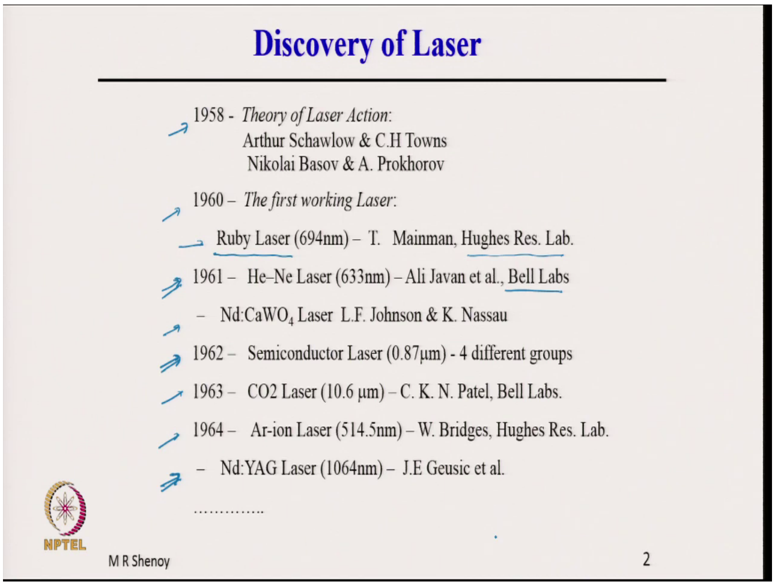
Introduction to LASER
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 33
Some Common Lasers

Welcome to this MOOC on Lasers. So, we come to the last part of this course. So, this is part 5, where we will discuss some laser systems and applications. I must mention that there are large number of laser systems and equally large number of applications where lasers are used. So, the objective, the attempt here would be just to introduce a couple of laser systems and a couple of applications which represent some standard applications.

So, let me start with this, in the first lecture here we will discuss Some Common Lasers; so 33, some common lasers.

(Refer Slide Time: 01:09)



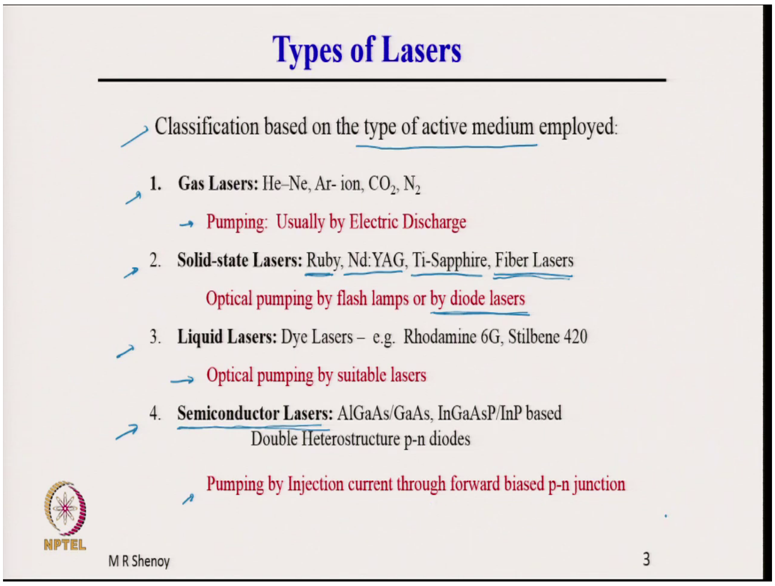
A very quick overview of the chronological developments which took place in the discovery of laser: So, in 1958 the theory of laser action was proposed by Arthur Schawlow and Charles Towns and almost simultaneously by Nikolai Basov and A. Prokhorov.

In 1960, the first working laser was realized in huge research laboratory by Theodore Mainman, it is a Ruby Laser. The first laser was a ruby laser giving output at 694 nanometer that is the pinkish red colored laser output. In 1961, the He-Ne Laser by Ali Javan and co workers at Bell Labs was developed and at the same time there was also Nd doped calcium tungstenite laser by Johnson and Nassau and in 1962, the semiconductor lasers were reported.

In 1963, the carbon dioxide laser was reported by C. K. N. Patel at Bell Labs and in 1964, the Ar-ion Laser and in the same year the Nd:YAG Laser was also reported. So, then onwards almost every year a number of lasers were developed and reported. So, this is chronological order in which the lasers were developed and it is interesting to see that one of the earliest laser that is the helium neon laser here, is also today widely used laser in laboratories.

And similarly, the semiconductor laser and the Nd:YAG laser are among the widely used lasers even to this day, after more than 50 years.

(Refer Slide Time: 03:19)



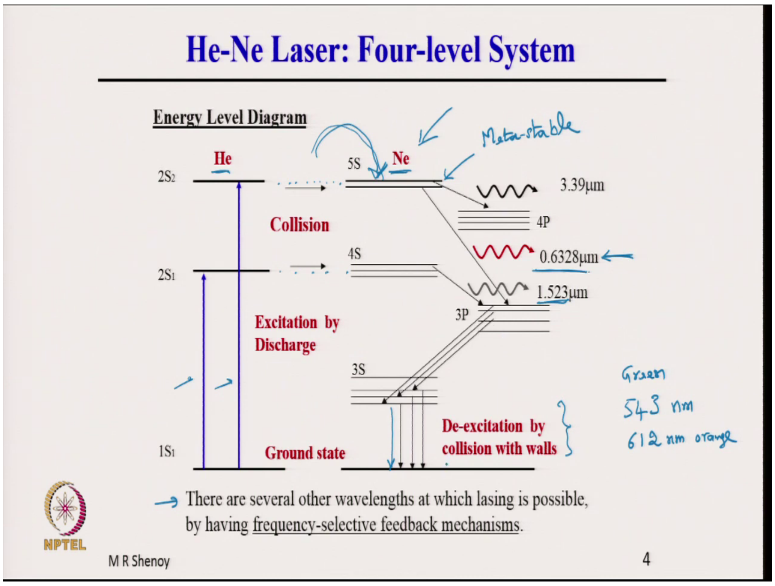
So, let us look at some of the types of laser and the classification in this case is based on the type of active medium employed. So, gas lasers first: the helium neon, argon ion, carbon dioxide, nitrogen laser and so on; all gas lasers. The active medium that is the medium which provides amplification when excited appropriately is a gas.

The pumping in these lasers is usually by electric discharge, because the electric discharge can excite atoms efficiently and therefore, pumping is usually by electric discharge. Then, solid state lasers: the most important are ruby the first one, the Nd:YAG laser, the titanium sapphire laser, fiber lasers and in these optical pumping by flash lamps or by diode lasers; more recently diode lasers find important application as pumping source.

Liquid lasers were usually the dye lasers such as Rhodamine 6G, Stilbene use liquid, the dye solution is used as the active medium and it is pumped by suitable lasers. The efficiency with the lamps is not sufficient that is why usually these are pumped by other suitable lasers. And semiconductor lasers is of course, an important class of lasers. The aluminum gallium arsenide, gallium arsenide based and indium gallium arsenide phosphide, indium phosphide based, double heterostructure p-n diodes.

I will discuss this semiconductor lasers in one separate lecture, I will also discuss fibre lasers, because these two lasers are currently the most important lasers from the point of view of industrial applications. And in semiconductor lasers, pumping is done by injection current through a forward biased p-n junction.

(Refer Slide Time: 05:47)



So, let me first take the He-Ne laser, helium neon laser. Almost all of us have seen this orange red coloured output from a helium neon laser. It is an example of a four level laser. Why He–Ne? Which is the active medium? The active medium is actually neon, the lines that we see. The laser lines that we get are transition lines corresponding to the excited neon head.

The role of helium is to efficiently excite the neon atoms. So, an electric discharge excites the helium atoms and by coincidence, there are energy levels of neon atoms which are almost at the same energy values. And therefore, the neon atoms get excited by resonant energy transfer. This is a helium neons colliding with the neon atoms, transfer their energy to neon atoms and raise the neon atoms to the excited state. So, it this collision excites neon atoms directly to the excited state here.

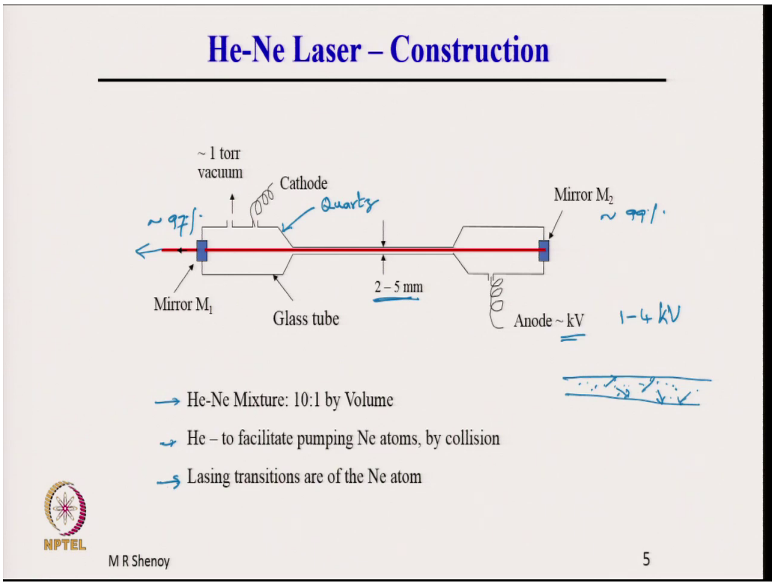
So, this is the electric discharge, so, the electric discharge raises the helium atoms from the ground state to the excited states and resonant energy transfer takes place to neon atoms and neon atoms get excited and the transitions of the neon atoms are shown here. So, this is the meta stable state of neon atom; so, this is the state which has long lifetime. So, meta stable and there are two transitions which are shown here: one which gives out from the 5S to the 4P level at 3.39 micrometer.

And the other lasing transition is the most widely used, because this is the predominant transition and therefore, most of the helium neon lasers are at 6328 Angstrom is 0.6328 micrometer or 632.8 nanometers. And there is another transition which is shown from 4S to 3P here, which is lasing at 1.523 transition. So, this is also an important line for certain applications.

And then from this level, it decays first through radiatively and then the last decay from here to here takes place by collision with walls of the container. So, the atoms which have energy here, in the 3S level, normally they are efficiently de excited to the ground state by collision with the walls of the container. We will see the schematic of the helium neon laser and try to understand what is this.

I must mention here that there are several other wavelengths at which lasing is possible in a helium neon laser by having frequency selective feedback mechanisms. For example, one of the wavelengths which is also used widely is 543 nanometer; that is the green wavelength, so green. There is also 612 orange line, so, this is orange color and the other lines which I have listed here 1.523, 6328. So, this is the most dominant and therefore, most of the common helium neon lasers have laser output at 632.8 nanometers.

(Refer Slide Time: 10:01)



So, the schematic of the laser looks like this. So, there are two mirrors at the output end, generally the mirror reflectivities are very high. So, mirror reflectivity could be 99 percent and 98 percent or 97 percent of that order very high reflectivities. Because, the gas is a very inefficient gain medium and therefore, the mirrors must be of very high reflectivity, so that the threshold can be reached or the resonator losses can be maintained as low as possible.

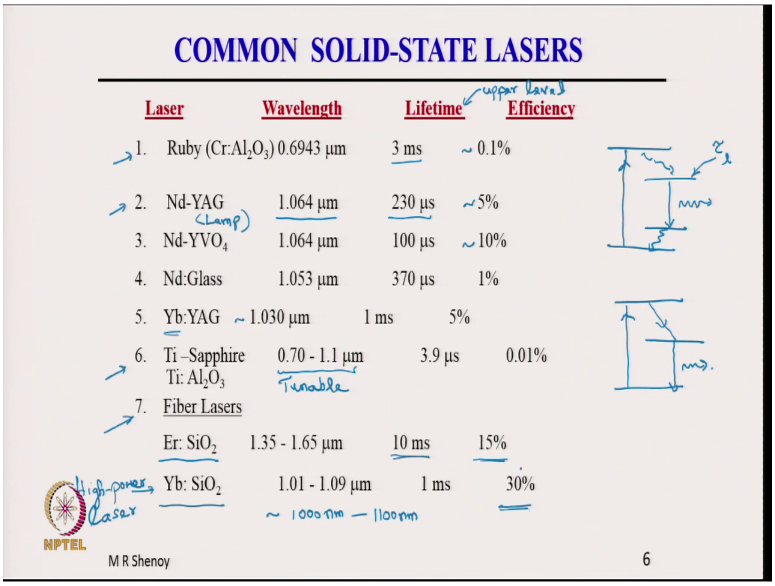
So this is a quartz glass tube; so, usually this is quartz glass tube and the red colored beam is building up here and coming out from the other end. So, it is coming out here, shown in this way. The tube has a narrow diameter of typically 2 to 5 mm here; this is to facilitate de excitation of the atoms to the ground state. So, that is what I mentioned in the previous slide.

So, this de excitation because finally, the atoms have to be de excited very rapidly to the ground state, so that the population inversion can be maintained and therefore, to facilitate this de excitation, the diameter of the tube is kept very small. So that if the diameter is small, then the gas atoms which are here would have more collisions with the walls of the container and in the process they get de excited and that is why usually the diameter here is very small.

A typical voltage is approximately of the order of 1 to 4 Kilo Volt, for electric discharge and the pressure is around 1 torr vacuum. Helium neon, the mixture is in the ratio of 10 is to 1; helium 10 parts to 1 part by volume. And helium, as I mentioned is to facilitate pumping neon atoms by collision and the lasing transitions are those of the neon atom.

So, this is in brief about the helium neon laser, there are various aspects of the engineering design, how the cathodes are designed. So, these are metallic cathodes usually hollow cathodes and there are various engineering aspects in the system.

(Refer Slide Time: 12:53)



So, let me now go to some of the solid state lasers. So, in this table here, I have listed some of the solid state laser. The first one the ruby laser: ruby is a chromium doped alumina is a crystalline alumina and the lasing wavelength.

So, this wavelength refers to the laser wavelength, lasing wavelength is 694.3 nanometers or 0.6943 micrometer. So, this lifetime here refers to lifetime of the upper level; so, it is the upper level of the laser transition. So, if it is a three level or four level system as you know the excitation takes place here, and then it comes down to an intermediate layer and from there the laser transition takes place; so this is our laser transition.

So, the lifetime is lifetime of this level; upper level of the laser transition and then of course, it rapidly comes down here. Ruby is of course, a three level laser. So, it is a three level system, a very quick recap. So, you have pump exciting to a upper level and then it rapidly comes down to an intermediate layer and this is the lasing transition. So, three level and four level lasers.

Nd:YAG we have discussed in detail, we have seen the energy level diagrams of Nd:YAG and the dominant line there is 1064 nanometer or 1.064 micrometer. The upper level lifetime is about 230 micro second; what is listed here efficiency is the overall efficiency of the laser. So, typical efficiencies are listed, helium neon has efficiency generally less than 0.1 percent.

Ruby laser is about 0.1 percent, the Nd:YAG laser, this is lamp pumped, we will also see diode pumped lasers; I have already mentioned about diode pumped solid state lasers. So, this one is using lamp flash lamps; so, lamp pumped and the efficiency is approximately 5 percent. The diode pumped ones will have slightly higher efficiency.

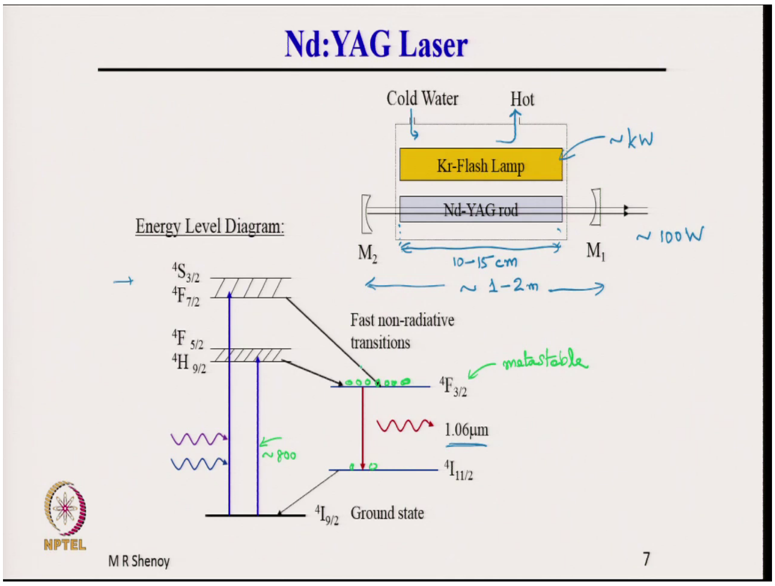
This is another host which is yttrium benedict, this is more efficient as compared to the YAG and otherwise the wavelength is the same, lasing wavelength and efficiency approximately 10 percent. These are all of the order of approximately depending on the design, the efficiencies can vary slightly.

This is ytterbium doped YAG which is lazing around 1030 nanometers and 1 millisecond is the upper lifetime of the level and the efficiencies could be typically 5 percent. Titanium sapphire laser, one of the widely used tunable laser, you can see that the wavelength is in this range. So, this is a tunable laser which means the output can be tuned over a range of wavelengths; although the efficiencies are quite poor.

Fiber lasers, this I will discuss in detail in the next lecture. So, there are erbium doped silica and ytterbium doped silica. Ytterbium doped silica is usually for high power applications; so, most of the high power lasers now use ytterbium doped silica. The wavelength is again tunable; typically in the range 1000 nanometer to 1100 nanometer typically.

And this is the lifetime of the upper level; the lifetime of the upper level indicates large lifetime. As we have discussed in the theory, large lifetime implies it is easier to create and maintain the population inversion. We note in particular that the efficiencies of the fibre lasers are very high; there are various reasons for this which we will discuss in detail in the next lecture.

(Refer Slide Time: 17:36)

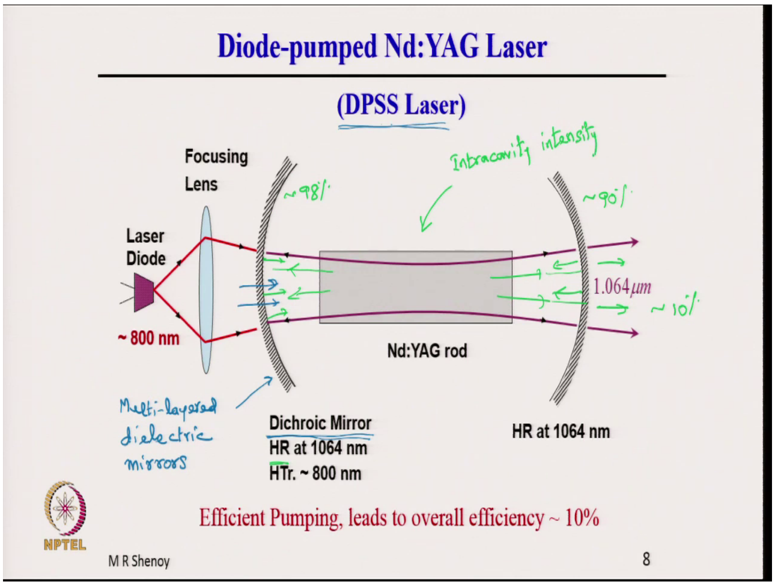


So, here I have shown a schematic of the Nd:YAG laser; this is a flash lamp pumped Nd:YAG laser where you have a Nd:YAG rod, this is not correct to dimensions. So, this rod length is typically 10 to 15 centimeters, the length of the rod and here is the flash lamp. The flash lamp pumped cavity is generally of the order of 1 to 2 meters in length; the cavity length is much longer compared to the rod.

Usually, we use a spherical mirror resonator and the energy level diagram we have discussed in detail. So, this is excitation to the upper level and 4 F 3 by 2 is the upper laser level. We have seen other transitions, I have already discussed this in detail and only what is shown is the dominant transition the most common and most efficient line is the 1064 nanometer or 1.064 micrometer line. So, we have discussed this mechanism in detail.

So, there is because the flash lamps are used; typical energy output power output could be of the order of 100 Watt and therefore, the flash lamps required are of the order of kilowatt power and therefore, you need cold water to keep the lamp cool. So, cold water and exhaust is hot water. So, it is a water cooled compartment here, to keep both the flash lamp and the Nd:YAG rod at a lower temperature.

(Refer Slide Time: 19:33)



So, what is now shown is the diode pumped YAG laser. So, diode pumped solid state laser, this is in the class of diode pumped solid state laser. So, a schematic is represented here, again it is not correct to scale. So, we have a laser diode pumping around 800 nanometer and the laser light is focused here on to the Nd:YAG rod.

This is a dichroic mirror; dichroic mirror means a mirror which has usually high reflectivity at one wavelength and high transmitivity, at another wavelength almost; all these mirrors are made by multi layered dielectric mirrors. So, these are multi layered dielectric mirrors; multi layered dielectric mirrors.

Because, metallic mirrors you cannot have a high transmission through them at very closely separated wavelengths, so, dielectric mirrors. So, the layer thickness and refractive indices are chosen, such that it is highly transmitting for the diode wavelength whereas, the Nd:YAG line which is generated here, the Nd:YAG wavelength which is generated inside. So, let me use a different color for the Nd:YAG line it is highly reflecting.

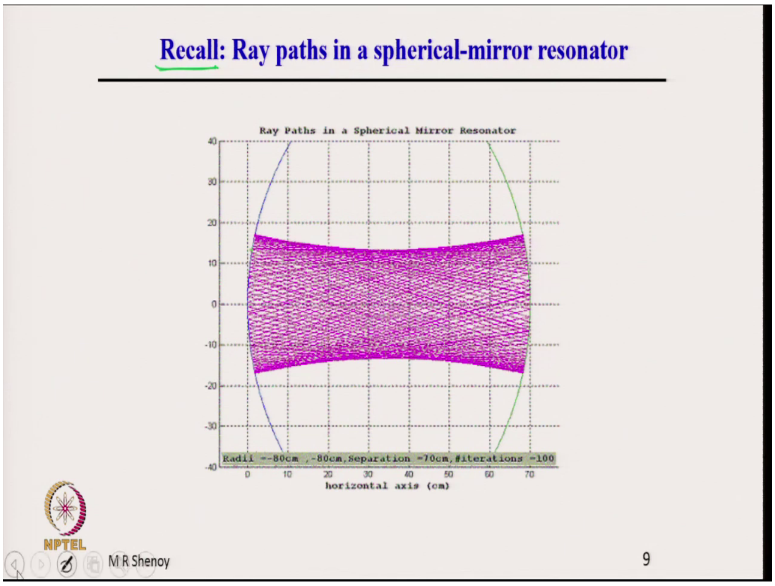
So, this is the Nd:YAG; so, this reaches here and also gets reflected back; so they are highly reflective. In fact, this mirror is almost 100 percent reflecting here; highly reflecting. So, approximately 98 percent or 100 percent reflecting and this reflectivity is slightly lower because, we also need the Nd:YAG output coming from here. So, this may be 90 percent just putting some numbers. So, it is a dichroic mirror which has high reflectivity at 1064 nanometer and high transmitivity at the pump wavelength which is around 800 nanometer.

So, the pump is efficiently absorbed in such a structure because if we see the diagram; I have already discussed this in detail that this wavelength here could be around 800 nanometer. So, this is 800 nanometer and then we have excitation to a upper level and from there it comes down to 4 F 3 by 2 which is the meta stable state. So, this is the state which has a long lifetime; so, meta stable.

The two thirty micro second time is for this level and atoms accumulate here; we have already seen and create population inversion between this level and the upper level. So, there is a population inversion which is built in here.

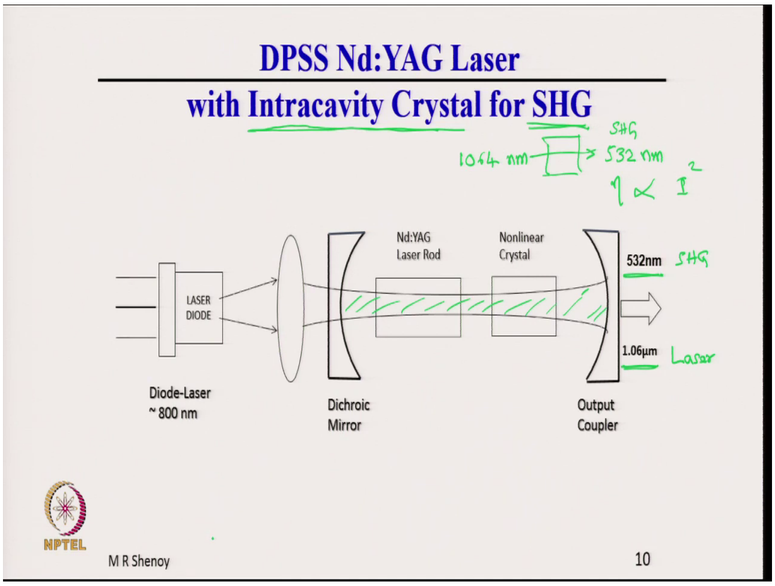
So, the diodes ensure that the pump is at the right wavelength, so that there is very little heat is generated. And therefore, the efficiency of diode pump lasers are typically 10 to 15 percent; the DPSS lasers, as compared to the lasers which use flash lamps for pumping where the efficiency is about 5 percent.

(Refer Slide Time: 23:17)



So, what is shown here is just to recall the ray paths which we had seen earlier in the spherical mirror resonator that the beam looks like a Gaussian beam which goes back and forth, when you draw the ray paths. And that is why we have shown here, a Gaussian beam which is going back and forth inside the spherical mirror resonate.

(Refer Slide Time: 23:47)



There is a Nd:YAG laser with the intra cavity crystal for second harmonic generation. The Nd:YAG laser which is shown here; if we can have an intra cavity crystal, intra cavity means inside the cavity crystal, then it can lead to efficient second harmonic generation. I will discuss this application of second harmonic generation in detail in a subsequent lecture.

When we have a laser the laser beam intensity inside; so, this is the laser beam which is going back and forth is much higher compared to the laser beam intensity outside. Let us look at the laser here, because 90 percent is the reflectivity of this mirror which means the output is of the order of 10 percent from the laser.

Therefore, the intensity inside the cavity, so, intra cavity intensity, so intra cavity intensity is much higher than the intensity of the laser beam which comes out. So, intensity is very high and therefore, we will see that in a non-linear optical experiment you need very high intensities for efficient second harmonic generation.

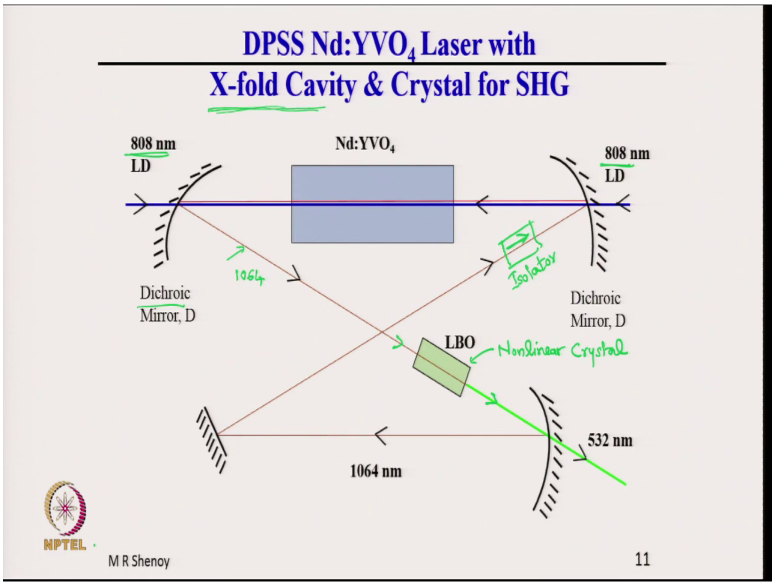
Second harmonic for those of you are not familiar, if we use a 1064 nanometer laser and pass it through a crystal which I will discuss in a little bit more detail. So, this is a crystal then we get half the wavelength or second harmonic that is double the frequency which corresponds to 532 nanometer.

This can be achieved without keeping the crystal inside the cavity, it is not necessary, you can have a high power laser passing through a crystal at a suitable angle and it is usually possible to get second harmonic generation SHG.

But, because the intensity of the laser beam is high inside the cavity rather than outside, if we place the crystal inside the cavity; then the second harmonic generation efficiency will be very high. We will show that eta is proportional to square of the intensity and therefore, if the intensity is high, then the efficiency will also be higher.

In such cases, we will get at the output the primary this is the laser line and also 532 nanometer SHG; the output will comprise of both of these. Of course, then you can have a filter to remove the 1064 line and get only the green at the second harmonic. So, this is the SH line and this is the laser line or the pump. So, this is a schematic of an Nd:YAG laser with an intra cavity crystal for second harmonic generation.

(Refer Slide Time: 27:18)



So, here what I have shown is an X fold cavity as you can see this is like an X; so, it is a folded cavity. The advantage of folded cavity is if we were to have more number of components along the same line, then the length of the system becomes much larger and it goes beyond the experimental table that we have. And therefore, if you have a folded cavity, then you can have much more compact setups.

In fact, in some of the experiments, there may be many many many many folds, so that the length can be contained within the experimental table right. So, what is shown here is a Nd YVO 4 system, neodymium doped yttrium vanadate and the pump is at 808 nanometer, it is pumped from both the sides the crystal is pumped.

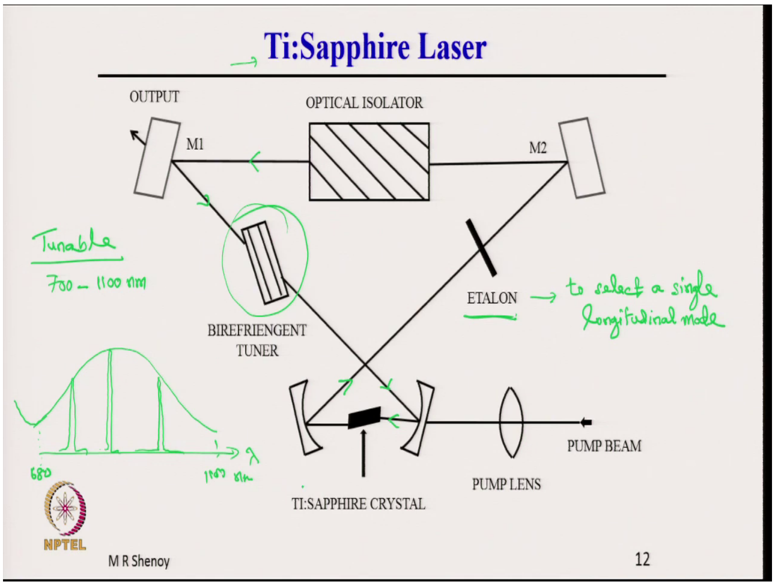
So, these are dichroic mirrors, both the mirrors here are dichroic which again I repeat it means that it allows the pump to pass through, but is a high reflecting mirror for the laser line so that we have a highly reflecting and highly resonant cavity. And the colors that show; so, this color here is for the pump and this is the color for the 1064, it is a Nd. Therefore, this is the 1064 line, it is folded this is a non-linear crystal LBO is the crystal.

So, non-linear crystal the laser beam passing through this generates the second harmonic. So, what you have from here is 1064 and at the output, you get 532 nanometer. Of course, there will be 1064 which will be reflected back again here and goes back along this path and then enters the active medium which is pumped and therefore, again builds up when it passes through this.

The cavity is built in such a way, that the light propagates only along one direction. In fact, you can have isolators, there are optical isolators probably I have it in another diagram. So, you can have optical isolators which permit the laser beam to travel only in one direction. So, this is an isolator, optical isolator is like a diode which permits light to pass through in one direction, but does not pass through in the other direction.

And then we see that the laser goes in only one direction, there is no reverse building up possible, because the beam is not permitted to pass through in the reverse direction. So, the advantage of X fold cavities is one; it is a folded cavity, it makes it more compact and then we can introduce several components in the path of the laser beam for certain applications. For example, here a crystal has been introduced to achieve the second harmonic at 532 nanometer.

(Refer Slide Time: 30:55)



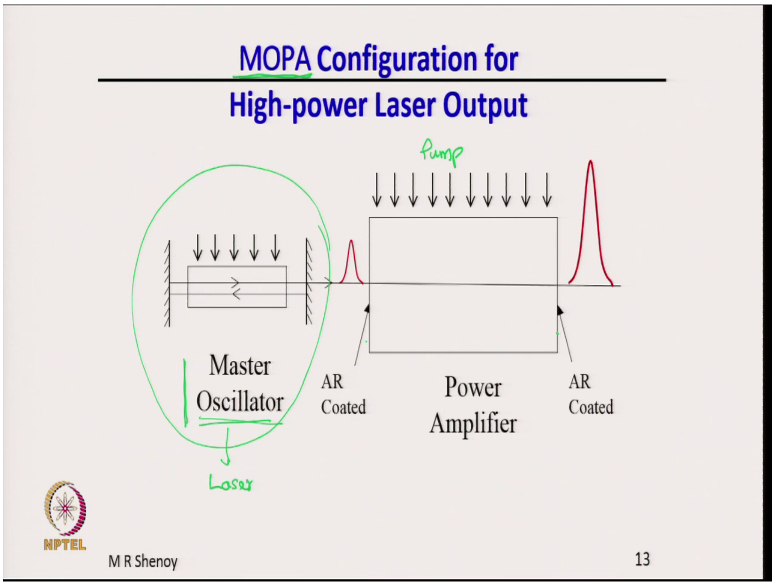
So, what is shown here is a schematic of the setup for the titanium sapphire laser. So, titanium sapphire is a tunable laser; so, this has a spectrum which is it is tunable over say tunable over approximately from 700 or 780; so in the range of 700 to 1100 nanometer, that is a very very wide range of tunability in the case of lasers.

So, the titanium sapphire laser has a broad spontaneous emission spectrum. So, it has a broad spectrum of spontaneous emission, over a certain region which could be approximately from 680 here to 1100 nanometers. So, this is wavelength and it is possible to tune the laser can be made to lase either here or it can be lasing here or it can be lasing here. So, how do you achieve this?

You can tune the wavelength, so that the laser lasers at one wavelength in this wide band and that is achieved by this birefringent tuner. I will discuss about this in the next slide. So, the system comprises of an optical isolator again as I mentioned the optical isolator allows light to pass through in one direction. So, it passes through the crystal and then it comes back.

There can be an intra cavity at etalon on; we know the purpose of an intra cavity etalon to select a single longitudinal mode, if you need; so, to select a single longitudinal mode; single longitudinal mode and the birefringent filter to tune it over a wide range of wavelengths. So, titanium sapphire laser is a very important laser with a broad spectrum of its output.

(Refer Slide Time: 33:34)



Here in this diagram, what I have shown is what is called as MOPA configuration. MOPA stands for Master Oscillator Power Amplifier configuration for high power laser output; so it is illustrated here. So, there is a master oscillator is a laser. So, here oscillator refers to the laser. So, when you need very high power laser output.

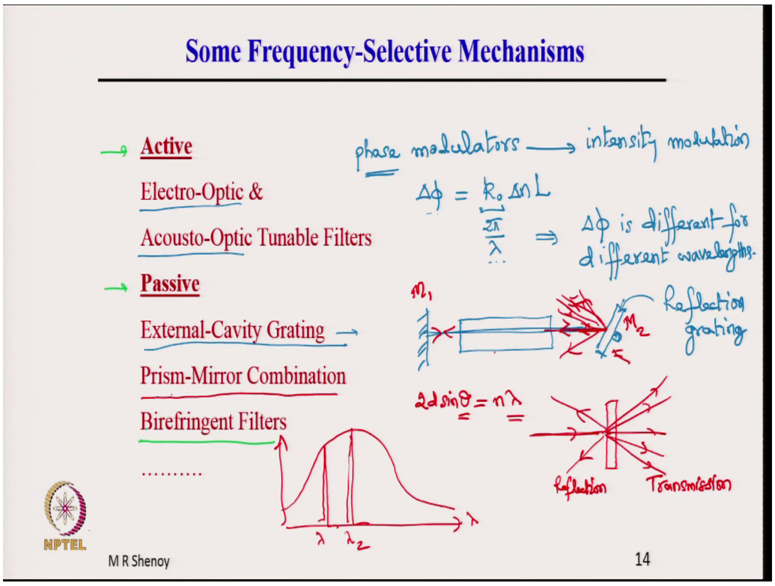
So, this is the master oscillator, in the sense, it is a master which gives out study output, it could be pulse or CW. And then there is a power amplifier, these are anti reflection coated ends; the ends are anti reflection coated which means there is no feedback coming from the ends. A pulse or the laser output which comes here simply passes through this medium.

Now, the medium is amplifying medium, because it is being pumped and there is a heavy population inversion built in this medium, so that when the laser pulse comes, it gets amplified by stimulated emission and it becomes a very large pulse. This is particularly important for high power lasers, because usually to build a high power laser directly is more difficult, because the issues involved with the high power laser are very different.

There are lot of issues related to thermal management, stability, small variations can make lot of difference in the case of a high power laser. And therefore, it is far easier to build a very good laser, very good laser means with a steady output at a stable frequency; it is very easy to build at low powers.

And therefore, you build a low power laser with very good quality output beam and then amplify that beam through a separate amplifier, to achieve very high output powers that is called Master Oscillator Power Amplifier configuration or widely known as the MOPA configuration for high power output lasers.

(Refer Slide Time: 36:08)



Here I finally, come to some frequency selective mechanisms. So, these mechanisms can be used to select different frequency lines or to tune the output of a laser. There are active methods and passive methods; so, active and passive methods for frequency selection. We will not go into the details, in the case of active methods usually electro optic technique or acousto optic technique which I have briefly discussed.

In both of these, basically the applied electric field or applied RF leads to a phase change; these are basically phase modulators. So, phase modulators are appropriately used to intensity modulate the output; so intensity modulator, intensity modulation. Now, important point to see is a change in phase is equal to k 0 into either change in refractive index delta n or change in the length L that is the path length; so usually it is a change in refractive index.

Therefore, by changing delta n by an applied electric field or an acoustic field, we can get a change in del phi. But there is a factor which is k 0; k 0 is 2 pi by lambda and therefore, the change in phase del phi also depends on the wavelength. This implies delta phi is different for different wavelengths, is different for different wavelengths. This is the idea which is used in selecting different wavelengths of oscillation; different wavelengths.

The details of this mechanism is beyond the scope of our course, so I will not go into it. Now, in the case of passive tuning mechanisms, there can be external cavity grating. So, let me briefly illustrate here; let us say there is a laser here which can oscillate. So, this is a laser with a mirror here, one mirror and the other mirror is here.

Instead of the other mirror, here if we use a reflection grating which is rotatable. So, this is a reflection grating. What is the reflection grating? The normal gratings that we study the diffraction gratings are if you have an input beam which comes here, then in the transmitted we see different orders of diffraction.

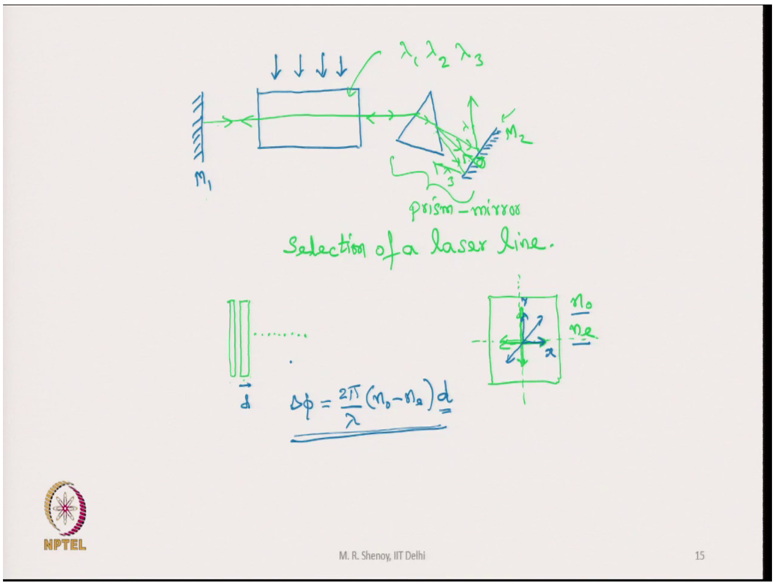
In a reflection grating, the reflected; there is no transmission on the other side, but there are reflections which come at different orders. So, this is reflection grating and this is transmission grating. So, here I have referred to reflection grating. So, the incident beam here can get reflected at certain angles; it could also get reflected back here, but only for certain angles. Because, we know that it has to satisfy 2 d sin theta is equal to n lambda.

The diffraction angle depends on the wavelength. Therefore, if we have a range of wavelengths on which a laser can oscillate. So this is the wavelength spectrum or the spontaneous emission spectrum of the medium here, then we can have a reflection grating here which gives feedback only at a selected wavelength and that wavelength is selected, because all other wavelengths will go at different angles like this.

So, all the other wavelengths will go at different angles, therefore, only one wavelength which goes back here will get built up inside the resonator. So, this is our mirror m 1 and this diffraction grating here is mirror m 2. The reflection grating reflects different wavelengths at different angles and a particular wavelength you can choose by ensuring that, that wavelength is reflected back along the laser along the path here; so, that it builds up back and forth only one wavelength out of this entire spectrum.

If you rotate the grating, then another wavelength which is sitting here maybe getting feedback; so this is lambda 1, this is lambda 2 and so on. So, this is what is written here as external cavity grating for selecting a wavelength. A second mechanism which is written here is prism mirror combination; this is a very ingenious and simple technique to select a certain laser wavelength. So, let me illustrate this prism mirror combination, let me show this in the next sheet here ok.

(Refer Slide Time: 42:46)



So, let this be the laser system here and this is mirror m 1; it is a very nice arrangement and so, there is a laser beam. At the other end we have a prism and then there is a mirror. This is the active medium, laser medium and prism and then the mirror. Now, let me use the red color. So, the laser beam which is incident on the prism goes here and then comes to the mirror at a certain angle. Here of course, the laser beam goes back and forth; it is a normally incident, but what is incident on the prism here comes to the mirror here.

Now, if the medium has a range of wavelength generated or if in this laser, there are several wavelengths lambda 1, lambda 2; like in the helium neon laser case, I mentioned that the laser can lase in several wavelengths: lambda 1, lambda 2, lambda 3; then when it comes to the prism here the prism is a dispersive element. So, one wavelength comes here, one wavelength comes here and another wavelength comes here, I have exaggerated a little bit.

So, lambda 1, lambda 2, lambda 3; they come at different angles after being dispersed by the prism. And the mirror here can be tilted such that depending on the angle of tilt of the mirror, only one of the wavelengths will be reflected back. For example, in the diagram that I have shown; this wavelength will go outside, this wavelength will get reflected back and this wavelength would come here.

So, only one of the wavelengths would go back and forth and therefore, the cavity comprises of mirror m 1 here and mirror m 2 here; in between so this arrangement is called prism and mirror arrangement. So, prism - mirror arrangement for frequency selection; this arrangements cannot select different longitudinal modes of a laser, because the dispersion in the prism is not.

So, much to separate very very closely spaced frequencies such as those of longitudinal modes; this is when the wavelengths are well separated. Like, if you take a argon ion laser; there is a very important line at 488 nanometer and 514.5 nanometer; they are well separated in wavelength.

Similarly, in the case of helium neon laser, there was a line at 543 and there is a line at 632.8, there is a line at 612. These are well separated in wavelengths which can be separated by using a prism mirror combination, this is called selection of a laser line; selection of a laser line using prism mirror combination. Then, the last method is birefringent filters; birefringent filters are widely used in titanium sapphire lasers.

So, this comprises of the birefringent filters comprises of a stack of birefringent material. So, I will not go here into detail because, many of you may not be aware of the birefriegent media and the physics of birefringent media. So, it has a stack of films or plates of a birefringent material and different plates provide different amounts of phase or phase difference between the two components of a birefringent plate.

If I show one of the birefringent plates as a square here, then the birefringent plate has two eigen modes or a polarization which is along the horizontal here will see one refractive index and the polarization here will see another refractive index. For example, more physics is beyond the scope of our discussion here. So, it shows a refractive index n o and n e.

Therefore, if we launch a light, which is polarized at an angle, let us say here at 45 degrees, then this is resolved into two components; one along n o and one along n e, along n o, along n e means one along this direction which will see a refractive index n o and one along so, let me call x and y direction; then one along n e which will see another refractive index.

And therefore, the two components will travel with the different phase velocity and after passing through the length of the plate; if d is the plate, then there is a phase difference delta phi between the two components which is equal to 2 pi by lambda into n o minus n e into the length or thickness of the plate. So, this is the phase difference introduced by a plate of thickness d by appropriately choosing different plates of different thickness and cascading them, it is possible to choose a certain range of wavelengths to pass through.

All other wavelengths will be blocked and by changing the tilt of the stack, it is possible to shift this wavelength and that is how we can tune the birefringent filter to select different wavelengths from the spontaneous emission spectrum. Out of the total spontaneous emission spectrum, the laser can be made to lase at a different wavelengths, required wavelengths by appropriately tuning the birefringent filter.

I will stop this discussion here, because this involves more physics of the birefringent media. But, the important point is using simple mechanisms passive or active; it is possible to tune the laser over a range of wavelengths, when the spontaneous emission spectrum is wide. We will discuss some more in the specific context of fibre lasers in the next lecture.

Thank you.