Laser: Fundamentals and Applications
Prof. Manabendra Chandra
Department of Chemistry
Indian Institute of Technology, Kanpur

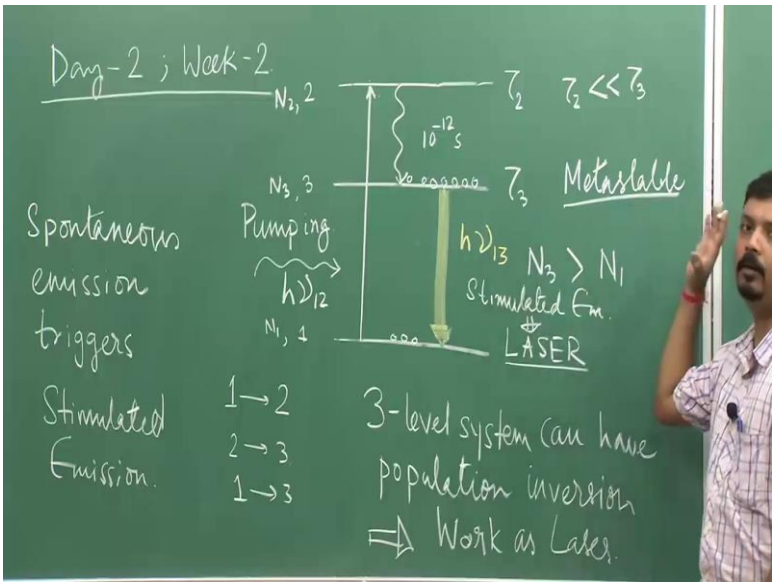
Lecture – 07
3-level System and 4-level system

Hello and welcome back today is the second day of the second week of this course. So, in the previous class we learnt about population inversion and we learnt that in order to have a laser action we need to have population inversion that is the population of the excited state should be higher than the ground state. And when I say excited state and ground state, it means that these 2 states are involved in laser action; that means that they are connected by downward or coupled by downward transition.

And we also learnt that it is not possible to have population inversion in a 2 level system and 2 level system is the one that we started with we did all our you know formalism using 2 level system. So, to at the end we paused a question that 2 level systems cannot work as a laser as it cannot have population inversion, can a 3 level system you know give rise to population inversion and hence can it work as a laser.

So, we started finding out about that one. So, we will start from the back point only.

(Refer Slide Time: 01:42)



So, we will have a 3 level system. So, for simplicity I am marking them as 1 2 and 3. So, I marked them in this way just to you know have simplicity. So, 1 and 2 if I forget about the existence of 3 is just like a 2 level system. So, I know in that case I will not have any population inversion hence, no laser action. Now what happens in a 3 level system? So, first we have to think about what are the transition probabilities here. So, I have total 3 states. So, there are you know total 3 pairs of system between which transition can take place. So, I can have a transition from 1 to 2, I can have transition between 2 and 3, I can have transition between 1 and 3.

So, these 3 types of transitions are possible. Now let us see what are the conditions under which these 3 level system can work as a laser. So, the answer of this question is yes 3 level system can work as a laser, now, under what conditions. So, first is the transition that I will consider from 1 to 2 as we have done already. So, we have to bring in a photon to make the atoms in this state 1 to have a transition up here all right. Now if it just comes back here I know it is not possible to have a lazing action, but if I have the properties of the states 2 and 3 such that level 2 transfers its population to level 3 non radiatively. So, in other word if I say that if state 2 decays non radiatvely to state 3 and if that decay happens very fast, so we show the non radiative transitions by this wavy arrow whenever I show transitions involving states not this part.

The transitions involving this states the you know solid straight line arrow means a transition in a radiative manner on the other hand the wavy arrows signify non radiative transition. So, if this the population in this state after this absorption brings back the system to level 3 and if that process is very fast what does that mean if I say this one state 2 has a lifetime of tau 2 and the lifetime of state 3 as tau 3 then if tau 2 is much much shorter than tau 3 what does this mean it means state 3 is very shortly whereas, state 3 is long live. So, under that condition it will non radiatively decay I am assuming that it decays down here non radiatively no radiative decay I am considering radiative decay will complicated the process. Now this non radative decay we put atoms here right.

Now, this first process that is this absorption, we are providing and external stimulus in form of photons to take this system from here to here and this is known as pumping and this photons that I that we use is called pump. So, I am providing a pump to take the system from 1 to 2 and then non radiatively this population is being transferred here,

now tau 3 is fairly large, tau tree will not decay down here very fast. Now another thing to consider here that this level 3 and level 1 must be radiatively coupled and a downward you know transition should be possible then only I can think about a laser action. If this state also non radiatively decays down to this state then I do not have any emission right emission means it will have a radiative process involved rate. So, the decay of a state from excited to ground state this decay should emit photon then we have a radiative process and here it should decay down to this state radiatively all right.

Now, if I consider a spontaneous emission then it will have its own time it will take its own time to come down here and you know that can be few nanoseconds that is 10 power minus seconds. Now if this say let us say we give certain number. So, this process suppose its 10 power minus 12 second or a picosecond. So, right after transfer of the population to this state 3 state 2 within a picosecond it comes over here, now I am continuously pumping this system right. So, every time I pump it goes and very fast it comes down here right. So, slowly what is happening the population of this state, state one is reducing correct, this population reduces and here we have barely any population you know developing because as soon as it goes here it comes down here by non radiative decay. So, over the period of time the population of this state grows while the population of this state shrinks. So, ultimately I will have a situation where the number of move atoms here will be larger than the population here. This is just to show you.

So, at that condition I have already achieved here if I denote the populations by N 2 N 3 and N 1 respectively then N 3 becomes greater than N 1 at some point of time right. At a 0 time this state has pretty much this you know total population and as soon as we start pumping it grows here. So, after certain time I will see that N 3 is greater than N 1. And now here this N 3 and N 1 is pretty much like what we had in our previous class as N 2 N 1. So, there I needed to have a you know condition that is N 2 greater than N 1 here also I have the same system where N 3 is greater than N 1 right. So, although we are not having a population inversion between the initial 2 states that is 1 and 2, but a third state which has a larger lifetime and we call this as a metastable state as we have mentioned, it is metastable it is not you know stable forever, but its life time is much more than this state. So, we ultimately achieve so called population inversion and therefore, this system can work as a laser.

So, 3 level system can have population inversion right so that means, it can work as laser. So, now, how it will work as a laser? So, let us talk about little bit you know practical products. So, when I am pumping I am giving the energy that is equal to this e 2 minus e 1 right and the lazing axin that is happening here that is let me use a different color, like this right. So, this is my stimulated emission and this will give me my laser action if I can have amplification right. So, I can see that clear of stimulated emission we can have right my aim is to amplify this stimulated emission. So, in order to amplify the stimulated emission; that means, we have to overcome the you know spontaneous emission we have to overcome that absorption then only I can have a net gain. So, we will have an amplification of stimulated emission and it is an optical frequency and we call it laser.

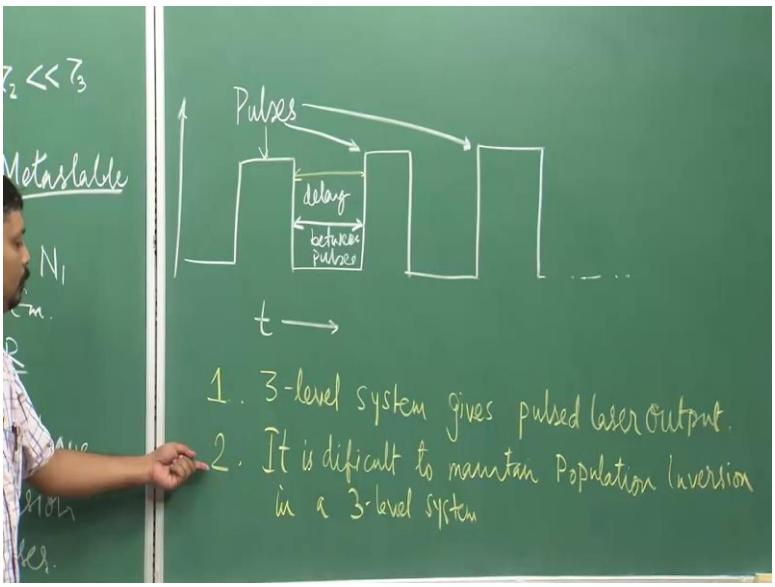
Now as I said earlier that I am using a you know photon say that is having energy h nu 1 2 and this light has energy h nu 1 3 let us you know put it in that way. So, it is equal to the gap between 3 and 1. So, how do we start the stimulated emission? Because stimulated emission requires a stimulus. So, it will not happen you know by its own, correct. So, how this stimulation you know take place? If you think about this state is coupled to this state by a downward transition; that means, from here a downward transition can happen radiatively. So, at some point of time, at some point of time there will be a spontaneous emission. So, one atom in state 3 can just drop to state 1 by spontaneous emission without need of any external stimulant.

Now, that photon exists in the system and that photon can interact one of this excited atoms and bring it down giving total 2 photons then those 2 photons can interact with another 2 excited atom and bring down total 4 give 4 photons and in that way it can you know keep going and going and going. So, in this system spontaneous emission triggers stimulated emission stimulated emission, this must be clear by now I do not need to put any light from outside to stimulate this process these photon which is coming due to spontaneous emission can trigger the stimulate you know stimulated emission. And what will happen in that case? In this 3 level laser system I know that it will take some time to build up the population here and it will certainly take certain amount of time to create the inverted population or to create the population inversion.

So, once the population inversion is created we will have on spontaneous emission taking place and that we trigger the stimulated emission and it is highly possible that then

it will create like an avalanche. So, one foot comes down that goes hits here 2 photons goes out those 2 hits these 2 giving 4 and so on. So, all together all the excited atoms at state in this state 3 can just collapse to the ground state. So, what does that mean? That I will get a bunch of photon within a very short period of time and then this whole state is empty this is all of them have gone down within a very short period of time correct. So, I get a large output now at that condition what happens, all the molecules are back to the ground state and the ground state population is way much higher than this state at that point of time. Again it will take its own time to build a population inversion and again some spontaneous emission will trigger the stimulated emission.

(Refer Slide Time: 17:25)



So, the take home message is that from this 3 level system I will get short bursts of photons. So, so this is time and this is my amplitude. So, I guess this point is very clear here right.

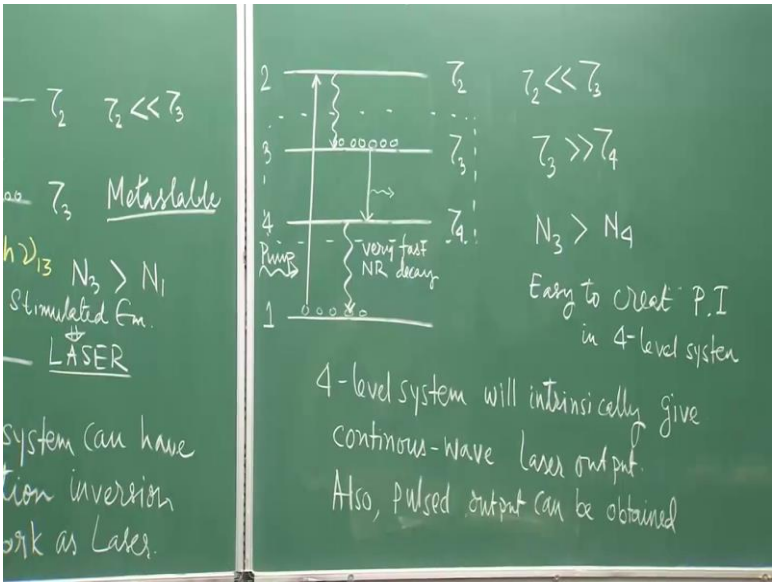
By the design it works in such a way that it cannot give continuous flow of photons or output of photon, but it gives as a burst of photon which is known as pulse. So, these are pulses. So, this is one pulse, this is one pulse, this is another pulse and this is the delay between 2 pulses right. So, this is delay between pulses. So, we get a pulsed output from 3 level system. So, this is first take home message that 3 level system gives pulsed laser output. So, this is what Theodore Maiman got in 1961. So, why this is happening because the actual ground state after molecule is involved in this laser process. So, this

ground state is the lowers you know state between the 2 states which are involved in lazing action.

So, what happens? Here it is difficult to maintain the population inversion. So, the second thing is that it is difficult to maintain population inversion in a 3 level system and because of these actually I have an inherently first laser output. So, if I cannot you know maintain my population inversion then again I have to create the population inversion and the time between the first you know laser output and then again the population inversion creation is essentially this time. And of course, one spontaneous photon emitted photon has to come and trigger the second burst all right. So, you know this was one the first laser that humankind invented essentially Theodore Maiman and this was one of the drawbacks that it cannot be operated in a continuous fashion. Also there were certain other things that it has you know had to be pumped really really hard.

So, what does mean is that you have to put a lot of energy and then pump it there so that you know the population created here is more than here. So, this is kind of drawback now when I go from a 3 level laser to a 4 level laser can we overcome this drawback which is given in this point 2 that is the problem of our difficulty of maintaining the population inversion. So, let us see if we can create population inversion in a 4 level system and also if we can then can it get rid of problem that 3 level system faces. So, let us take a 4 level system in a very similar manner.

(Refer Slide Time: 23:03)



So, again I will name it in the same way. So, first level is 1 and the top most level is 2 and then I have 3 and level 4. So, we will follow the same convention we come with a photon and take the atoms which are here to this level. So, when I send the pump in. So, this is very necessary to you know get familiar with this terms pump.

So, let us pump this to level 2. So, I create some population. Now if this level 2 is just like level 2 here in this system that is if this level has lifetime time tau 2 and this has tau 3 and say tau for then if tau 2 is much shorter than tau 3 and tau 3 is much greater than tau 4 then what happens. Now one more thing also I must tell that this state 2 can non radiatively decay very fast to state 3 and also this state 4 non radiatively decays to the ground state very fast. So, this process and this process are extremely fast and non radiative. So, this is non radiative decay and very fast and the same is true for this one also in that case what will happen after I pump here immediately it will bring the population over here correct and this will take its own time because the lifetime of this state is much higher than this one. So, it will keep building up here.

So, now look at this condition look at this particular system level 3 or level 4. So, level 4 has 0 population according to my drawing I have pumped it here and it has transferred the population over here and they are waiting there. So, there is a waiting period, they are waiting there, there is no population here.

So, at a very beginning when I start pumping I have actually created a population inversion between state 3 and state 4 right. So, in 3 is higher than in 4 and its pretty much all the time as soon as I start pumping it creates this condition. So, it is very easy to create population inversion in 4 level system. For a moment just come back to this picture where level this level and this level were coupled by downward transition and they are involved in lazing. So, population inversion had to be established here with respect to the ground state. So, if you have to do that you had to really pumped it hard we told that right. So, we have to put in lot of energy lot of photons inside to actually create a condition where this state has more population than the ground state which is highly you know which is not the case here. So, this is a contrasting case. So, here creation of population inversion is rather difficult, here creation of population inversion is very easy we and also we need to you know put little energy much lower energy than this case all right.

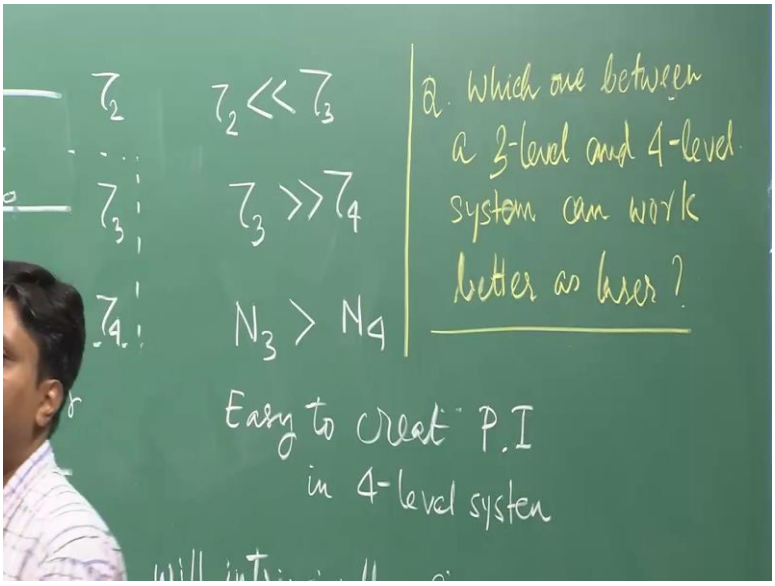
So, now, after saying all these things if I also add that state 3 and state 4 are radiatively coupled by downward transition meaning that it can emit from here to here so; that means, this atoms excited here they can come down to state 4 by emitting a photon. Then just imagine again if there is a spontaneous emission. So, one photon due to the spontaneous suppose this is making this transition. So, this is giving rise to a spontaneous emission or one photon which triggers the decay of all these photons into this state all right now it will give a you know intense light as output.

Now, see the contrast between this and this here it is continuously pumping in here and whenever there are you know photons here this is almost empty because I have already said that this state decays to this ground state non radiatively and that is very fast. If you just look at this you know timescale that is you know 10 power minus 12 second compared to a lifetime of you know say much much longer than that nanoseconds and beyond. So, it will have ample of time to have a population inversion. So, it is therefore, always having a situation where it is having population inversion so that means it will give, a 4 level system will intrinsically give a continuous output of laser light which we say continuous wave laser output because it maintains the population inversion it is not difficult for the 4 level system to maintain or sustain the population inversion. So, I can have a continuous wave laser output.

What is the advantage? Advantage is that whenever I need a continuous source of light I can use it as such. If I need a pulsed output then I can bring in some other technique to make it pulsed I can store the light and keep storing storing storing and whenever I want I open the gate a huge amount of light comes out in a burst. So, thereby I get a pulse all right. So, I can have continuous wave as well as also pulsed can be obtained by putting in some pulsing technology which we will talk about after 2 3 classes there are techniques called queue switching or cavity dumping or mode locking. So, these are certain techniques by using which we can create a pulsed output from an intrinsically continuous wave laser all right.

So, now at this point we will ask you a question that is, which you should try to answer.

(Refer Slide Time: 33:00)



So, out of this 2 level and 4 level system, which one between a 2 level sorry it is 3 level 3 level and 4 level system can work better or more efficiently as lasers. So, you try to answer this question otherwise I will answer it in the following class.

Thank you very much.