Introduction to LASER
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Lecture - 09
Laser Rate Equations: 3-Level System

Welcome to this MOOC on Lasers. In this lecture, today we will see Laser Rate Equations in a 3 Level System. A very quick recap that in the last class, we discussed about 2 level, 3 level and 4 level systems. In particular in 2 level systems, we saw that population inversion cannot be achieved in steady state even by external pumping.

And then we saw that the 2 level system would in general act like an absorber and we also discussed about saturable absorbers. So, today we will take the 3 level systems, write down the laser rate equations and then find out the condition under which amplification by stimulated emission is possible,.

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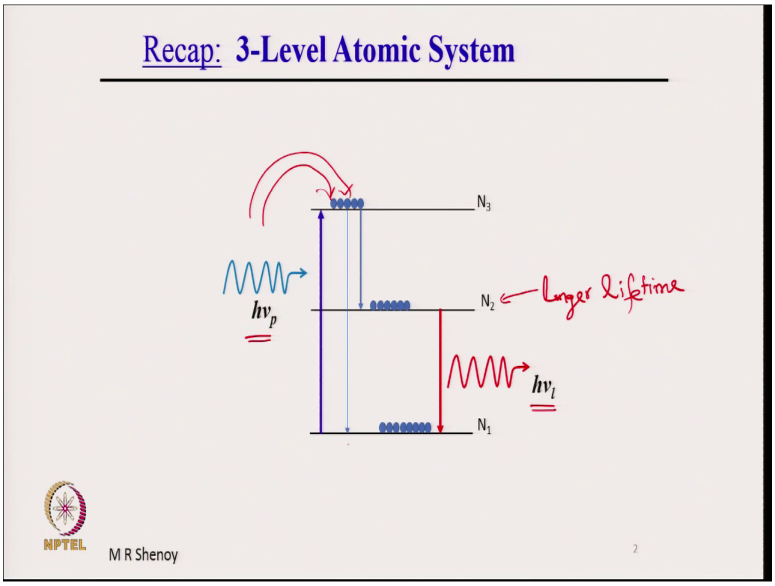

So, a very quick recap of what is the 3 level atomic system. So, basically the 3 levels which participate in the interaction are the ground state and two excited states are the upper levels. N 1, N 2, N 3 are the population in these levels and the possible transitions we have shown that, from ground state, we can have absorption go to the third level and then the atoms can come down directly to the level 1 or they could also come down to level 2 and then come down to level to the ground level.

Any other transition we have neglected in this. Now, h nu p is the energy of the pump photons and h nu l is the energy of photons corresponding to the transition from 2 to level 2 to level 1. So, what we have discussed is, it is possible to have population inversion between level 2 and level 3 if we pump sufficiently fast to this upper level and if the atoms come down rapidly to the level 2 and then they stuck get stuck or wait here for a longer time.

In other words if this level 2 has a longer lifetime, if this has a longer time, then it is possible that the atoms will life time. Then the atoms can accumulate in level 2 and soon they can become more than the number of atoms in the ground state N 1 and population inversion can be achieved. So, we will write the rate equations for this system and see what is the method, whether this condition is correct or not, alright.

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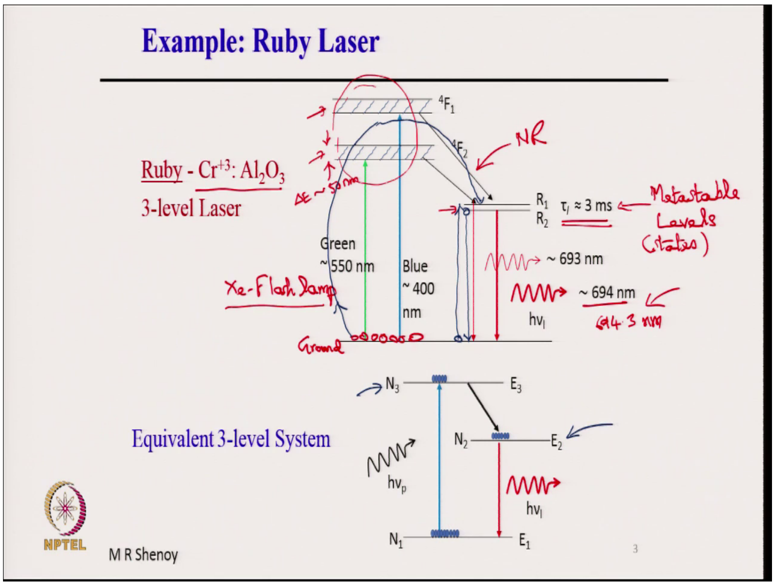

So, before we write the rate equation; the system that we are discussing is typical of a ruby laser; a ruby laser is a 3 level system. But the actual levels of ruby are shown here. So, this is the ground state. So, ground and there are two bands which are shown here 4 F 1 and 4 F 2 at the excited level, which correspond to wavelength. So, these are approximately 50 nanometer wide; the energy delta E corresponds to delta E is corresponds to; it is not delta E of about 50 nanometer.

So, they are two absorption bands. Therefore, green light around 550 nanometer will be absorbed will excite atoms from this ground state here from the ground state to the 4 F 2 level and blue light around 400 nanometer wavelength will excite atoms to the upper state. These atoms rapidly come down to two intermediate states, which are called R 1 and R 2; these are traditional nomenclatures of R 1 and R 2. The level R 1 and R 2 have a long lifetime, typically about 3 millisecond in the case of ruby.

Ruby is chromium doped alumina; it is a chromium doped alumina crystal, which has levels. So, these levels which have long lifetime are called metastable states; so, metastable, metastable states, levels or states, metastable states. So, whenever you have energy levels which have a long lifetime, atoms can accumulate there. So, what is happening is, atoms are excited to a higher energy bands 4 F 1 and 4 F 2, usually they use a xenon flash lamp.

So, X e flash lamp, flash lamp is used to excite these atoms; we will discuss ruby laser when we discuss about the laser systems towards the end of this course. But right now a very quick outline of this ruby laser, just to show that this is a 3 level system. There are several levels participating, 4 F 1 and 4 F 2 are the excitation bands that is atoms; if they are excited to these bands, they rapidly come down to levels R 1 and R 2. So, these are rapid non radiative transitions, non radiative transitions, very fast non radiative transitions.

But the transition from level R 1 and R 2 are slow and that is why the lifetime of the level is of the order of 3 milliseconds. And this transition gives down two lines, the 694.3. So, this is 694.3 nanometer is the predominant line of the ruby laser and this is 692.9, which is about 693 nanometer is less dominant. So, this is the ruby laser line which is the dominant laser line.

Now, the important point to note is, the role of these two bands, the role of these two bands is to populate the metastable level through the excitation mechanism. In other words, essentially let me change the color here. So, essentially atoms are excited to this level or this band and then from there, they come down here.

In other words, the band helps in populating this; because if we were to pump atoms directly from here to here, they will come down with the same probability. And therefore, we can never achieve; we have already seen in a 2 level system, we cannot achieve population inversion.

However, if we pump atoms from ground state to a third level or a third band or a multiplicity of levels, from where atoms rapidly come down to an intermediate level; then we can have inversion, population inversion between this intermediate level and the ground state.

And therefore, an equivalent 3 level diagram is shown here. So, the upper excitation here, upper level is actually the combined bands which are shown here. So, there is a third level, atoms are excited to the third level; from where they come down to the second level, where population inversion can take place.

So, right now I have not shown population inversion, but population inversion can take place. And the transitions which are shown are the predominant transitions; in the sense, atoms are absorbed to this higher excited level or multiplicity of levels, from where they come down rapidly to the second level and from there this second level could also be a multiplicity of levels, from there it comes down to the ground state.

And again just to repeat that, if the second level, here intermediate level has a long lifetime or it becomes a meta stable state; then atoms can get accumulated here and create population inversion, which is the necessary condition for amplification by stimulated emission. With this picture in mind, let us write down the rate equations, ok.

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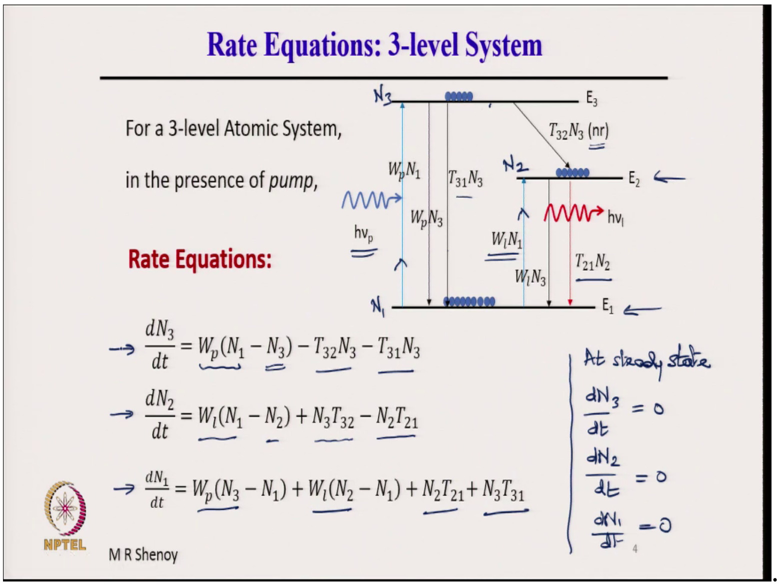

Rate equations for a 3 level system. So, for a 3 level system in the presence of a pump, so this is the pump; a pump which is exciting atoms from the ground state to the third level; the rate equations are, first we are writing d N 3 by d t. So, if N 3 is the number of atoms in level 3, N 2 is the number of atoms here and N 1 is the number of atoms.

Then d N 3 by d t tells us the rate of change of population in level 3 that is N 3. Now, N 3 would increase because of an absorption W p times N 1. So, this is absorption, W p is the pumping rate per atom, but and therefore, W p into N 1 will tell us the number of atoms excited to the upper state per unit time per unit volume.

Now, the same W p will also bring down atoms here by stimulated emission and therefore, we also have. So, W p into N 1 will increase d N 3 by d t that is N 3 will increase and W p into N 3 is the atoms coming down here. And therefore, it is negative; it will reduce N 3 and that is why we have here minus N 3 term, W p times minus N 3. What are the transitions?

There is T 32 into N 3; so, T 32 into N 3. So, atoms which are spontaneous transitions, in this case it is primarily non radiative transitions. So, n r here referring to the non radiative transition. So, T 32 into N 3 and one more term atoms could also come down here, it is written here.

So, T 31 into N 3, atoms from here could spontaneously come down here or spontaneously come down here. They may come down by stimulated emission, which is W p into N 3. So, these are the only possible transitions as far as level 3 is concerned. So, we have taken care of all the four terms. So, 1, 2, 3 and 4 four transitions.

Now, let us look at d N 2 by d t that is rate of change of N 2 at level 2 here. So, at level 2 you can see there is transition coming from level 3 and from level 2, there is stimulated emission, spontaneous emission and then absorption. And therefore, we have four transitions here as well; therefore we have 4 terms as before W l into N 1, that is this one absorption, the one which is going up here W l into N 1, will increase N 2, therefore it is positive number.

W l into N 2 will come down and therefore, it is a negative minus. And then T 32 into N 3 will add atoms to level 2 and therefore it is positive, N 3 times T 32 and minus N 2 times T 21; because from T 21, atoms are coming from level 2, the T 21 transition will bring down atoms, which means there is a loss of atoms at level 2 and therefore, it is a negative sign.

And therefore, this is for this level. And what about the last level N 1? So, the rate of change d N 1 by d t will be equal to, you will see that there are six transitions here; therefore six terms will be there, W p into N 3 atoms coming down from here then atoms coming down by spontaneous emission, stimulated emission; atoms coming down by spontaneous emissions, stimulate.

So, four positive terms spontaneous, spontaneous, stimulated and stimulated and then two negative terms which are absorption, so one going up here and one going up here. So, two negative terms, there are six terms. So, these are the rate equations, which describe the rate of change of population of levels 1, 2 and 3.

So, that is why these are called rate equations for a 3 level system, alright. So, now, let us pick up the first one here, d N 3 by d t and at steady state, each one of them must be equal to 0. So, at study state, at study state, maybe it is written in the next page; at steady state each one of these equal to 0, that is d N 3 by d t equal to 0, d N 2 by d t equal to 0 and d N 1 by d t equal to 0, alright. So, let us use the first equation here, d N 3 by d t equal to 0.

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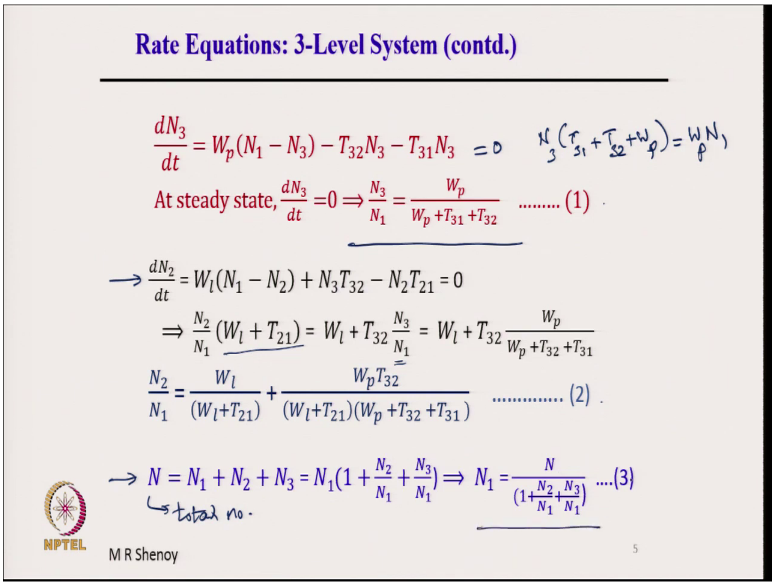

So, this term here is equal to 0. So, if we put that equal to 0; then we get we can simplify this d N 3 equal to 0. So, we take N 3 terms to one side that will leave N 1 only here. So, we have N 3 into; when this goes to the other side, so N 3 into T 31 plus T 32 plus W p. So, will. So, we have N 3 into T 31 plus T 32 plus W p equal to W p into N 1 that is the first term. And therefore, N 3 by N 1 is equal to W p divided by W p plus T 31 plus T 32.

Similarly, the second term d N 2 by, second equation d N 2 by d t equal to 0 gives us. So, we can write, take the N 2 terms together and N 3 terms together and then we can write N 2 by N 1 into W l plus T 2 1 is equal to W l plus T 32 into this. Now, N 3 by N 1 we have already got the expression here; therefore that is equal to W l plus T 32. And for N 3 by N 1, we substitute one 1, which is W p divided by this.

So, which comes out therefore, N 2 by N 1 this term goes to the other side and you have W l divided by W l plus T 21, this term here plus W p into T 32 divided by. So, W p into T 32 divided by this term into the other term. So, this is equation number 2. So, we have got expression for N 3 by N 1 and N 2 by N 1.

Now, recall that, N 1, N is the total number of atoms. So, total number of atoms will be equal to N 1 plus N 2 plus N 3. So, if we take out N 1. So, N 1 into 1 plus N 2 by N 1 plus N 3 by N 1; so, we have expressions for N 2 by N 1 and N 3 by N 1, equation 1 and 2. And therefore, N 1 is equal to N, total number of atoms divided by the terms in the bracket. So, this is equation 3, very simple algebra. So, let us continue further.

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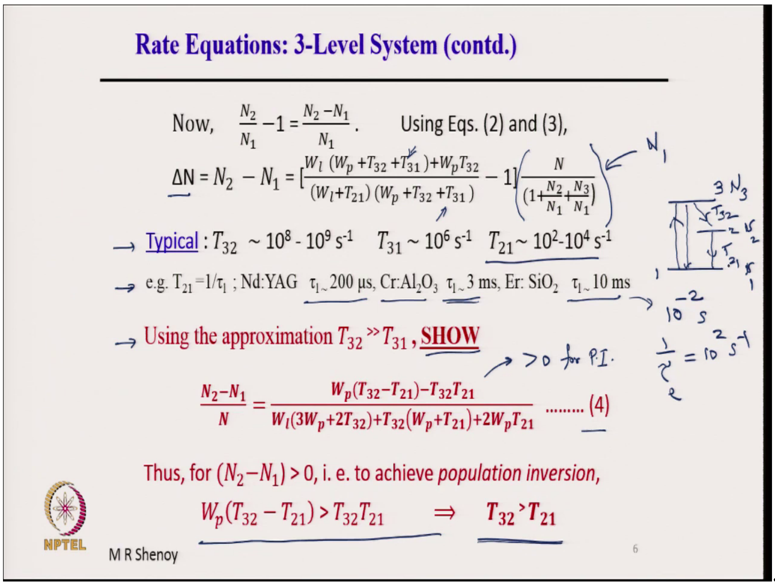

And therefore, now N 2 by N 1 minus 1 is equal to N 2 minus N 1 by N 1. Therefore, N 2 minus N 1; why are we interested in N 2 minus N 1? Because we want to get population inversion; which means N 2 should be greater than N 1. Therefore, if we call N 2 minus N 1 as delta N; then N 2 minus N 1 is equal to N 1 into. So, this is N 1, the whole thing here is N 1. So, this is N 1. So, N 1 into N 2 by N 1 minus 1. So, minus 1 is here and this expression is N 2 by N 1; please see the equation, previous equation. So, N 2 by N 1 is this expression here.

So, we can have a common denominator and then we can get this expression. So, this is N 1. And up to this we have made no approximation at all. Now, we want to see typically, instead of keeping all the terms, some practical approximations can be made. In general in all the subsequent derivations as well, we will try to simplify the expressions by applying practical approximations.

If we have some number which is very big, which is being added by a small number, it makes hardly any difference; but mathematically if you want to do rigorously, you have to keep all the terms, which makes finally at the end of the calculation may be less than one percent difference. And therefore, we will make these practical approximations as and when they are relevant in obtaining simple analytical forms.

So, now let us look at the typical numbers, T 32 that is that non radiative transitions; if we recall the picture here, the 3 level system. So, you have this pump and this is T 32 and this is T 21. So, this is T 21, this is T 32. For practical systems, we know that this non radiative transition is very fast; typically T 32 the numbers are 10 to the power of 8 to 10 power 9 per second. And T 31, that is the transition which is coming from level 3 to 1. So, this is 1, level 2, and level 3.

So, T 31 is typically 10 to the power of 5 to 10 to the power of 6 per second and T 21 is the slowest; because for meta stable states, we are looking at practical laser amplifiers, where there is a metastable state which helps us in creating population inversion. So, typically T 21 is of this order. Let us say, let us take some practical examples; T 21 is one divided by tau l, tau l is the lifetime. In the case of Nd:YAG laser tau l is approximately equal to 200 or 230 micro second.

In the case of ruby, the lifetime is of the order of 3 millisecond; in the case of erbium doped silica, we will see this later, erbium doped silica optical fiber amplifiers, where the lifetime tau l of level 2 is of the order of 10 milliseconds, 10 milliseconds is 10 to the power of minus 2 seconds. And therefore, 1 by tau l is equal to 10 to the power of 2 second inverse.

So, that is what we have written here, T 21 is of the order of 10 power 2 or to 10 power 4 second inverse. The point to note is T 21 is much smaller compared to T 32 and T 31. So, therefore, using the approximation, T 32 is much greater than T 31; for example, here there are two orders of difference typically is much greater than T 31, which means we are neglecting this term T 31 here and here. In comparison to T 32, we neglect T 31.

Then the expression simplifies to this expression here, W p N 2 minus N 1 by N; please see there is a minus 1 here from where these negative signs have come. So, W p into T 32 minus T 21, this is the only. So, we have neglected T 31 comparison to T 32. And then you simply simplify show this that, N 2 minus N 1 by N is equal to this expression, expression number 4.

From this we see that, for N 2 minus N 1 to be greater than 0; that is to achieve population inversion. Please see N 2 is the number of atoms here, N 1 is the number of atoms here, and N 3 is the number of atoms. So, N 2 greater than N 1 means, there is population inversion; to achieve population inversion, the numerator must be greater than 0.

So, this numerator here must be greater than 0 for population inversion. So, let me write as P I. So, that is what is written here, W p into T 32 minus T 21 is much greater than this. This implies first condition T 32 must be greater than T 21. What was this T 32 and T 21? Look at this, this is T 21, rate at which atoms coming and T 32; T 32 has to be greater than T 21.

So, that is what we discussed even before we wrote the mathematics. So, when we discussed here, even before we wrote the mathematics; we said that if this rate is slower compared to this rate, then accumulation can take place at this level. So, now, mathematically we have got this expression that T 32 must be greater than T 21. So, naturally T 21 should be as small as possible; which means 1 by T 21, which is tau l lifetime must be as large as possible or we need a metastable state.

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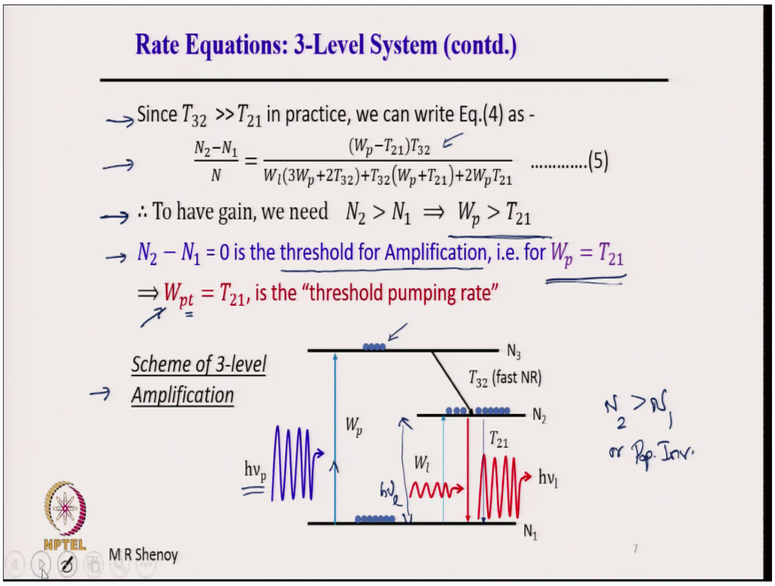

Since T 32 is much greater, the requirement is T 3 should be greater than T 21; but we know that T 32 is much much greater than T 21. Again go back to see the practical numbers, T 32 is of the order of 10 power 8, 10 power 9 and T 21 is of the order of this in practical laser systems.

And therefore, we have T 32 much greater than T 21; then we can neglect. So, in this expression look back, if T 32 is much greater than T 21; so T 21 can be neglected here and then we have W p into T 32 minus T 32 into T 21. So, T 32 comes out and we have W p minus T 21 into T 32.

So, that is what is written here; W p minus T 21 into T 32 in the numerator and denominator is written here. Now, to therefore to have gain, we need N 2 greater than N 1; which implies

W p must be greater than T 21. What is W p? W p is the pumping rate per atom and when W p equal to T 21, we have N 2 equal to N 1 or N 2 minus N 1 equal to 0.

So, N 2 minus N 1 equal to 0 is called the threshold for amplification, it is the threshold for amplification. Why is it called threshold? Because N 2 minus N 1 equal to 0, implies there is no population inversion; but a any additional atoms N 2 in the level will make N 2 minus N 1 greater than 0 and suddenly amplification will start. And therefore, the value W p equal to T 21 is called the threshold pumping rate.

So, W and we add the small subscript t to indicate that it is the threshold value; the threshold pumping rate is simply equal to T 21. What is T 21? One by lifetime and lifetime tau l is a measurable quantity; tau l can be measured in practice and therefore, you know the value of T 21. If you know the value of T 21, you know what is the threshold pumping rate which is required before amplification starts; so, you know the pumping rate required to start amplification.

Now, once we know the pumping rate, then we can calculate what is the power; because in practice we would require to know the pumping power and we will see how to calculate the practical pumping power in watts or kilowatts or whatever, so units that what is that number, rather than just writing W p, alright.

So, finally, therefore, the scheme of 3 level amplification is summarized here. You have a pump of energy h nu p which is raising, that is which is exciting atoms from the ground state to level 3 and from level 3 they come down rapidly; therefore you can see the steady state number in N 3 is very small and therefore, numbers are the number of atoms shown qualitatively is very small.

And because T 21 is small, the spontaneous transition rate from here to here is very small compared to T 32, atoms will start accumulating here. T 21 is small means what The lifetime is larger. Lifetime is larger means what? Atoms will accumulate here, atoms take the average time taken by atoms to make a downward transition or to get d excited is large and therefore, we have accumulation taking place here.

And soon it is possible, if you pump sufficiently hard, sufficiently hard so that your pumping rate is greater than T 21; then it is possible to have N 2 greater than N 1 or population inversion, which implies population inversion. So, when population inversion takes place, it the system can provide amplification by stimulated emission. Amplification to which radiation?

The radiation corresponding to this gap, radiation corresponding to this energy difference; because any incident radiation which we call as h nu l, l standing for laser subscript, if radiation h nu l corresponding to this energy difference will get amplified by stimulated emission, coherent amplification by stimulated emission.

So, this is the pump causing a population inversion which results in amplification of the signal or the laser radiation, which corresponds to the energy difference here. This is the principle of operation of a 3 level amplifier, a scheme of amplification of a 3 level system, ok. Let us discuss something more, an important concept of gain saturation. Now, recall equation 5, it is the same equation I have rewritten; so equation 5 which is here, in this page here. So, this is equation 5. So, it is rewritten here, recall.

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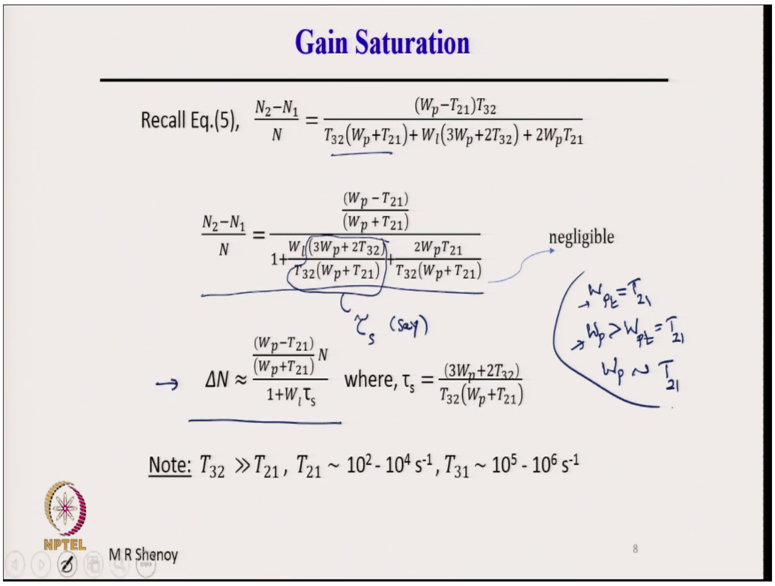

In this equation if you see, if we divide the denominator and the numerator by this term, T 32 into W p plus T 21; then what in the numerator of course T 32, T 32 cancels and we have W p. So, the expression is written here. So, this is the same expression, where we have divided by this first term to all the three terms.

If we look at this last term, T 32 is 1 by T 32 is in the denominator and T 21 is much smaller than T 32. W p is almost of the same order as T 21; because the threshold value is W pt equal to T 21 and in practical systems, W p will be slightly greater than W pt if you want to get amplification.

Because this is the threshold value W pt; so W p pumping rate must be greater than W pt which is equal to T 21 for amplification; but in general, W p is of the order of T 21 and therefore, W p is of the order of T 21; but T 32 is much bigger compared to this number and therefore, this number is, the third term here in the denominator is negligible. So, we neglect this term.

And then we can write delta N as what you have in the numerator plus 1 plus W l into all of this, W l into all of this. So, this we call as tau s, tau s; say tau s, if we call this as tau s, tau is the unit of time. You can see that it is unit of time, because this is time, inverse time, inverse time, inverse time, inverse time.

So, this cancels, but there is another inverse time; therefore, it goes to the numerator, which must be time and therefore, we call this as. So, say. So, we say that let this be tau s; then we can write delta N nearly equal to this, we have neglected the third term, that is why this nearly equal to sign. W p minus T 21 divided by this, where tau s is equal to the term which is within the circle.

So, note that, T 32 is much greater than T 21 and this we have already discussed, typical numbers are here and therefore, this term was neglected. So, the term last term was neglected and we have an expression for delta N here; we will take it further and discuss it in the next.

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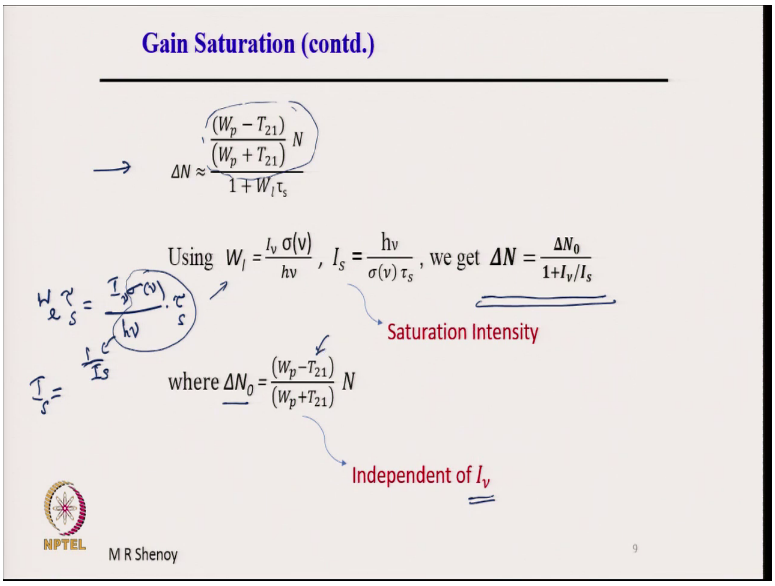

So, here delta N is equal to, this is what we had written there and tau s. Using W l is equal to W l is I nu into sigma of nu, the cross section divided by h nu; this we have derived earlier there in the definition of W l. And I s, if we define I s as h nu divided by sigma of nu into tau s; then we can write delta N is equal to delta N 0. So, we call everything on this numerator as delta N 0 and W l into tau s. So, W l is here, so W l into tau s here. So, maybe I can write here W l into tau s in the denominator is equal to; this is the definition of W l sigma of nu into h nu into tau s here.

Now, what we are saying is, leaving I nu; if you take these three terms together and call this as 1 by I s or I s is equal to as defined there h nu. So, I s, so this term is 1 by I s, 1 by I s. If we define this as 1 by I s or I s is equal to h nu by sigma of nu into tau s; then we can write this as delta N is equal to delta N 0 into 1 plus I nu by I s. So, we have called this quantity as I s; s standing for saturation intensity. Why we are calling it as saturation intensity? We will see in a minute.

And what is delta N 0? Delta N 0 is everything which was in the numerator that was here. So, this was delta N 0. Note that, delta N 0 does not contain I nu or delta N 0 is independent of I nu. I nu is what? I nu is the intensity of the radiation passing through that medium or atomic system, and I s is called saturation intensity. Why it is called? We will see in a minute.

So, delta N is equal to this. We have got an expression, where delta N is intensity dependent; delta N 0 is not dependent on the intensity, it depends only on the pumping rate. Delta N 0 depends on W p, pumping rate; if you change the pumping rate, delta N 0 changes. T 21 is the characteristic of the given medium, it is characteristic of the medium; because it is the inverse of life time.

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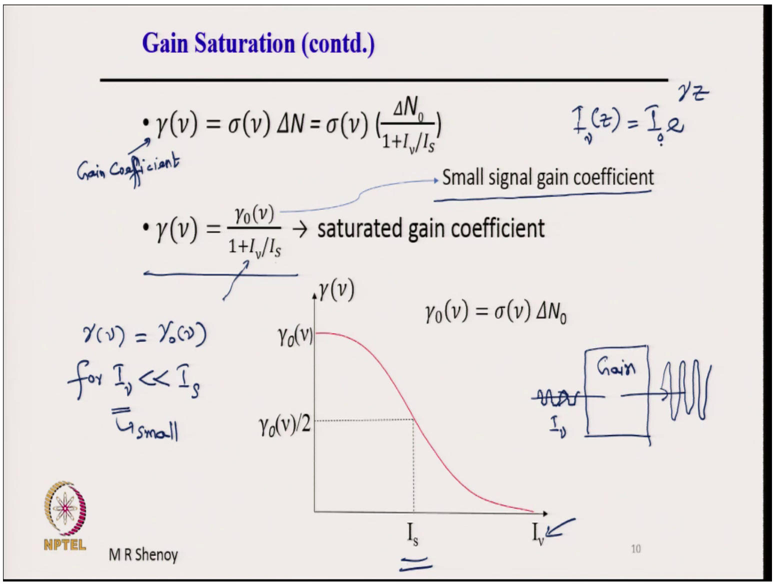

And therefore, gamma of nu, that is the gain coefficient. So, this is the gain coefficient. So, gain coefficient, gain coefficient, gamma of nu is equal to sigma of nu into delta N, we have already derived this. And sigma N into, now we are substituting for delta N, delta N 0 divided by this.

And if we call this numerator sigma of nu into delta N 0, this independent of intensity as gamma 0 of nu; then gamma of nu can be written as gamma 0 of nu divided by 1 plus I nu by I s, where I s is called the saturate, where this expression is called the saturated gain coefficient. I s is the saturation intensity, but this expression is called the saturated gain coefficient.

Why it is called saturated gain coefficient? We can see that, the gain coefficient is a function of intensity of the radiation. So, here is a plot which is showing the variation of gamma of nu with I nu. As you can see, when I nu is equal to I s, which is the saturation intensity the term will become 1 or the gain drops to half of its value, that is the definition of saturation intensity. So, one can measure the saturation intensity by observing that the intensity of the radiation passing through the medium. So, what we are saying is this.

So, you have a medium, which is a gain medium; when light intensity passes through this, you get an amplified output. So, if I can show it as a small sinusoid with small amplitude; then after amplification, you get an amplified output here. Depending on the, this is I nu, intensity of the radiation which is entering and then of course, inside also it is I nu; but I nu will go on increasing.

But if I nu remains small compared to even when it comes out here is small compared to the saturation intensity; then the gain coefficient, if I nu is much smaller than I s, then gamma of nu is equal to the small signal gain coefficient gamma 0 of nu for I nu much less than I s.

So, that in the denominator, the second term can be neglected and this is called the small signal gain coefficient; small signal, because the intensity I nu is small, when this is small, this means this is small. When the intensity is small, then the gain experienced is gamma 0 of nu, which is called the small signal gain coefficient; whereas as the intensity increases, then we will have the saturated gain coefficient. In other words as intensity increases, the gain coefficient drops down as shown in the diagram which is here.

And for large intensity, literally the gain coefficient comes down to 0; gain coefficient comes down to 0 means what? We have I of I nu of z at any intensity is equal to I 0 at the input into e to the power of plus gamma times z; if gamma becomes zero, that means output will be equal to input. Let us discuss this as an application in, it is more clearly illustrated here small signal amplification.

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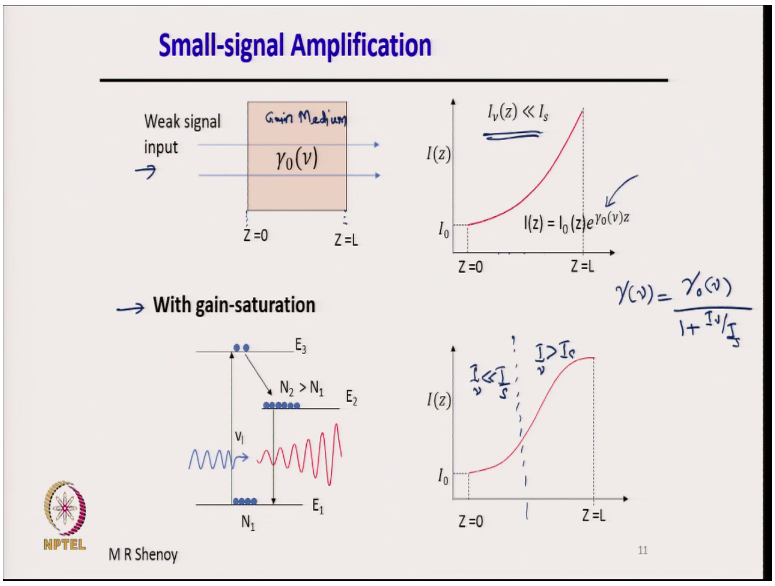

If we have a weak input signal passing through the gain medium, so this is the gain medium, so the gain which provides a gain coefficient gamma 0 of nu; then the input I 0 will exponentially get amplified, exponentially it will build up by this expression I of Z, that at any Z here, starting from Z equal to 0, Z equal to 0 is this point input.

And Z equal to L, L because length of the gain medium is L. So, from Z equal to 0 to Z equal to L, the intensity will build up exponentially by this formula, provided the signal intensity for I nu of Z at any value of I Z, I nu is much less than the saturation intensity and this we call small signal amplification.

But what if there is saturation? That is we have a small signal which is incident, after pass as passed through the, as it passes through the medium, it is getting amplified; but if the intensity becomes larger, then the gain coefficient will drop down. And therefore, the intensity will initially build exponentially and then it will slow down and then it will almost saturate. That is why it is called gain saturation; the intensity variation through a medium when, so initially here. So, if I can show, somewhere here I nu is much less than I s.

And here I nu is greater than I s, that is why it starts saturating, the gain drops down; because gain coefficient is given by gamma of nu is equal to gamma 0 of nu into divided by 1 plus I nu by I z I s, the saturation end. So, when I nu becomes greater than I s, in the denominator this term continuously increases 1 plus 2, 1 plus 3, 1 plus 4 and so on; that means the gain is continuously dropping down.

If the gain is dropping down means, the intensity, the rate at which the intensity is increasing is slowing down. And when the gain becomes, the gamma becomes 0; that is if I nu becomes much larger than I s, then gamma would tend to 0, that means the material no more provides any amplification and we say that the gain is saturated.

This is the concept of gain saturation; very important concept of gain saturation, which is fundamental to steady state oscillations of lasers. As we will see later that, this is the fundamental concept; gain saturation is the fundamental concept, which will lead to steady state oscillations of lasers.

We will stop here and in the next lecture, we will take up the 4 level system and we will see what is the advantage of a 4 level system over a 3 level system. So, practical lasers such as Nd:YAG laser and Helium neon laser are 4 level lasers. We will discuss the laser systems towards the later part of the course; but in the next lecture, we will discuss the physics of operation of a 4 level laser.

Thank you.