser is concern you just take an amplifier you provide feedback you just loop the output back into the input ok and that type of a cavity where you have taken the output of a amplifier and loop it back to the input is called a ring type cavity or in short it is called a ring laser ok. So what you will be building is a ring laser you would just take the output of the amplifier that you already build you are not giving any input right.

Take the output and you just connect it back to the input so when you pump that medium there is going to be spontaneously emission emitted photons and that is going to loop back and they are going to see their amplification ok and they are going to stimulate the transitions in the erbium fiber and then that is going to recirculate in a loop ok. So what you will be building in the laboratory is actually a ring laser and that is just an extension of the amplifier that you already learned how to build right so it is a very simple extra step but then now what we are looking at is what are the characteristic of laser that we have build. Like this what is the output power as a function of input power, what are the spectral characteristics? So that is what you are going to look at next week.