Introduction to LASER
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Lecture - 32
Methods of Mode Locking

Welcome to this MOOC on LASERs. In the last three lectures, we saw various methods of pulsing lasers and today, I will discuss a couple of methods used for mode locking.

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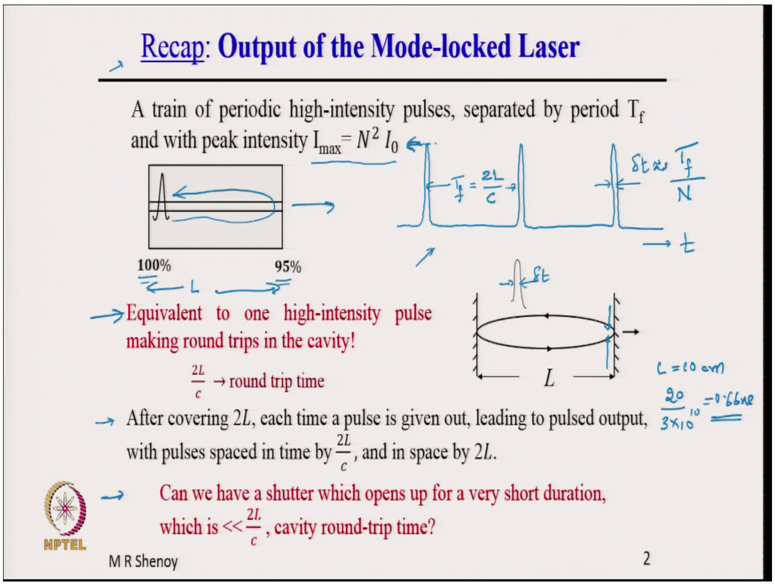

So, a very quick recap. In the last lecture, we had seen that the output from the mode locked laser comprises of a train of periodic high intensity pulses, separated by period T f and with peak intensity I max is equal to N square I 0 where I 0 is the intensity of one mode.

For example, if we think of this as the laser, then the output would comprise of peaks, periodic peaks so, periodic with a separation between them is equal to T f which is equal to the cavity round trip time that is 2L divided by c and the width of each resonance here is approximately delta tau or delta t is of the order of approximately nearly equal to T f that is the period divided by N, the number of modes and the peak intensity here, we had seen is N square I 0 where N is the number of modes.

So, this is the kind of output that we get which means an output pulse is emitted from the laser for every time T f that is for one cavity round trip time and therefore, it must be equivalent to one high intensity pulse that is making round trips in the cavity. So, there is a pulse which is making round trip in the cavity so, it goes back and forth like this and every time when it hits the output mirror here so, I have just taken some number 100 percent 95 percent, 5 percent of the energy would go out in the form of a pulse.

So, the mode locked output or the mode locked the situation is such that there is an equivalent one high intensity pulse that is making round trips in the cavity. Therefore, after covering 2L, 2L is the round-trip distance because this is L, the cavity length is L each time a pulse is given out leading to a pulsed output as shown here in this figure.

So, this is the time axis so, this is with time. Now, looking at this, if it is an equivalent situation like this that is one pulse which is hitting here and coming back, then can we have a shutter because our objective is how to obtain mode locking. Suppose we had a shutter here at one end, there was a shutter let us say there is a shutter here which opens up for a short duration which is equal to the duration of the pulse.

So, this is the duration of the pulse delta t. Let us say the shutter opens just for the duration of the pulse, then the pulse would travel and then get reflected back and then, the shutter is closed when the pulse goes back and then, again when the pulse comes after one round-trip, then if the shutter opens, then the pulse will again get reflected.

All other energy coming at any other instant will be blocked because of the shutter because of the shutter, there will be no feedback. Therefore, if we have a shutter which opens up for a very short duration which is much less than the cavity round-trip because this is the cavity round trip, from here to here T f is the cavity round-trip time.

And the pulse width is much smaller than that and therefore, if we can have a shutter which opens up for a very short duration which is much less than 2L by c that is the cavity round-trip time, then we should be able to get mode locked pulses.

But this is not easy because the time taken, round-trip time is very very small, this is the time required in a normal cavity for example, let us say L is equal to 10 centimeter, then the round trip time is 2L that is 20 centimeter by c that is 3 into 10 to the power of 10 which is 0.6 nano second so, 0.66 nano second. Its very difficult to have shutters which open and close so, that is the round-trip time, this is the round-trip time.

Now, the shutter opening time should be much smaller than this and this is very very difficult and therefore, there are different methods which are used for mode locking. So, we will discuss a couple of methods which are used for mode locking.

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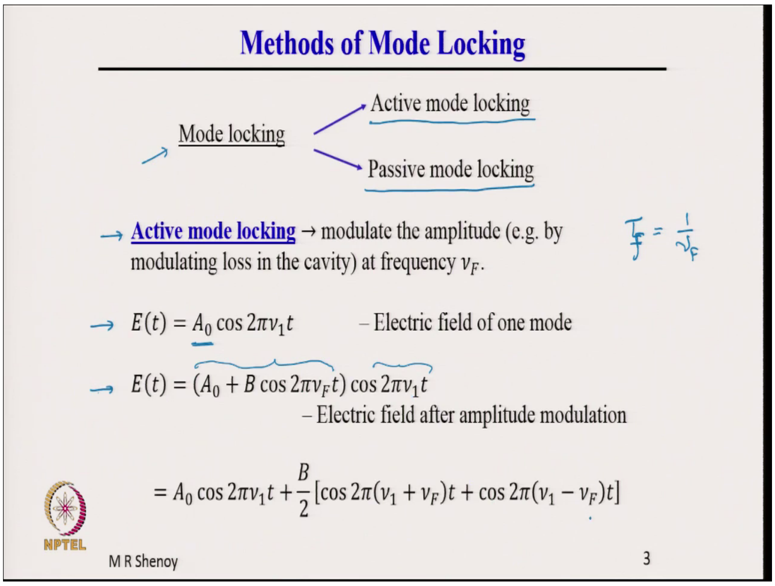

So, methods of mode locking. There are two methods which are used broadly classified into active mode locking and passive mode locking. Let us first look at active mode locking, then we will see what is the difference.

In active mode locking, if we modulate the amplitude for example, by modulating the loss in the cavity at the frequency nu F, then we should be able to get mode locking. What do we mean by this? Please see that the cavity round-trip time T F, capital T F here, T F is equal to 1 by nu F and therefore, if we modulate the loss at the rate of nu F, that is the rate at which the pulse would go back and forth, then it would be possible to have mode locking effect.

Let us see whether this is right or not. So, let E of t is equal to A cos 2 pi nu t be the electric field of one mode. So, we have a number of longitudinal modes oscillating, consider one of them and let A 0 cos 2 pi nu t be the electric field, time evolution of the electric field. Now, if we modulate its amplitude, amplitude in this case is A 0, if we modulate this amplitude which means the new amplitude is A 0 plus B cos 2 pi nu F t, nu F is the frequency at which we are modulating the amplitude.

So, we can write the amplitude modulated electric field as A 0 plus B cos 2 pi nu F into t into the frequency phase term that is cos 2 pi nu t, the electric field after amplitude modulation. So, the amplitude is modulated sinusoidally at the frequency nu F. So, now, this is the net amplitude, this is the amplitude term, and this is the phase term. So, the amplitude is now modulated with the time at the rate of nu F.

So, if we apply simple trigonometry here and open this up so, it is A cos 2 pi nu t plus B by 2 into cos 2 pi nu 1 plus nu F into t. So, we have cos A cos B is equal to cos A plus B by 2 plus cos A minus B by 2. So, we use this trigonometric formula, and we get B by 2 into cos 2 pi nu 1 plus nu F that is nu F plus nu 1 and nu 1 minus nu F t.

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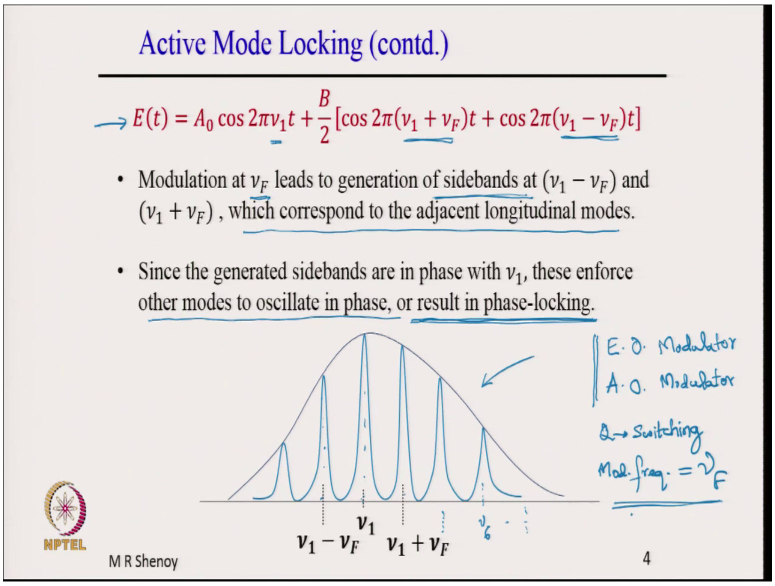

So, E of t is given by this expression, the same expression I have written. What does this mean? This means that the modulation at the frequency nu F leads to the generation of sidebands. Now, there are three terms 1, 2, 3. The first one is at frequency nu, the second one is at frequency nu 1 plus nu F and the third one is at frequency nu 1 minus nu F and in communication technology, these are called sidebands.

A sinusoidal modulation leads to two side bands at plus and minus the modulation frequency which correspond to the adjacent longitudinal mode this is important to note. What do these frequencies correspond to? If nu 1 is this frequency see the diagram here, then nu 1 minus nu F is the next longitudinal mode what is shown are the longitudinal modes of the laser.

We first considered a mode at frequency nu 1, modulated the amplitude of this mode at the rate of nu F and then, it generated two sidebands at frequency nu 1 minus F and nu 1 plus F, nu 1 minus F overlaps the generated sideband, overlaps with the mode or is superposed with the mode at nu 1 minus nu F, the other longitudinal mode and similarly, nu 1 plus nu F corresponds to the adjacent longitudinal mode on the higher frequency side.

In other words, the modulation of a mode leads to generation of sidebands which correspond to the adjacent longitudinal modes. But more importantly, the sidebands are in the same phase as that of the nu 1 frequency that is the frequency being modulated, there is no additional phase term, this is simply 2 pi into frequency into time, there is no additional phi or additional cos or sin term which means the frequencies they are in phase with nu 1.

The sidebands generated are in phase with the frequency nu 1 and therefore, now all the three modes are in phase. But please see that we had considered an arbitrary longitudinal mode of frequency nu 1. It could have been here, the mode could have been here, let us say this is nu 6, then this would generate one sideband here nu 5 and another side band here, if there a mode exist and all these sidebands are in phase with the modulating frequency and therefore, all the longitudinal modes are now forced to oscillate in phase.

So, the resultant is since the generated sidebands are in phase with the frequency nu 1, these enforce other modes to oscillate in phase or result in phase locking. So, this is the idea of phase locking. So, the generated sidebands are one at the same frequency as the adjutant longitudinal modes, but also, they are in phase with the frequency nu 1 and therefore, they force other modes also to oscillate in the same phase.

In other words, this results in phase locking of the longitudinal modes that is what we require that the modes have to be phase locked to get mode locked output.

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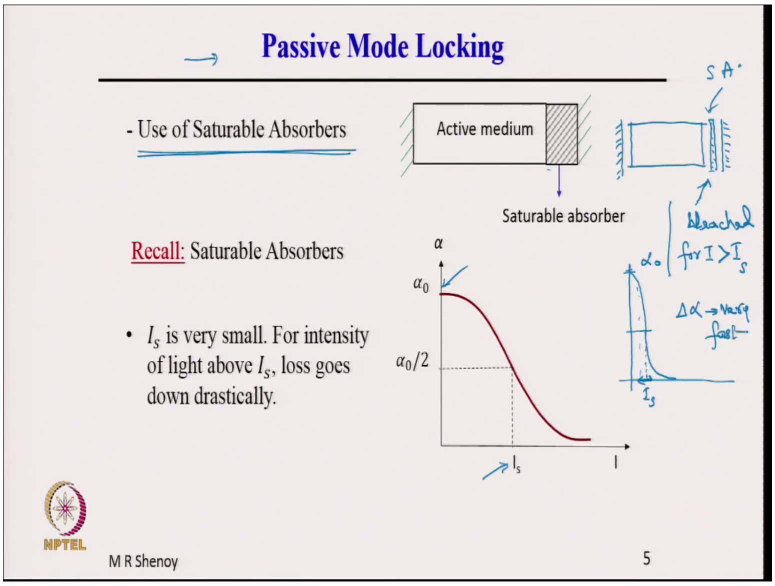

Now, a second method which I briefly discuss is the passive mode locking. So, how can this be done? For example, modulating the amplitude, you could have as before I had mentioned about electro optic modulators EO modulator; electro optic modulator or acousto-optic modulator any one of them can be used, AO modulator.

What does the modulator do? Modulator acts like a shutter, modulating the loss in the cavity at a desired frequency and that is what we have done. We have modulated the loss or modulated the amplitude, modulating the amplitude means modulating the loss in the cavity. So, the same method which I had discussed earlier for Q switching is also applicable for mode locking or modulating the longitudinal modes or cavity loss in a laser.

However, the difference between Q switching, modulation for Q switching, here we could change the repetition rate I discussed this that we could change the reputation rate by changing the modulation rate. However, here if we require phase locking of the longitudinal modes, the modulation frequency or modulation rate frequency must be equal to nu F. It is a fixed frequency at which you need to modulate the loss. That is the primary difference between modulation in Q switching and in the case of mode locking.

Let me look briefly at the method for passive mode locking. What is done is to achieve passive mode locking, one uses saturable absorbers. So, what is shown here in the diagram is the laser medium and a saturable absorber at the end of the medium. So, it is like this, the laser is here, we have shown it in contact, it need not be in contact so, the laser medium is here and very close to the mirror, you have the saturable absorber and then, you have this reflector here.

It is very easy to understand if it is close to the mirror. So, this is the saturable absorber SA so, saturable absorber, the mirrors are here, and this is the laser medium. Now, recall that in saturable absorbers, we have a large loss coefficient, but a small value of I s. In other words, as the intensity increases from 0, the loss rapidly comes down. So, I can equivalently depict it here that the loss rapidly comes down as we go.

So, it has a large value of alpha 0 that is the loss coefficient at very low intensities and drops down to half of its value at some value I s, but this I s in general is much smaller compared to other general absorbers and that is the saturable absorber and therefore, what happens? Let us see how the saturable absorber results in passive mode locking.

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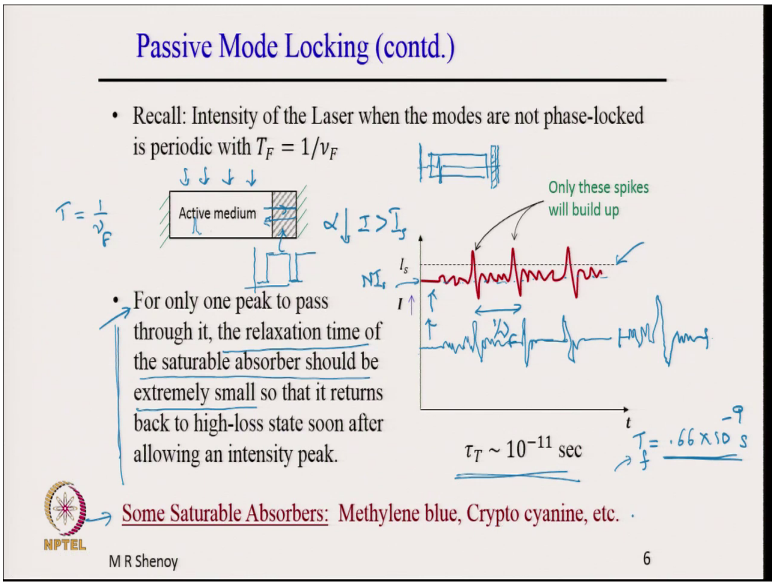

Recall that the intensity of the laser when the modes are not phase-locked is periodic with a period T F, but the variation looks like this. So, this is the average intensity, if there are N modes, then this is N times I 0. So, we had seen this in the last lecture that when the modes are not phase locked, then we have a average level at N times the intensity of the individual modes, when the intensities are identical for all the modes.

And then, there is a variation which is periodic with a period equal to if this is time axis, then this period will be equal to 1 by nu F, this we had seen in the last class. Now, in this periodic fluctuation, there may be some peaks which appear. The peaks may appear anywhere inside the period for example, if I consider one period here, then there is a fluctuation which is taking place, there may be one peak which does like this, but this will repeat.

So, this is basically due to spontaneous emission noise, but noise is random and sometimes you get peak, but that will be periodically appearing in the output. And if the level which I have shown here, if this corresponds to I s, then the peaks have intensity more than the saturable intensity and therefore, the absorption coefficient of the saturable absorber drops down rapidly for this alpha, the absorption coefficient drops down rapidly when I intensity becomes greater than I s.

So, slowly if we increase the pump power in a laser, then the level initially, we have N times I 0, the level may be somewhere here like this what I am plotting here is the output intensity may be here like this. Now, as I increase the pump power this goes up, this goes up and at one stage that the peaks have intensity which is more than I s and if we look back here, the moment intensity increases beyond I s, then the loss coefficient drops down rapidly.

Loss coefficient drops down means what? The saturable absorber becomes transparent, it is no more absorbing, this gets bleached that is the correct technical word it gets bleached for I the intensity greater than I s. Now, what has happened from this? Here, when the peak has pass through the saturable absorber here, the peak passes through the absorber and then, because this gets bleached and then, it gets reflected back. So, the peak passes through and then, gets reflected back.

When the peak has come back, the intensity level again goes below I s and therefore, the absorber acts like an absorber. So, in effect, what has happened is only the peak has been reflected back. So, there is a small peak which is reflected back, now this comes again, it gets amplified, this peak as it passes through the medium gets amplified, gets reflected back and again because its intensity is high, it is already amplified, it passes through the absorber and comes back and so on.

We have done nothing, it is a passive material which has been used in the cavity and because of the intensity peaks, bleaching the saturable absorber certain peaks pass through it. Now, the peaks are periodic in the output with a period T is equal to 1 by nu F and therefore, it means that a peak or a pulse which is going back and forth in the medium with a cavity round trip time of T is equal to 1 by nu F that is what we require in mode locking.

So, for only one peak to pass through it, the relaxation time of the saturable absorber should be extremely small so that it returns back to high-loss state soon after allowing an intensity peak. Please try to understand this. So, there is a peak which is passing through the medium. So, let me draw it again here, a fresh diagram.

Initially, the output from the laser here was study output. So, in the cavity also, there is a output which is in this form with certain peaks which are here. So, the peak is periodic with a time equal to round-trip time.

So, when the peak passes through the saturable absorber, the saturable absorber gets bleached, but as soon as the peak passes through, the loss must again become high for the saturable absorber otherwise, the rest of the beam will also, rest of the intensity, rest of the power would also pass through the saturable absorber.

In other words, this saturable absorber should go to low loss state when the peak comes and then again switch back to high loss state. Again, when the peak comes, it must switch to low loss state and then, again to high loss state. So, this is actually loss switching, but we are not doing, it is passively doing on its own because of its property and that is the importance of saturable absorber.

But if the loss has to switch low and switch high, let me explain here looking at this graph. So, when the intensity becomes more than I s, when the intensity increases here, loss comes down.

When the intensity again goes back, loss must again go to high value and this must happen at a very fast rate so that only the peak should be allowed by the saturable absorber and that means, the change of loss coefficient that is delta alpha must occur very fast then only it is possible very fast and that means, the relaxation time of these saturable absorbers must be very small.

So, in general, relaxation time that is the time when it comes back to its original state is of the order of 10 to the power of minus 11 seconds because the round-trip time, I just calculated the round-trip time was in the previous example 0.66 into 10 to the power of minus 9 second 0.66 nanosecond. The pulse width is much smaller than the cavity round-trip time so, this is the cavity round trip time. In my previous example, this is 0.66 nano second is the cavity round-trip time.

If a pulse has to pass through, then the saturable absorber must have a response time which should be even faster because the moment the peak passes, it should again act like a shutter namely the loss must be switched to higher values and that is why the relaxation time of the saturable absorber should be extremely small, how small? It must be much smaller than the cavity round-trip time T F.

Some of the widely used saturable absorbers are methylene blue and crypto cyanine. So, I have briefly discussed an active method and a passive method of mode locking lasers. There are other methods by which one can achieve mode locking ok.

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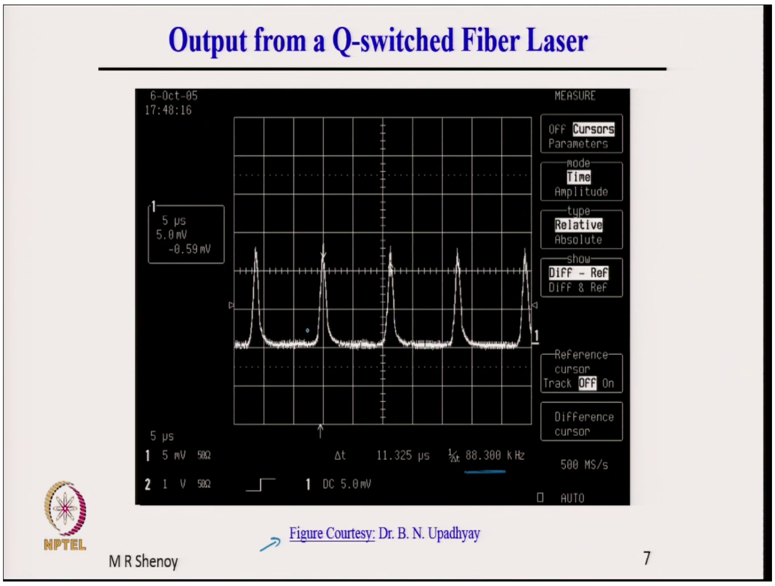

Now, before I proceed further, I want to show here in this picture, I have shown pulsed output from a Q-switched fiber laser. So, what you see is pulsed output in the form of nice periodic pulses from a Q-switched laser. So, this has been provided by Dr. B. N. Upadhyay was our PhD student. So, this is from a fiber laser. We can see that the rate at which the pulses come is here 88.3 kilo Hertz and the pulse width is typically hundreds of nanosecond.

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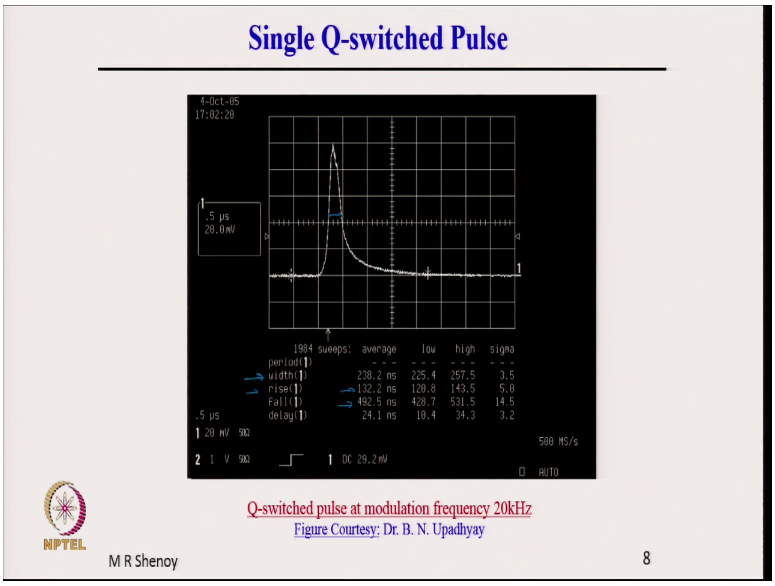

So, let me show a single pulse. For example, let me take a single pulse here so, it is the same from the same pulse time one of the pulse has been expanded and shown here and we can see that the pulse width here is about 238 nanoseconds, it has a very fast rise time and relatively slow fall time.

So, rise time is time taken for the amplitude or intensity to rise from 10 percent to 90 percent and it is shown here, the rise time is 132 nanosecond, the fall time is 432 nanosecond that is this time here, but the pulse width which is FWHM here is about 238 nano second. This is a measured pulse from a Q-switched fiber laser.

So, we can see that the pulse is of course, not very symmetric, but the pulse train is periodic and very nice pulses of the same amplitude which come out. So, these are 100 nanosecond or 200 nanosecond pulses.

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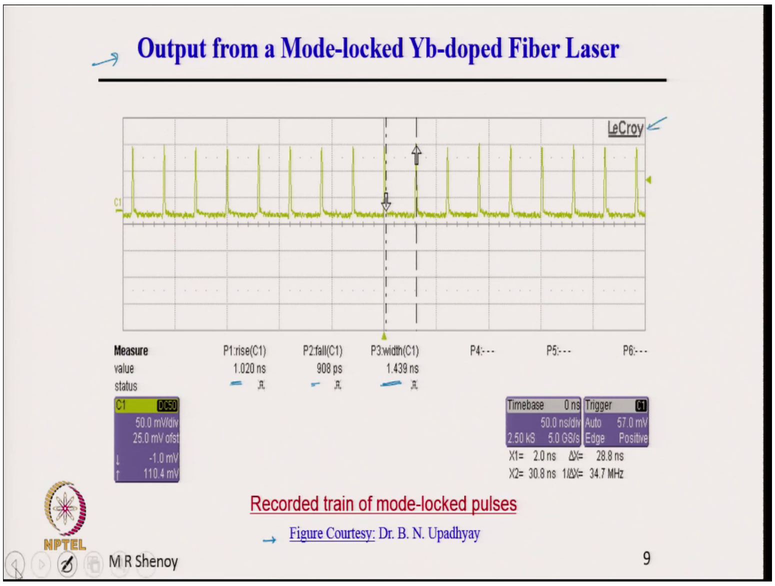

Now, let me show another diagram here. This is output from a mode locked ytterbium doped fiber laser. This is again courtesy Dr. Upadhyay. It is a recorded train of mode locked pulses. We see that the pulse rise time is about 1 nanosecond and the fall time is about 0.9 nanosecond which means the pulse width is approximately 1.439 nanosecond. This is also again from ytterbium doped fiber laser.

Note that the pulse width in the case of mode locked laser is much smaller compared to the pulse width in the case of Q-switched laser and we again see a periodic train of pulses and the pulse width of the order of 1 nanosecond. These are real measurements done in the lab alright.

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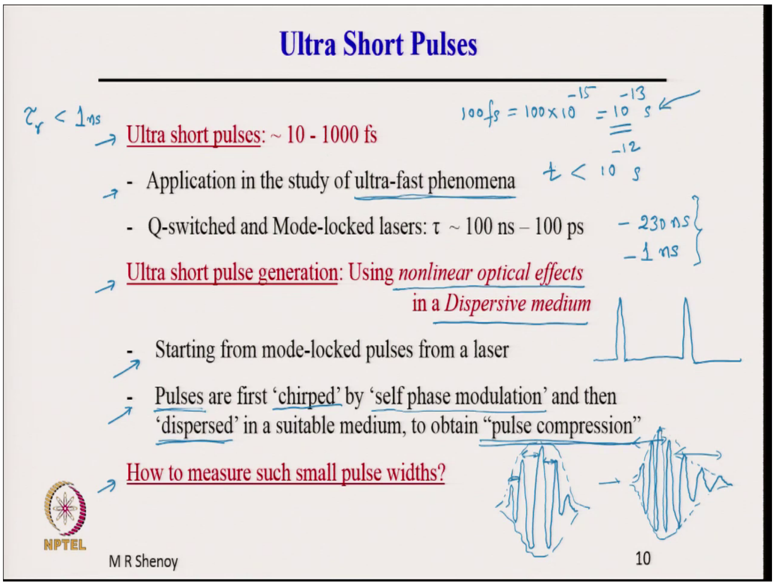

Before I close, I want to briefly talk about ultra short pulses. These are very important now ultra fast lasers or lasers which give out ultra short pulses, they are very important. When we say ultra short pulses, we typically refer to pulse width of the order of 10 femtosecond to 1000 femtosecond, 1000 femtosecond is 1 picosecond. Anywhere in this range, we normally call them as ultra short pulses, sub picosecond pulses.

What are the applications? These are widely required to study ultra fast phenomena which means a phenomena which takes with the time scale t which is less than 10 to the power of minus 10 or minus 12 seconds let us say minus 12 second or minus 13 seconds, a change which takes place so fast has to be probed by light or light pulses which are much shorter than the time scale itself and that is why we go to time scales of the order of 100 femtosecond.

So, 100 femtosecond is 100 into I am sure you are familiar femto is 10 to the power of minus 15 second which is equal to 10 to the power of minus 13 seconds. So, that is the kind of time scale which we are talking of. In almost all cases, Q-switched and mode locked laser typically have pulse widths in the range of 100 nanosecond to 100 picosecond.

Here, the upper range I have shown as 1 picosecond, but Q-switched and mode locked laser typically give 100 nanosecond to 100 picosecond width of pulses. The two examples which I had shown, one was about 230 nanosecond that is the Q-switched one and the other one was about 1 nanosecond, the pulse width in mode locked and Q-switch.

So, this was in Q-switched and the other one was in mode locked. You can see that it very well is in this range. Therefore, how to get ultra short pulses? This is a very detailed and important topic, my objective is only to mention to you the importance and the contemporary interest in this topic, this is not part of our syllabus, but just for curiosity sake.

So, ultra short pulse generation is achieved by using non-linear optical effects in a dispersive medium. I have just summed up the methodology, we use non-linear optical effects in a dispersive medium, in one or more dispersive media. So, the starting point is always in almost all cases is mode locked pulses from a laser, nice mode locked pulses from a laser.

So, we start with mode locked pulses of let us say 1 nanosecond duration, then we need to achieve pulse compression, we have to compress this down to 100 femtosecond, of the order of 100 femtosecond. So, this is achieved by again it is summarized here, the pulses are first chirped by self phase modulation, this is a non-linear optical phenomena based on intensity dependent refractive index.

It is chirped, chirped means for those of you are not familiar if we have a nice sinusoidal of a pulse with a sinusoidal frequency and an envelope like this, then if you chirp the frequency is the same, the instantaneous frequency everywhere this separation in time is the same because frequency is one by time taken for one cycle.

And therefore, if this pulse is chirped that means, if the frequency varies let us say the frequency is very very close here and then, the frequency opens up like this. So, you see now, what I have shown is a pulse. So, this is the envelop and this is the electric field variation rapidly varying sinusoidally oscillating electric field, but what has happened is the frequency, this portion of the pulse is higher, and the frequency here is lower. So, there is a chirping.

So, chirping refers to varying frequency inside the pulse itself. So, the mode locked pulses are first chirped by self phase modulation and then, they are dispersed in a suitable dispersive medium to obtain what is called pulse compression. I mentioning these terminologies so that it would probably interest some of you to pursue these ultra short pulses.

One last point, how one can measure such small pulse widths? If we refer to pulse widths like this, I showed you oscilloscope traces so, these are real traces on an oscilloscope, you can see these LeCroy oscilloscope and this is also oscilloscope traces which means the pulses were detected by detectors which means the detection time.

So, the detector should be fast enough to detect the rise time of the detector should be less than 1 nanosecond if it has to detect a pulse of width 1 nanosecond and indeed, we have fast detectors, photo detectors I am referring to, fast photo detectors which have rise time which is less than 1 nanosecond, sub-nanosecond rise time.

However, now, we are talking of 10 to the power of minus 13 seconds and we do not have any detector which can detect such small-time scales, a detector detects by absorbing the incident energy and generating an equivalent current, a current which is proportional to the incident light energy. The detector response time is generally of the order of 1 nanosecond or so.

Therefore, if pulse which is of 10 to the power of minus 13 second duration is incident on a detector, how will the detector respond? The detector cannot respond. Therefore, how this can be measured? This is measured by a beautiful technique which is called autocorrelation.

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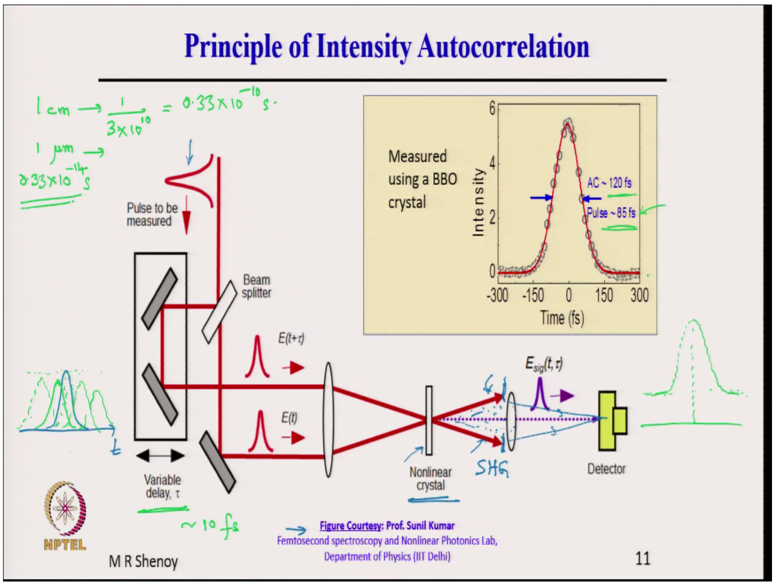

So, this is my last slide in this topic. Again, I am putting this only for kindling some interest in you that the principle of intensity autocorrelation. Assume that there is a pulse which is coming, an ultra-short pulse incident here, we have to measure the width of this. So, first the pulse is split into two-half so, 50-50 beam splitter in two-half's and then, they pass through a lens and focused on to a non-liner crystal, this is a non-linear crystal.

The diagram and the result which I am showing is courtesy by my colleague Professor Sunil Kumar from our department. So, this is the principle of autocorrelation where the two pulses are incident on a non-linear crystal which gives rise to second harmonic generation SHG, second harmonic generation. The second harmonic comes here, the red line is the main pump beam, the ultra short pump beam.

We have to block this here. So, we do not want it beyond this and the second harmonic which is generated here is collected by the lens and is focused on to the detector, the lens focus is on to a photo detector. Now, the intensity of the second harmonic generation depends on the intensity of the pump pulses which are incident here.

In an autocorrelation, a variable time delay is introduced between the two pulses so that there is if I show the time scale here, let us say at one of the pulses I am showing like this. And the second pulse, if the second pulse slides in time over this that is it goes from here slowly, slowly it passes through this exactly coincides with this and then, it comes here and so on that is the second pulse slides over the first pulse.

Then, during the time when the two pulses overlap here, the intensity of the second harmonic generated is maximum and when the pulses are apart, then the intensity would correspond to the power or the intensity of the individual pulses. The net result will be if we see the output from the photo detector here, then it will have a certain background level and then, it will have a pulse shape riding on the background.

The background corresponds to the second harmonic generation due to individual pulses and the peak here, shape corresponds to so, this corresponds to the time when both of them are completely overlapping. The point is we can vary this delay very carefully, the delay can be changed of the order of 10's of femtosecond by moving for example, what is this delay?

The delay is introducing a path difference between these two. A path difference of 1 centimeter corresponds to a time difference of 1 divided by the velocity that is 3 into 10 to the power of 10 centimeter which corresponds to a path difference of 0.33 into 10 to the power of minus 10 seconds for 1 centimeter length.

If it is 1 millimeter, it will become minus 11. If it is 1 micrometer, suppose the path difference is 1 micrometer, then the separation or then, the delay would correspond to 0. 33

into 10 to the power of minus 14 seconds. Now, we see that we are in the regime of the width of the pulse, pulse width is 10 to the power of minus 13 seconds and you are able to slide them that you are able to give a time difference a delay between the two pulses of the order which is smaller than the pulse width.

And from that you can extract the pulse width and that is what is shown here the autocorrelation has a pulse width of 120 femtosecond from which you can calculate the actual pulse width which is 85 femtosecond. This is the measured pulse width of an ultra-short pulse. So, I have just shown this technique only as a very interesting technique to measure ultra-short pulse width.

So, with this, we summarize that nanosecond pulses, picosecond pulses and even femtosecond pulses can be generated by appropriately modulating a laser.

Thank you.