Applied Optics

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Lecture 59
Introduction to Lasers - II

Hello everyone, welcome to the class. Today, we will proceed ahead with the lasers. In the last class, we started with the basics of the lasers and there we discussed Eisenstein's A and B coefficients, we understood what a population inversion is? And why it is not possible to have two level system or two level lasers?

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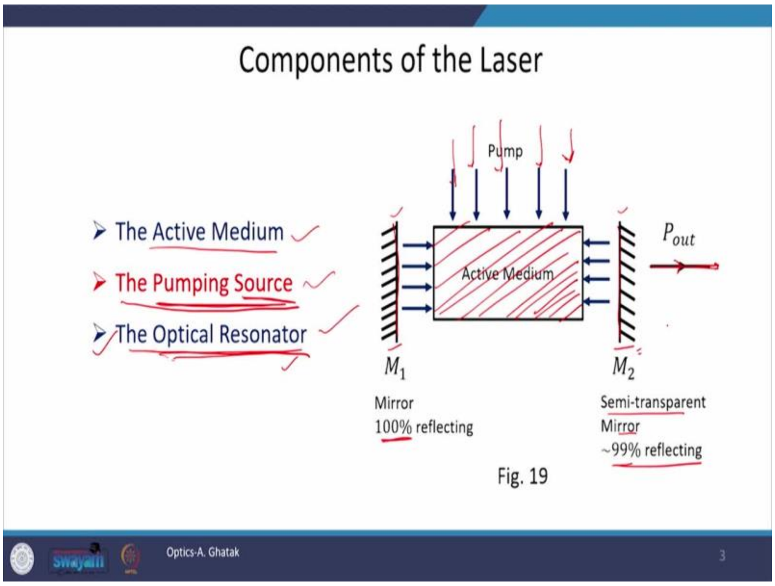

And today, we will formally start with the laser. Now, this slide is dedicated to the component of a laser. The laser consists of three main components, the first one is active medium, active medium consists of ions, atoms and molecules. Now, these atoms, ions and molecules provide the discrete energy levels where in we after achieving population inversion, we get lasers, we get light out of the out of these systems.

The second important component for laser is the pumping source. Now, we know that in a two level system to achieve lasing we require population inversion that means, we want most of the electrons or most of the atom to be in excited state or to be in its upper energy state. And for this we need to provide energy and the electrons sitting in the ground state they absorb this energy and then they move up to the upper level. Now, the process of providing this energy or the process of pumping is furnished by some source either optical or electrical and this is done by pumping source.

The third component of a laser is optical resonator. Now, suppose we have achieved population inversion, now, the electrons or the atoms will go down to the ground state and then it will emit photons. Now, these photons if they are put between two mirrors, they will then bounce back and forth.

Now, these two mirrors they constitute or they work as the oscillator because the photon oscillate between these two mirrors and once it interacts with the inverted atomic system, it initiate the downward transition which in turns provide us the gain. Therefore, optical resonator is a very important part of a laser and the simplest example of optical resonator is two plane parallel mirrors as is shown here in this figure.

Now, here you see that, this region is the extreme medium where our atoms molecules or ions are sitting and then we pump it externally and due to this pumping population inversion is achieved and these mirrors they constitute or they behave as an oscillator and these mirror thus create optical resonator with compel the photon to bounce back and forth and ultimately gives a very high energy directional, almost monochromatic coherent beam of light, which we name as a laser.

Now, out of the two mirror, one mirror is highly reflecting and it has reflectivity of around 100 percent and the other mirror is semitransparent, which has a slightly small reflectivity. And, due to this small value of reflectivity, we get some transmittance and laser output is received from this end of the cavity.

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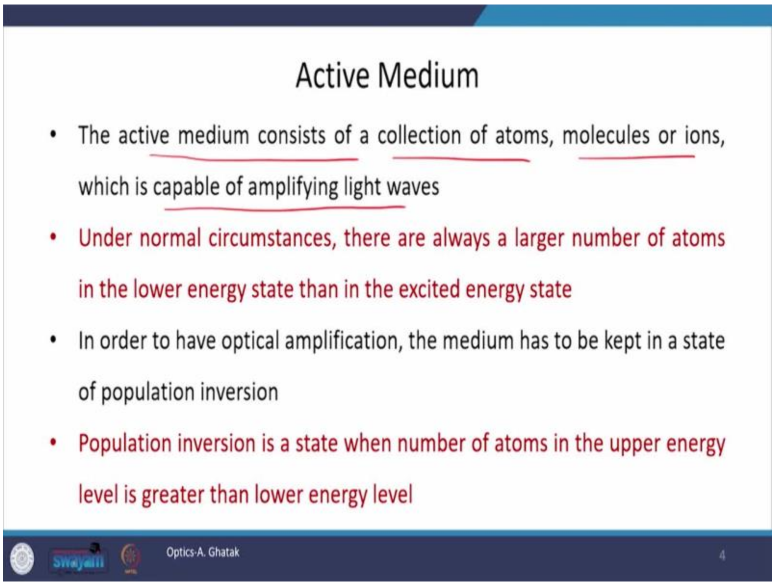

Now, as I said before, acting medium consists of a collection of atoms molecules or ions, which is capable of amplifying light waves. Under normal circumstances, there are always a large number of atoms in the lower energy state then in the excited energy state, but what we do is that in order to have optical amplification, the medium has to be kept in a state of population inversion and we know that population inversion is a state when the number of atoms in the upper energy state is larger than that in the lower energy state and that is achieved through pumping.

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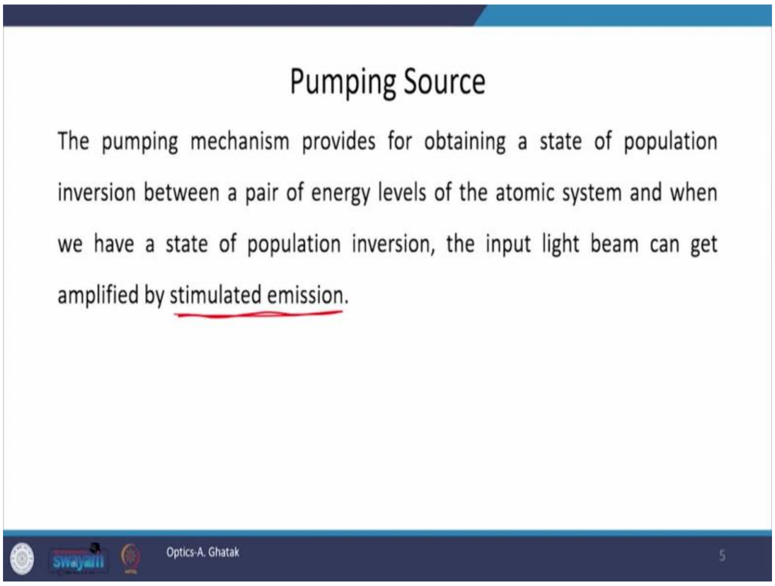

Now, pumping mechanism provides for obtaining a state of population inversion between a pair of energy levels of the atomic system and when we have a state of population inversion, the input light beam can get amplified by stimulated emission. If you remember in the last class we studied about three phenomena, stimulated emission, spontaneous emission and absorption.

Absorption is sometimes called stimulated absorption because it always happen in presence of some external field, some external photon. In laser, we require stimulated emission because out of a stimulated emission, we get coherent output.

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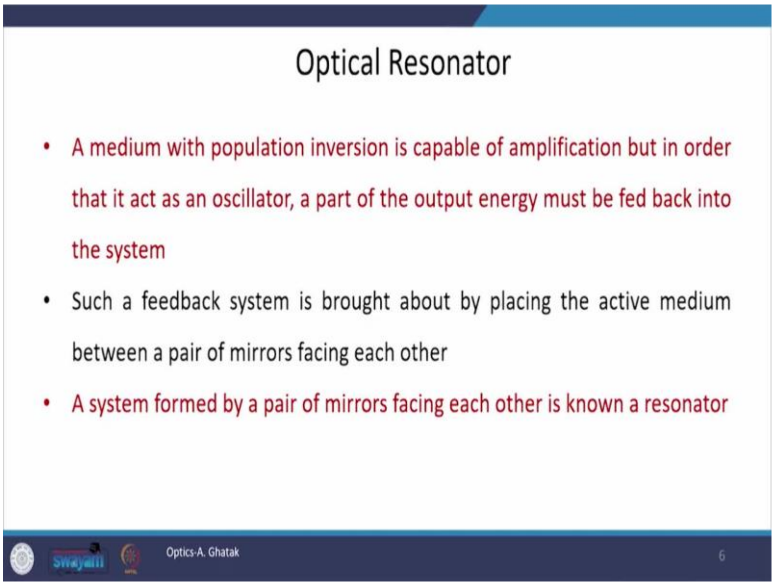

Now, coming back to optical resonator as you know it provide feedback to the system and a medium with a population inversion is capable of amplification, but in order that it acts as an oscillator a part of output energy must be fed back into the system such a feedback system is brought about by placing the active medium between a pair of mirror facing each other or the active medium must be kept inside a cavity. The only rule of cavities to provide feedback, system formed by a pair of mirror facing each other is known as the resonator.

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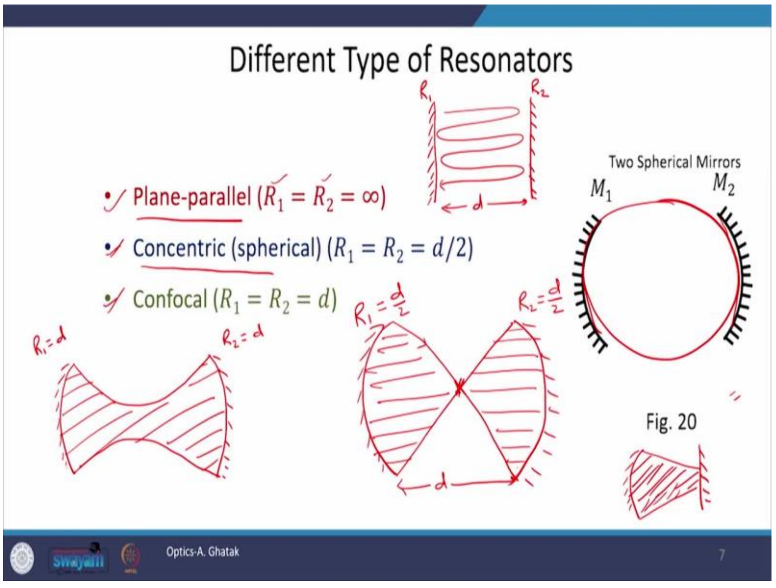

This is the simplest example of a resonator and there are different kinds of resonator, the simplest one is shown here, you see there are two curved mirror facing each other and this region is called resonator which is surrounded by this is bounded by these two mirrors to spherical mirrors.

Now, out of different kinds of resonators, the three important ones are mentioned here, the first one is plane parallel resonator. In this plane parallel resonator we place two plane mirror facing each other and then it provides feedback by reflecting photons back and forth. And here the radius of curvature of left mirror is R_1 while right mirror is R_2.

Since we know they are plane parallel mirror R_1 and R_2, they both will be equal to infinity. The second type of resonator is concentric spherical one, in this case, we have a spherical mirrors and they share the same center therefore, reflection would be such that the light would be there in this shaded region only and this point will work as center here R_1 would be equal to d/2 and R_2 the radius of curvature of the second mirror is again d/2, where d is the spacing between the mirror, the length of the cavity. Here too, d is this the separation between the two mirror or the length or you can say width of the cavity.

Another important kind of resonator is confocal kind and in these kinds of resonator we have two mirrors which are a spherical here the radius of curvature of first mirror is d and radius of curvature of second mirror is also d. Now in confocal mirror the energy or the photons would be in this shaded region, these are the different kinds of resonators which are predominantly used.

But apart from this there are also resonators in which one mirror is curved while other is flat, here the photons will exist in this region in this shaded region. There are other kinds of resonators also exist, but these are the important ones.

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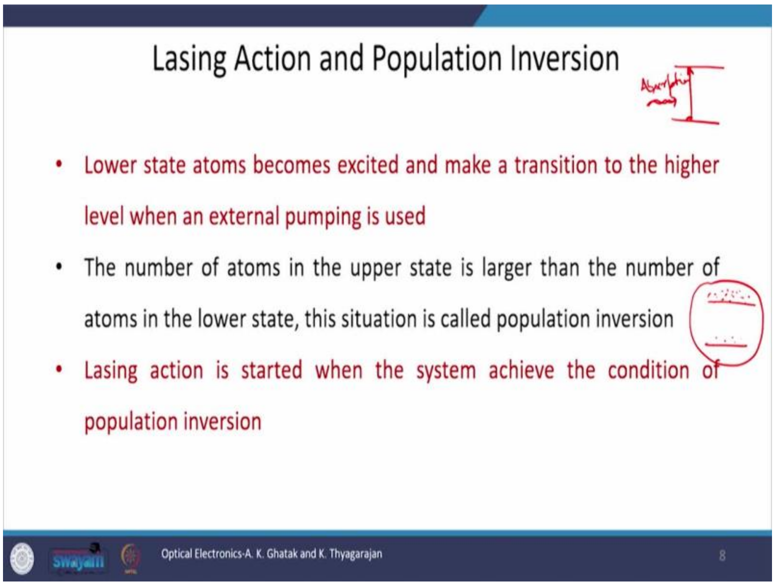

Now to achieve lasing, we require population inversion, lower state atoms becomes excited and make a transition to the higher level when an external pumping is used this we know. If the electron is here, then if you pump it then it goes into the upper energy state. And it only happens when we have some external source and this is called absorption.

Now when the number of atoms in the upper energy state is larger than the number of atoms in the lower energy state this situation is called population inversion and this is represented by this, the most of the electrons are in the upper energy state, and this is called Population inversion.

Now, lasing action is a started when the system achieved the condition of population inversion whenever the number of atoms in the upper energy state is larger as compared to the to the ground level then only the number of downward transition will be larger than number of upward transition and in this case only we get some output and this is called lasing. Therefore, leasing action is started only when the system achieves the condition of population inversion.

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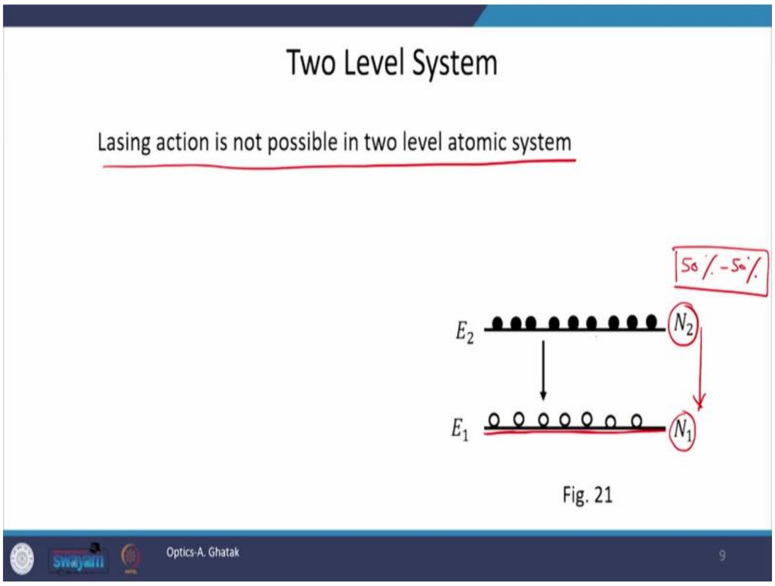

Now, lasing action is not possible in the two level system and we have already understood it because we know that the rate of transition from lower energy state to upper energy state is proportional to N_1 which is the carrier density in the ground state and the rate of transition from upper state to lower a state is proportional to N_2 and in two level system we can at most have 50-50 distribution of carriers or electrons.

We cannot go beyond 50 50 percent distribution in two level system this we can prove using Einstein's A and B coefficients and using this Einstein's formulation, we therefore, can predict that lasing action or population inversion is not possible in two level atomic system. Because say initially in the lower energy state the population is less, then what will happen is that the rate of downward transition will be larger and after a while a situation will come where in the population of lower and upper energy state is equal.

In this situation, the upward rate of transition would be equal to the downward rate of transition and this is the state of equilibrium and we cannot go beyond it as long as only two levels are involved and therefore, we cannot make a laser out of a two level atomic system.

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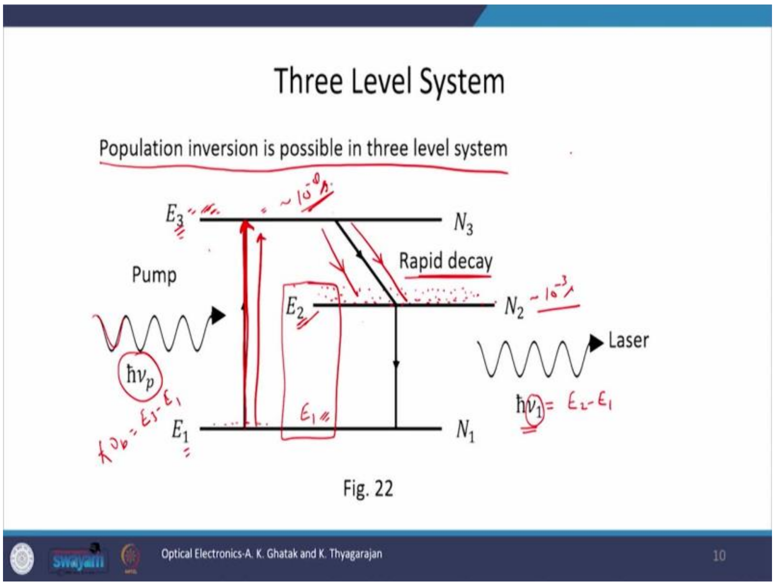

Fig. 22

But in three level atomic system we can make a laser, why? because, now, the atoms or electrons from E_1 level is pumped to higher energy state which is E_3 here. The pump has a frequency which is equal to $E_3 - E_1$, here $\hbar\upsilon_p = E_3 - E_1$ and in this situation the electron will directly go to the third energy state.

Now, the lifetime of this third energy level is very small, it is almost equal to roughly 10^{-8} seconds and therefore, they quickly go downward and in three level system apart from this E_1 and E_3 state there is a E_2 state which lie midway between E_3 and E_1, not exactly midway which lie in between E_3 and E_1 and this transition which electron make from uppermost level to E_2 level it is very fast and therefore, it is called rapid decay.

This is a transition and as soon as the electron reaches in E_3 level since the lifetime of E_3 level is very small, lifetime means the duration in which the electron stay in a particular level. In E_3 level, the lifetime of E_3 level is 10^{-8} second. Therefore, the electrons which are coming in E_3 level from E_1 level they will stay there only for 10^{-8} second.

I repeat the lifetime for atomic level is the time duration for which the electron stay in that particular level. And this time duration here is very small therefore, the electron population will quickly go down to E_2 level and E_2 level usually have a longer lifetime and it is roughly 10^{-3} seconds which is much-much longer than 10^{-8} seconds the lifetime of E_3 level.

Now, since the lifetime of E_2 level is very long, very large therefore, the electron will start to accumulate here and therefore, population density of E_2 level will increase rapidly and due to this increase between E_1 and E_2 or state of population inversion would be achieved and as soon as we have population inversion, we will get lasing between E_2 and E_1.

I repeat, once we have population inversion between E_2 and E_1, we will have lasing action between E_2 and E_1 and a laser would be emitted of frequencies such that $\hbar\upsilon_1 = E_2 - E_1$, υ_1 is angular frequency in the equivalent to ω. Now, therefore, we can easily make laser out of three level atomic system.

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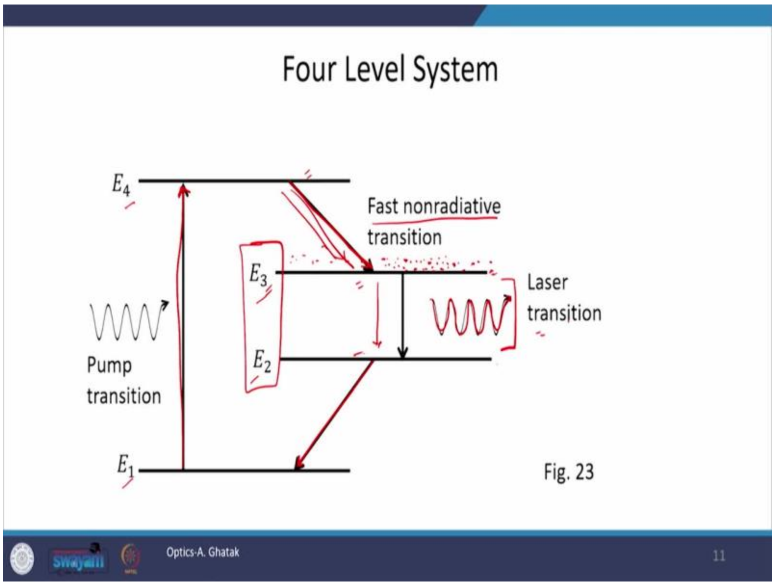

Similarly, we can also make a laser out of four level atomic system, in four level atomic system we have four energy levels and pumping is usually done between E_1 and E_4 and then there is a rapid decay of electron or rapid transition of electron from E_4 level to E_3 level and these rapid transitions are most of the time non-radiative in nature.

It means, while transiting down the electron or atom does not radiate any light, does not radiate any energy. The excess energy is lost in heating the atomic system. Now, due to this fast transition, the charge carrier population increases rapidly here in E_3 level and slowly we achieve population inversion is stayed between E_3 and E_2.

Therefore, between E_3 and E_2 we see lasing and lasers light come out of the system due to the downward transition stimulated emission happening between E_3 and E_2. Once the electrons are in the E_2 state they again go down to the E_1 state and this transition because of the established population inversion gives us laser.

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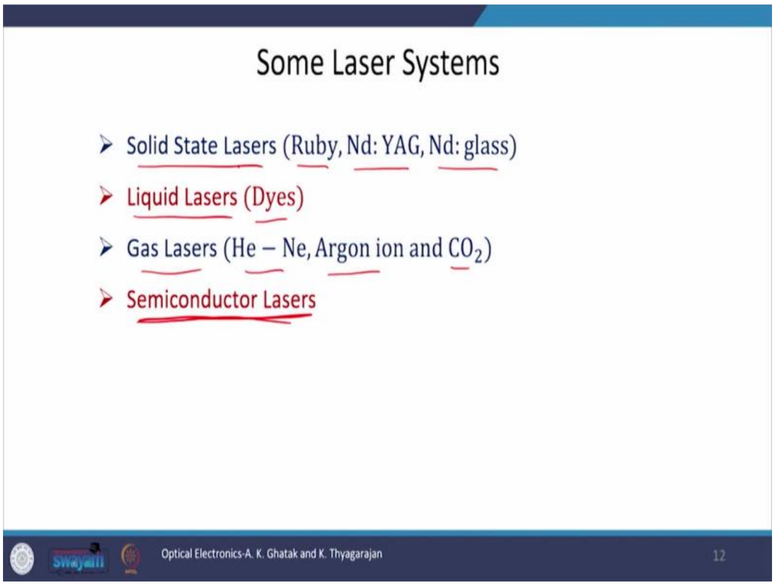

Now, a few examples of laser systems are solid state lasers, liquid lasers, gas laser, semiconductor lasers. Now, in solid state laser, Ruby, Nd: YAG, and Nd: glass are most famous ones. Dyes lasers are examples of liquid lasers. Helium, neon, argon and CO2 lasers are examples of gas lasers. In modern communication system, it is now semiconductors laser which are dominating the field, we will study about these lasers.

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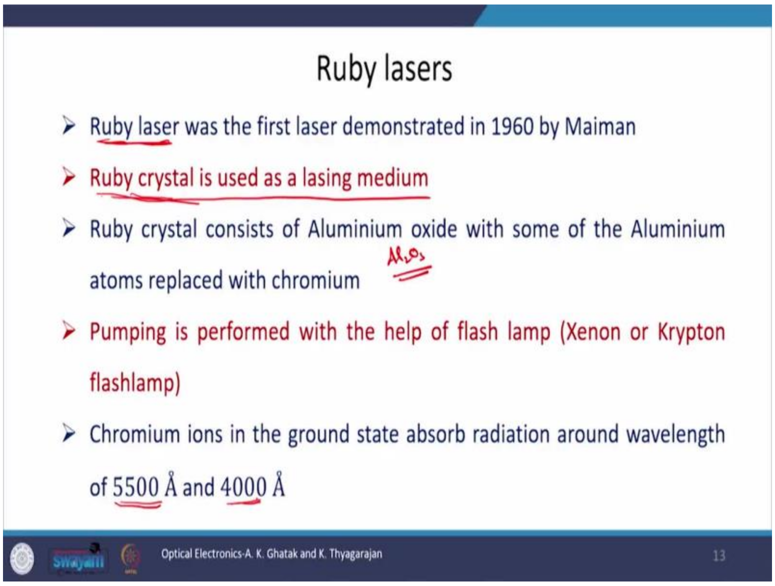

Now, Ruby laser was the first laser demonstrate in 1960 by Maiman. Now, Ruby crystal, as the name suggests, the Ruby crystal is there in this laser. Therefore, Ruby crystal is used as a lasing medium in ruby laser. Now, in this laser, it is not the pure Ruby crystal, because Ruby crystal is made up of aluminium oxide, Al_2O_3.

Now, in this aluminium oxide, some of the aluminium atoms are replaced with chromium. Now, to pump the system we use Xenon or Krypton flash lamp. Now, these flash lamp they pump periodically the Ruby crystal, chromium doped Ruby crystal and all the lasing happen in chromium ion. Chromium ion upon receiving the light from the flash lamp, it absorbs the radiation and this absorbed radiation are of wavelength 5500 Angstrom and 4000 Angstrom.

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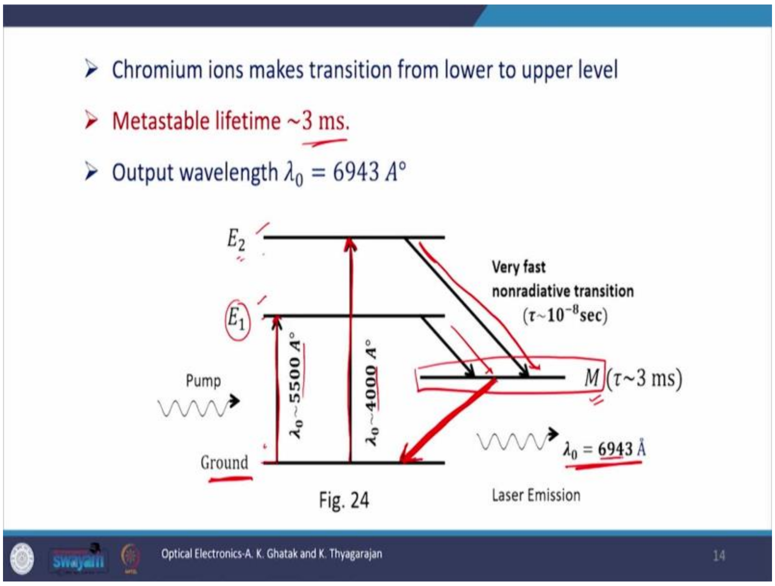

Now, here you can see the energy levels of chromium ion. This is the ground state and you see that it is absorbing 5500 Angstrom and it is going in energy level E_1 while the absorption at wavelength 4000 Angstrom lead the electron to the uppermost energy level which is E_2 level.

Now the lifetime of E_1 and E_2 energy levels are very less and the electrons in these excited state, they rapidly decayed down to this level which we call M level. The M level is called metastable state and it has a lifetime of around 3 milliseconds. Due to this longer lifetime we achieve population inversion between metastable state and the ground state of the chromium and this transition is the most important transition. Due to the population inversion this radiative transition leads to laser and we receive a laser output at wavelengths 6943 Angstrom.

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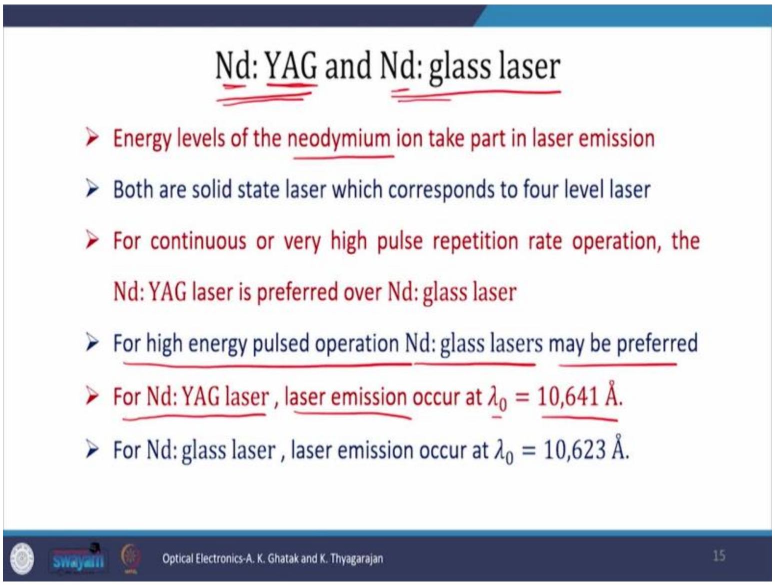

Now, similarly Nd: YAG and Nd: glass lasers are also important, the energy levels of neodymium ion take part in laser emission. Now, both of these laser Nd: YAG and Nd: glass they are solid state laser and they both are 4 level. Now make it a point Nd in both the laser stand for neodymium while YAG stands for Yttrium Aluminum Garnet.

Now Nd: YAG laser, it has very relatively smaller line width and therefore continuous or very high pulse repetition rate operation, the Nd: YAG laser is preferred over Nd: glass laser. Since the line width of Nd: glass laser is large for high energy pulse operation Nd: glass lasers may be preferred. Now, coming to the wavelength of operation Nd: YAG laser has gives us laser emission at wavelength 10,640 Angstrom while Nd: glass laser gives us emission at wavelength 10,623 Angstrom.

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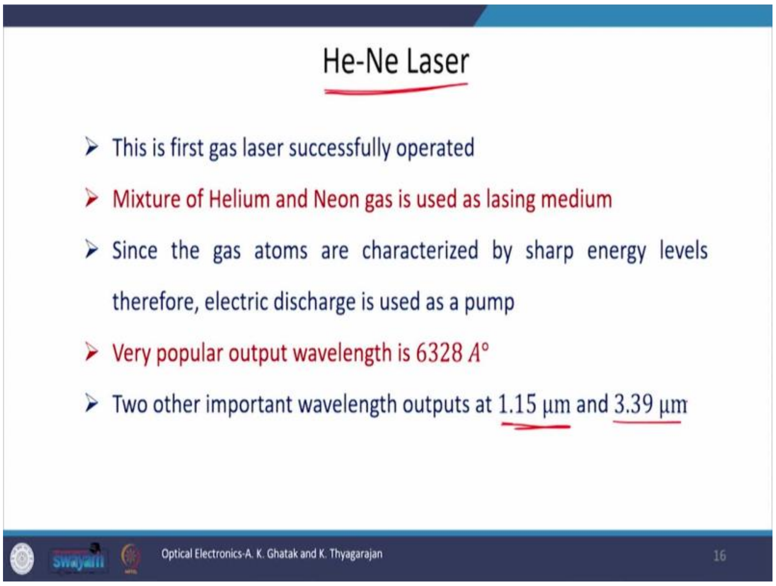

Now, coming to gas laser, the most important and widely used in street laser is helium neon laser. This is the first gas laser which operated successfully in this laser helium neon is the active medium, mixer of helium and neon gas is used as a lasing medium in this laser since the gas atoms are characterized by sharp energy levels.

Therefore, electric discharge is used as a pump here and very popular output wavelength which is 6328 Angstrom, 6328 Angstrom is emitted in helium neon laser that is why it has wide application. Apart from this wavelength, this laser emits two other wavelengths which is also very important and these two outputs lie at 1.15 micrometer and 3.39 micrometer.

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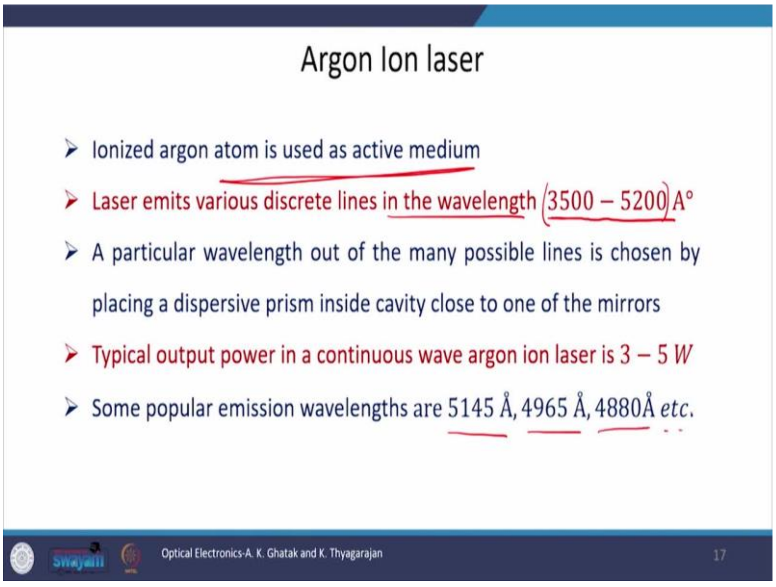

Apart helium neon laser, argon ion laser is another important gas laser. In argon ion laser ionized argon atom is used as an active medium. Now, this laser emits various discrete lines in wavelength reason lying between 3500 to 5200 Angstroms and this wavelength band this laser emits several wavelengths, its emit several discrete lines. A particular wavelength out of many possible line is chosen by placing a dispersive prism inside cavity close to one after mirrors.

Now, if you put a prism close to one of the mirror then what will the prism to do is that it will disperse the light in different directions. Now, one wavelength will go in one direction while other wavelengths will go in different direction. Now, since the path of travel of different wavelengths are different, we can easily pick a particular wavelength of our interest. The typical output power in a continuous wave Argon ion laser is between 3 to 5 Watt and some popular emission wavelengths are 5145 Angstroms and 4965 Angstroms, 4880 Angstrom and so on, there are several other.

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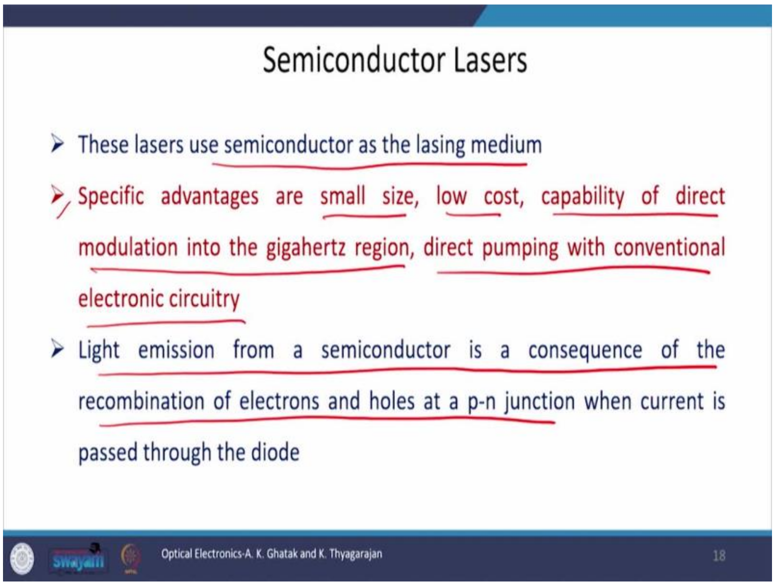

The next important laser is the semiconductor laser. They are widely used in our communication system nowadays as the name suggests, these lasers use semiconductor as the lasing medium since it is a solid state laser. And therefore, they are not bulky of course here and therefore the specific advantages of semiconductor lasers are small size, low cost, capability of direct modulation into gigahertz region. We can directly modulate these lasers at a very high speed gigahertz region.

And direct pumping with conventional electronic circuitry. Here we do not require to pump optically, we do not require flash line, the electric pumping will do and it will give us population inversion. And therefore, they are very easy to operate, they are low cost. The light emission from a semiconductor is a consequence of the recombination of electrons and holes at a p-n junction when current is passed through the diode. p-n junction is the main component of this semiconductor device.

Now when a light is passed, then electron and holes at p-n junction they recombine due to the specific design and out of this recombination we get a photon and these photons at the output they give us a laser.

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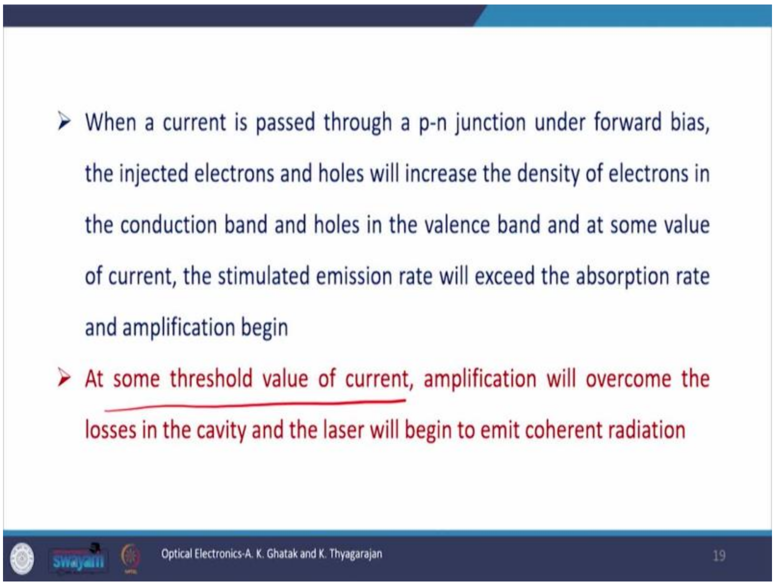

Now, when a current is passed through a p-n junction, under forward bias, the injected electrons and holes will increase the density of electron in the conduction band and holes in the valence band. And at some value of current the stimulated emission rate will exceed the absorption rate and amplification begins.

Keep it in mind that we have a laser cavity and this laser cavity is bounded in lateral direction that is they are bounded here, but then they are not bounded here or they are not bounded here from the top and bottom side they are open and therefore, out of diffraction some light may leak through and it will contribute to the losses, the mirrors are also not perfect, the coupling to the mirrors are also not perfect, there are absorption losses in the active medium also, out of these losses we always lose a part of the light which is generated into the active medium.

Now, when the generated light is larger than the loss which the system is seeing within the optical cavity then only we see some output and then only we see some amplification of the light. Now, at some threshold value of current this amplification happens, because if you increase the current, it will result into larger rate of stimulated emission more photons would be emitted, but these photons would be lost in compensating the loss of the system.

But if you keep pumping the system if you keep increasing the current then at some threshold value the loss would be equal to gain. And soon after if you increase a current a bit more, you will have huge amount of gain at the output, huge amount of amount of light would be seen at the laser output. Therefore, at some threshold value of current amplification will overcome the losses in the cavity and the laser will begin to emit the coherent radiation which we see in all types of laser.

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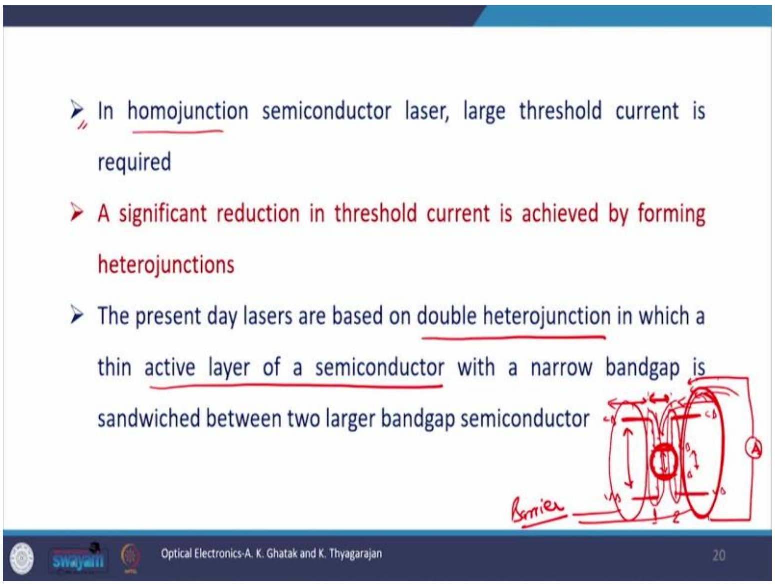

These were the different kinds of laser but, a few more important properties of the semiconductor laser is that, there exists two configurations of the semiconductor laser, one is called homojunction semiconductor laser and another is called heterojunction. In homojunction semiconductor laser, the large threshold current is required while a significant reduction in threshold current is seen in heterojunction semiconductor laser.

I repeat a significant reduction in threshold current is achieved by forming heterojunction, in hetero junction semiconductor what happens is that the energy bands they do not match. But in present day lasers are based on double heterojunction in which a thin active layer of semiconductor with a narrow bandgap is sandwiched between the two larger bandgap semiconductor, this can be understood through this diagram.

This is the conduction band and this is the valence band. This is the conduction band edge and valence band edge here. Now, this is the thin active layer inside the semiconductor laser. Now, in case of double heterostructure laser, we will have conduction and valence band of other semiconductor which is sandwiching this thin layer.

Let me explain it, no this is again conduction band edge and this is valence band edge. Now, this region here is our thin active layer of semiconductor lie, the thin layer of semiconductor lie in this region and its bandgap you can see it is a smaller this difference between conduction and valence but band edge here is smaller as compared to this difference, this is called sandwiching layer or barrier layer.

Now, the conduction band lower band edge of this material is different from this material. And similarly, the valence band edge of this material is different from this material. Due to this difference we see that the conduction band of thin active layer of semiconductor is closer to that of valence band and therefore this energy gap is smaller.

Similarly, the material lying here it has different conduction and valence bands. Now you see that the energy gap difference appears and appears here and here at two places, this was first place, this is second place, and these two points the energy level difference appear there is a step and since and this step is called heterostructure or heterojunction and there are two such steps therefore, this structure is called double heterojunction.

Now, if you pump the system suppose we are pumping it electrically, we are doing some pumping here and ammeter is here which is measuring current there what will it do is that it will put charge carriers here and ultimately all charge carriers will come down to the lowest part of conduction band and therefore, the most probable transition would be in this region, this thin region. And this increases the efficiency of double heterojunctions.

The barrier level not only confined the charge carriers, this is called barrier levels, they not only confined the charge carriers, but they also play a role in guiding the light therefore, they make a waveguide out of the laser and we see a very beautiful output directional monochromators almost monochromatic light from the semiconductor double heterojunction semiconductor lasers.

And this is all about the laser and I end my lecture here, and thank you for joining me and see you in the next class.