Introduction to LASER

Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 11
Laser Amplifiers

Welcome to this MOOC on Lasers. Today we will discuss Laser Amplifiers in this class and the next class we will discuss about Laser Amplifiers. So, today we will take up the Nd YAG laser amplifier which is an example of a 4 level system.

Optical amplifiers; optical amplifiers are based on laser action that is amplification wise stimulated emission of radiation. Amplifiers when we say amplifiers these are coherent amplifiers, these are different from intensifiers. There are intensifiers which increase the intensity of an image for example, or intensity of an the image of an object.

So, these are called intensifiers, but in contrast amplifiers are coherent amplifiers which means if there is an input a signal, then it will be coherently amplified and that happens because these amplifiers are based on stimulated emission of radiation.

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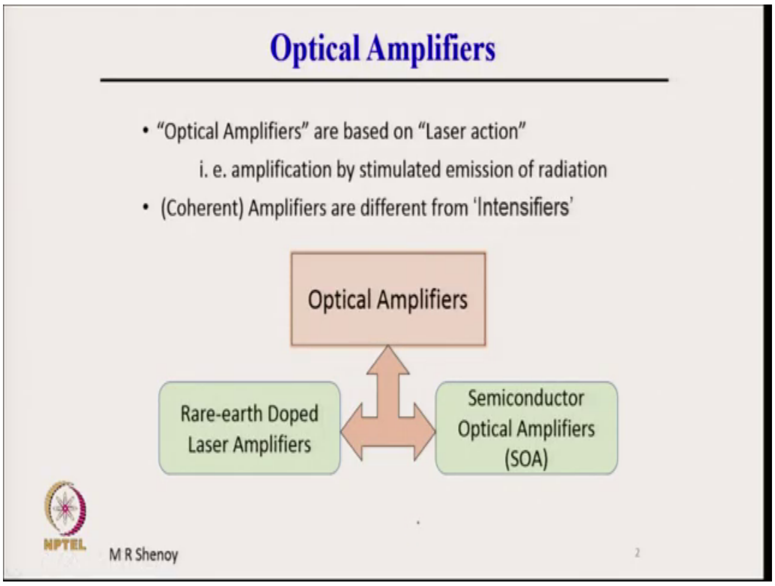

So, optical amplifiers are, there are two types of optical amplifiers, which are widely used. One based on rare-earth doped materials and they are called rare-earth doped laser amplifiers and the other one is semiconductor optical amplifiers. Both are based on stimulated emission amplification by stimulated emission. This is semiconductor; semiconductor optical amplifiers which are the basis of semiconductor lasers and rare earth doped laser amplifiers are the basis or the amplifier in rare earth doped lasers such as Nd YAG lasers. So, in this course we will primarily focus on rare earth doped laser amplifiers.

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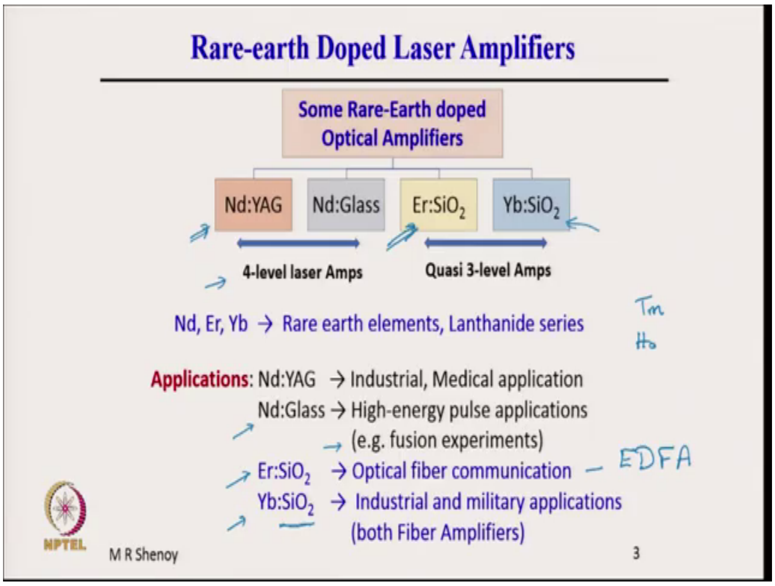

Rare earth doped laser amplifiers; some of the rare earth doped optical amplifiers which are widely used are Nd YAG laser amplifier, Nd glass neodymium doped glass and erbium in silica and ytterbium in silica. These two the second erbium silica and ytterbium in silica are widely used as fiber amplifiers.

The first ones Nd YAG and Nd glass are examples of 4-level laser amplifiers, well erbium in silica and ytterbium in silica are Quasi 3-level amplifiers. So, I will discuss the examples of Nd YAG and one from here that is erbium in silica. So, where neodymium, erbium, ytterbium are rare earth elements, these are of the lanthanide series of the periodic table and hence, the name rare earth doped laser amplifiers. There also some other rare earth elements which are used for specific amplifiers such as thulium Tm thulium also holmium Ho. These are also used as rare earth doped amplifiers for specific applications.

The applications of Nd YAG Nd glass are here indicated that Nd YAG lasers are widely used in industrial, medical applications and Nd glass lasers mostly as lasers, but also as amplifiers for amplifying high energy pulses, high energy pulse applications because we will see later that Nd glass has a wide spectrum and therefore, when we generate pulses, then we can get very high peak intensity pulses using Nd glass lasers.

So, these are some of the early lasers used for fusion experiments Nd glass. Erbium in silica is widely used in optical fiber communication as EDFA Erbium Doped Fiber Amplifiers, I will discuss this briefly in the next class. So, optical fiber communication most widely used amplifiers in long distance optical fiber communications EDFA Erbium Doped Fiber Amplifiers.

Ytterbium doped silica amplifiers are also used in industrial and medical application military applications because where you need very high powers then you also go for ytterbium doped silica or both are fiber amplifiers both ytterbium in silica because silica is the normal fiber, silica fiber, glass fiber based on silica which is used for communication and these ytterbium and erbium are doped in the silica matrix to get rare earth doped medium and then amplification can take place in these medium. So, we will discuss two one Nd YAG and second erbium silica in a little bit more detail.

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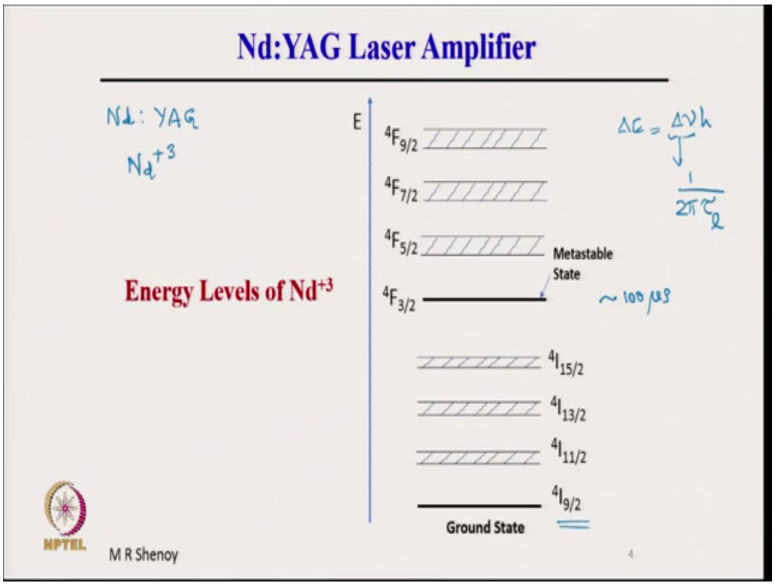

So, let us first start with the Nd YAG laser amplifier. So, what is shown here is Nd levels of energy levels of neodymium because in Nd YAG when we say it is Nd doped in YAG YAG is Yttrium Aluminium Garnet. So, it in YAG it is replacing the ytterbium here yeah yttrium here, why? It is replacing the yttrium and therefore, it exists as Nd plus 3 ions and what are shown here are the energy levels of the Nd plus 3 ion.

The ground state is 4 I 9 by 2 and the other levels are indicated here. Some of the levels are broad; broad means the life time is very short and narrow means the life time is long because, we know that delta E is equal to delta nu by h. So, h into delta nu; so h into delta nu and we know that this delta nu is the line width given by 1 by 2 pi into tau l.

Therefore, once the level is broad, it means its life time is small; life time is small means delta E is large. And the delta E the spread is small means the life time is large that is why you see that the meta stable state here 4 F 3 by 2 which has a relatively large life time of hundreds of micro second we will see the precise numbers a little later of the orders hundreds of micro second is relatively narrow. So, I will first discuss the nomenclature a little bit and then we will discuss the scheme of amplification.

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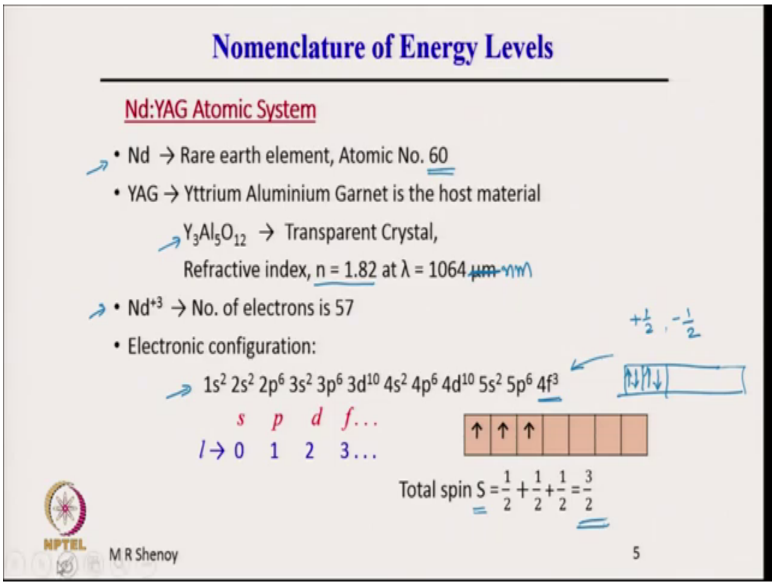

So, the nomenclature of energy levels Nd YAG atomic system. So, Nd is rare earth element atomic number is 60 neodymium; yttrium aluminium garnet is the host material. The chemical formalized here Y 3Al 5O 12 it is a transparent crystal refractive index n is equal to 1.82 at lambda is equal to 1064 micrometer.

Therefore, 1064 nanometer is 1.064 micrometer. So, Nd plus 3 here the number of electrons is 57 because it is a plus 3 ion. The electronic configuration is shown here this is very familiar way of writing 1 s 2, 2 s 2 the first shell, second shell as 2 s and p. So, we have 2 s 2, 2 p 6, then 3 s 2, 3 p 6, 3 d 10, 4 s 2, 4 p 6 4 d 10, but also 5 4 f but 4 f will be filled later the shell therefore, 5 s 2 5 p s 6 and 4 f 3 that is in the last shell is this 4 f 3. There are 3 electrons in the outer most shell that is 4 f in the case of neodymium.

Therefore, the three electrons the corresponding we know that s p d f the electronic shells are assigned an orbital angular momentum quantum number which is 0 s is 0, p is 1, d is 2 and f is 3 and so on. S is the total spin quantum number, total spin is the sum of so each one of this is half, half, half.

This is the outermost f shell f which has which can take 14 electrons which means there are 7 slots here. So, you can have a s you are aware. So, the electrons can have up spin down spin; up spin down spin. So, up spin means plus half and down spin means minus half is the spin quantum number.

Now, capital S is the total spin. So, total spin quantum number is the sum of these spins. So, that is why half half half which is S is equal to capital S is equal to 3 by 2.

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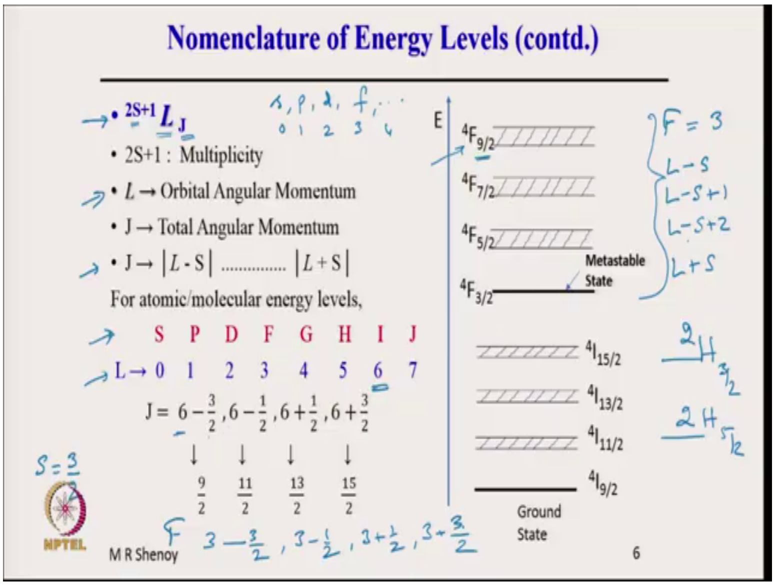

So, let us continue with the nomenclature a little bit more, the energy levels you saw these numbers as 4 f 9 by 2 4 f 7 by 2 what are these numbers? So, usually these are numbers which are given in spectroscopy.

So, these are representing 2S plus 1 L J, S here is the total spin quantum number, L is the total orbital quantum number and J is the total angular momentum quantum number. So, 2S plus 1 represents multiplicity of the levels. So, you can see that here this one this set has there are 4; 4 F shells, so 4 F 9 by 2 4 F 7 by 2. So, there are 4 level, then you have 4 F.

If there are only 2 for example, you might have in some other case 2 H 3 by 2 or and 2 H 5 by 2. So, this means that there are only 2 levels which are there. So, there is there are only 2 levels multiplicity of levels is 2 here multiplicity for the f shell is 4 and therefore, we have 4 F

9 by 2, 7 by 2, 5 by 2 and 3 by 2 how did these numbers come? This is J 9 by 2 here represents J.

Now, L is the orbital angular momentum, now we are talking atomic energy levels and therefore, the L is used is capital L, it is not the small l and the corresponding s p d f are capital S P D F G H the F for example, which appears here this F corresponds to 3, S in the case of electronic structures also we had s p d f and so on. So, s was 0 1 2 3 4 and so on exactly like that we have S, but now it is written in capitals.

The capitals referring that we are now referring to atomic energy levels not electronic energy levels, but atomic energy levels or molecular energy levels and there the notation used is capitals S P D F, but the numbers assigned for the capital L are the same 0 1 2 3 4 etcetera. Now, J goes from mod minus L minus S two L plus S for example, if we take this upper state where F is F is equal to 3. So, this is L, this is the value of L. Now, L can go from L minus S, L minus S plus 1, L minus S plus 2 etcetera up to L plus S.

From L minus S up to L plus S which means what is S? S we have already seen that S is equal to 3 by 2 for the Nd 3 plus ion S is equal to capital S is equal to 3 by 2 total spin quantum number therefore, we will have levels ok. So, here I am describing the I has 6. So, I is 6 for the lower level which means J takes values from L 6 minus 3 by 2, 6 minus 3 by 2 plus 1 which means 6 minus half, 6 minus 3 by 2 plus 2 which means 6 plus half and 6 up to L plus capital S. Therefore, there are 4 levels 4 J values corresponding to this 4 multiplex.

So, 4 is the multiplicity of the shell I and these are the corresponding J values therefore, we have got J is equal to 9 by 2, 11 by 2, 13 by 2 and 15 by 2 and here we had correspondingly 3 minus 3 by 2, 3 minus half for the F for the F shell 3 plus half and 3 plus 3 by 2. So, 3 minus 3 by 2 is here 3 by 2, 3 minus 1 and half is 1 and half then, 5 by 2, 7 by 2 and 9 by 2 that is how we got these numbers. So, this is a small note on nomenclature for those of who you are not familiar with the spectroscopic notation. So, these are spectroscopic notation where 2 S plus 1 L J is the; is the nomenclature for energy levels

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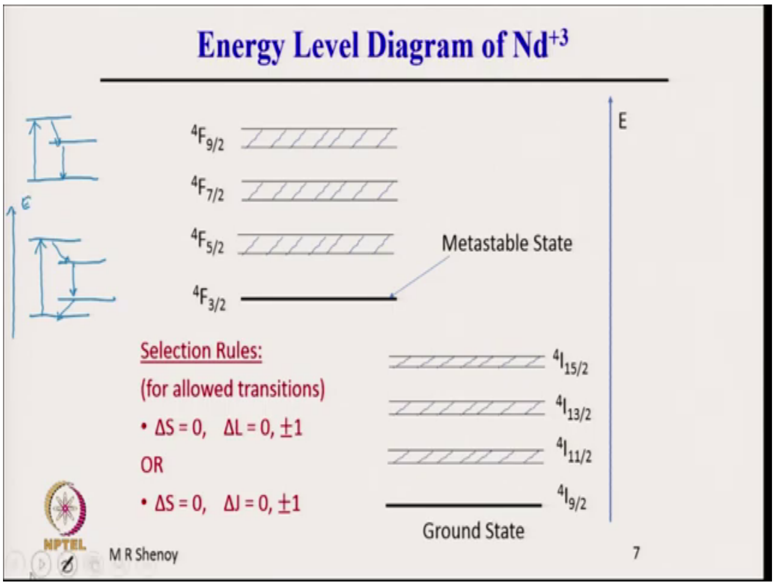

Now, let us look at the again continue with the, let us look at the laser transitions now. So, I have now shown this shifted. So, please remember in the case of a 3 level laser we showed that energy levels like this that is just for convenience atoms are excited to upper level it comes down rapidly to this level and from here it comes down to the ground state. In the case of a 4 level system we normally show it like this atoms are excited here from here it rapidly comes down to an intermediate level from there it comes down by laser transition and then it comes down here.

The point I am making is we show that the levels are shifted just for convenience otherwise all of these levels indicate what is this; this is the energy axis E. So, that is why in the previous case when I showed the levels I showed all of them one over another because simply it is indicating that this is at a higher energy this is at a higher energy and so on. There is nothing like shifted levels, but only for convenience we show that the that is why now I have shifted this for convenience because I want to show that transition takes place from the ground state to an upper state and then comes down to a lower state.

An important point to notice in showing this if a transition where to take place from for example, from here to here or from here to here or from here to here transition where to take place then they have to satisfy the selection rules selection rules for allowed transitions these are quantum mechanical selection rules based on the overlap integral corresponding to each level or each state there is a wave function associated in quantum mechanics, in the quantum theory and then the overlap of the wave function of this with the higher level will give the strength of the interaction.

Now, the allowed transitions are characterized by certain conditions and they are called selection rules. So, those transitions for example, the transition which is shown here those transitions which satisfy the selection rules either this or this satisfy the selection rules are called allowed transitions what do we mean by allowed transitions and those which do not satisfy these conditions I will explain I will take some numbers and show this those which do not satisfy the selection rules are called forbidden transitions. So, forbidden transitions.

So, let me write here forbidden transitions which do not satisfy the selection rule; forbidden transitions which do not satisfy the selection rules. What does that mean forbidden selection rules? Forbidden literally means that such a transition cannot take place for example, if this is a forbidden transition; that means, from here to here then it means it should not take place forbidden literally.

But in practice what it means is, forbidden transition means the probability of occurrence of this transition is very low. Allowed transition means the probability of this transition occurrence of this transition is high whereas forbidden transition means the probability is very low and therefore, when we say that selection rules are satisfied if selections rules are satisfied such transitions are called allowed transitions.

Let us see what we mean by this? Let me take again the example let me change the color now. Let us take an example of this transition here for this transition we see that this level is characterized by 4. This also has S 4 therefore, delta S is equal to 0 is satisfied. So, for this transition delta S is equal to 0 satisfied. Now, let us look at this transition 9 by 2 and this is 5 by 2 9 by 2 minus 5 by 2 is 4. What is this is delta J?

So, delta J is equal to 2. So, 9 by 2 minus 5 by 2. So, delta J is equal to 2, but delta J equal to 2 is not an allowed transition which means the transition that I am showing here is not an allowed transition according to this; however, we see that delta L is F and here also F it is 3, L is 3. Therefore, delta L is equal to 0 which means delta S is equal to 0, delta L is equal to 0 is satisfied and therefore, this is an allowed transition similarly we will see that this is also an allowed transition this is also an allowed transition.

Now, let us look at this transition or a transition from here to here. Let us look at this transition here from 4 F 3 by 2 to 4 I 9 by 2 first point for this transition. So, let me write here delta S is equal to 0 because 4 and 4 therefore, delta S is equal to 0, what about delta L; delta L is this is I, I means L is 6, F means L is 3 and therefore, delta L is 3, 6 minus 3 delta L is equal to 3 I am referring to this transition from 4 F 3 by 2 to 4 I 9 by 2. What about delta J? Delta J is here it is 3 by 2 and here it is 9 by 2. One and a half and four and a half which means delta J is also equal to 3 clearly this is a forbidden transition because it does not satisfy.

So, this satisfies, this does not satisfy this does not satisfy and therefore, this transition is a forbidden transition which means the probability of this transition is low. Probability of transition is low means what if atoms are here, atoms are at this level the probability that the atom makes a transition to this level is low which means, the atom will tend to accumulate here which means, the atoms lifetime is larger and therefore, this is a metastable state what I am trying to answer is why some states are metastable states? A metastable state is one which has a long lifetime, why it has a long lifetime?

It has a long lifetime because the transitions from that state to the lower state is forbidden by the quantum mechanical rules, the selection rules. So, forbidden means the probability is low if the probability is low; that means, the atoms tend to accumulate their atoms spend more time in that level because the probability of getting d excited or making a downward transition in energy is low and therefore, such states are called metastable states.

So, metastable states are ones which do not satisfy the selection rules for transition from that state to the lower excited states. So, we have marked this as metastable state because as you can see all of these do none of these satisfy whether it is this transition or this, none of these satisfy the selection rules only delta S is satisfied, but delta L and delta J are not satisfied for example, if we go to this transition here delta J is even higher. So, del this is seven and a half this is one and a half. So, delta J is 6. So, this energy level diagram is very important in indicating what is meant by a metastable state alright.

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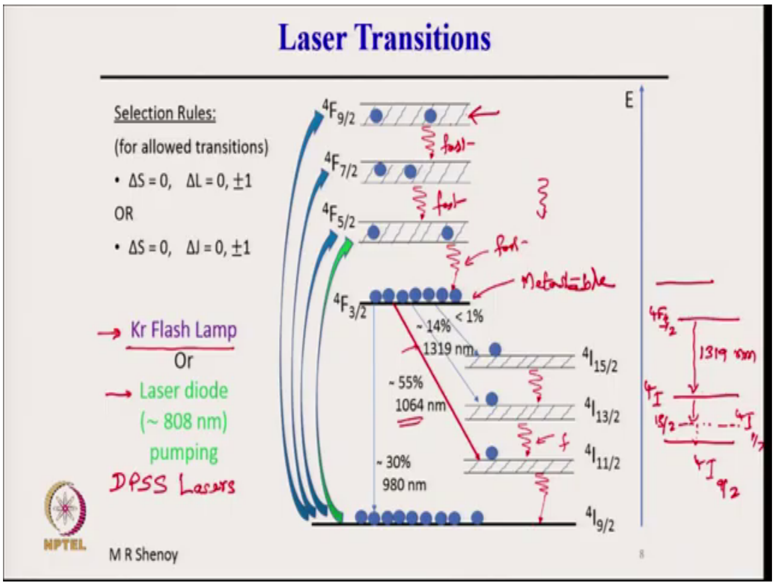

So, let us continue from here. So, let us now come to the laser transitions of an Nd YAG laser. How does the Nd YAG laser amplifier work the scheme of amplification? So, we have a metastable state. So, this is the metastable state and you can see atoms are accumulated here I have shown already the atoms accumulated in that level. So, when you use a krypton if we take an Nd YAG laser amplifier then usually either it is pumped by krypton flash lamp or laser diodes.

So, laser diode pumping is called diode pumped solid state laser. So, there is a class of lasers which are called DPSS Diode Pumped Solid State Lasers. DPSS lasers we will discuss about this a little later, but let us look at what is happen in if we use a krypton flash lamp.

This has several pumping bands or there are several lines in this flash lamp several wavelengths it gives out several dominant wavelengths which excite atoms from this ground state to higher state. So, usually these amplifying bands are in the blue green region and therefore, these excite to from the ground state to the higher state.

Now, let us say atoms have reached this upper most state, from here they rapidly come down because delta S is equal to 0, delta L is equal to 0 and therefore, it is a allowed transition. So, this is fast transition, this is also a fast transition allowed transition. So, even if you pump all the atoms here they will come down and they will come down up to this, this is also fast all are fast transitions that is why we have shown this like this. So, fast transitions.

So, if you pump to any of these excited bands atoms will come down trickling down and get accumulated here. Why do they get accumulated here because this state is a metastable state; that means, from here the transitions to lower levels do not satisfy the selection rules and therefore, this is metastable state?

Now, from here there are different transitions possible to different levels, the probability of transitions are approximately indicated if the total probability is 1 then about 30 percent would make downward transition directly to the ground state, about 55 percent would make transition here the corresponding wavelengths are shown.

So, this the energy difference corresponds to about 975 or 980 nanometers. The energy reference from here to here is about 1064 nanometers; energy difference corresponds to 1319 nanometers and so on. The Nd YAG laser the dominant wavelength of the Nd YAG laser is 1064 nanometers which is shown by this red transition because as we see that the probability out of these 4 transitions, the probability of 1064 nanometer line is highest 55 percent and the Nd YAG laser corresponds to this transition from 4 F 3 by 2 to 4 I 11 by 2.

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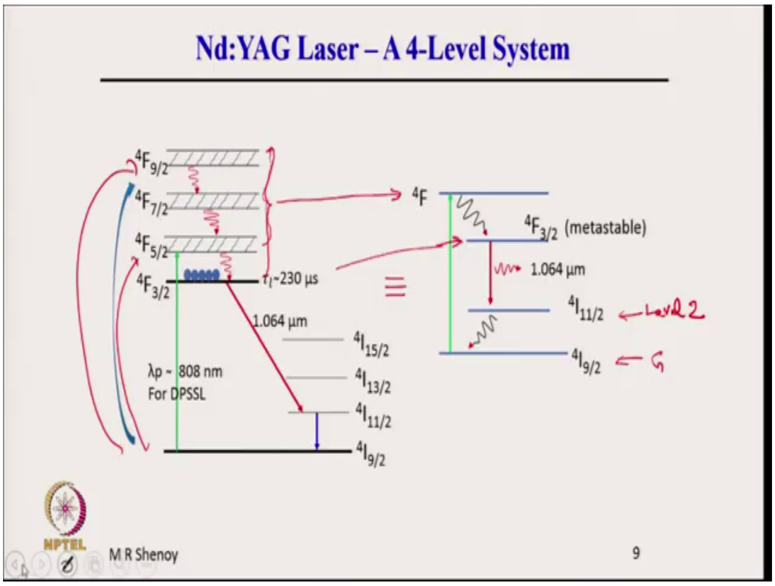

So, if we look at the equivalent picture now let me simplify this. All of this here the same diagram I have shown all of this. So, you are pumping from here to any of the levels; any of the levels all the atoms would trickle down and come and accumulate here. Therefore, the role of these levels is simply to populate this lowest level and therefore, this level is our 4th level, in a four level laser that 4th level is these multiplex of levels are equivalent to the higher level.

Because, the role of this higher level is to populate the metastable state due to a pumping mechanism. This state the lowest state here which is metastable state is equivalent to the third level which is here in our simple 4 level systems and for the Nd YAG laser, this transition that is 4 F 3 by 2 to 4 I 11 by 2. So, I have shown only 4 F 3 by 2 and 4 I 11 by 2 as the level 3 level 2. So, this is our level 2 and this is the ground state. So, this is the ground so this is level 2.

Out of all the levels now, we have shown where is the 4 level laser of Nd YAG laser which is a 4 level laser system. So, when we say I mentioned this that, when we say a laser is a 4 level system it does not mean that it has only 4 levels, it does not even mean that only 4 levels are participating, but equivalently it can be considered as a 4 level system, if I am looking at the Nd YAG laser emitting at 1064 nanometer.

But if I was looking at the other Nd YAG line that is 1319 nanometer then I would have had the 4th level here which comprises of the top 3 the third level is 4 F 3 by 2; 4 F 3 by 2 and, the second level would be 4 I 13 by 2 because, 4 F 3 by 2 to 4 I 13 by 2 this transition is 1319 nanometer another line of Nd YAG although 1064 is the dominant line, but 1319 is also a transition a laser transition of Nd YAG.

There are lasers Nd YAG lasers emitting at 1319 nanometer are also available commercially and from here the ground state is 4 I 9 by 2, but the atoms which I have reached here will trickle down to the intermediate state of 4 I 11 by 2 and then they come down from there to 4 I 9 by 2 please see that 4 I 13 by 2 to 4 this is a fast transition is very rapid transition.

So, there are 2 rapid transitions one after another, but as far as the 4 level system is concerned from here atoms are going down directly to the ground state through the intermediate state therefore, this is also the 1319 line is also a 4 level scheme, whether it is a 1064 line or the 1319 line they are 4 level schemes and therefore, they are called 4 level systems, alright.

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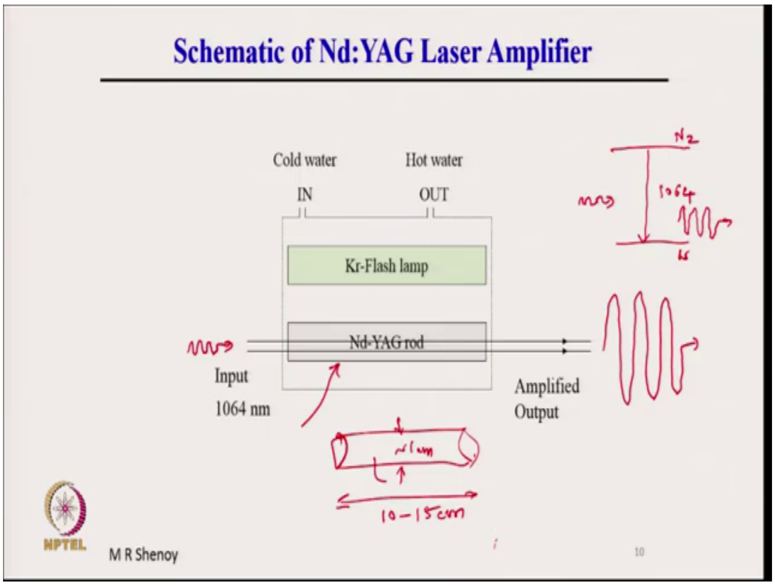

Let us continue a typical schematic what is shown is a schematic of Nd YAG laser amplifier, how does it look like? So, typically there is an Nd YAG laser rod this is a rod which is generally about 1 centimeter in diameter and 10 to 15 centimeter in length in a practical system. So, this L is generally 10 to 15 centimeter and the diameter is approximately 1 centimeter of the order of 1 centimeter.

This is pumped by a krypton flash lamp and the whole thing is kept together in a cavity and as an amplifier it will have if a low intensity 1064 radiation passes through this then that will get amplified and comes out here. So, this is the schematic of the amplifier.

So, input 1064 will get amplified by stimulated emission because recall that the stimulating transition here is at 1064 nanometer population inversion is between this. So, this is N 2 and N 1 and therefore, any photon or radiation coming here will get amplified by stimulated emission because we have maintained population inversion between the 2 levels. So, this is the scheme of operation of a Nd YAG laser.

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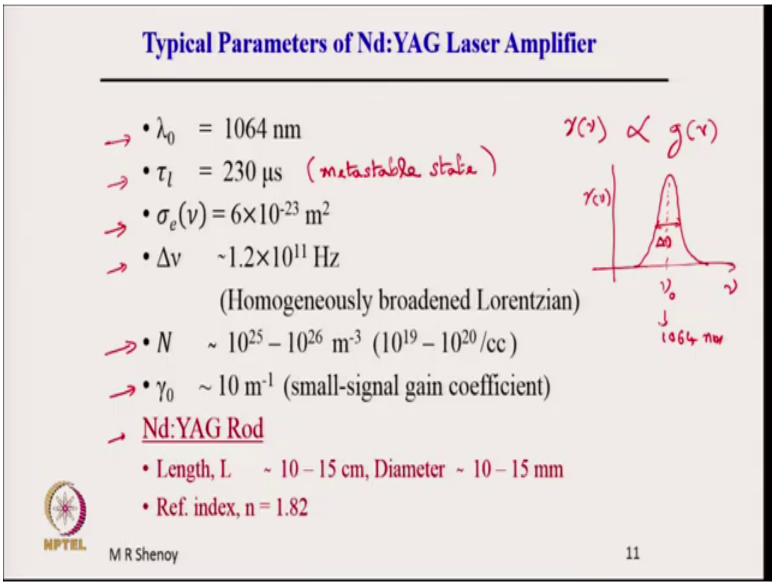

Finally typical parameters of an Nd YAG laser amplifier. So, the wavelength of operation is 1064, depending on. The host it may slightly vary the upper level lifetime is given here 230 nano second, so this is the lifetime of the metastable state. So, this is the metastable state sigma e is the emission cross section typical numbers I had mentioned that it is of the order of 10 power minus 23 minus 24 meter square.

And delta nu this is the line width the bandwidth of the amplifier which is nothing but the full width at half maximum, we know that the bandwidth. So, the gain coefficient gamma of nu is proportional to g nu and the delta nu here refers to the full width at half maximum. So, this delta nu number which is given is this. So, what is plotted is gamma of nu verses nu.

And the gain is maximum at nu is equal to nu 0 which corresponds to 1006. So, 1064 nanometer and this is the delta nu that we are talking of. So, delta nu is typically of the order of 10 to the power of 11 Hertz and usually this is homogenously broadened Lorentzian. We have already seen that when it is homogenously broadened it is characterized by a Lorentzian

So, Nd YAG laser amplifier is characterized by a Lorentzian, N is the number of Nd atoms. So, typically 10 to the power of 19 per cc and gamma 0 is the small signal gain coefficient typical numbers are 10 meter inverse; that means, 0.1 centimeter inverse and the rod dimensions are shown here Nd YAG length as I had just mentioned 10 to 15 centimeter diameter is 10 to 15 millimeter and refractive index of the rod is 1.82.

So, that gives us an idea of how a practical Nd YAG laser amplifier would be operating with all the physical parameters. So, in the next class. So, here I will stop in the next class, we will take erbium doped fiber amplifier that is erbium in silica which is a Quasi 3 level laser.

Thank you.