Fiber - Optic Communication Systems and Techniques
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Lecture – 32
Basics of lasers-I (Structure of lasers, Process of photon emission)

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module, we begin our study of lasers first we will discuss a few principles of lasers which are applicable to different kinds of lasers. So, we do not really need to worry what is the actual laser that we are studying because these general principles are valued for all the different type of lasers.

The reason why we want to study these principles is because you will be using these principles in studying various lasers. To study each laser would probably take a course of its own since our objective would not be satisfied with that one or would be served by that kind of an approach; what we do is we will give you basic ideas of lasers which you can then if you desire. So, or if you the need arises you can apply two different lasers as you know of course, that is the first point.

The second point is that by studying these basics of the lasers then you will be you know able to better appreciate the semiconductor lasers, which is the workhorse of optical fiber communication systems. There once we go to semiconductor lasers study of semiconductor lasers; we will be employing most of the terminology techniques that you would study in this module and perhaps in the next module and at that time you do not have to go and relearn all this basic things.

And the third point why we would like to study these laser basics is because there is an intimate connection between a laser and an amplifier.

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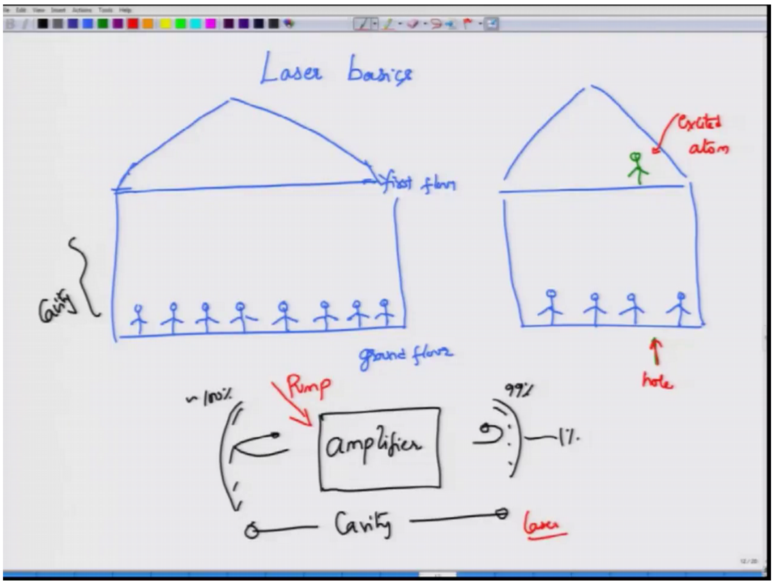

In fact, the connection between them is so interesting that all lasers in themselves will employ an amplifier. So, there is an amplifier inside a laser and then you enclose this amplifier by a certain thing called as cavity ok.

So, you actually make a cavity which is usually bounded on all sides, but of course, if you bound everything and then put the amplifier inside then you will not be able to get light out ok. So, this and cavity is usually found with mirrors with such a way that one of them is very nearly reflecting ok. So, any radiation that comes could be just reflected back; whereas, the other one would still be reflecting, but it would only be about say 99 percent. So, that 1 percent of light that comes out from these lasers is sufficient for us to actually work with it.

Of course the numbers 99 and 1 percent are not to be taken in this manner because some lasers actually work with 90 percent and 10 percent; some of them work with 65 percent and 35 percent. So, depending on different lasers you and depending on how much power you want you can adjust this output coupling ratio ok.

But nevertheless every laser has three main components; the first component even amplifier because without an amplifier you cannot have a laser, but having an amplifier is quite different from having a laser. So, to go with the a amplifier you also need to enclose this amplifier in a enclosure and that enclosure is what you do by having these mirrors so, that light cannot escape, but has instead forced to go into the amplifier by these cavity mirrors.

And third and most important component of a laser is what is called as a pump source or what we call as a pump. What is the pump and what is the amplifier made out of? We are going to start looking at that one, but if you now just look at this picture which actually is a laser most lasers have these three components and then you take away the mirrors and in addition to that you retain the pump and the amplifier.

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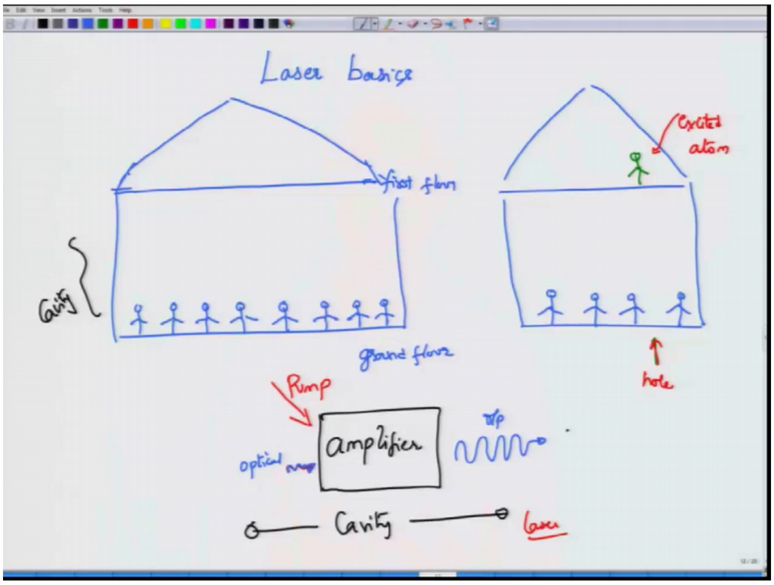

But now supply weak signals from the outside. So, this is the optical signal that I am sending in and what you would get would be a amplified optical output.

So, in that case this is acting like a simple amplifier. In fact, the ideas of amplifier, the ideas of oscillators lasers is essentially in oscillators is not something new; you have already studied this in your electronic circuits. So, you have studied perhaps Hartley oscillator, Colpitts oscillator and if you look at the circuit diagram of those you know oscillators; you would find that there is an amplifier and there is a pumping source. The pumping source or the external energy is coming from the DC power supplies that we are going to connect to the amplifier.

So, if you are going to implement this Hartley or Colpitts oscillator using a bipolar junction transistor. Then you connect the connector to certain you know VCC and collect that emitter to VEE and this VCC VEE supplies are DC signals that are coming in and it is this DC energy that will be converted into AC energy; when you complete amplifier or convert an amplifier by putting in a feedback circuit right and convert an amplifier into an oscillator.

And this cavity mirrors that I talk to you about does exactly the same kind of a job; that a typical say shift network or a feedback network in a Hartley or Colpitts oscillator does. So, going from amplifier oscillator there is a huge connection between the two. In fact, all lasers essentially are amplifiers or include amplifiers, but their radiation is self sustaining, their oscillations are self sustaining once the initial transition period or the transient period is finished.

So, we are going to study these lasers, but I am not going to go very deep into the mathematics I will leave lot of these steps as exercises for you. These steps are not very hard, they just involve you know combining a few equations and then substituting one into the other, but when you do that you will realize how simple the initial ideas of lasers are, but of course, it is not just these ideas or mathematics that is important, but to actually build these lasers, fabricate these lasers and get them to market is the most challenging aspect.

Unfortunately this is a course on physics technology and other things not a course on how to fabricate and then get it out on to the market. So, since that is not the purpose we are not going to look at that aspect your of course, going to look at the detailed theory behind these lasers and what takes it to you know components or what components are required to make a good laser is what we are going to study.

Now, before we can jump in and start studying semiconductor lasers or in general any laser; we need to study a little bit of the call few topics from blackbody radiation. So, what is this blackbody radiation that I keep talking about?

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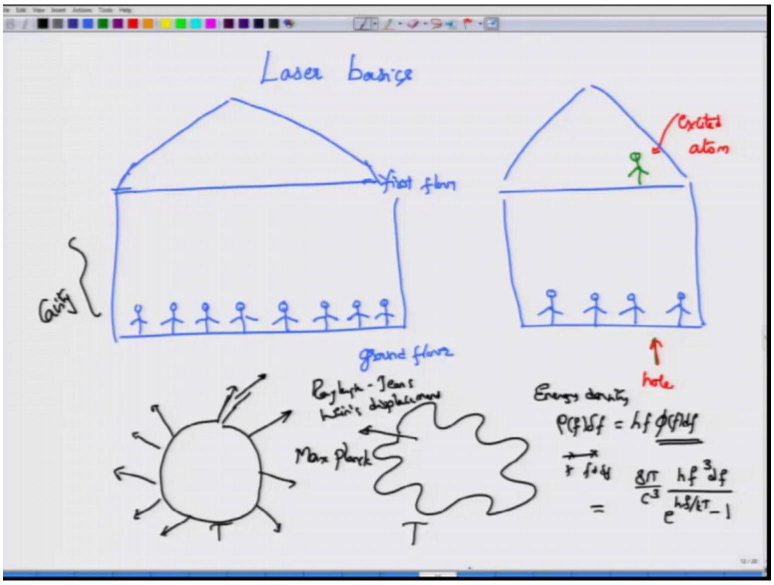

Well if you take a cavity and you take this cavity and heat it up at temperature T, then it can be shown that this cavity would emit radiation. This is something that you would have studied in your physics; every material which is at a temperature T, where T is the characteristic temperature of the blackbody would emit radiation and of course, the body can actually absorb radiation at the same frequency range and as it we would emit.

So, the radiation emitted from a black body which is essentially just a nice manner to talk about a completely closed enclosure. Of course, you will not have completely closed enclosure there will be a small hole in this cavity so that radiation can be actually emitted from that. Although schematically I have shown that this is emitting light everywhere, but actually it will be light will be emitted by this small hole that is necessary to draw out the radiation. And this black body is characterized purely; purely by its temperature no other consideration is necessary.

So, you may have a cavity in this manner or you may have a cavity in this manner which a small hole as I said of the same nature. Then if both cavities are at the same temperature T then the radiation emitted by these two bodies will be identical.

And the radiation that is emitted we call this as rho f delta f; where rho f delta f corresponds to energy density between the frequency f and f plus delta f or the energy that is emitted in that region is given by h f which is the energy of the photons that are emitted from this region times the photon density that is the number of photons between the frequencies f and f plus delta f which we will call by phi f df.

So, phi f df is the photon density in the frequency range f to f plus delta f and hf is the energy of the photons. The product of these two is the total energy density; this is the energy density that we are talking about. And this as I told you is a characteristic completely of the black body temperature itself.

Of course, this radiation is given by a nice equation which I will write it down it is 8 pi by c cube h f cube df; df is the frequency interval that I am considering divided by E 2 the power hf by k T minus 1.

You might ask what are these different variables. c is something that you know c is the velocity of light in free space and it has a value of 3 into 10 to the power 8 meter per second, h is the Planck's constant and this; Planks constant is a very very small, but finite number.

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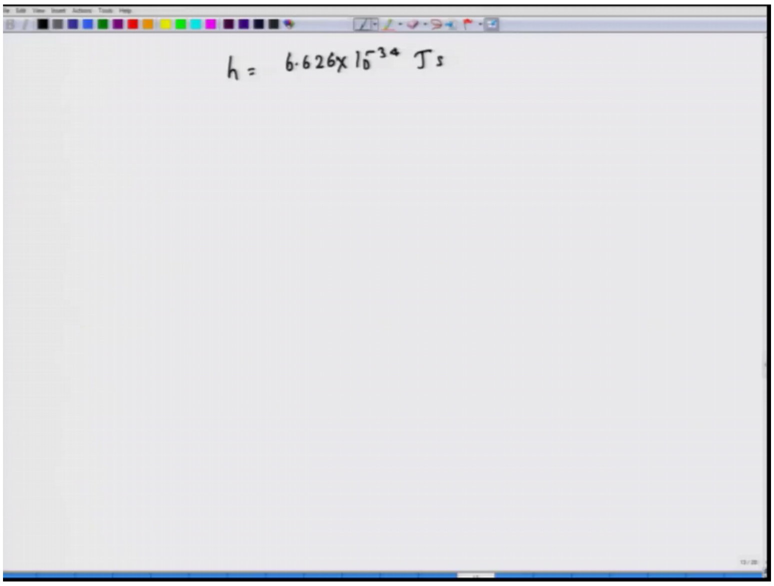

h is about 6.626 into 10 to the power minus 34; I think the units of this one are joule second. And this Planck's constant implies that this radiation that is coming out is actually quantized radiation. The history of this quantized radiation is something that we do not want to go, but some names like Rayleigh law or Rayleigh Jean's law and then you know other thing Wein's displacement law; all those things are associated with the same thing that Max Planck worked on. And his ideas of radiation quantization have led to the development of quantum mechanics as something that you already know from here 10th or 11th and 12th class physics or maybe in your engineering first year as well.

But the important point to note here is that this formula the radiation formula as given by Planck involves c; which is the constant, h which is the constant. Of course, frequency range is defined by whatever the frequency range that you want and then you have e to the power hf by k T minus 1. So, this term if you see as dependent is dependent only on f and T.

Now, this is the blackbody formula and please keep, this particular formula in mind we are going to use this formula later on. But now let us go back to something else; blackbody radiation as we talked about is specific property of the matter. But if we look at what the matter is right matter consists or matter consists of these atoms and these atoms typically have these energies.

However, in matter there will be different energy levels or energy bands ok; we will talk about energy bands later on, but intuitively if you think of a single isolated hydrogen atom for example, then the level n equal to 1 will have a, certain energy then n equal to 2 will have a certain other energy and so on.

Similarly, when you talk of matter instead of single isolated energy or energy levels; you will have isolated energy bands. So, you will have a band of energy we will call this as E 1, then the next band of allowed energies we will call as E 2 and the next band of allowed energy levels we will call as E 3 so on and so forth.

So, this concept of matter having these different energy levels should be something familiar to you from your simple hydrogen atom kind of a study. So, keep that in mind and to simplifier analysis instead of considering bands I am going to consider discrete energy levels; I am going to assume that we have this discrete energy levels.

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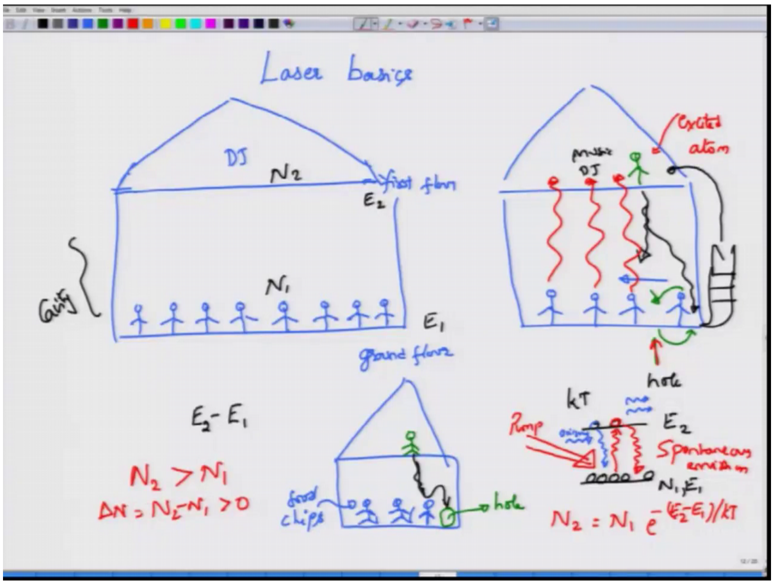

And call these energy levels as E 1, E 2 and so on ok. For now we will simply consider only two energy levels which is you know typical that we would be studying. And the difference between the two energy levels we will denote it or we will give it by E 2 minus E 1.

A crude analogy I want to show here is you can see this one; I have a house or someone has a house and there is a party going on and there are lot of these people attending the party ok. So, you have certain population in the ground floor because the party is being held in the ground floor and in the normal condition of this party everyone is occupying the ground floor ok.

So, there is a certain occupation density or the number of people occupying this particular floor; means since this floor corresponds to a certain energy we have you have call it as E 1 and this people occupying this the density will be denoted by N 1 and you would see that the energy level N 1 or at the energy level E 1; the population density N 1 is quite high almost everyone is in the energy level N 1.

But suppose and now if we look at the population of people at the energy level E 2 and population of energy level E 2 means that you are talking now about first floor. When the temperature is 0; then there will be no people at the top. So, you can in the analogy why is imagine that no one has an energy to climb the stairs and then go to the first floor. And that would happen in the matter condition when the matter is kept at temperature T equal to 0.

So, most of the energy levels are or the energy and most of the population is actually filled or inside all of the population is filled and existing only at the ground level energy which we have called as E 1. Now suppose that you are now at a higher temperature which means that there is some now some music or something that has been turned on in the first floor.

And there will be some people who are actually who like music and what they will do is that they will climb up the stairs ok. So, these are my stairs very crude manner and they will actually go into the first floor; we call them as excited atom in the matter kind of a thing.

So, in the matter when there is non-zero temperature then there will be certain energy associated or in certain energy available to the atoms which are sitting in the ground floor. And these atoms can absorb that energy usually its electrons which would absorb this energy and this electrons would then jump to the next available elect you know electronic level or the energy level ok. I am assuming since there are only two energy levels; they can go from E 1 to E 2 right.

So, in the party scenario this is analogous to someone being excited by the presence of music or a DJ and then taking the steps to go from lower you know for the for ground floor to the first floor and enjoy the music out there. But when a person leaves from the ground floor to the first floor; they would have created an empty or a vacant space in the ground floor and this empty or vacant space in the ground floor is what we call as a hole ok; so, hole has been left.

Now, suppose the host of the party brings some interesting food here on from the left hand side ok. So, maybe this would be some potato chips that are brought in and what would happen? People are hungry and each of them would start walking towards the food. So, people would line up to get food; so, here are people lining up in the direction of the food.

And because there was a space here I have kept the space as it is and of course, you still have a first floor where one person is definitely enjoying music not caring about the chips. So, what you have actually seen is a very interesting phenomenon; the person here moves to the left and then starts eating the chips you know because you cannot move or the person she cannot move to the left anymore, but the idea is that as the person moves to the left the empty or vacant space has moved to the right.

So, you can see that the vacant space or the hole has been moved to the rightmost corner of the ground floor ok. And this can be thought of instead of keeping track of people moving to the left; we will keep track of the vacant spaces moving to the right.

Now, in ordinary matter when the matter is at a temperature T greater than 0 ; the only way the electrons in the ground energy state can move to the next available energy state is by you know absorbing this kinetic energy that is obtained from the non zero temperature and the amount is k T. But let us say once this person has moved up he or she cannot always remind at the first floor and would occasionally want to drop back to the ground floor because maybe they also like the food or maybe; they just got bored or maybe they just exhausted all of the energy they would like to just you know jump back to the first floor.

And when they do so, they are going to combine usually into the hole right; of course, they have to combine with the hole because they cannot land on a person's head. So, what they will actually do is to land on the hole and then what we say is that they have recombined.

So, in the same manner in an ordinary matter; electrons will be mostly located in the ground level with an energy level E 1 with a population density N 1. At energy level E 2 the population will be sparsely present because whatever the energy that is there has to come only from k T; unless you send out external energy. So, you send in external energy in whatever form usually in the form of electrical signals or in the form of another optical signal ; causing the electrons in the ground floor to excite into the next available or ground state to the next available energy state.

And of course, the excited electrons cannot remained continuously there; they will drop back after a certain characteristic time. This characteristic time and energy are actually related by Heisenberg's uncertainty principle; which means that if we know the excited energy or if you have a excited the electron into the next available energy slot ; then because we can predict the energy of that electron ok; the time at which it stays in that position will become uncertain and there is a characteristic time scale after which the electron spontaneously you know drops back to the ground state or the ground energy state.

So, there are two kinds of things that are happening right. So, one is that there is a pumping going on; this pumping causes or gives certain amount of energy to the electrons in the ground state, which will then allow the electrons to go from the ground state energy E 1 to the next energy state E 2. And once they have reached the energy state E 2; they will not linger on there forever, they will actually start falling off to the ground state and after a certain characteristic time and that falling off on their own is called as spontaneous emission.

So, this is called as spontaneous emission ok; there is also another way in which this exact electrons can fall down is when a certain photon or certain optical packet arrives or photon arrives let us say of the energy which is just sufficient for the exit electron to actually drop down. So, it is kind of going there and then saying hey my friend why do not you drop down.

And when it does so ok; you will actually get two photons one because the atom has moved from energy state E 2 back to the energy state E 1; that if it has combined into the vacant hole here ok; which leaves us one photon. And there was already an original photon here which was initiating this interaction; which does not get absorbed with remains as it is; its only goal or its only effect is to nudge the inserted electron. So, that there existed electron can actually go down to the; ground state and then recombine and generate another photon.

And you can imagine that if the number of you know excite electrons in the level two are much higher than the number of electrons in the ground level a one or two photons are incident or sufficient to drop a large number of electrons from E 2 to E 1; generating a large number of photons ok. So, with very few photons to begin with which could come from noise in the system or externally you know indicated then you can actually build up to an extremely large optical power at the output of the laser.

And we should of course, have certain materials with certain energy gaps E 2 minus E 1 which will be in the particular wavelength range as we will talk about it in the next class or in the next module. So, that this stimulated emission can happen in the wavelength range that we want and we should have the ability to pump the electrons which are usually occupying the ground state onto the excited state.

So, which means that in the party analogy we should you know have music or a DJ music in such a way that most of them would like to be excited onto the first floor and very few people would be allowed in the ground floor. And when most of them actually excited and go to the first floor and then when something else happens like potato chips are brought in ; when people will drop from the first floor to the ground floor and then you know one or two chips is sufficient for many people to drop down and then generate you know photons which will then be amplified.

So, you start off with one or two noise photons and that output of a laser you have this huge number of photons coming out and this can be sustained by you know having this feedback mechanism. So, people once they have dropped down; you again excite them by nice music. So, in the matter case once the pump has taken the electrons in the ground state and excited them to the next available state you again and again excite though.

So, the atoms which fall down are continuously excited back into the state and you should essentially create a situation, where the number of you know atoms in the energy level E 2 or the excited state an electrons their density in is much larger than the density in the ground state.

Normally ground state is the one that is completely filled or mostly filled and the population at the energy level E 2 will be very sparse ok. When the temperature is non zero there is a certain relationship which will allow you to tell how much would be the population density that one can expect in the energy level N 2 and you can see that the energy level N 2 will be something like N 1 e to the power minus E 2 minus E 1 divided by k T.

So, if you have sufficient energy k T; then you can still see that N 2 would normally this is under the simple equilibrium no pumping. So, what would be the condition is that N 2 will be sparsely populated, but when you pump and then excite; then it is possible for you to create a situation where N 2 will be greater than N 1 or the difference N 2 minus N 1 will be greater than 0.

We denote this difference N 2 minus N 1 by delta N and call this delta N as the population inversion means inversion right. So, you had most of the electrons in the ground state, but after pumping most of the electrons have been pushed into the higher order or higher energy state. And if they sustain there for some time when you actually put some noise photons here; then they would all drop down and you know generate a stimulated emission. And then you can sustain the stimulated emission by taking this light which is coming out of the laser or the amplifying medium and then pushing it back why are the mirror feedback right.

So, you have this cavity mirrors which will then take these photons and then push them back. So, repeatedly this light goes back; gets amplified goes back gets amplified sustains itself and essentially comes out as a stimulated emission of radiation ok. So, in the normal un pumped case there is only thermal energy which is available for the electrons; they would go to their higher energy state, but then they would drop down after a certain time by what is called a spontaneous emission.

This spontaneous emission results in a photon, but many such spontaneous emissions do not give you a sustained radiation and spontaneous emission by itself does not give you lasers. However, spontaneous emission is very important; in a light source called as light emitting diode. Because in the light emitting diode there is no feedback, there is no you know sustained stimulated emission; all of the light that comes out is because of the spontaneous emission.

And we can show that spontaneous emitted light will be highly incoherent therefore, it has a wide spectral range and suitable only for low data rate optical communication applications. We are still not done with the laser basics; what we will now do is to write down certain equations for N 1 N 2.

And we will see that only two level systems will not or we will not show that, but we will we will tell you that only two level energy systems cannot sustain lasers or laser lazing is not possible; so, you need another level a third level. So, materials with three levels at least for a laser to work.

Of course in practice you will also have more than three levels you will also have four level lasers, but for majority of the lasers that we are interested we can approximate our material amplifying material as having three energy states E 1 E 2 and E 3. In the equilibrium case the population density will be like N 1 much much higher than N 2 which is much much higher than N 3.

But once the inversion has happened; N 2 will be much higher than N 1 and N 1 will be much higher than N 3. How do we bring this about? What are the conditions, what is the pumping rate that is necessary and once that pumping rate is achieved what happens to delta N all that relationship is what we are going to study in the next module.

Thank you very much.