Introduction to LASER
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Lecture - 29
Pulsed Lasers

Welcome to this MOOC on LASERs. Today, we will start discussing about Pulsed Lasers. We will first address the question what are pulse lasers, then why go for pulse lasers and then, how to obtain pulse lasers or how to achieve pulsing of lasers. So, first what are pulsed lasers.

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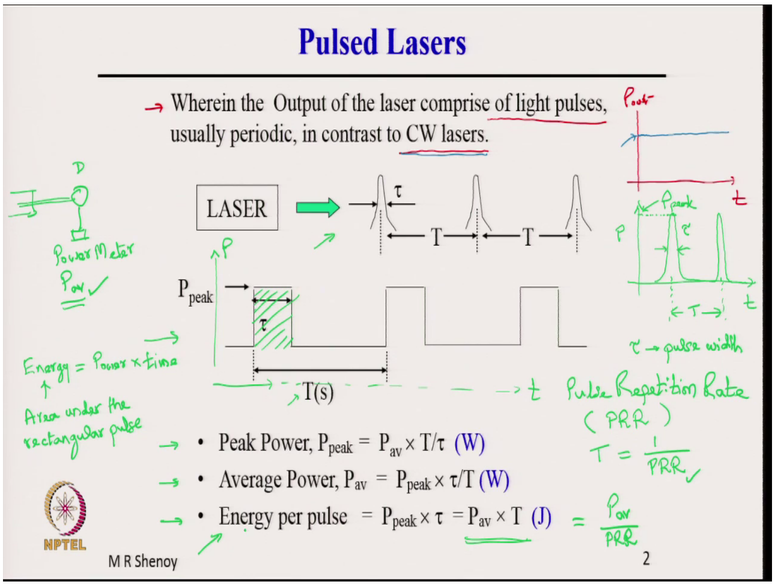

So, pulsed lasers where the output, so wherein the output of the laser comprises of light pulses. So, it comprises of light pulses. Usually, it is periodic, in contrast to CW lasers. CW lasers stand for Continuous Wave lasers. So, in CW lasers, if we plot the variation of output power with time, so time verses P out. Then, it would have a study variation; here. So, the output would look constant.

So, this is the P out. So, P out as a function of time. So, these are CW lasers or continuous wave lasers. But in the case of pulse lasers, if we plot the output as a function of time, let us plot it as a function of time. So, that is what is shown. The axis are not shown there.

So, time versus output P out, then typically it will vary like this, like pulses that is energy comes out over a finite duration and this width, the width of the pulse, full width at half maximum is designated as tau and the period, here is designated as T. That is what is shown in this figure here. So, what we see is in pulse lasers, the output comprises of a series of pulses.

Usually, these are periodic pulses separated with a constant time T or the period and tau here is the pulse width. So, width of the pulse, full width at half maximum is called the Pulse width.

So, tau is the pulse width and T is the period. If we for simplicity, ideally the output would look like this comprise of pulses which are not rectangular; but for simplicity, just to understand the various parameters, if we show the output as rectangular pulses like this, as shown in this diagram here, where tau is the width of the pulse and capital T is the period that is 1 by pulse repetition rate.

So, PRR, pulse repetition rate that is the number of; so, pulse repetition rate which is also called PRR. Then, T is equal to 1 divided by PRR. So, of the pulse repetition rate tells us the number of pulses per second and therefore, the period corresponding to 1 pulse is 1 divided by pulse repetition rate.

There are three important parameters which characterize the output of a pulse laser. The first one is the peak power and then, average power and then, energy per pulse. We will take some example and make this clear. Now, the peak power its illustrated here. So, this axis is power; so, this is P and the axis, which is not marked here is the time.

So, this axis is time T; P verses T. So, for a rectangular pulse, the top of the pulse is flat and we designate this maximum power as P peak, it is called the peak power. In this case for example, in a real pulse, so this would be the peak power. So, this is P peak, peak power; P of peak. But for simplicity, we have shown a rectangular pulse of width tau and peek power P peak and a period which is capital T.

Now, the peak power will be equal to the average power. So, average power is if this power was distributed over the entire period. For example, the area under these pulse will indicate the energy. So, energy of the pulse energy is equal to power into time. So, power into time because power is rate of change of energy.

So, the area under the curve represents the energy of the pulse area under the curve; area under the rectangular pulse is the energy of the pulse. So, that is why we can see here, energy of the pulse which is here energy per pulse is P peak that is this value multiplied by tau that gives us the area that is the energy of the pulse.

The peak power is equal to average power into T divided by T that is the peak power is given by average power that is the power over 1 period into T divided by tau and therefore, if we substitute for P peak from here, we get the energy per pulse is equal to P average into T.

This will become clear, now if you take a normal laser and let us say the laser output is coming from here. If we measure the output using a power meter, let us say you have placed the detector here and power meter. So, what is measured on the power meter is P average. So, P average is the measured power, that is why if you know the average power and the period T or the pulse repetition rate, then you can determine energy per pulse.

Alternatively, if you know the average power, then you can also calculate what would be the peak power provided, we know the pulse width and the pulse repetition rate. So, generally, pulse repetition rate is measurable because we can put the output and measure the pulse repetition rate, we can put the output on a fast detector and connected to an oscilloscope and then, we can determine what is the pulse repetition rate. This is a measurable parameter.

P average is also a measurable parameter and therefore, all the parameters whether the peak power or the energy per pulse can be determined in terms of the two measurable parameters which are the average power and the pulse repetition rate. For example, here this is equal to P average divided by PRR, pulse repetition rate.

Both are measurable and therefore, we can determine the energy per pulse. So, these three parameters are very important in the case of pulse lasers. So, we will discuss more about this as we go further.

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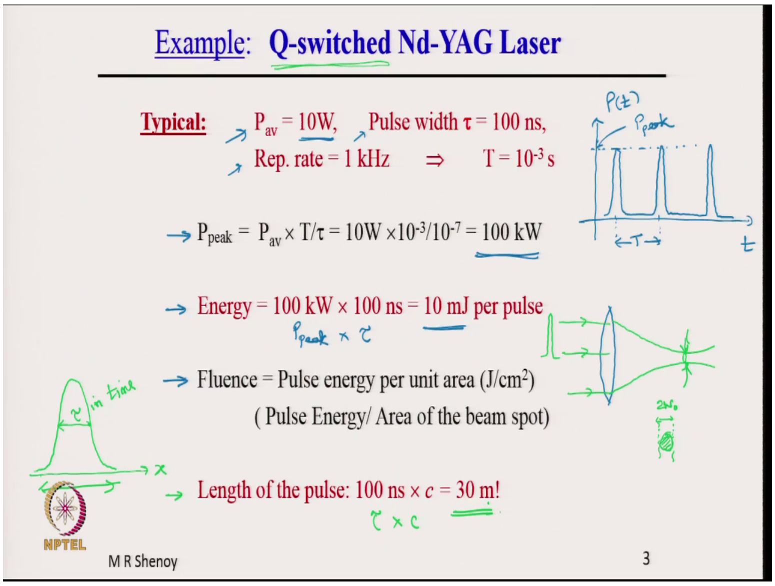

Now, I have taken an example here typically a Q-switched Nd-YAG Laser. Q-switched here is a pulse laser. We discuss Q-switching in the next lecture. Typically, if we have the measured average power. So, the measure power there is 10 Watt, pulse width is 100 nano second and pulse repetition rate is 1 kilo Hertz; that means, T the period is equal to 10 to the power of minus 3 second that is 1 by 10 power 3; 1 kilo Hertz that is 1000 Hertz.

So, T is equal to 1 by 1000, that is 10 to the power of minus 3 second. The pulse width tau is 100 nano second. Typically, in Q-switched Nd-YAG Lasers, the pulse width is of this order. It could be anywhere from 10s of nano second to a few 100 nano second. Now, the peak power can be estimated. So, peak power here refers again, let us have the picture. So, what we have is a series of pulses coming out of the laser.

So, what we are plotting is the instantaneous power P of T as a function of time. Now, this is the peak power. So, this is P peak and this is the time T, one period. So, the P peak is equal to P average into the period time divided by the pulse width tau which is we can calculate here and we see that the peak power is 100 kilo Watt.

Although, the average power is only 10 Watt, the peak power is 100 kilo Watt. Because the power spread over one period is the average power; whereas, the peak power refers to the maximum power, the instantaneous maximum power of the pulse. The energy per pulse is here.

So, the peak power multiplied by pulse width. So, this is P peak multiplied by the pulse width tau. If we substitute here, we see that it is 10 milli Joule per pulse; some typical numbers which we have. There is a third parameter which is used with short pulse lasers which is also called fluence, which is the pulse energy per unit area; per unit area of the beam. So, the pulse energy divided by area of the beam spot.

Let us say we have a laser which is focused, need not be focused; but let us say we have a focused laser beam here and then, the beam is focused. So, let us say this is the Gaussian spot size at the focus, then the area of this spot here; so, there are pulses. These are not CW, these are pulses which are arriving.

So, we are getting pulses, a series of pulses. Now, the pulse energy per unit area divided by area of the beam spot. So, if we see the spot like this, if is a Gaussian beam, then we know that this spot size, we have already discussed is 2 W 0 at the waist. This diameter is 2 W 0. So, W 0 is the spot size. So, the pulse energy per unit area, area of the beam spot is called fluence.

This is important because when we say pulse energy, certain energy per pulse is coming out. Now, that energy whether it is spread over a wide area or spread over a small area, that will determine the energy density and therefore, the energy density determines the number of photons per unit volume. This is very important in particularly what are called multi-photon processes.

The density of photons per unit volume is important and that is why in many applications, people use fluence as one of the parameters to characterize the laser process. A third point which is indicated here is the length of the pulse. What do you mean by length of the pulse? So, all the while, I am drawing here time versus power. Now, what about the physical length of a pulse?

That is, let us say we have a pulse. If this was x and if the pulse spread like this, then what is the width of this or length of this pulse? We know that in time, this is tau in time. So, tau in time, but we want the length of the pulse; physical extent of the pulse. The length of pulse is given by tau into that is the pulse width into velocity of light and that is about 30 meters.

So, this is in space. The spatial extent of a pulse. One is the temporal width of the pulse. When we say the width of the pulse, tau is 10 nano second or 1 pico second. We are referring to the width in time. But what about the physical width? The physical width is also important in certain processes which determines the duration over which the interaction takes place or the length over which the interaction takes place and that is why we have to have an idea about what is the length of the pulse.

As we will see, this will also determine the resolution in certain applications alright. So, the length of the pulse is pulse width into the velocity of light. So, if you multiply 100 nano second multiplied by 3 into 10 to the power of 8 meters, then we have 30 meters here ok.

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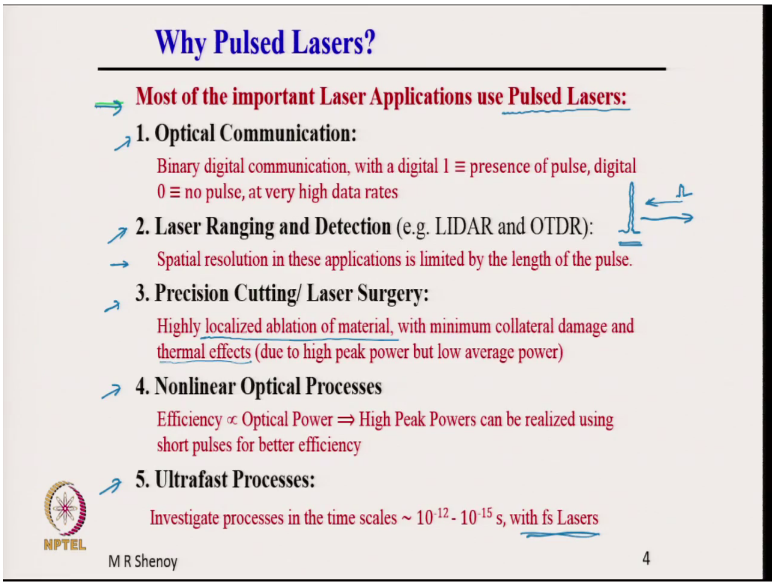

So, now, why pulse lasers? So, far we have addressed the question, what are pulse lasers and what are the parameters used to characterize the output of a pulse laser. Now, why pulse laser? The most important applications use pulse lasers and therefore, pulse lasers are very very important in laser applications. I have just mentioned certain applications here as indicated right at the beginning, there are other courses which will discuss laser applications in detail.

Our primary objective is to discuss the basics of laser physics, the fundamentals of laser physics; but maybe I will take 1 or 2 applications as we proceed. Now, first point optical communication; optical fiber communication for example, which uses binary digital communication that is the signal is transmitted in the form of digital ones and zeros ok. Let me illustrate here.

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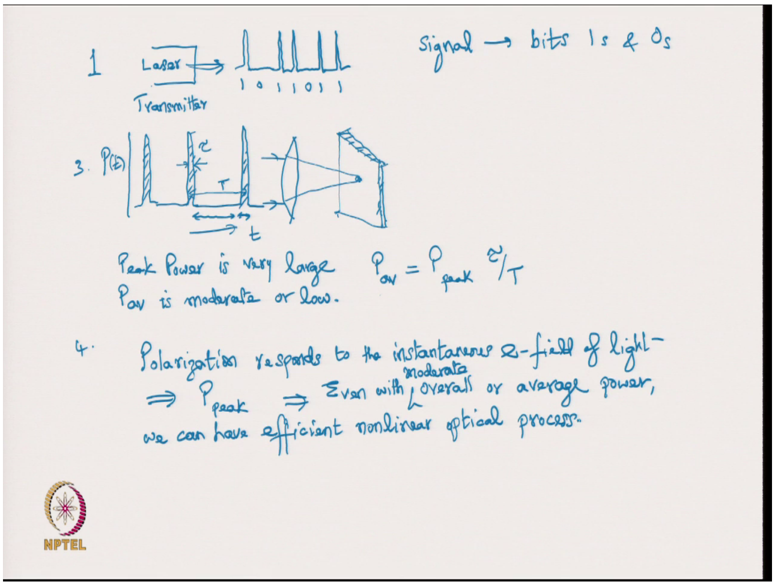

So, in optical communication, you normally have a source, a laser source which gives out pulses; digital pulses 1s and 0s; 1 1 0 1 1. So, this is 1, here there is 0, they are equally spaced, but there is no pulse here. 1 1 0 1 1 and so on. So, the output from the laser; so, this is the laser, transmitter. Laser, transmitter, we will discuss this in a little bit more detail later.

Laser, transmitter is in the form of optical pulses; the presence of a pulse is a digital 1 and the absence of a pulse is a digital 0. We know that in digital communication, the signal is represented in the form of binary digits; signal is in the form of bits or binary digits. So, 1s and 0s.

In this case, the presence of a pulse is a digital 1 and the absence of a pulse is digital 0. The laser output is modulated, it is modulated according to the signal to be communicated. We will discuss this more later on. But the important point at this juncture is that what is used is digital output or pulsed output from the source in optical communication.

So, a binary digital communication with the digital 1 equivalent to presence of the pulse and digital 0 means no pulse at that time at very high data rates. A second application which I have indicated is laser ranging and detection. This is LIDAR, so light detection and ranging and OTDR, optical time domain reflectometer; both of these work on the principle of sending laser pulses.

So, sending laser pulses to a target and looking at the back scattered or back reflected signal which is also in the form of pulse; but usually, the pulse energy is much smaller. And then, depending on the time difference between the initial pulse and the received pulse, one can estimate the range or the distance from where the reflection has taken place.

That is the principle of working of a LIDAR or an OTDR, optical time domain reflectometer. The point here is that this application also uses pulsed sources; the output of the laser is in the form of pulses.

Now, here I have also mentioned that the spatial resolution in these applications is limited by the length of the pulse. This is why I calculated the length here; the length of the pulse. When the length of the pulse is 30 meters, it cannot resolve a spatial object or a spatial location better than 30 meters. That is what is meant by spatial resolution is determined by the length of the pulse.

So, smaller the pulse, smaller will be the length of the pulse and therefore, better will be the resolution. One can look at the application of laser ranging and detection and understand the importance of the pulse width in determining the spatial resolution. The other very important application is precision cutting and laser surgery.

So, the lasers used in these cases are high energy pulse laser. The pulse laser leads to highly localized ablation of the material with minimum collateral damage and thermal effects due to high peak power, but low average power. Let us look at this, what this means is. So, this I am discussing. So, if you have a stream of pulses which are incident on the material, it could be in surgery or cutting; let us say a sheet of stainless steel, then these are high energy pulses which are in.

So, this is in time to time and this is the power P of t. So, the incident laser output. Let us say it is incident on a material. So, here is a material and let us say this is focused using a lens and then, it is incident as a spot, a fine spot on this material. So, this is some sheet. Let us say a steel sheet which needs to be cut.

So, at this point, there are high energy pulses which are constantly incident on this but separated in time. Whenever a high peak power pulse is incident, the material is ablated from this portion; evaporated from this portion. Then again, there is a gap and again, the next pulse comes and it ablates or evaporates the material in that portion leading to cutting that is removal of the material or cutting of the substrate or the material as per choice, as per the shape or size which is required.

The point is there is energy over certain duration and no energy over certain duration and therefore, the average power is low the peak power is high. So, peak power is very large; whereas, average power P average is moderate to low is moderate or low. Why? Because the average power P average is equal to P peak into tau divided by capital T and tau that is this width of the pulse is much smaller compared to the period which is this.

So, this is period T, recall that this is T and this is tau and therefore, although the peak power is very large the average power is very small. Now, most of the thermal effects are determined by the average power of the laser because the energy which is incident determines the thermal effects; energy and the duration.

So, the thermal effects are determined primarily by the average power, but the ablation is determined by the peak power and that is what is meant by the statement which is given here, highly localized ablation of material with the minimum collateral damage and thermal effects. Because locally the material is removed without creating much collateral damage.

Collateral damage means damage to the surroundings and that is very important in precision cutting and laser surgery. The other important application of laser is non-linear optical processes, again it can be shown that the efficiency of non-linear optical processes is proportional to the optical power density or the intensity of the laser beam.

Now, high peak powers can be realized using short pulses for better efficiency. In non-linear optical processes, the let me again explain briefly to this is for 3 and this is for 4. So, non-linear optical processes, where the polarization in the medium; the polarization in the medium response to the electric field, instantaneous response to the instantaneous electric field.

Instantaneous e-field, electric field of light, which implies it responds to the peak power, P peak and therefore, this implies even with moderate power even with overall or average power. So, with moderate overall or average power we can have one can have very efficient have efficient non-linear processes efficient non-linear optical processes.

So, either you must have a lot of power or you can have moderate power lasers; but you pulse it so that the peak power is very high in the non-linear optical processes are determined by the polarization, the induced polarization in the medium and the polarization responds to the instantaneous electric field and mod square of the electric field is the intensity and therefore, higher the intensity, higher will be the electric field.

And that is why we have to have very high peak powers, if you want to observe non-linear processes with moderate powers alright.

So, let me go to the and then of course, the ultra fast processes. To investigate very fast processes in the times scale of 10 power minus 12 to 10 power minus 15 seconds, one usually uses the femto second lasers. So, all of these applications are some of the most important applications of lasers which use pulse lasers, that is the importance of having pulse lasers ok.

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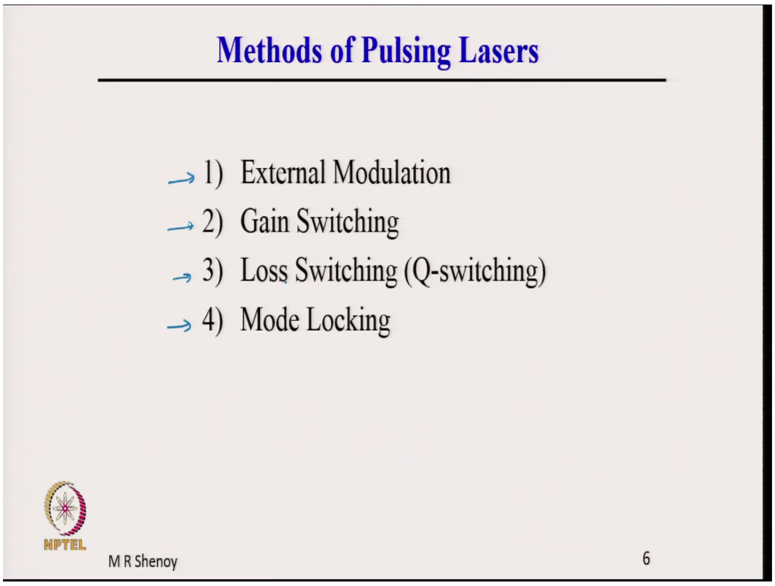

Let us see some of the methods of pulsing laser. So, I have listed a broad category of four methods. One external modulation, gain switching, loss switching and mode locking. So, we will discuss one by one these different processes of obtaining pulsed lasers.

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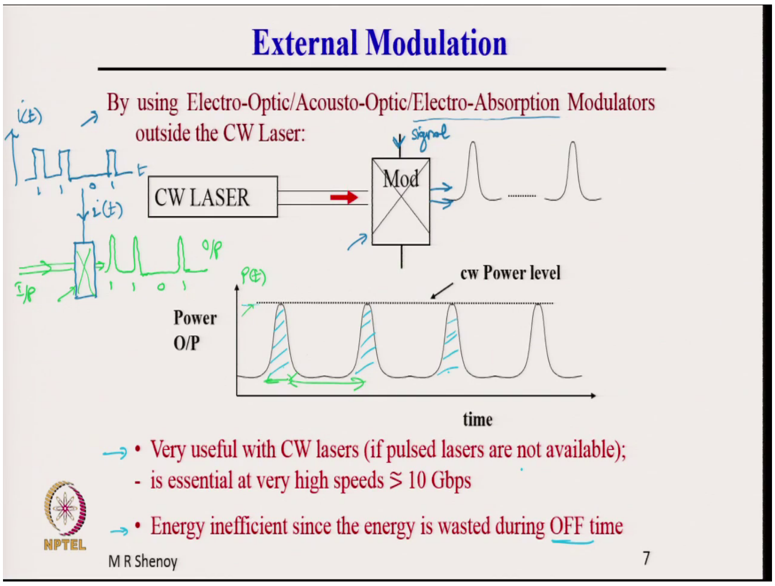

First, let us discuss external modulation. What is external modulation? As the name indicates the modulator is outside the laser. If we did not have a pulse laser, but an application requires pulsed output. Then, one can use the continuous wave laser with a modulator which can be placed outside; one can use a modulator to obtain pulsed output from the laser. The laser gives a continuous wave outputs; but once it passes through the modulator, we have modulated output. What is this modulator? Ok.

So, there are different types of modulators. By using electro optic modulators or acousto optic modulators or electro absorption modulators, these are important semiconductor modulators or quantum-well modulators, electro-absorption modulators outside the CW laser that is why it is called external modulation. So, the process looks like this.

There is a CW laser, continuous wave laser which gives study constant output which passes through the modulator at the output of the modulator. So, this is the output of the modulator, it is pulsed output.

Pulsed according to the signal which is fed to the modulator. So, there is a signal which is fed to the modulator. So, this could be an RF signal, it could be an electric field or whatever the signal is applied to the modulator and depending on the signal, we get the output. Essentially, the modulator for example, in digital communication, the modulator is like a shutter.

Whenever current signal comes, then it blocks or vise versa that is we have a shutter here, an electronic shutter let us say. So, there is a digital pulse stream which is fed to this. So, here that is basically current variation i of t and let us say i of t varies like this. So, this is the variation of i of t. What I have plotted is i of t as a function of time.

So, this is a digital 1 1 and there is a 0 in this slot and there is 1. So, if you feed such a current variation to this shutter, the laser beam is coming from here. So, the laser beam comes a CW laser beam; but the output would look like this. So, just as the current pulse. So, the output will represent the same digital 1 1 0 1 when you have the output after the modulator. So, this is the model.

So, essentially the modulator is like a shutter. So, the shutter opens or shutter closes, depending on that the output can be digital output or pulsed output. So, this is the input and this is the output. So, output looks like this. So, this is modulation. There are different types of modulators; but these are external modulation which means the modulator is placed outside of the laser.

So, that is what is shown here. The CW power is at this level. What is plotted here is power P of time. So, with the time, the laser the input to the modulator is this. This is the input to the modulator, which is the CW power level; whereas, the output will be varying like this, that is you have blocked the output. So, over this duration, the output is blocked; whereas, here the output is allowed.

So, output allowed, output blocked; output allowed, output blocked and like this. Now, what we are doing is we are blocking the output here. In some portion, we are allowing the output. So, for example, here we are allowing the output over this duration and we are blocking the output at other durations. If the modulator were not there, we would have got a constant output like this. What is the point?.

The point is this output is energy inefficient. Since the energy is wasted during OFF time, that is when the modulator is OFF, there is no output. When you feed a signal, the modulator opens the shutter and you get the output. And therefore, although the laser is continuously giving out power, the modulator gives output only during the ON times and during OFF time, the modulator is blocking the laser power and therefore, we say that this is energy inefficient.

Now, this is of course, very useful we the CW lasers because if pulse lasers are not available, one can essentially use a modulator and get the output modulated at very high speeds. In fact, one has to use external modulators at very high speeds of the order of 10 giga bit per second. We will see shortly how to modulate the laser directly modulate the laser and obtain pulsed output.

However, the techniques that we will describe will work only at certain speeds at very high speeds. That is, if we want output switched ON OFF at very high speeds; what is this very high speeds? Let us say 10 Gbps; 10 giga bits per second and that rate if you have to switch ON and OFF a laser, it is almost impossible and we have to use external modulators.

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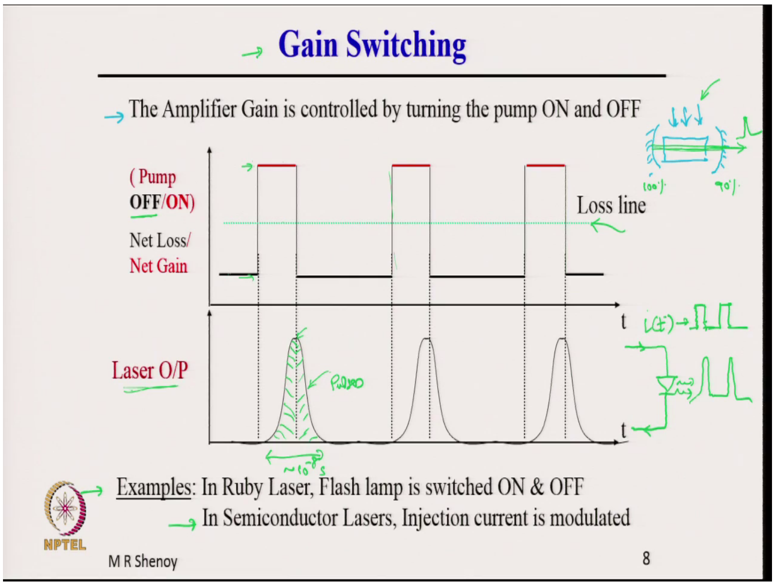

Although, it is energy inefficient alright. So, let us see the second method. So, the first one is external modulation; second is gain switching. As the name indicates the amplifier gain is controlled by turning the pump ON and OFF.

So, recall our laser, so we have the laser here; two mirrors. I have shown two spherical mirrors and the gain medium in between here and there is a pump. The pump creates population inversion and then, there is a laser buildup which takes place here; energy buildup which takes place and the beam comes out.

Suppose, the pump is switched ON and OFF, gain in the medium is provided by the pump. If the pump is switched ON and OFF, then we can have gain modulation in the medium. Gain modulation means in simple terms, we can have higher level of gain when the pump is ON;

when the pump is OFF, there is no gain and we have absorption. When there is absorption in the medium, we will have no laser output.

Because we already know that the gain must be as shown here in this graph, what is shown is gain and loss. When the pump is off, we are here, there is no output. When the pump is OFF, there is no output because the medium is simply absorbing and therefore, the gain in the medium is less than the loss. There is no gain or less than the loss.

When the pump is on, then there is gain in the medium and the gain exceeds the loss. So, this is the lose line of the resonator. We have discussed this in detail in laser dynamics and when the gain is more than the loss, then the laser starts oscillating and gives out output. Now, what is the step function?

The pump is switched OFF switched ON; the pump is ON corresponding to this level and the pump is OFF corresponding to this level which means essentially this is 0 here. Corresponding to that, there is a net loss and net gain.

So, net again because the gain is more than the lose line and that is why either this figure represents pump ON and OFF or equivalently, the figure represents gain loss. So, this is net gain because gain is more than the loss line. This level is net loss because loss is less than the loss line. So, the overall loss is less.

When the gain becomes more than the loss line, then the laser starts building up and then, when you switch OFF the laser, then the energy inside drops down and when the laser builds up. So, please remember that if this is 100 percent reflecting and this is 90 percent reflecting as an example, then 10 percent of light comes out from here.

And the energy build up inside the cavity is shown with respect to time. It takes the shape of a pulse because the pump is switched ON and OFF in the form of a rectangular pulse. Correspondingly, the laser output will also be in the form of pulses. So, this is the time taken to build the pulse.

So, the pulse is building up during this period here because the pump is switched ON and there is gain, population inversion building up inside the medium and accordingly, energies building up. Here, at this time the pump is switched OFF and therefore, the energy also starts dropping down because the population inversion gets depleted.

The time scales which we are thinking of here is of the order of 10 to the power of minus 8 seconds or 10 to the power of minus 9 seconds in this process. So, the amplifier gain is controlled by turning the pump ON and OFF leading to pulsed output. So, a very good example is ruby laser in which the flash lamp is switched ON and OFF and the laser gives out the red colored rubies pulses as the output.

More importantly, in semiconductor lasers this is the method used to get output from a semiconductor laser by modulating the injection current. So, let me briefly explain this here. So, in a semiconductor laser, we have its a diode laser. We will discuss a little bit about more detail, when we look at the laser systems.

So, there is a current i of t passing through the laser. When the current passes through the laser, the laser gives output. So, there is output which comes out, if the current is of course greater than the threshold current, we will discuss this at a later stage. Now, if i of t is a pulsed output to if i of t varies like this let us say i of t varies, then the output will also be in the form of pulses.

So, what are we doing here? To get pulses, we are modulating the injection current. In a semiconductor laser, the pumping mechanism is launching injection current in a forward biased laser diode. In a forward biased laser diode, if you inject current, then you get the corresponding output.

If the injection current is in the form of pulses, the laser diode output will also be in the form of optical pulses. So, it is simply switching ON and OFF of the pump or grain switching of the laser. So, the direct modulation of laser diode is an example of gain switching.

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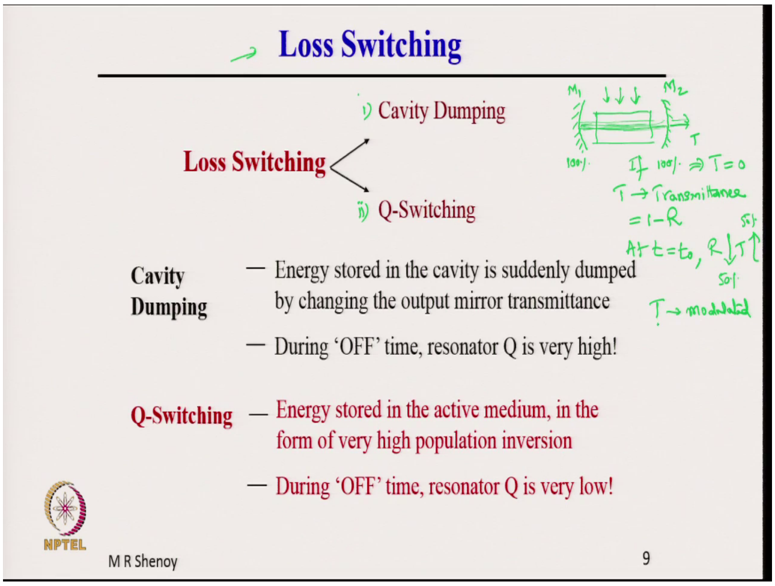

The next method is loss switching. In loss switching, there are two mechanisms. The first one is called cavity dumping and the second one is Q-switch. Please see this, let us see the points first and then, we try to understand. In cavity dumping, energy is stored in the cavity and is suddenly dumped by changing the output mirror transmittance. So, let me explain this cavity dumping.

We have a laser here; a very good resonator very very high Q resonator here. This end is 100 percent reflecting. I always take for simplicity. So, the laser is here; the pump is constantly on and therefore, there is energy build up which is taking place. Assume that the transmittance of this mirror T; T is the transmittance of the second mirror.

So, mirror M 1 is fixed, 100 percent; mirror M 2 has a transmittance which can be changed. There are methods by which transmittance can be changed. So, if the transmittance is 0 which means if this mirror is also 100 percent reflecting; if the second mirror is also 100 percent reflecting, this implies the transmittance T is equal to 0.

Here, T is the transmittance; not the time or period. So, T is the transmittance; T is transmittance which is equal to 1 minus reflectance of the mirror. So, if the reflectivity is 90 percent, then 10 percent is the transmittance. If the reflectivity is 100 percent; 0 percent will be transmittance. So, T is equal to 1 minus R. Now, if T is equal to 0, then the energy will build up inside the resonator continuously and it will reach a certain level of saturation.

Because there is always finite loss in the resonator; the pump is continuously on. At some time T, let us say at T is equal to T 0, you suddenly drop the reflectivity from 100 percent to let us say 50 percent. Then, transmittance T will go to 50 percent. In other words, 50 percent of the energy will come out from here. At that instant, there is a high energy built up inside the resonator.

But at T is equal to T 0, if I suddenly drop the reflectivity or suddenly increase the transmittance of the mirror, then I have 50 percent of the energy suddenly going out of the resonator. And that way, if I modulate T, if T is modulated, then I get the output also modulated. Modulated means what? Like a step function alright.

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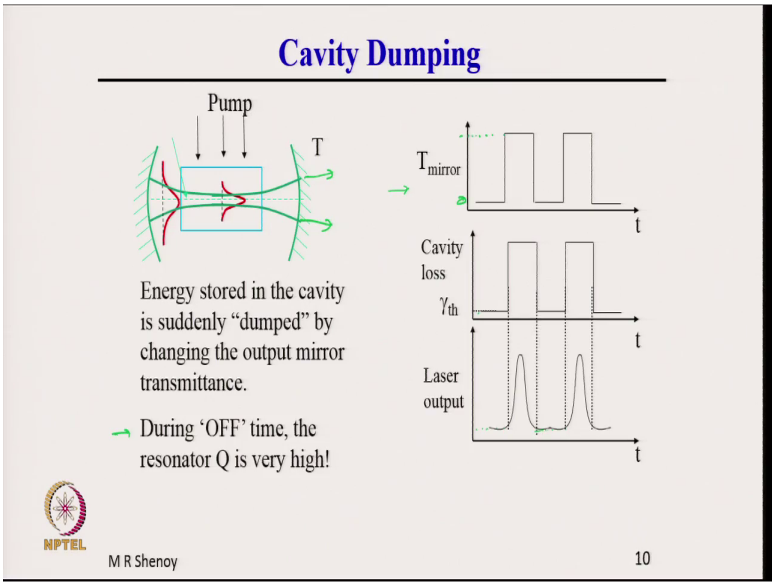

So, let me show here now. So, there is a laser which is building up energy here. So, at T is equal to 0, this is 100 percent; at T is equal to some T 0, if I make it 50 percent or 40 percent or 90 percent, then the energy would suddenly come out from the laser. And then, if I close the shutter or that is if I reduce the transmittance again to 0, then there will be no output.

So, that is what is shown in this diagram. The transmittance of the mirror varies from 0 to some number, some suitable number; it could be 50 percent, it could be 90 percent. So, if the transmittance suddenly varies, the node that the laser output was 0 earlier because transmittance was 0 and therefore, laser output was 0, but when the transmittance goes high, suddenly we get laser output coming.

And then, when the transmittance again brought down, the energy comes down and remains at the 0 level. So, if you modulate the transmittance of the output mirror, then we get a modulated output. This is called cavity dumping because energy is stored in the cavity and suddenly, the cavity is opened and the energy from the cavity is dumped, that is the useful energy for us.

So, when you require energy as a pulse, as a burst of energy, the mirror transmittance is temporarily increased from 0 to 100 percent or 90 percent and then suddenly, we get a burst. This is called cavity dumping. It is like we have a bucket of water, there is a tap from which water is dropping continuously into the bucket. When the bucket is full, suddenly if you open the bottom of the bucket, then the entire water in the bucket would simply fall down and that is why it is called dump.

So, you have dumped the water in the bucket. Because suddenly, you opened. Assume that there is a sheet at the bottom which is closing the bucket or it is possible to open and so, when it is closed, water is continuously falling into the bucket from a tap and when the bucket is full, you suddenly open. So, it is called cavity dumping, where the transmittance of the mirror is variate.

Now, the point to be noted is during 'OFF' time, that the OFF means there is no output, the resonator Q is very high because the reflectivity we have made 100 percent. Off time means output is off, but therefore, the reflectivity is very high and therefore, the quality factor Q of the resonator is very high and suddenly, when you increase the transmittance, the resonator will become highly lossy as shown here.

The cavity loss will switch high, the reflectivity of the mirror is very small and therefore, the cavity loss is switched high. But that is the time when we get the output. So, this is the technique of cavity dumping.

In the next lecture, we will see Q-switching and then, we will compare what is the distinction between the cavity dumping technique and the Q-switching technique.

Thank you.