Introduction to LASER

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Lecture - 30
Q-Switching

Welcome to this MOOC on LASERs. We have been discussing about pulse lasers and methods of pulsing laser. Today, we will discuss Q-switching which is one of the widely used technique for pulsing lasers, particularly to get high energy pulses of short duration.

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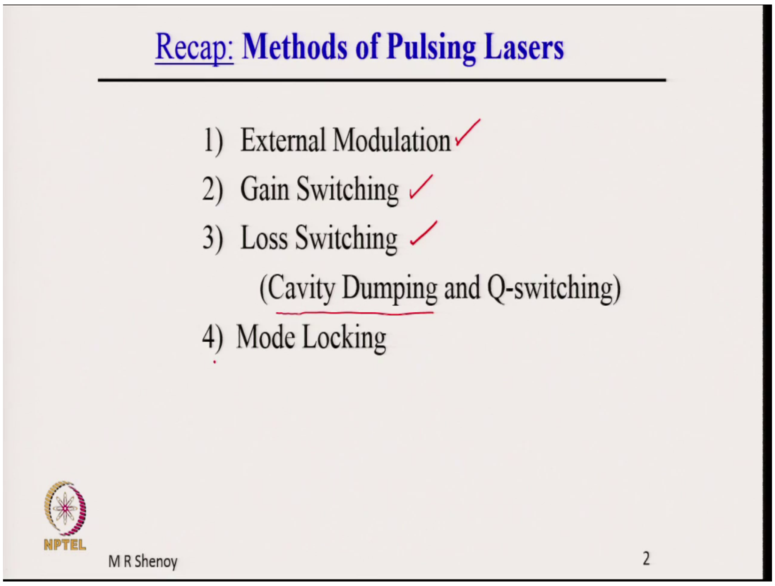

So, a very quick recap. The methods of pulsing laser external modulation so, we discuss this in the last lecture, gain switching and loss switching. In loss switching, I have discussed the cavity dumping in the last lecture and therefore, today we will discuss Q-switching and then, in the next lecture we will discuss mode locking.

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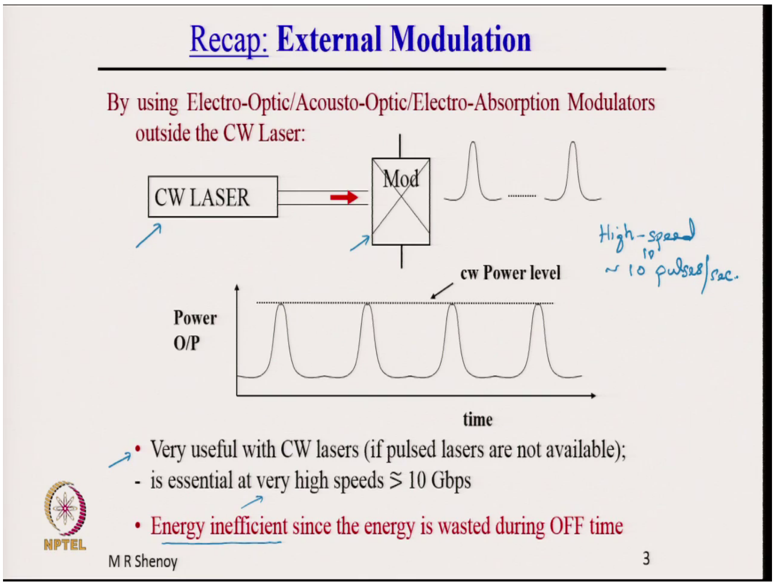

Before I go to discuss Q-switching, a very quick recap of the methods which we have discussed. First, external modulation where we have a CW laser here, we have a continuous wave laser, the output is constant with time, there is a modulator which modulates essentially the modulator is like a shutter, a controlled shutter which therefore, gives output in the form of pulses that is energy packets over short durations.

The modulator may be working on any of the principles, electro optic modulators, acousto-optic modulators or electro absorption modulators, but the modulators are placed outside the laser system. We have also discussed that the power output of course, is in the form of pulses, but it is very energy inefficient, it is energy inefficient since the energy is wasted during off time. Basically, you are chopping the output, you are blocking the output during the off times.

But as discussed, its very useful with CW lasers, when pulse lasers are not available and also this is the method to be followed when the modulation is required at very high speeds. A laser in itself cannot be modulated at very high speeds and therefore, external modulators are used when the output is required to be high speed output. High speed means the number of pulses per second.

So, high speed here refers to so, high speed when we say high speed, we refer to very large number of so, of the order of 10 to the power of 10 pulses per second; pulses per second. So, 10 to the power of 9, 10 to the power of 10 pulses per second, then we need to use external modulators.

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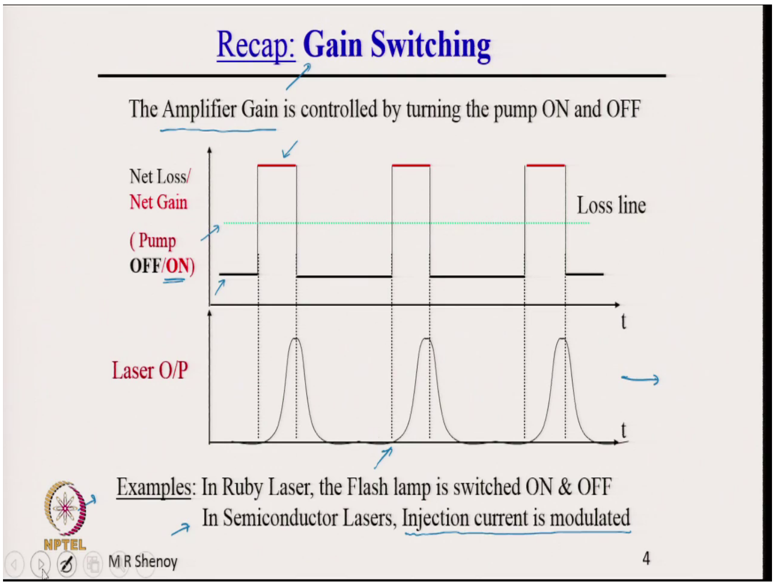

The second method which we had discussed is gain switching where the amplifier gain is controlled by turning the pump on and off. So, we have discussed this. So, what is shown here is the pump off, on. When the pump is off, pump level is off, then there is net loss in the system, this is the loss line of the cavity resonator, this is the loss in the system that is there is no gain provided by the amplifying medium.

But when the pump is on, then there is gain provided by the amplifying medium here and therefore, we have gained more than the loss and therefore, the laser energy starts building up inside the resonator and a part of it would obviously, come down. But if the gain is switched off that is if the pump is switched off, then again, the energy decays down to 0 and it remains 0 till again, when the pump is switched on at this point.

Therefore, the rate at which the pulses come out is determined by the rate at which the pump is switched on and switched off. The pulse duration is determined by the duration over which the pump is on. Practical examples include ruby laser which is usually operated in the pulsed mode has the flash lamp being switched on and off at regular intervals.

And as I discussed in the last lecture that this is an important method of pulsing semiconductor lasers because one can directly modulate the output of a laser by modulating the injection current passing through the laser. So, this is gain switching is a very important technique.

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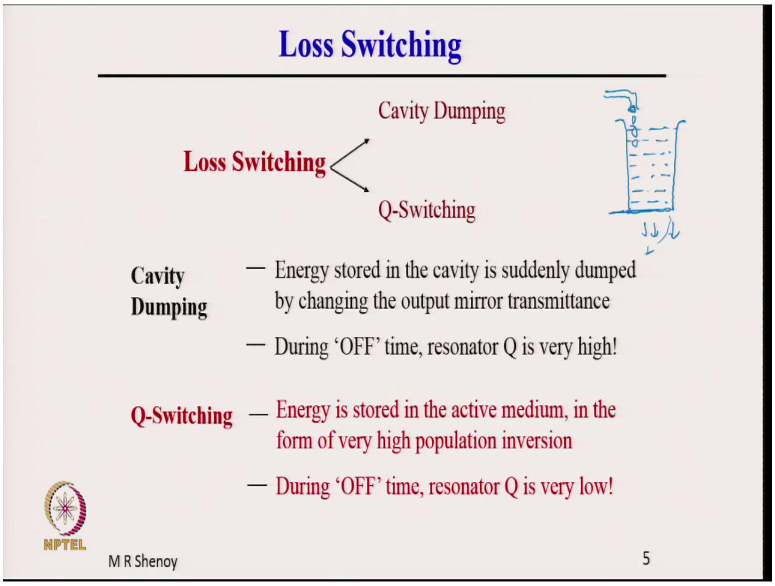

Then, we said loss switching. In loss switching there are two methods which are used cavity dumping and Q switching. In the last lecture, we discussed cavity dumping which is very easy to understand if we consider a an analogy of a bucket here with flap which could be opened so, let us say there is a flap and we could open this flap like this.

So, there is a tap through which water is continuously; water continuously drops into this and when the bucket is full; when the bucket becomes full, then if we just open the flap, then the entire water content from the bucket will be emptied and then, again, close the flap so that water again accumulates in the bucket.

So, similarly, in the case of cavity dumping so, its just like dumping the water, if you open the bottom that means, you are dumping the water there. So, it is the energy stored in the cavity is suddenly dumped by changing the output mirror transmittance and today, we will discuss Q-switching.

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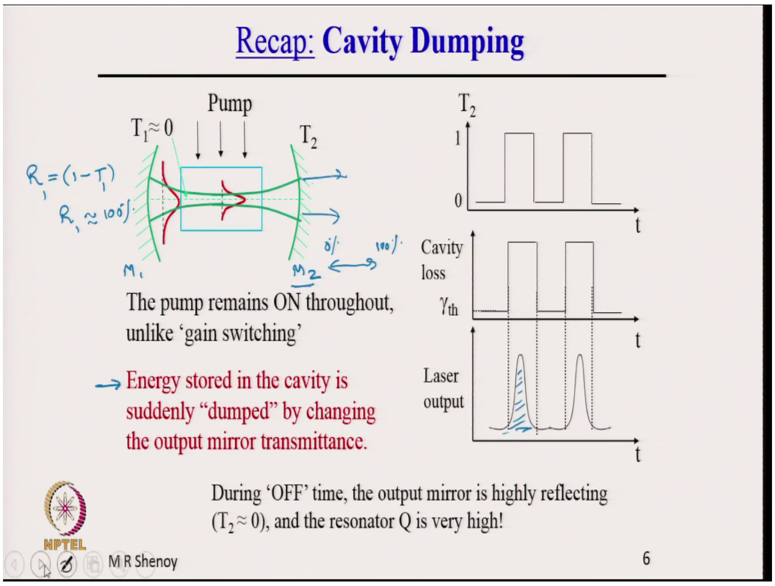

So, let us just look at the cavity dumping very quickly. So, here is the laser with the mirrors M 1 and M 2; so, mirror M 1 and M 2. M 1 has a transmission which is T 1 which is nearly equal to 0 which means the reflectivity or reflectance is equal to 1 minus T is nearly equal to 1 which means R 1 so, this is T 1 which is R 1 is nearly equal to 100 percent, the reflectivity of the first mirror is 100 percent.

And M 2, the transmittance of the mirror M 2 is switched between 100 percent and 0 percent almost 100 percent and then, 0 percent. If the transmission is 100 percent which means the entire power comes out from the laser cavity.

If the transmittance is 0 percent which means this is highly reflecting, 100 percent reflecting and therefore, the energy is contained in the resonator, energy is stored in the resonator and that is illustrated here that the transmittance T 2 that is T 2 is the transmittance of the second mirror M 2 is switched between 0 and 1, 1 means 100 percent transmitting.

And when it is 0, there is no output, the cavity loss is very low because both the mirrors are highly reflecting mirrors and therefore, the cavity loss is very low. Therefore, the threshold of this laser is very low and suddenly, it is as if the mirror is removed suddenly, then the energy stored so, the mirror is removed which means the loss is very high, transmittance goes to 1 which means loss of the cavity is very high which means the energy contained in the resonator suddenly comes out in the form of pluses.

So, these are the pulses which come out when the mirror transmittance is switched. Again, the mirror transmittance is switched back to 0 so that energy is stored in the resonator and then, again the transmittance is switched. So, essentially, the transmittance of the output coupler is switched between 0 and 1 that is transmitting, non-transmitting to get the output in the form of pulses.

So, the pump remains on through unlike in gain switching. In gain switching, we switch the pump, pump is switched on, off, but in the case of cavity dumping, pump remains on throughout. The energy stored in the cavity is suddenly dumped by changing the output mirror transmittance and of course, during the off time, off time means this off time, the output mirror reflectivity transmittance is 0 which means reflectivity is very high and the resonator Q is very high.

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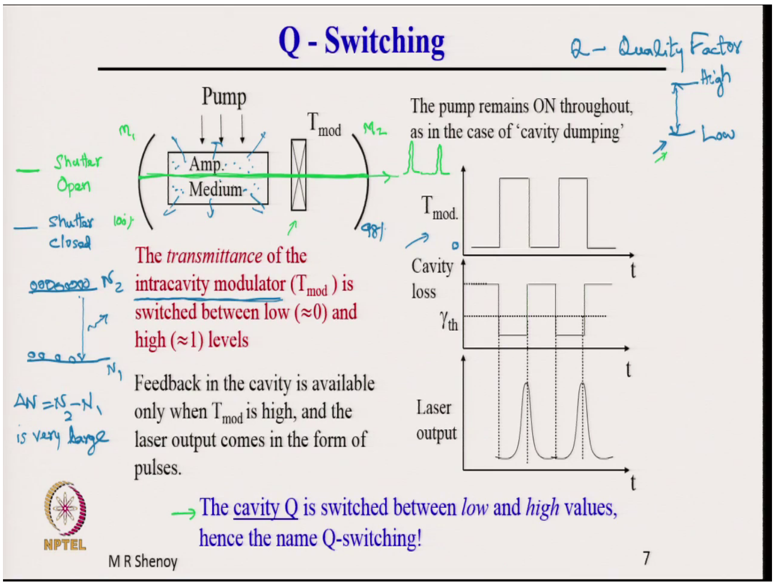

So, now let us see what is the difference between Q-switching? In the case of Q-switching, there is an external modulator, there is a modulator which is placed inside the resonator, its a intracavity modulator. In the case of external modulation, we had this modulator outside the cavity. Now, in this case, the modulator is placed inside the cavity the modulator is essentially a shutter which is open or closed.

Let us assume that when the shutter is open, let us say the shutter is open, then when the shutter is open, light would go back and forth completely. When the shutter is open, the light would go back and forth. I am showing this by red ink. And of course, let us say this is about 100 percent. Usually, we show that the mirror M 1 is almost 100 percent reflecting and mirror M 2 is the output coupler which means a part of the output comes out here. So, this corresponds to shutter open.

So, shutter open laser beam building up inside the resonator and a part of the laser beam coming out. Suppose the shutter is closed. So, when the shutter is closed, let me show this with the blue ink. So, shutter closed, when the shutter is closed, there is no beam going back and forth because the shutter is closed therefore, there is no feedback coming from mirror M 2.

And therefore, the light which is generated here is scattered in various directions only the spontaneous emission is coming out in different directions, there is no stimulated emission building up because for simulated emission, we need feedback and therefore, whatever light which is coming from the excited atoms is given out from the medium, but there is no concentrated focused output which is coming.

Second point, when there is no feedback, the atoms in the excited state lead to a very large amount of population inversion. So, this is let us say N 2 and this is N 1 the ground state, then we have very large number of atoms here in the excited state and the population inversion that is the extent of population inversion delta N is equal to N 2 minus N 1 is very high, is very large because this is not being depleted.

There are some atoms of course, which will get de-excited giving out spontaneous emission, but there is no stimulated emission which is depleting the atoms and therefore, delta N remains high when the shutter is closed. Now, assume that the shutter is closed that is the modulator is closed, then delta N is very large.

Suddenly, the shutter is opened, then some of the photons which travel towards M 2 will be reflected back and as they pass through the medium with very high levels of population inversion, they will build up rapidly and therefore, they build up very rapidly inside the laser resonator and a part of the light would be given out.

Now, when the shutter is closed again, there will be no output and now that is illustrated by this graph here. So, want happens is the modulator T stands for transmittance of the modulator. So, transmittance of the modulator. So, if the transmittance of the modulator is 0, then the cavity loss is very high because there is no reflection coming from the mirror M 2 therefore, R 2 is very small reflectance or reflectivity of this mirror is very small and therefore, the loss is very high, cavity loss is very high.

When the transmittance of the modulator is 0 which means when the shutter is closed, then the cavity is a poor Q cavity, low Q, Q standing here for quality factor. So, maybe I should have mentioned this earlier itself so, it is the quality factor; quality factor of the resonator. We have discussed this property quality factor of the resonator.

So, when the shutter is closed, quality factor is very low and when the shutter is open, then the resonator becomes very low loss resonator and therefore, the quality factor of the resonator becomes very high. So, essentially, Q-switching refers to switching the quality factor from a high value to a low value. So, this is high to low.

The quality factor is switched between high and low how do we do that? If the shutter is closed, I repeat again, if the shutter is closed, then there is no reflection coming from the mirror M 2 and therefore, it is as good as the reflectivity of M 2 is very low which means the resonator is highly lossy which means the quality factor is low.

If the shutter is open, it is as good as there is no modulator in the cavity. We have two highly reflecting mirrors, one is 100 percent another is let us say 98 percent, then the quality factor of the resonator is high and therefore, a huge amount of energy will be built up inside the resonator. Now, the difference between ok.

Before we go to the difference, let us look at this curve. So, when the quality factor is switched to very high value that is when the modulator transmittance is very high, then the loss goes down and the laser energy builds up inside the resonator and of course, a part of it comes out here; a part of the laser input comes out here in the form of pulses. Why pulses?

Because the shutter is again closed, the shutter is closed and opened periodically to have periodic output pulses from the laser. So, the transmittance of the intra cavity modulator is switched between low and high levels. The feedback in the cavity is available only when the transmittance of the modulator is high that is when this completely transmits and the laser output comes in the form of pulses.

So, this part, the laser output comes in the form of pulses. I will explain this in a subsequent slide. Therefore, the cavity Q is switched between low and high values as illustrated here, it is switched between low and high values and hence, the name Q-switching.

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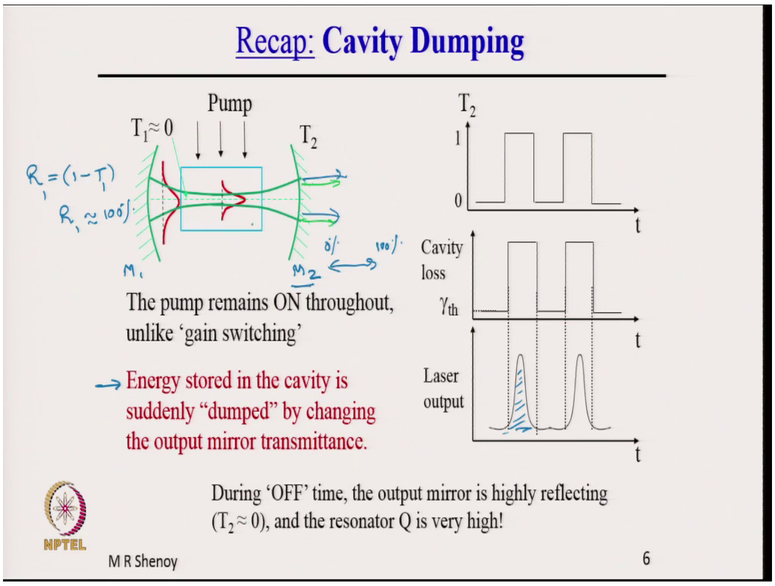

So, what is the difference between Q switching and cavity dumping. Let us have a look at cavity dumping. In the case of cavity dumping, the energy was stored inside the resonator. When the transmittance was 0, which means the reflectance of this mirror is nearly 100 percent, the energy is stored inside the resonator and when the mirror transmittance suddenly switched to 1 which means the reflectivity became 0, the laser output came as a flash from the mirror 2.

So, the energy was stored in the resonator which comes out. Now, let us look at Q-switching. In Q-switching, the energy was stored in the amplifying medium in the absence of a feedback. When the shutter was closed, there was no feedback and building up of radiation inside the resonator because the pump is continuously on, pump remains on throughout as in the case of cavity dumping.

And therefore, the energy was stored in terms of a heavy population inversion, a built up population inversion, very large population inversion and suddenly, when the shutter is opened, the population inversion is depleted by the feedback which comes out and that results in an output pulse.

So, in this case, the energy was stored in the medium in terms of population inversion whereas, in the previous case, the energy was stored in the resonator because of high reflectivity of the mirrors. It is as if the generated energy is not allowed to come out and then, it is suddenly allowed to come out. The photons were already generated, the light energy was already generated, but it was confined here.

In the case of Q-switching, the photon energy, light energy was not generated here because there was no feedback. When I say light energy, I am referring to energy by stimulated emission. Spontaneous emission is always there that is what I have shown here with the blue arrows.

The spontaneous emission which is in small number compared to the simulated emissions is always present, but at the output, there is no light coming because the shutter is closed. This is the distinction between Q-switching and cavity dumping. Although, both of them qualify as loss switching techniques.

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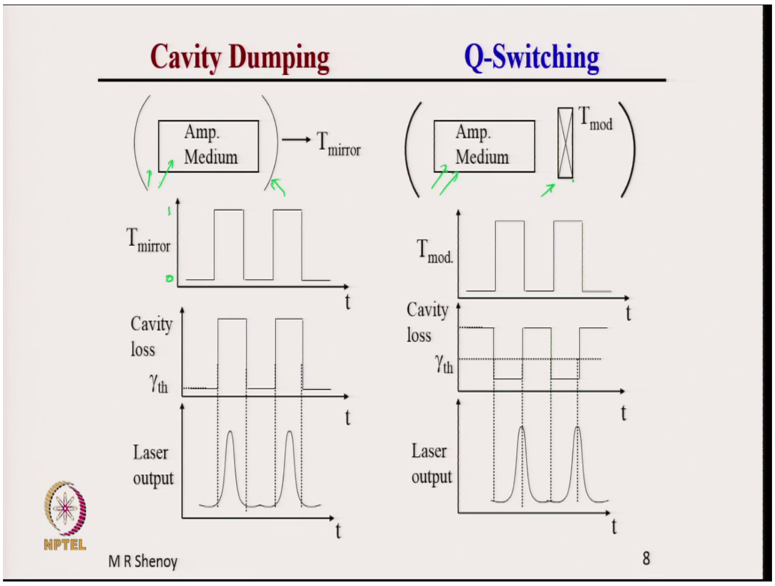

A comparison which is again shown here side by side. So, see the comparison, here the transmittance of the second mirror is what is modulated switched between 0 and 1. Accordingly, the cavity loss is switched and accordingly, we have a pulse output which comes out.

In the case of Q-switching, there is an intracavity modulator where the shutter is switched on and off that is shutter is presence and removed that is the transmittance of the shutter is modulated. The mirror reflectivity's remain constant. Here, the mirror reflectivity of the second mirror is what is modulated and therefore, the cavity loss gets modulated, and we get a pulsed output.

The methods look similar. In one case, the energy is stored in the resonator, inside the resonator here because of 100 percent reflecting mirrors. In the other case, the energy is stored in the medium in terms of population inversion.

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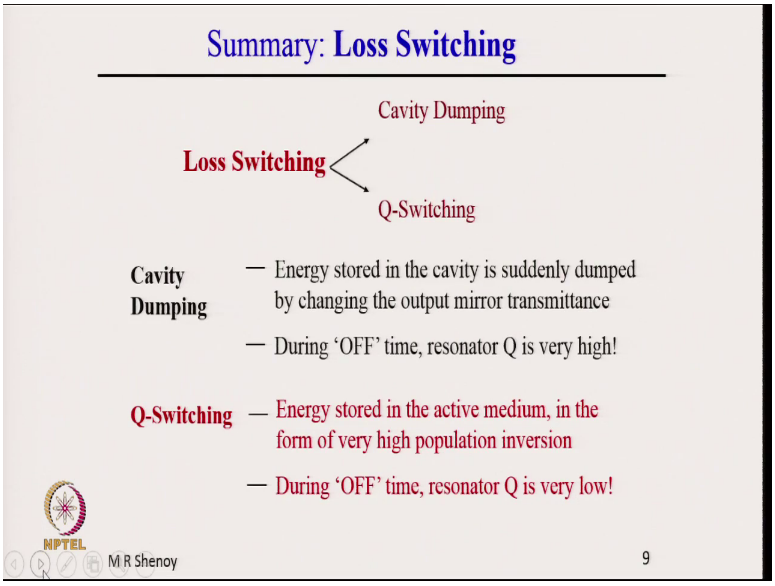

Let me summarize therefore, so, that is the summary slide which I had shown earlier. Cavity dumping energy stored in the cavity is suddenly dumped by changing the output mirror transmittance. During off time, the resonator Q is very high. Off means when there is no output that means, the reflectivity of the second mirror is almost 100 percent which means the resonator Q is very high.

In Q-switching, energy is stored in the active medium, in the form of very high population inversion. During off time, the resonator Q is very low. Off time means when there is no output. When will be no output there? When the shutter is closed which means the reflectivity of the second mirror is not seen and therefore, the resonator is very lossy. So, this is the summary of Q-switching and cavity dumping, both qualify as loss switching as we have illustrated.

In the remaining part of this lecture, I will explain some of the methods of achieving Q switching. Initially, I had not planned so, I will work this out with you.

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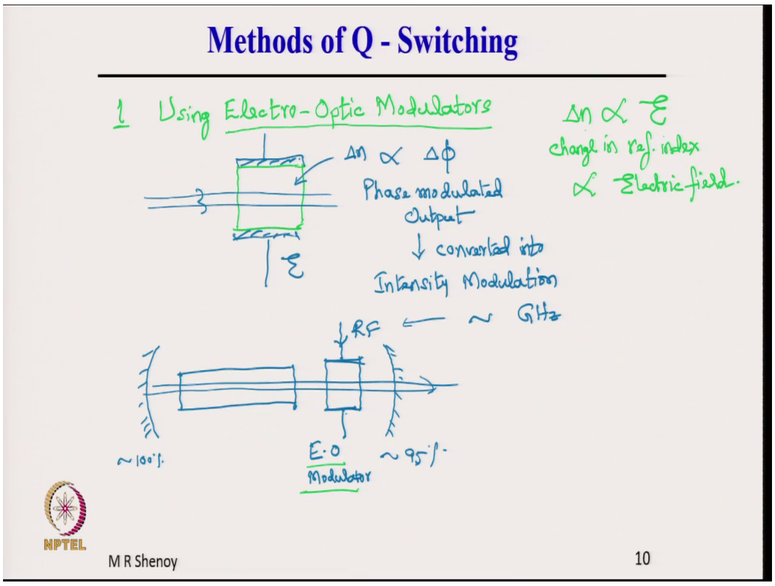

So, methods of Q-switching. There are two important methods, one is by using electro optic modulators so, using electro optic modulators. So, please recall the diagram here. So, I am referring to this modulator here. So, the modulator here could be electro optic modulator or acousto-optic modulator, these are the two popular methods of using Q-switching. So, let me discuss these in brief.

Electro optic modulator so, this works on the principle that the refractive index of a medium of certain medium is proportional, there is a change in refractive index when you apply an electric field, this E stands for electric field, this n stands for refractive index so, change in refractive index; so, change in refractive index.

It could be proportional to the first power of E or second power of E accordingly, it is called Pockels effect or care effect so, refractive index and change in refractive index delta n is proportional to the electric field; electric field, the applied electric field. So, in electro optic modulators so, you generally have a crystal, let me use the blue pen, a crystal with two electrodes.

In simple terms, I am illustrating this. So, these are two electrodes, and an electric field is applied. Light propagating through this undergoes phase change, there is a phase change because if we apply an electric field, then there is a change in refractive index of the medium delta n. So, delta n leads to a change in phase so, delta phi and what we get at the output is phase modulated output; phase modulated output.

Phase modulated output can be converted into intensity modulated output. So, this is converted by use of wave plates and polarizers, it is possible to convert, we will not go into the details converted into intensity modulation; intensity modulation and in the actual system like Nd:YAG laser so, you have the mirror M 1, the Nd:YAG crystal, I am showing all of them with one color.

So, here is the electro optic modulator, this could be in the next example I will show that this is could be acousto-optic modulator. So, this is an RF or an electric field. So, RF applied to this and here is the second mirror. So, generally we take output from one side. So, output comes out through this. Therefore, this reflectivity could be hundred percent reflecting and this could be 90 percent or 95 percent reflecting.

As before, when the shutter is closed, there is no feedback so, this is the electro optic modulator, EO modulator which acts as a shutter and typically, we can modulate this at speeds of the order of giga Hertz, easily of the order of giga Hertz rate. We can modulate, modulate means we can switch on and off, on and off, the shutter close open, close open at the rate of giga Hertz that is 1 billion times per second and accordingly, we get the output here.

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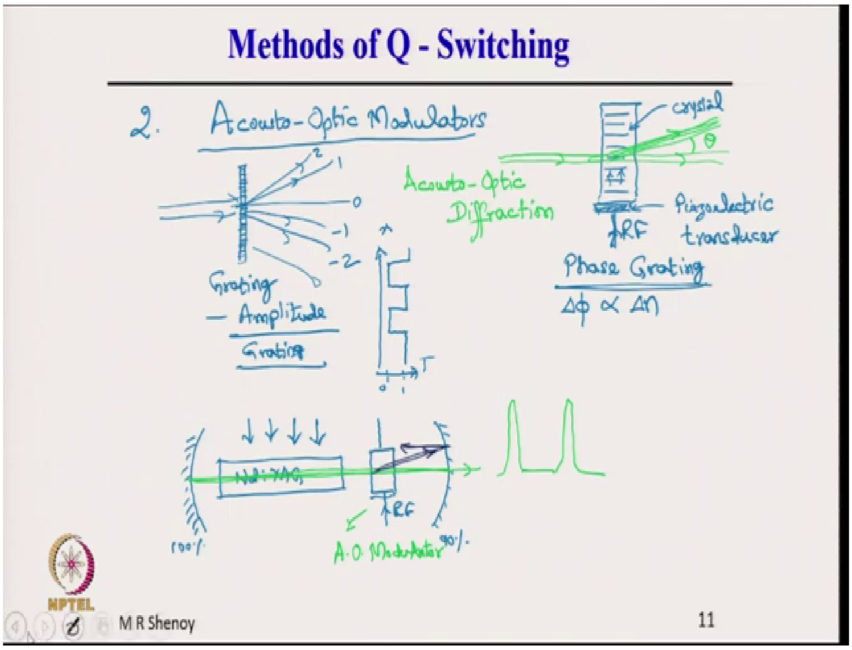

The second method which is used is by using acousto-optic modulators. The basic principle of acousto-optic modulator, there is a crystal here and you apply an RF radio frequency a RF modulator using a transducer so, this is the crystal; crystal, this is a peso electric crystal and therefore, the RF leads to mechanical waves travelling through the medium. There are compressions and rare fractions in the medium that leads to a refractive index variation along the medium.

So, the RF travels here. So, there are mechanical waves travelling through the medium because the RF is applied to a piezoelectric transducer. So, this is a piezoelectric transducer and if now, light is incident on this modulator here so, light incident let us say laser beam is incident.

In the absence of the RF the laser beam would go straight whereas, in the presence of RF, there is a diffraction grating here because of compression and rare fractions, there is refractive index modulation across the crystal which is a phase grating.

So, this leads to a phase grating and the beam, therefore, gets deflected. So, the beam is diffracted into a certain order with a certain angle theta, and this is called acousto-optic diffraction so, acousto-optic diffraction; optic diffraction. We are familiar with the diffraction grating where we use an amplitude grating, a very quick recap here for about the diffraction grating, let me show the refraction grating in which we have a glass plate which is scribed by a diamond scriber.

So, the incident light here sees transparent opaque; transparent opaque, a periodic transparent opaque regions here and that leads to diffraction coming at different orders. So, diffraction coming at the first order, second order and so on so, this is the 0th order, 1st order, 2nd order and minus 1 order, minus 2 order. So, this is a grating, the normal diffraction grating.

This is called an amplitude grating. So, this is an amplitude grating is an amplitude grating because the transmission of the grating, the transmission of the glass plate is 0, 1, 0, 1 where you have scribed it, it is opaque and therefore, it does not permit light to pass through. If I zoom this portion, then I have a periodic transmittance which is like this. So, I have plotted the transverse axis x versus transmittance.

So, transmittance goes between 1 and 0, 0 or may be somewhat smaller value, but this is a grating, it is a periodic grating which leads to diffraction into certain orders. So, this is an amplitude grating because transmission, no transmission.

This is a phase grating in contrast, this is a phase grating. Phase grating means instead of transmission 1 and 0, we have higher refractive index, lower refractive index, higher refractive index, lower refractive index and the phase is proportional to delta N, the change in phase delta phi is proportional to delta N.

If we have a refractive index modulation across the grating, then there is a phase variation across the grating and that is called a phase grating.

What we usually have in a laboratory that so called diffraction grating is an amplitude grating and this is a phase grating, but both of them lead to the same diffraction and whenever the RF is applied, whenever we have applied the RF, then there is a grating here and the beam gets deflected. Completely, it is possible to have complete deflection of the beam to an angle when the RF is not there, then the beam comes straight forward.

Now, how this method is used in Q-switching? So, let me show this here. So, we have the same laser, a spherical mirror resonator, let us say housing an Nd-YAG crystal, an Nd-YAG laser and here is the acousto-optic modulator so, this is the acousto-optic modulator to which we apply an RF. So, this is the Nd-YAG, just as an example I am taking this as the Nd-YAG laser.

The pump is of course, all the while on, it is a CW pump. The second mirror is here. The mirrors are no change in the reflectivity of mirrors. Let us say this is 100 percent reflecting and this is 90 percent reflecting, 90 or 95 or whatever.

When no RF is applied, when there is no electric field applied to the transducer here, then the beam goes through and through that is there is complete laser beam going back and forth and output coming out, but when an RF is applied, the beam which was coming here is deflected at an angle, let me use a different color to just show alright, let me use dark blue color here.

When the RF is applied, the beam which was coming here is deflected at an angle. When it is deflected at an angle, after reflection, it comes out somewhere else, it does not get into the laser again and therefore, there is no feedback. So, we have blocked the feedback which means energy is again stored in the medium. Till the beam comes back to its original position, there is no depletion of the population inversion and energy is stored in the medium.

When again there is no RF, the beam comes back and then suddenly, it gets feedback and then we have a pulsed output coming from the laser and this is the mechanism of operation of the laser. So, the Nd-YAG laser with an acousto-optic modulator now, this is an AO modulator.

So, I have briefly discussed these two methods of Q-switching, one using an intra cavity acousto-optic modulator where the beam is deflected when not required. When we want a low Q that is when we do not require the energy to build up and in the other case, it is an electro optic shutter which is use. So, this is an EO modulator which means it is an electro optic shutter, the shutter is switched on and off to switch the cavity Q. So, these are the two techniques which are widely used to achieve Q-switching.

I want to show one last point what controls the frequency of repetition of the pulses ok. Let me show you with time, how the evolution of the population and the pulse energy comes out.

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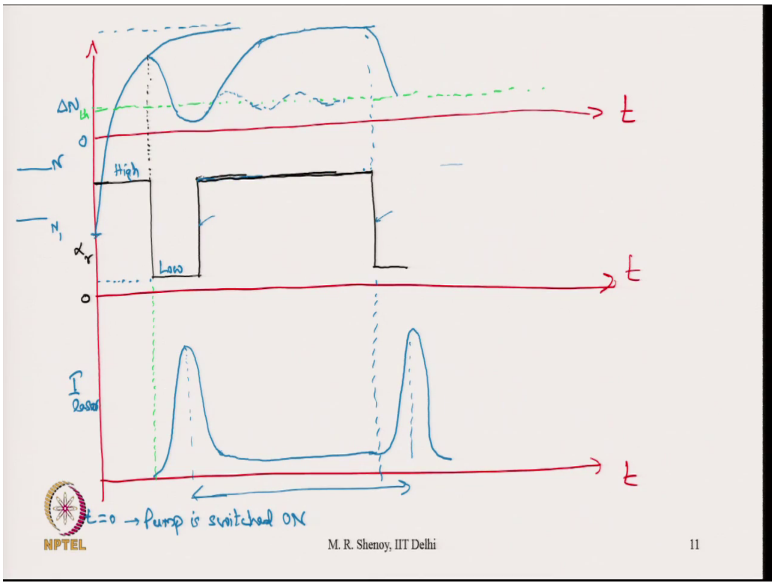

So, let me show a diagram here. There are three parameters which I want to show. This axis is time. So, all the x-axis is time scale. First, when the pump is switched on. So, this is t equal to 0 when the pump is switched on. So, in the first diagram, the population starts from a negative value so, this is 0, I am plotting delta N. So, the population is initially negative. So, please recall that delta N is N 2 minus N 1 before the pump is switched on at t is equal to 0, pump switched on, pump is switched on; switched on.

So, the population immediately starts increasing and it reaches population inversion, and the population inversion reaches a saturation value depending on the pump power. So, what I have shown here is the variation of delta N depending on the pump power, it will reach a saturated value, a maximum value of delta N would be reached.

Now, the delta N crosses the 0 here, when the delta N crosses 0, there is population inversion however, there is no feedback. Now, what I am going to show is the loss, switching of the loss, initially the cavity loss is very high. So, now, let me use a different color here. Maybe let me use black color.

So, here I am showing the cavity loss. So, the cavity loss is kept very high and therefore, the delta N required will be even higher the delta N threshold. So, this is 0, the loss so, this is alpha R or the cavity loss, alpha R is kept very high and suddenly it is switched to very low value here.

The cavity loss is switched to a low value, if the cavity loss were kept high, then the population inversion would have saturated. Now, look at this, when the cavity loss is switched to a low value at this time, we have a population inversion which is greater than at very low value, the threshold I must also show the threshold delta N threshold is somewhere here. So, this line corresponds to delta N threshold. So, this is the threshold value, delta N threshold.

The population inversion is much above the threshold value and therefore, immediately, the laser will start lasing and then, we have the intensity here, let me show with blue ok. The laser starts building up here, the output starts building up so, this is output, laser output so, intensity I of the laser, I laser.

The third curve is I laser, this is loss, the black one is loss, the blue first one is delta N variation of the population inversion, this starts building up and as the population inversion depletes so, this starts depleting continuously and the intensity starts building up.

When the population inversion comes below the threshold value, there is no more lasing and therefore, the intensity will start dropping down. So, the intensity would start dropping down. When the intensity starts dropping down, this will again, the population inversion will again start increasing. We have discussed this in showing the laser dynamics to reach a steady state value. So, the population inversion again starts increasing.

Now, if we had kept this loss very low, then this would have gone up and then, it would have had this laser dynamics and finally, saturated here giving out a constant output, but what happens is at this time, if we switch the laser to a high loss position again, if we switch this to a high loss condition, then the population inversion will start building up again; the population inversion will start building up again and going towards the saturation value here.

So, if I keep the loss high here, there will be only one pulse. After some time, if I switch down the loss here, then the population inversion which had reached saturation here so, if I switch down here, then this population inversion will again start depleting and at this point, the pulse again starts generating. So, this was coming down to 0 and then, until this point, when the loss is switched down, the intensity again starts going up and then, depletes.

So, the pulse repetition rate that is the number of pulses that would come out is determined by the rate at which the loss is switched between high and low. Suppose I had not switched down this at all; suppose I had not switched down the loss, then if the loss were continuing to be very high, I would have got no pulse here.

So, there is a certain flexibility of the duration over which the loss can be switched up and down that is high value and low value and that will determine the instant when the pulse starts coming or the pulse repetition rate is controlled by the rate at which the loss is switched. So, I do not know how much I could make this clear. So, please think over this.

There are three curves which I have shown, the upper one is variation of the population inversion and the second one is the loss switching between two-levels between high and low so, this is high loss so, high loss and this is low loss, and it is necessary that the loss is switched again to a higher value otherwise, the laser will reach steady state oscillation.

If the loss is kept low, the laser will reach a steady state oscillation and give a steady output power. If the loss is continuously kept high, there will be no laser output and therefore, the loss has to be switched between a high value and a low value at appropriate timings so that we get pulsed output from the laser. The pulse repetition rate is determined by the rate at which the loss is switched between the low value and the high value.

However, the pulse width is primarily determined by the material properties, how fast the material responds and how fast the material gets deexcited to give out the pulse. So, in general, the pulse repetition rate in a Q-switched laser can be controlled very well, but the pulse width does not vary much with the pulse repetition rate. So, we will discuss in the next class, the next method which is called the mode locking.

Thank you.