**Implementation Aspects of Quantum Computing**
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**Lecture - 17**
**Pulsed Lasers**

We have been discussing about Lasers in the last couple of lectures and we have covered almost everything to deal with Continuous Lasers. In this lecture we will be doing the last part of the lasers which are necessary for our course which is going to be the Pulsed Lasers. So, until now we have been focusing on continuous lasers; the principle of blazing and all that now we are going to look at Continuous versus Pulsed Lasers.

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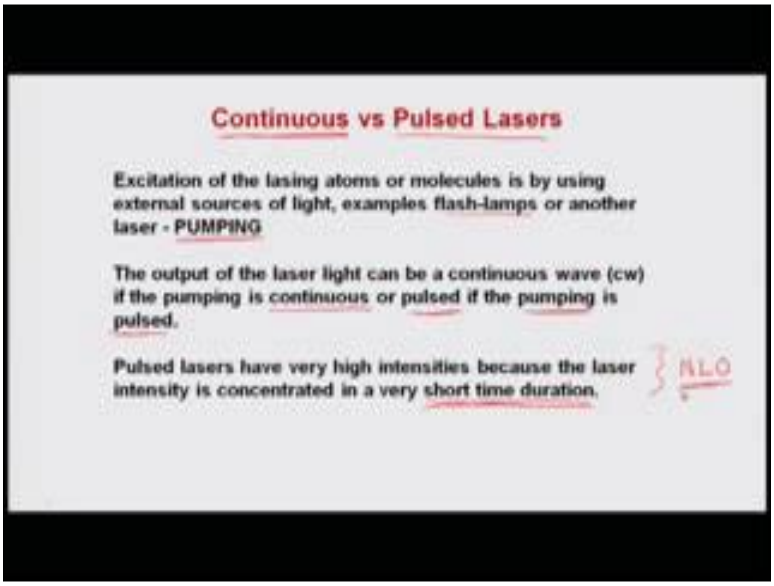


What we have looked at has been excitation of lasing atoms or molecules by using external sources of light or radiation for example, flash lamps or another lasing another laser which is pumping by using electromagnetic radiation or other things, but basic idea has been pumping; the output of the laser light can be a continuous wave as we have been discussing. If the pumping is continuous or pulsed; this is the second part which you are going to look at. Most of the cases until now have been continuous and so the pumping part in our case could be of various kinds.

The pulsed lasers have very high intensities because the laser intensity is concentrated in very short time duration and that is one of the critical reasons for studying this part because this is the one which gives rise to non linear optical properties. So, there are two waves are looking into quantum computing and quantum related aspects. One is in the linear region which is very easily possible with the continuous lasers and principles that we are looking at also under the condition where the photons are very low in number which is low photon count regions where would like to actually have very low number of photons to be dealing with.

So, that is one kind which you have almost done now, but the other kind where we would like to deal with a lot of photons possibility of having lot of them simultaneously so that it can induce events or phenomena which are not possible to be explained by under the linear domain that is the part which you are necessary to have short time pulses or other kinds of things also for measuring time scales which are very short.

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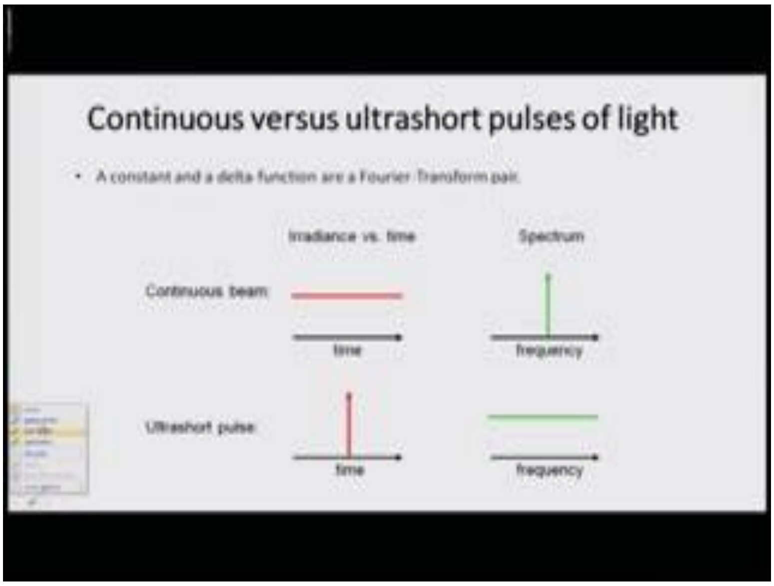


So, this is the region where we are now entering which is Pulse lasers. Now linear optics is one of the things which you have been looking at.

So, what is that is important for the continuous versus ultra short pulses of light? The continuous beam for instance if you look at with time is constant and it gives a spectrum which is ideally a single frequency, but we know that is some very small bandwidth where as on the other hand ultra short pulse again very short, time (Refer Time: 03:24) has say constant frequency in the ideal case. A constant and a delta function which are basically Fourier Transform pairs is what we have in the ideal scenario.

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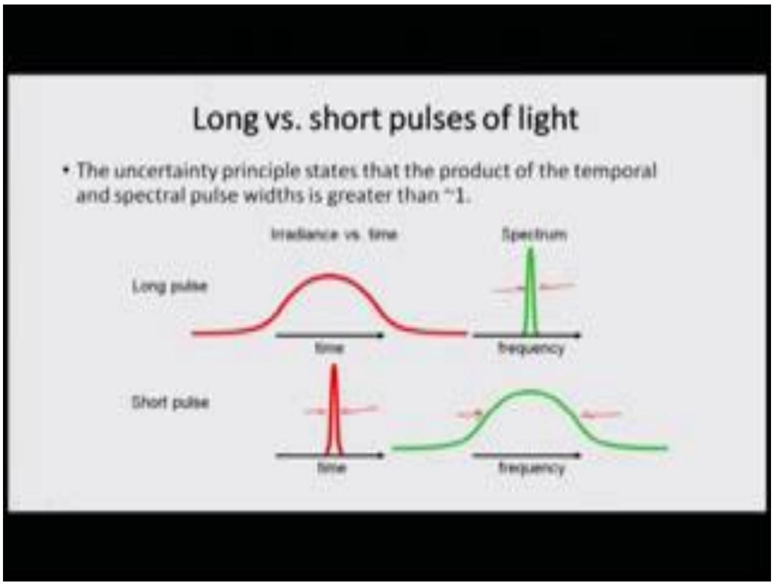


But in reality this is what we have. We have the irradiance versus time for a long pulse can be looked at a very narrow spectrum in the frequency band and vice versa a very short pulse in time corresponds to a very wide frequency or energy band in the frequency spectra. So, by using the Fourier relation between the two which is also the same as the uncertainty principle states that the two are transforms each other in time versus frequency.

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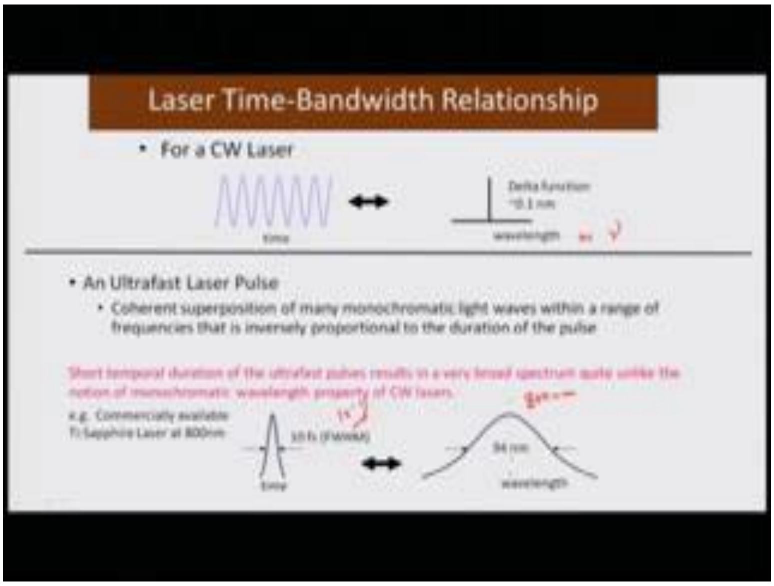

So, whatever is long in one domain is short in the other domain. As we mentioned in the last slide; it is a sort of like the extreme cases where we have continuous versus line, a line versus a continuous; in reality it is some width with respect to a very narrow width again the short width with respect to a long width that is what we are looking at.

The laser time band width relationship therefore, can be summarized in this slide as we said. For a continuous wave laser we have roughly a single frequency which corresponds to the delta function in wavelength or frequency and an ultrafast laser Pulse is therefore, a coherent superposition of many monochromatic light waves within a range of frequencies that is inversely proportional to the duration of the pulse. So, for instance 10 femtosecond pulse width femtosecond is 10 minus 15 seconds corresponds to say in wavelengths 94 nanometers around the center frequency. This is a Titanium Sapphire laser. It has say 800 nanometer center frequency and that is how this is a commercial laser and we will discuss that in a minute. So, that is how the relation works for the time and frequency and this is known as a Time-Bandwidth relationship which will be very useful when we are in this domain or ultra short laser pulses.

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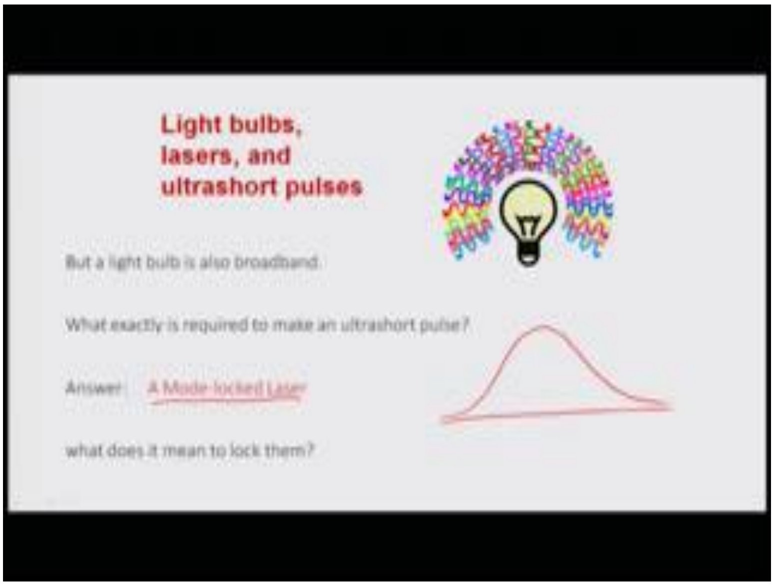


What is the main difference here between let us say wide band source for instance Light Bulbs which is also broad band, but as we have discussed many times over and over again sources which are not going to have coherence or anything (Refer Time: 06:29) stimulated emission I am not going to be relevant in this picture. So, a Light Bulb is the kind of scattering or spontaneous emission process which is sort of illuminating me, but for ultra short laser pulse we need something which is coherent and so we need something called a Mode-locked System.

We have already shown you spectral features where we have several modes; longitudinal modes present within the mode of the laser being measured and within the profile of the laser. Once we are talking about locking all the modes what does it mean how and how do we go about doing that that is what we have to look at.

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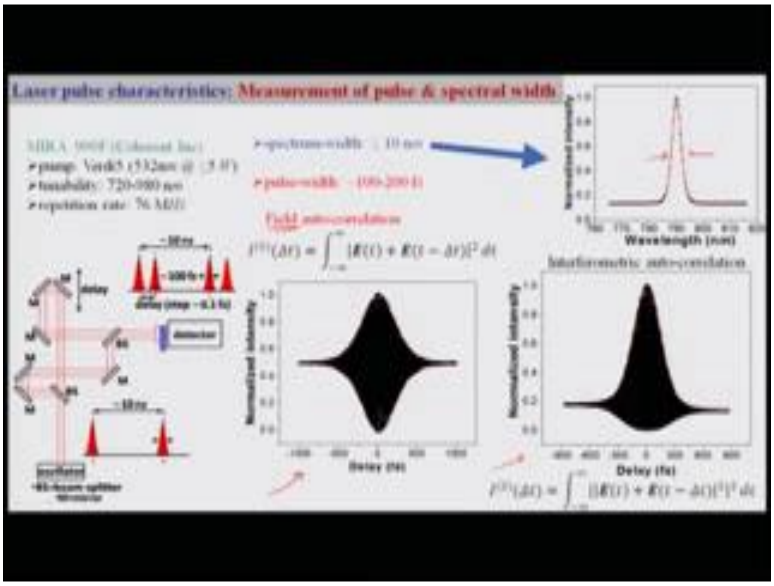


So, in order to look at these pulses we have to also recognize that they have to be measured in a particular way. So, the laser pulse characteristics in these cases are done in typically two ways. One is to note the spectral width which is comes from monochromator. So, for example, in this particular commercial laser that we were discussing 800 or 790 nanometers centre frequency we have a bandwidth which is associated to the measurement made in the spectrometer; monochromator.

Whereas, for in time with pulses which are so short it is not possible to measure directly, so see the measured by using a auto correlating system or cross correlating system, but generally the first principle is to use an interferometric way of measuring a correlation between the pulse and itself and that is one of the ways it is measured. You can see in this particular case the pulses we just separated at certain distances have been measured by delaying one pulse with respect to the other, and you can see how the interference pattern and fringes look like.

If you make a square measurements with the detector actually does it squaring of the system then you can pick up the difference between the two fields and so it could be interferometric auto correlation or which could be two types one is the field auto correlation which looks like this or it could be intensity auto correlation where it looks like this square of what we are looking at the field auto correlation so on and so forth.

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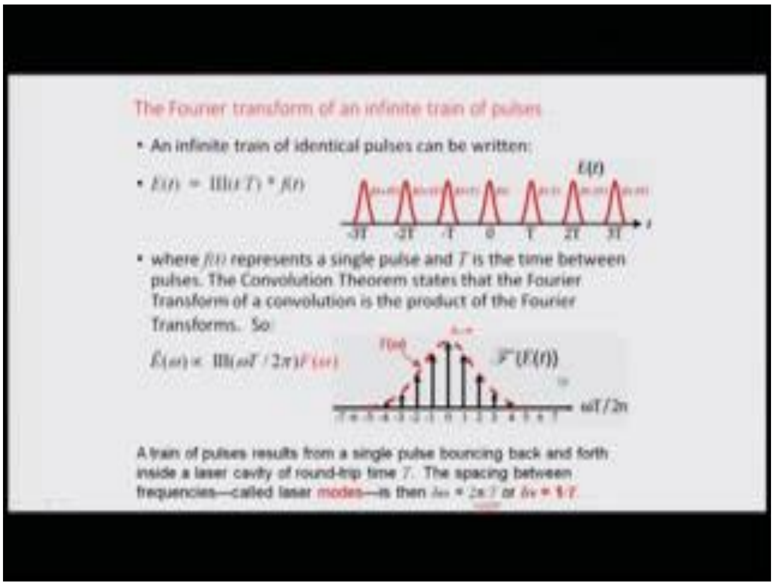


So, the Fourier Transform an infinite train of pulses can be written in terms of how it looks like where the single pulse and the time between the pulses the convolution theorem can be used and what we can look at is that there is a frequency band over which these different frequency components can be appear in the Fourier domain. Train of pulses results from a single pulse bouncing back and forth inside the laser cavity of round trip time T the spacing between the frequencies called Laser Modes and that is the one which is given as 2 pi over the round trip time T.

So, that is why the delta nu which is separation between these pulses on these modes which we are looking at which is this. So, that is generally what is the situation which is happening is that we have these round trip times within which the light is been rattling around the within the amplifying cavity and that is what we a measuring when we look at the pulses which are coming out.

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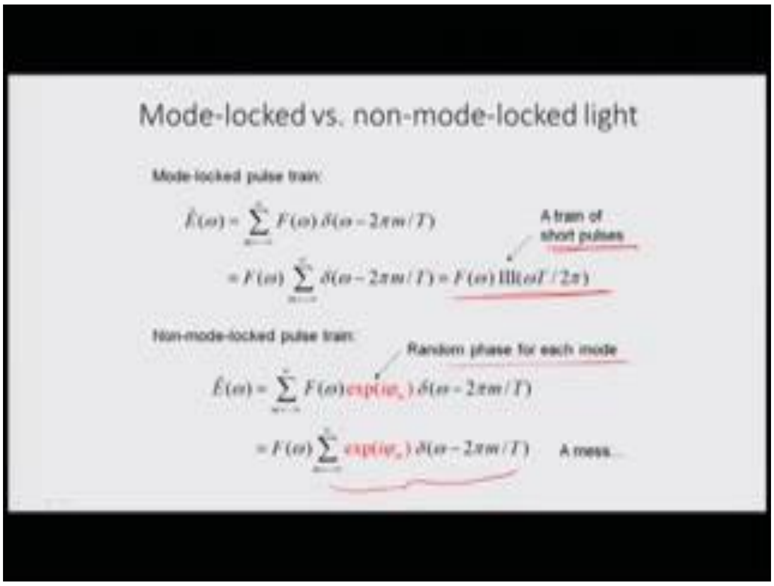


Mode Locked Pulse train therefore has this field which has this profile where as a train of short pulse is which is particular for the as we just mentioned; this is what we have just looked at. When we have non-mode locked pulse train then we have a random phase for each mode and so the overall function essentially has a summation all these different modes which is quite difficult to certain and they can be all over the place. So, there is they can (Refer Time: 10:54) all kinds of things. However all of these do not happen when you are looking at it and the mode-lock condition when the phases are all the same. So, the basic idea about the non-mode-lock versus mode-lock is that the phase distribution is fixed for the mode-lock pulse train.

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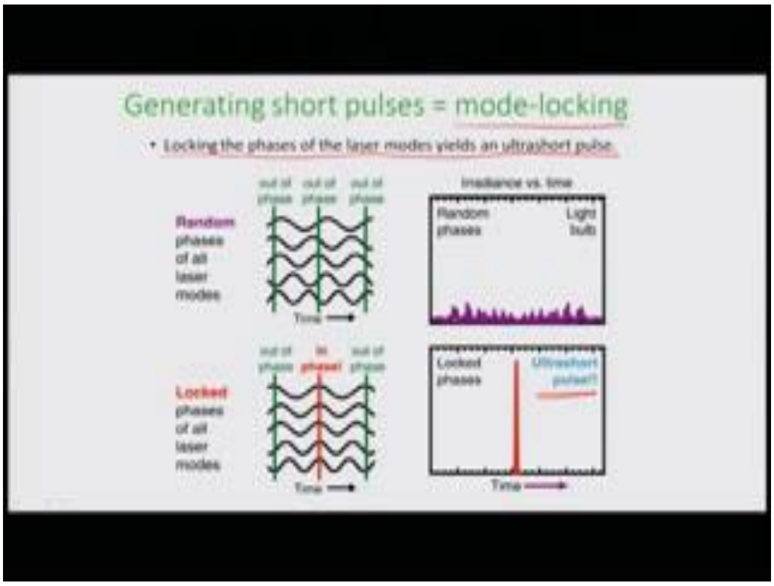


So, here is the pictorial output we are looking at. Locking the phases of the laser modes yields an ultra short pulse and that is the mode-locking. So, if you have random phases of all laser modes; it is a like this radiance with time; it is similar to what we have in case of Light Bulb also. So, the phases are all random where as when they are all one kind they are all in phase with each other then the period of time and when they are all in phase gives rise to the time over which all the lock phases are there.

So, all this other unlocked phase conditions are not possible to be seen only the ultra short period of time over which all the phases are in all the laser pulse; laser is in time is in phase is the one which looked at. So, this is the ultra short pulse during which all the phases are the same.

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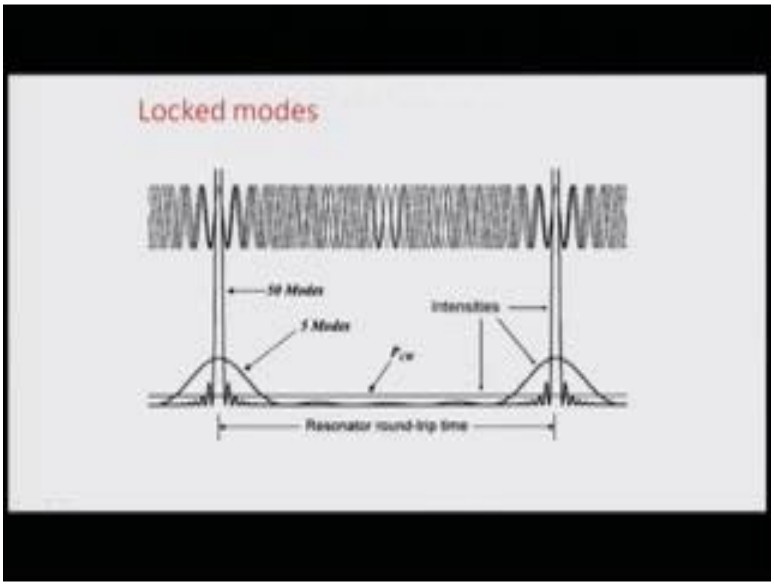


So, here is how it looks like; then there is all this are different modes that will coming out from the laser is a resonator round trip time and as the modes get to have the same phase and they overlap and they get amplified more and more at this points with respect to the time where they are not in phase and so they randomly are all over the place. So, statistically they average out where are the amplified ones are the ones which are happening exactly at the laser round trip time.

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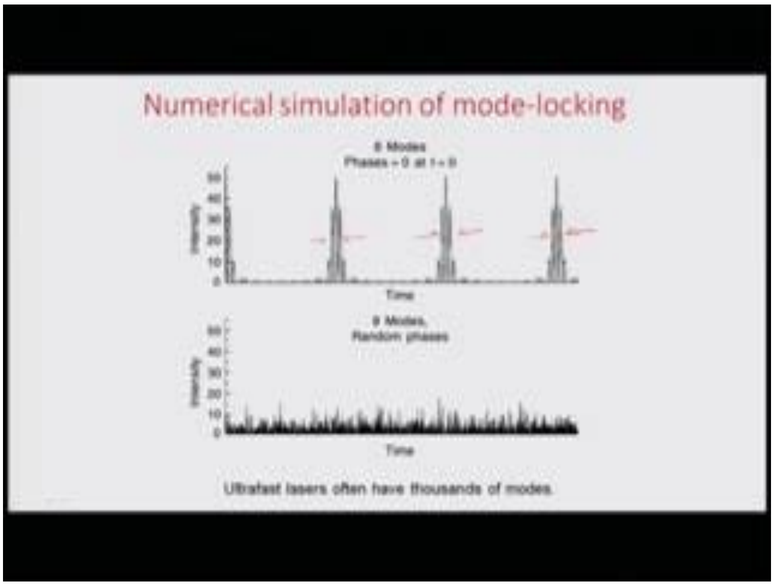

And we get the Locked modes at those places. So, you can actually go ahead and do numerical simulations of mode-locking going to see how you can have different time frames and these modes appear exactly locked at a period of time and you can have the very short period of time over which all the modes are equivalent and the rest of the time they are not there. So, if you have for instance you can do it for simple 8 modes and you can do simulations.

And here it is doing an example case where the phases are 0 at time equal to 0, but at other time whenever they are in phase have a fixed phase between all of them then they come together and for a very short period of time and that is the ultra short pulses for me and if they are always random and there is no time possible where they will all get amplified simultaneously to give rise to their short period.

So, ultrafast lasers often thousands of modes.

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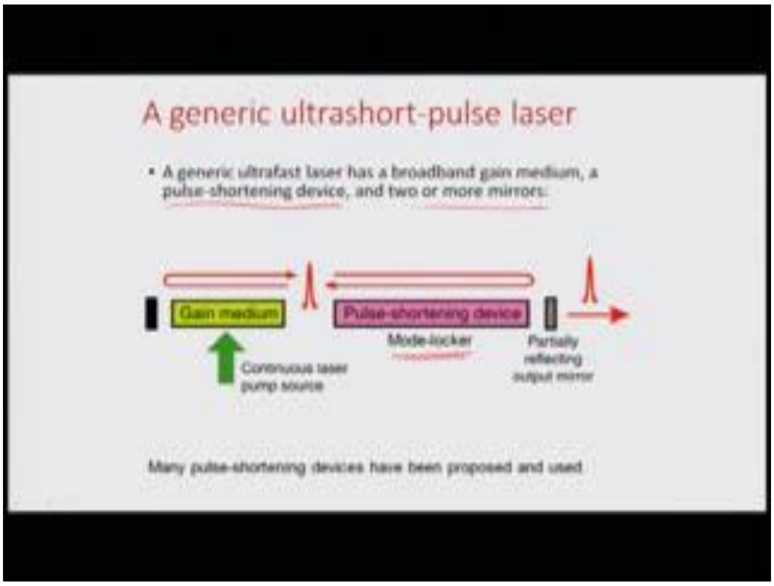


So, a Generic ultra short pulse laser as a broad band gains media; a pulse shortening device and two or more mirrors that is typically the case. This pulse shortening device is known as a mode-locker. So, there are many pulses shortening device which has been proposed and over the years.

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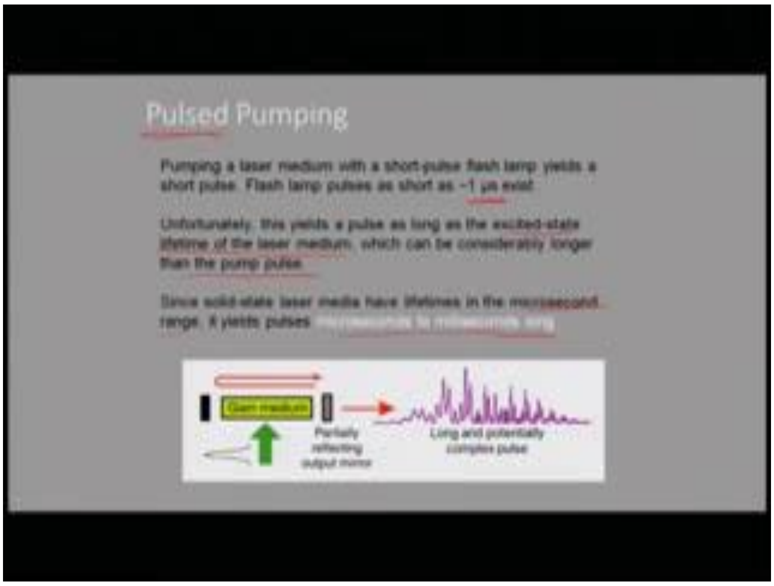


So, one quick option is to actually use pulse pumping; instead of using a pulse shortening device if you already have a pulse pumping device then pumping a laser medium with a short flash lamp yields a short pulse; flash lamp pulse is a short as 1 microsecond can exists. Unfortunately this yields a pulse as long as the excited state lifetime of the lasing media which can be considerably longer than the pump pulse. So, that is one of the issues here since the solid state laser media have lifetimes in the microsecond range it yields pulse of microseconds to milliseconds long.

So, this is typically how it looks like; these are long and potentially complex pulses that come out from partially from a laser which is being pumped with a pulse laser. So, this is based on the pulse pumping idea. There is no mode-locking device inside the laser in this case. This is another approach which is known as Q-switching. Q is a typically known as the quality factor.

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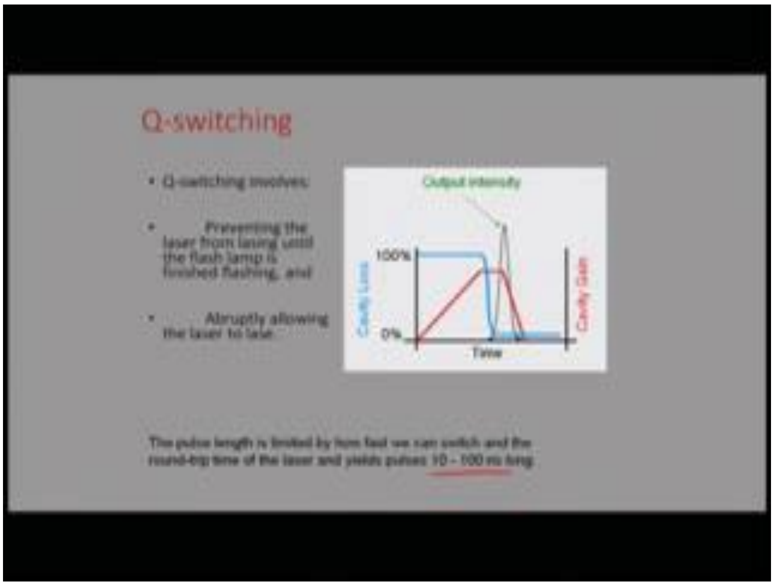


So, this is what it is done in case of lasers like this. This is a Q-switching involves preventing the laser from lasing until the flash lamp is finished the flashing and abruptly allowing the laser to laze. The pulse length in this case is limited by how fast can we switch and the round trip time of the laser and yields pulses of 10 to 100 nanoseconds long.

So, this is basically based on the idea that you are building up cavity within the building up the gain within the cavity and then at a certain point of time we just let the system switch so that the output can go up; output can go and then you get the pulse.

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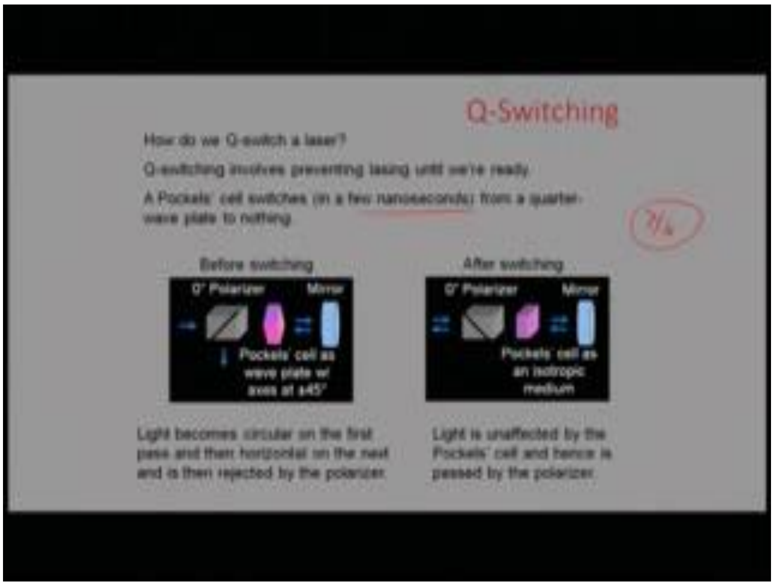


So, it is a switching system. So, how do we Q-switch a laser for example, Q-switching involves preventing a lasing; until we are ready; a typical Q-switching system is a pockel cell which switches in a nanoseconds from a quarter wave plate to nothing. So, pockel cell is a basically a wave plate which is set at 45 degree. So, wave plate this is a roughly a quarter wave plate which is placed and light becomes circular in it is first pass and then in horizontal on the next and is rejected by the polarizer in this particular case.

So, basically whenever we have this lambda over 4 it goes through first time it becomes circular, it comes through here and then it is a having opposite polarization of the incident one and so it reject and it comes out, so the wave plate is respect to that. After switching light is unaffected by the pockel cell and hence it is passed by the polarizer. So, the pockel cell is something which makes the material undergo a lambda by 4 shifts when it wants to switch it, otherwise it remains, it does not do anything to light coming through. And that is how it is access like a switch.

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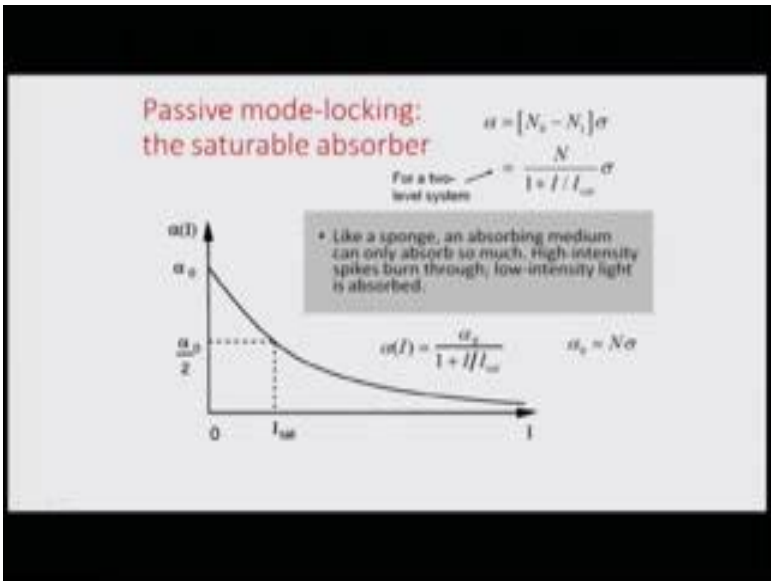


So, that is the basic idea behind Q-switching. Now there are different waves of looking at mode-locking. So, until now we have not looked at mode-locking yet we have been looking at the gain modulation process as have to do this. Now passive mode-locking there can be two different kinds one is the passive mode-locking and the other one is the active mode-locking. So, in case of passive mode-locking the idea is to use something called Saturable Absorber which means that an absorber which can keep on observing until it gets saturated when it does not absorb any more. So, like a sponge an absorbing medium can only absorb so much high intensity spikes burn through low intensity light is absorbed.

So, it is an intensity getting in that sense beyond the certain intensity just lets it go. So, that is passive mode-locking principle for example.

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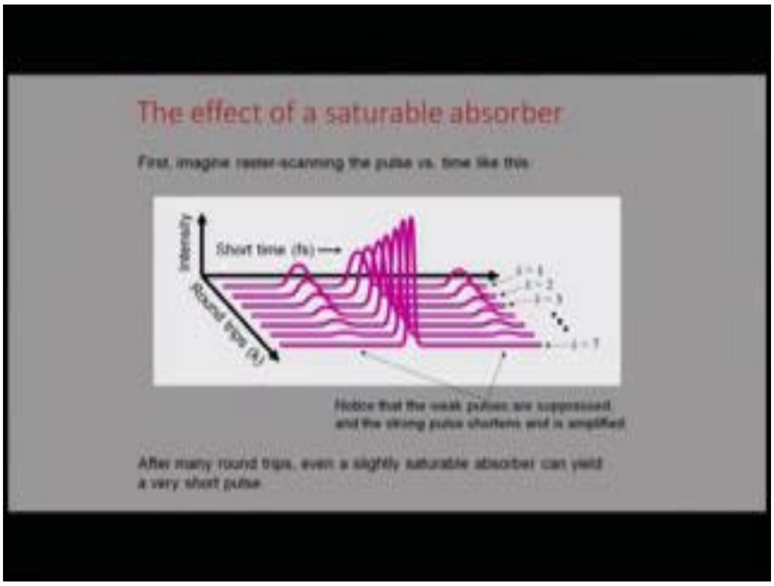


So, here is the effect away saturable absorber. First imagine Raster Scanning of the pulse by time for instance. So, with the passive mode-locking we can almost act it like a gate. So, for example, here is the case which is shown of a saturable absorber. So, let us consider the that we are looking at the pulse at every point of time, what we see the that the weak pulses are suppressed and the strong pulse shortens and gets amplified after many round trips even a slightly saturable absorber can yield very short pulse.

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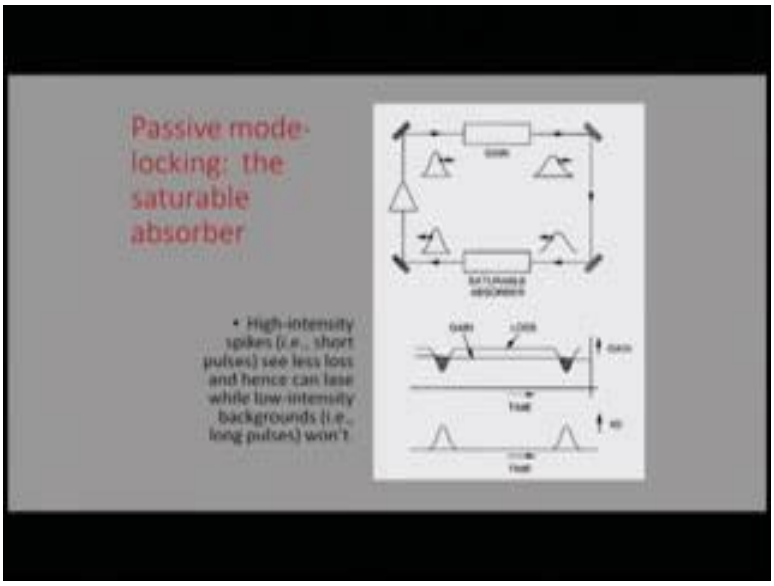

So, that is one way of looking at how you can generate a short pulse like this; again looking at passive mode-locking whenever we have high intensity spikes because of this principle of letting the system go through this idea of intensity which can be only high intensity which can go through and there is a spikes where the laser can output and so the gain goes through a dip and again goes up; goes to a point where it reaches the maxima and then again it goes to through the saturable point where it can get out of the system and it keeps on going.

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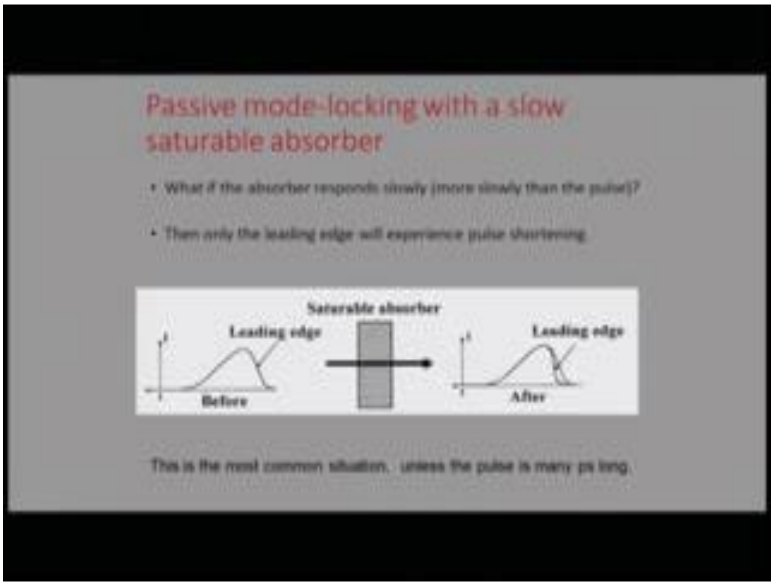


So, this is basically the principle of creating a short pulse; this was actually one of the first ones which you are used for producing very short pulses. It can have different effects when you have a slow saturable absorber versus a fast saturable absorber. If the absorber responds slowly more slowly than the pulse only the leading edge will experience pulse shortening.

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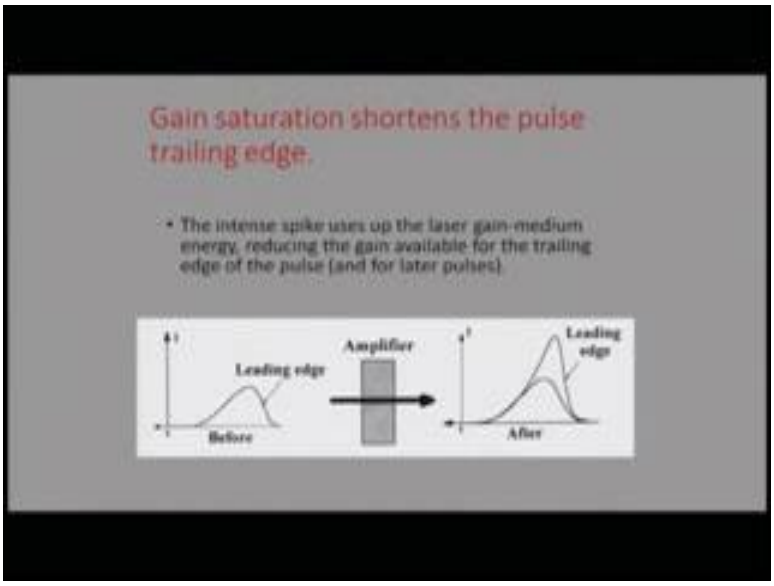


This is which the most common scenario is unless the pulse is many picoseconds long. The gain saturation essentially shortens the pulse trailing edge and so the leading edge becomes faster and reducing gain is available for trailing edge of the pulse and for the later pulses.

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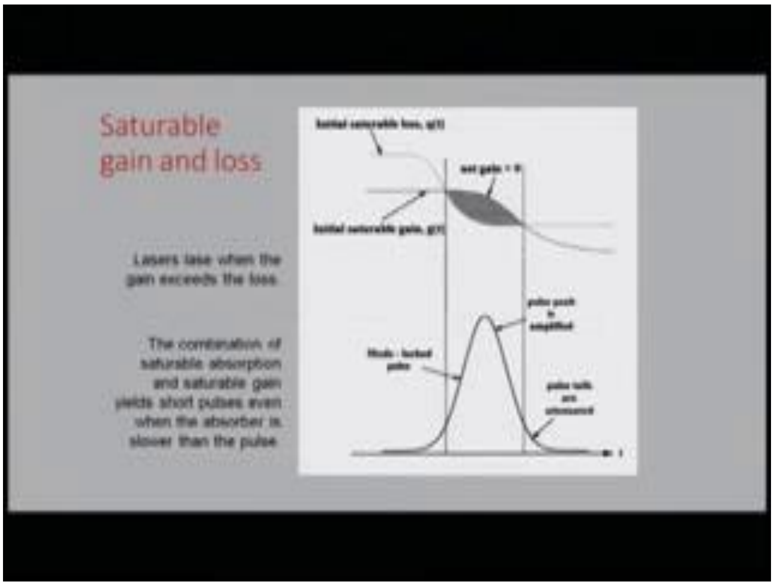


So, there is this particular over all curve that you can look at when you have this initial loss versus gain and you can see that basically the peak pulse is getting amplified more and more where the mode-locking is going to be achieved and tails are getting attenuated.

So, the combination of saturable absorption and saturable gain yields short pulses in the when the absorption is slower than the pulse. This is one of the ideas.

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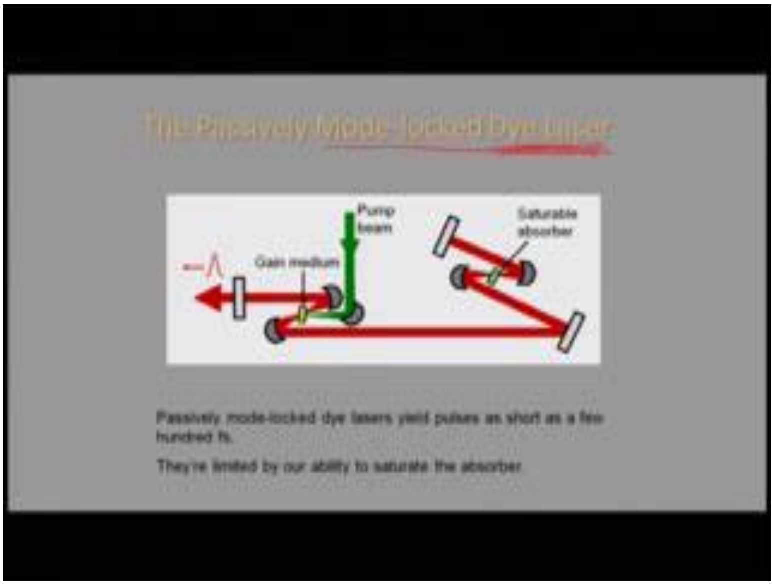


So, this was first applied for Dye Lasers where the gain media; it is a dye laser was and the advantage of using it for a dye laser was because that the dye laser had the capability of a very broad spectral condition. So, this is one of the things which we mention about dye lasers they had a very wide absorptions and that is the advantage of using this passively mode-locked dye lasers yield pulses as short of few 100 femtoseconds they are limited by ability to saturate the absorbers. So, if it can have a fast (Refer Time: 22:08) absorber then all the combination of the processes that we mentioned was possible to do this kind of results.

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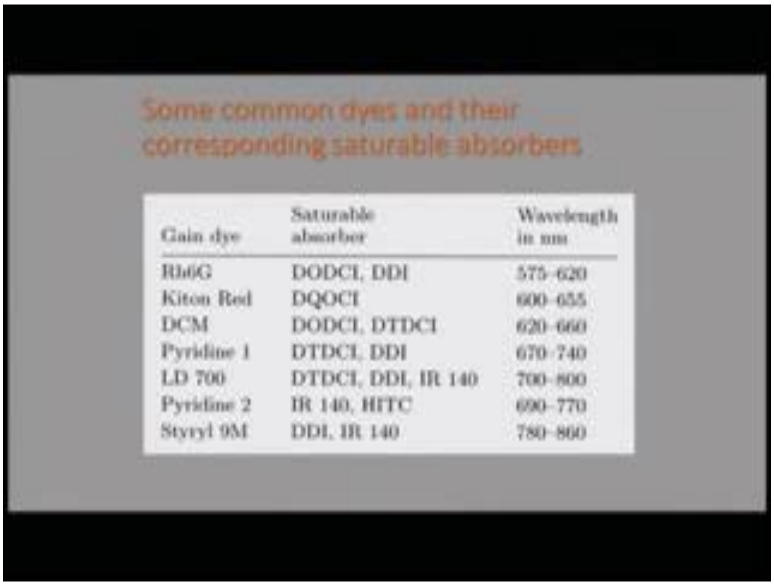


So, here some of the dye laser which were used for producing the initial short pulse lasers. In fact, the Nobel prize which went to Zewail, who is no more for demonstrating the first very short time dynamics was incidentally using these kinds of lasers; dye lasers which were able to go down to very short pulses.

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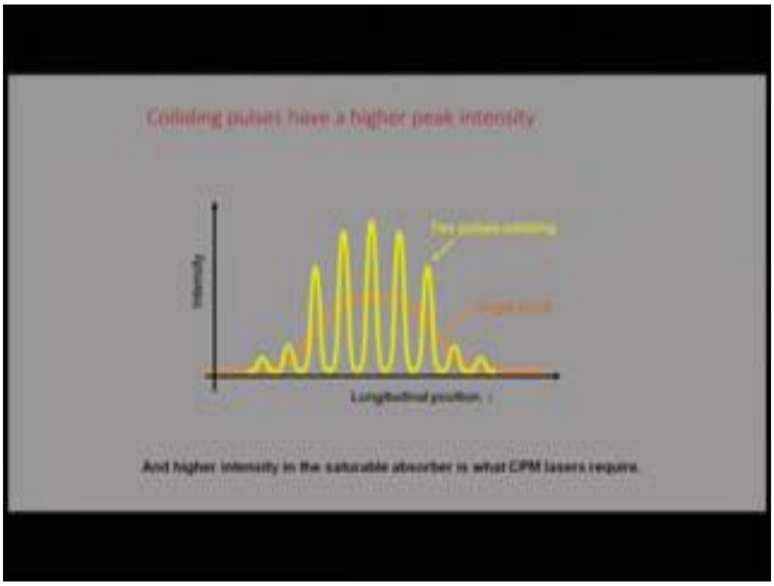


And this is essentially the first of it is which are used which was a Ring dye laser where the pulse were made to collide and higher intensity of the saturable absorber is what was being used. So, it is called a Colliding Pulse mode-locked laser where two pulses colliding resulted in even shorter pulse and that was one of the principles which were used to get better shorter pulses.

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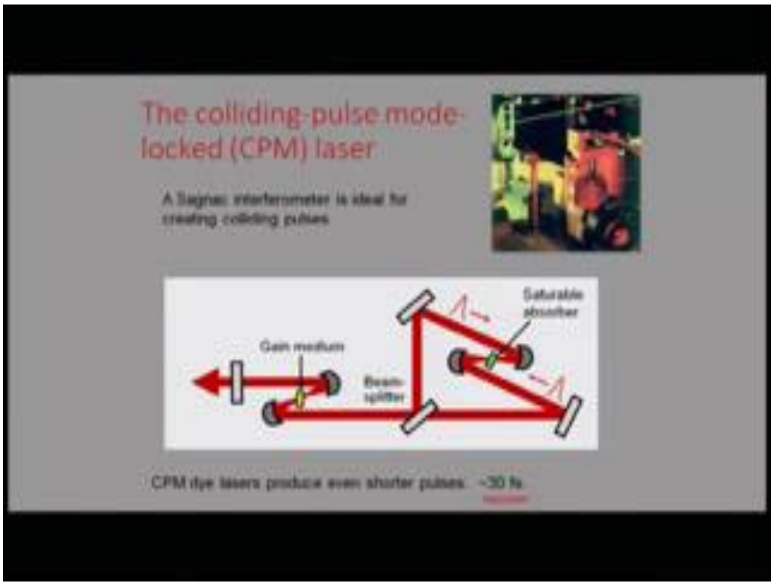


So, this is the one which was originally used to produce very short pulses sub 50 femtoseconds for the first time which were then shorten further to produce the real fast dynamics measurements which were finally, led to many other important developments.

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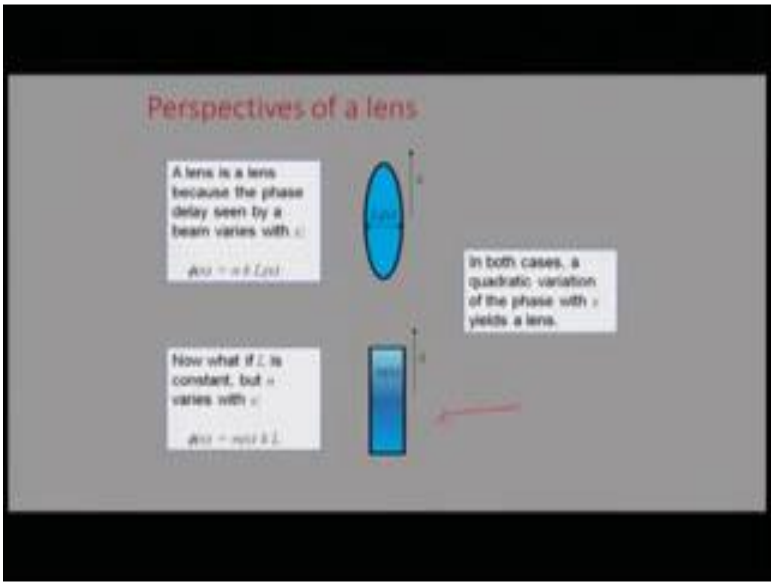


So, the other principle which is really helped in terms of generating short pulses is the idea of the fact that many materials actually behave like lenses. So, lens can be something which has which is due to the phase delay can be seen the beam varies with the distance that we know and that is how we get the lens effect of that. However, they can be medium which can undergo the length is constant, but it is a refractive index varies with the distance and that can also act like a lens both cases quadratic variation of phase with distance yields a lens.

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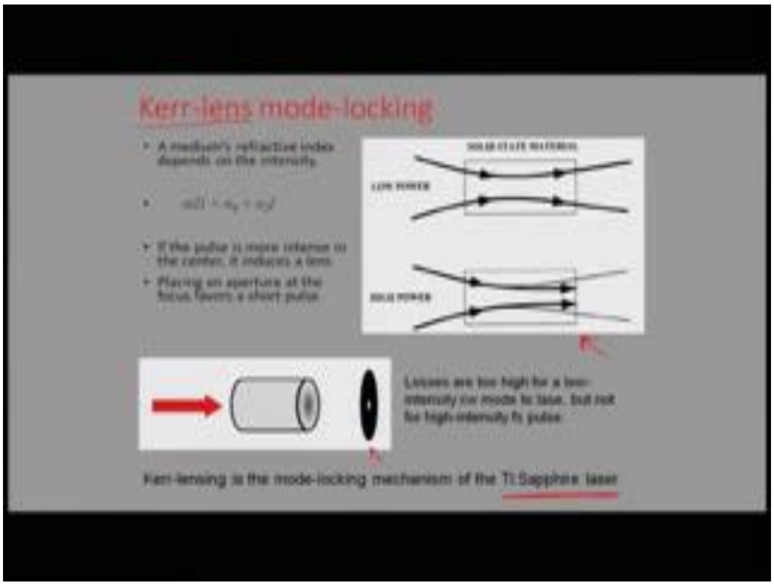


And. So, this is the second principle of this has been seen of late to be giving rise to a lot of mode-locking principle and that is the Kerr-lens principle which is used in solid state lasers; today which gives rise to this phenomena of producing short pulses and this is the mechanism which is used in the most popular laser of today which is Titanium Sapphire laser. Titanium being the active material in this sapphire crystal where its non linear process of refractive index which at high powers give rise to additional focusing effect which limits the available zone over which the system can keep on going back and forth.

So, it is sort of works like a very short aperture and losses are too high for low intensity c w mode to laze, but not for high intensity femtosecond lasers. So, these acts like a very sharp aperture like which only the peak of the intensity can go through producing a very short pulse.

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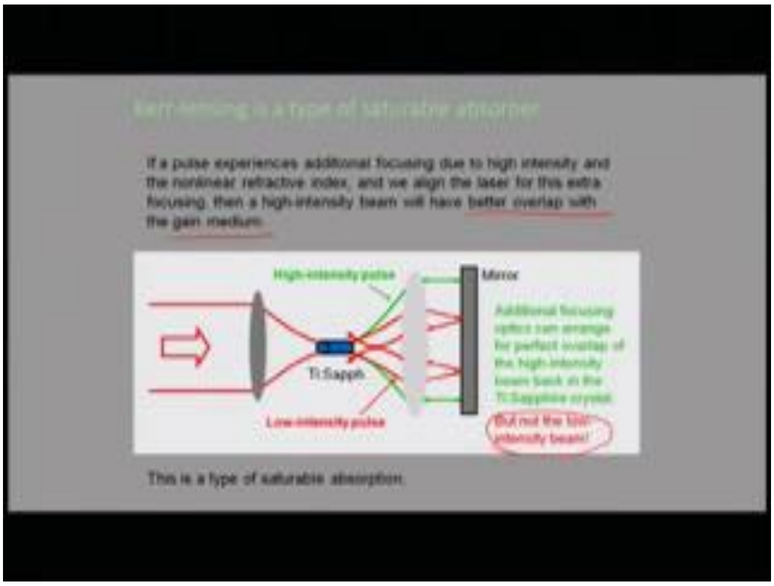


So, it is a type of saturable absorption in some sense we have pulse at experience additional focusing due to high intensity and the non linear reflective index; then we align the laser for this extra focusing; then a high intensity beam would have a better overlap with the gain medium and this is a type of saturable absorption which is used for the case of Titanium Sapphire laser and this additional focusing optics can arrange for perfect overlap of high intensity beam back into the Ti Sapphire crystal and that is what has been used for this particular purpose. The low intensity beam unfortunately does not have the advantage and so it gets lost. So, only the high intensity beams survive and finally, produce the short pulses.

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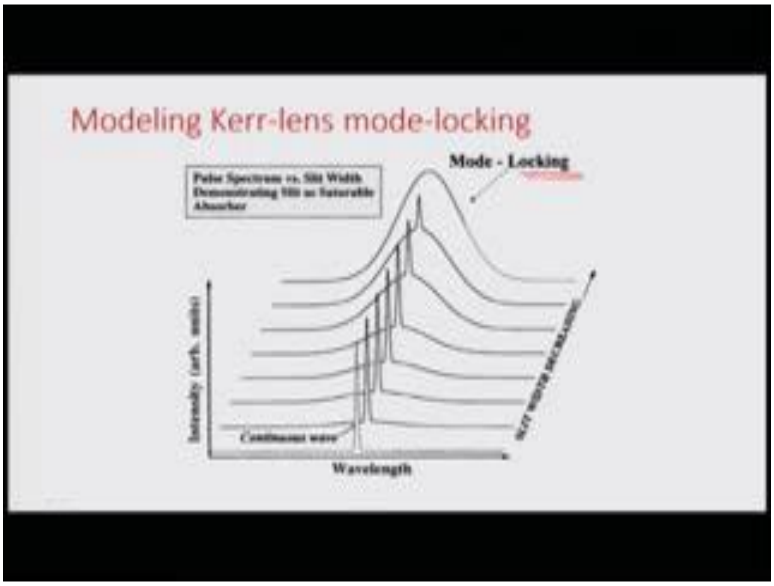

So, here is an example how this mode-locking works for a saturable absorption being generating through Kerr-lens. So, this is the model of the idea as to how it happens and mode-locked laser is seen which as a wide band width and a short pulse.

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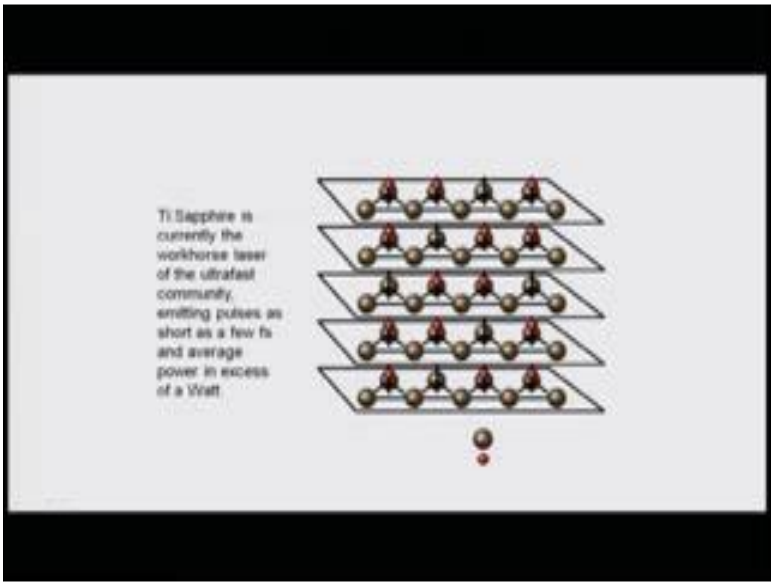


So, it is a currently as I mentioned Ti Sapphire is the currently the work house laser for most of the ultra fast community emitting pulses as short as a few femtoseconds and average power in excess of a watt and more.

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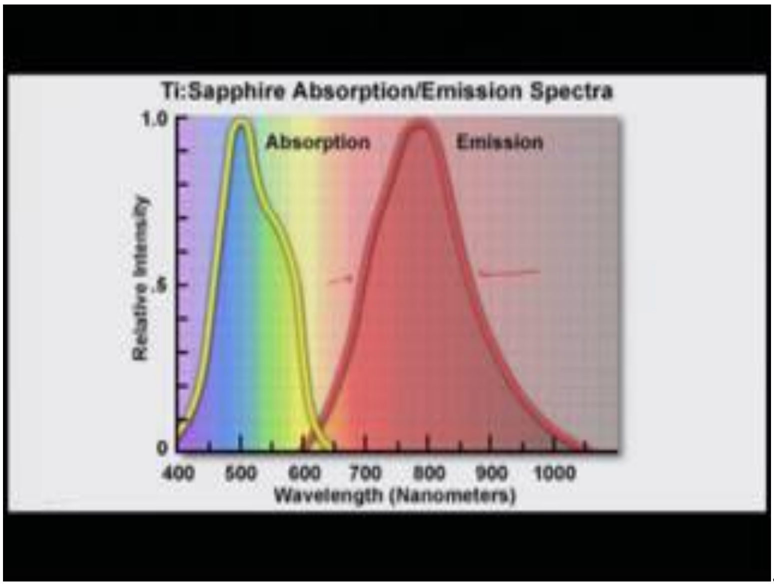

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It has this wide band width which is necessary for this kind of a short pulse of operation to happen.

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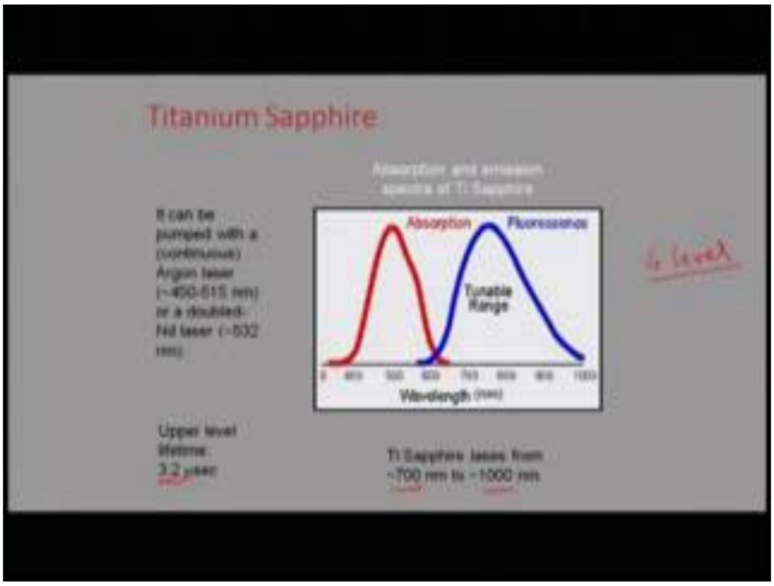


So, this is near infrared region which is what is been used. It ranges; lazes from 700 to about a micron. It has a very nice life time also of the (Refer Time: 27:20) state which let us say two remain inverted for a quite a while it is 4 level amplifier system as I mentioned before.

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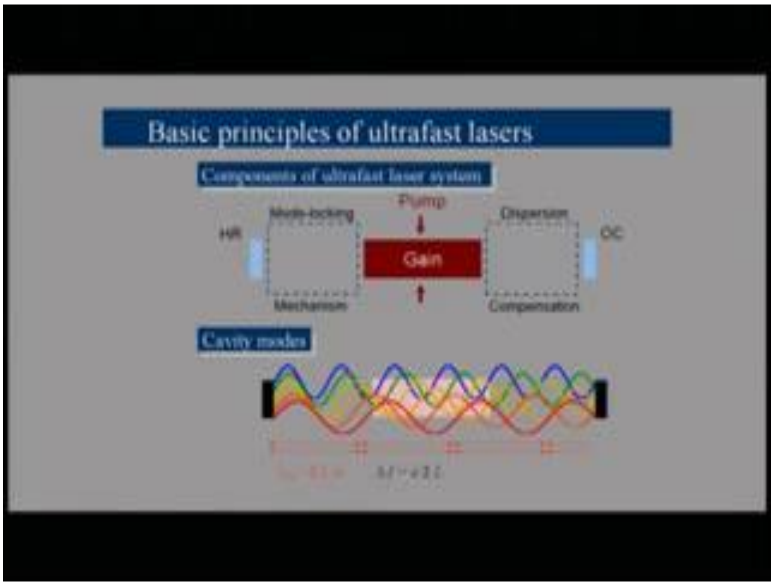

So, what we have learnt here is that; here is the principles that; we have learnt here. We have the components of the laser system is like this what we are trying to do in this process is we are going to lock the cavity modes in such a ways that only for a brief period of time they overlap to get the maximum gain which is mode-locking mechanism.

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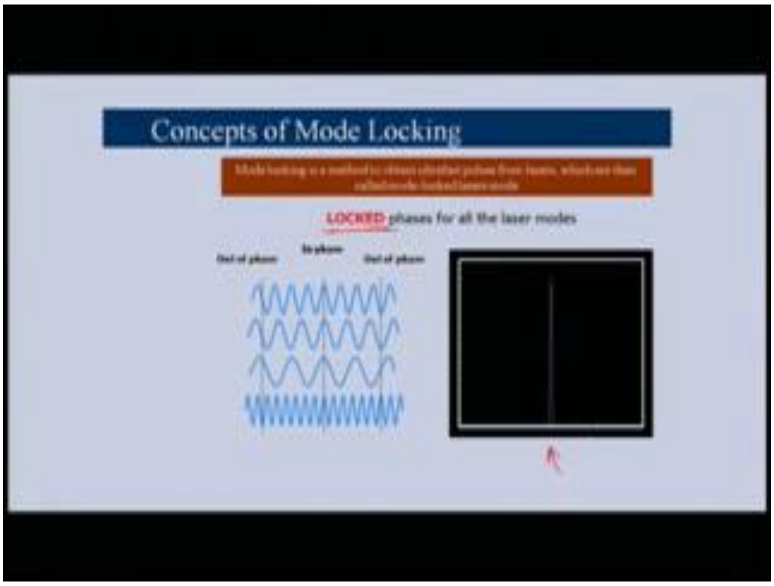


And this is additional help with the help of dispersion compensation and then case of mode-locking we realize that only at a very short point of time in phased locked phases for all the pulses giving rise to short pulse.

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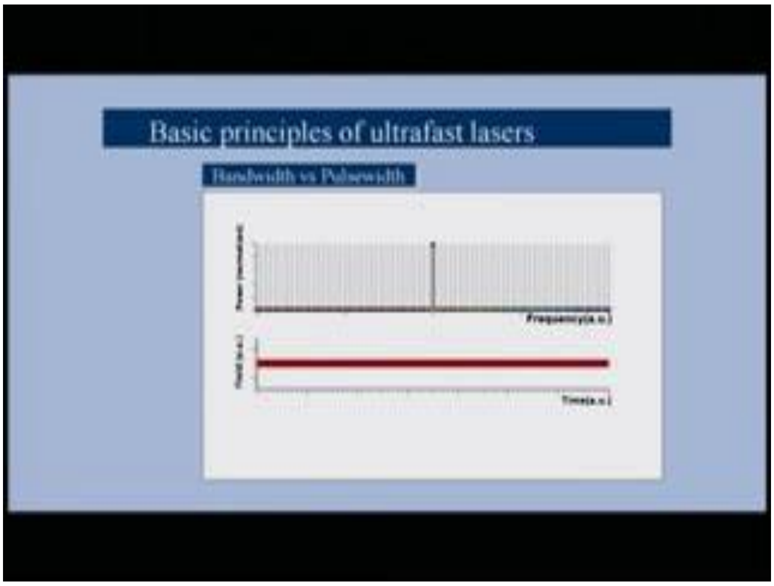

Otherwise they are random, and therefore they go away. The bandwidth results in this point over which the pulses will be wide.

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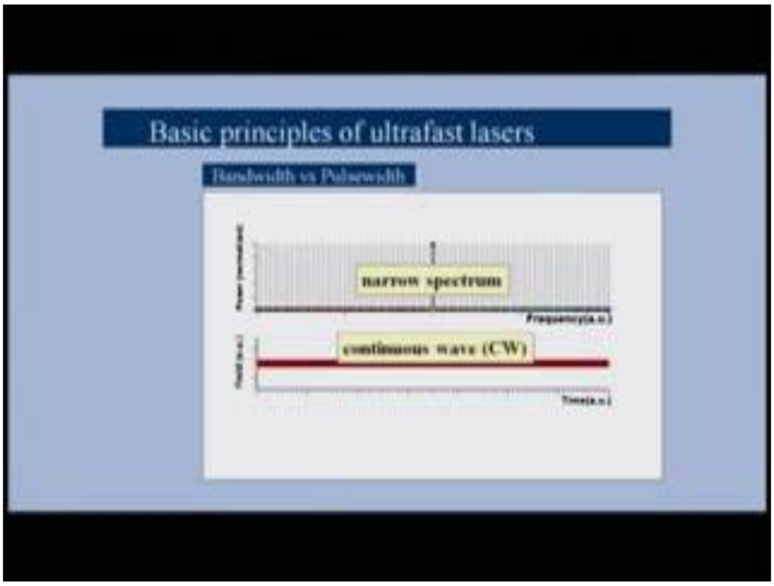


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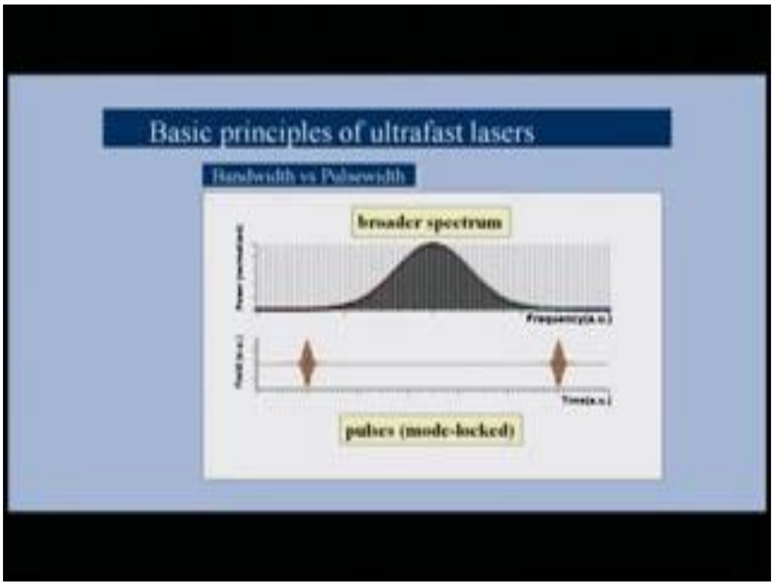


And as with the narrow spectrum it will start getting broader the pulse will get more locked and you will get a broader and broader spectrum.

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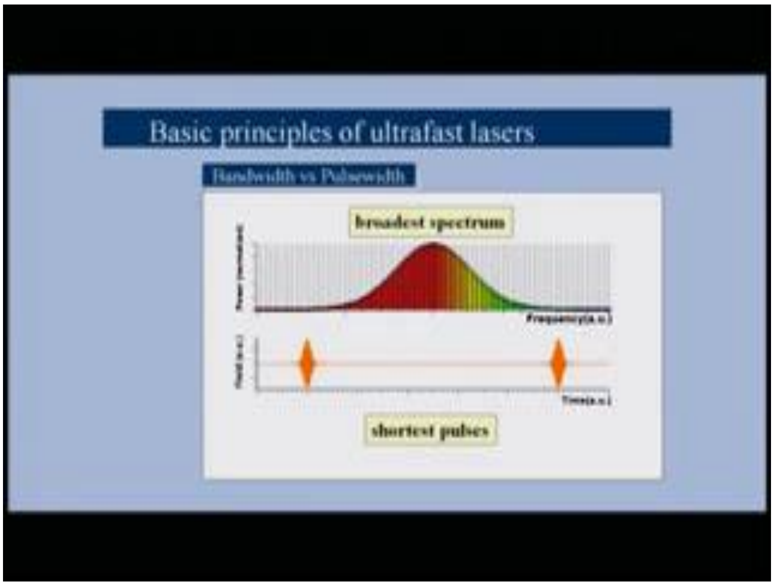


And finally when all the pulses are the shortest possible you get the maximally broadened spectrum. This is the broadest spectrum for the shortest possible pulse. That is the basic idea behind this principle of ultra short pulses; that what we have learnt.

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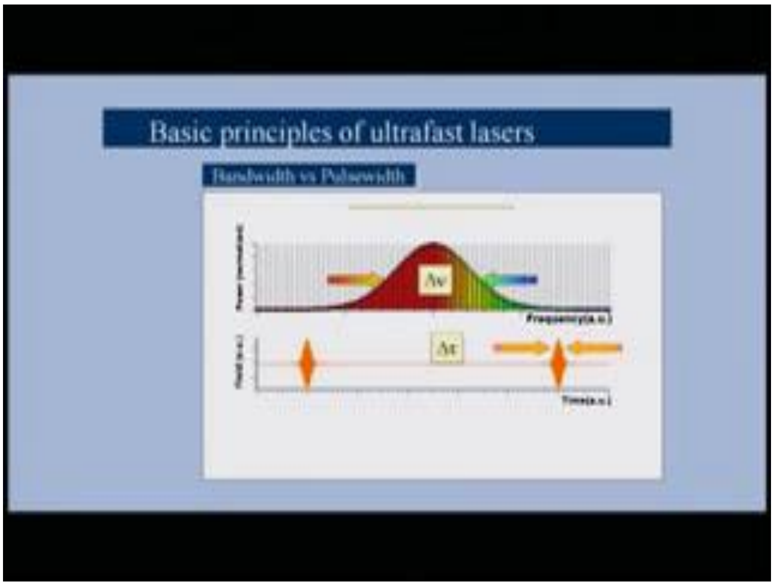


This is the bandwidth to a looking at it. And this is the time width you are looking

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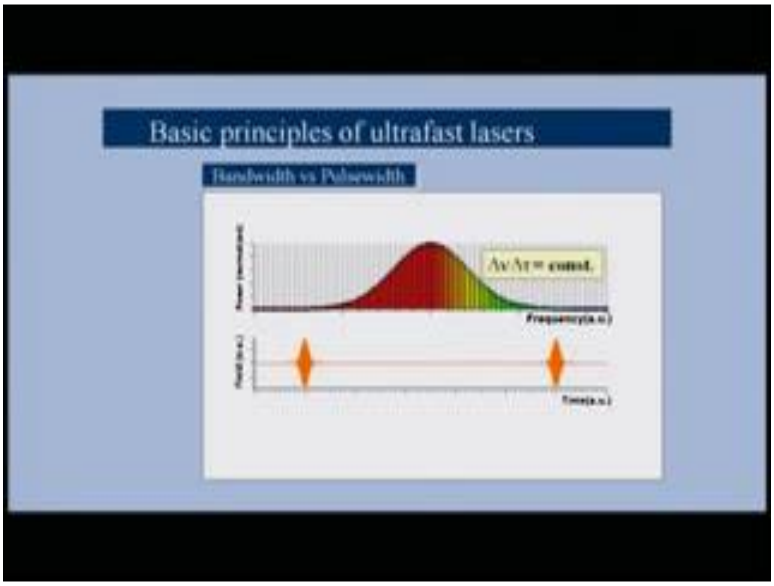


And what we have found is delta nu delta t is constant. So, respective of what we do when w have a short pulse we have a long band of the pulses.

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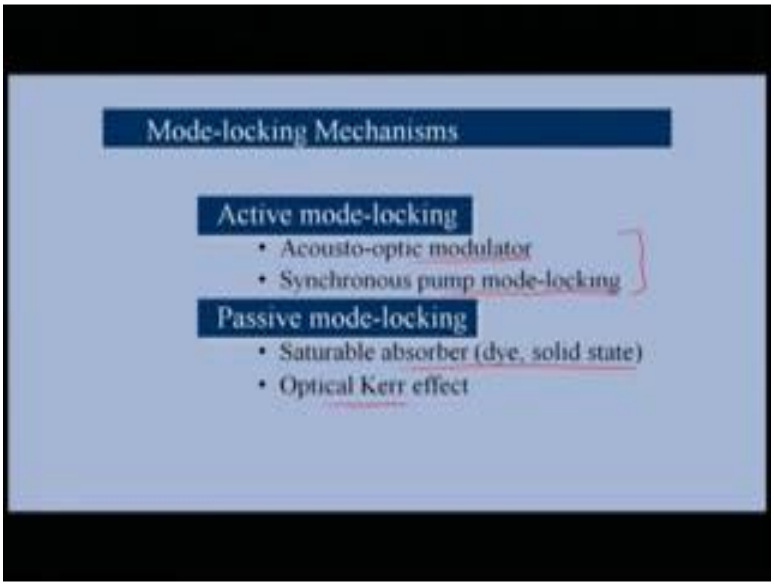


We have looked into the different mode-lock mechanism; active versus passive. The active ones actively modulate the gain in the medium or it could be something like a pump which already changing, pulsed; that is a synchronous pump mode-locking, the other one is use to acousto-optic modulator which is a loss modulation which kind does that, the other one which is these are active. The other cases the passive mode-locking which is a saturable absorber like dye, Solid State and the Optical Kerr- effect that we have mentioned.

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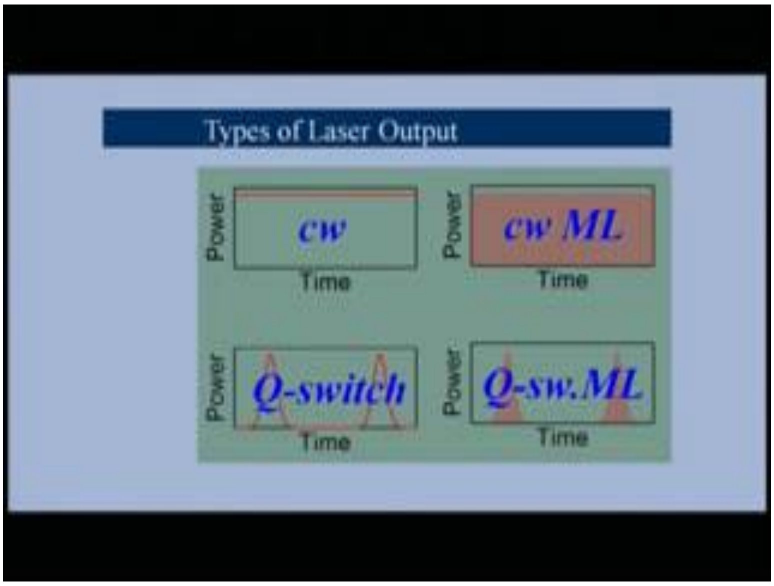


So, the outputs are of these different kinds which we mentioned; c w versus c w mode-lock, Q-switched Q-switched mode-lock; all four possibility exit.

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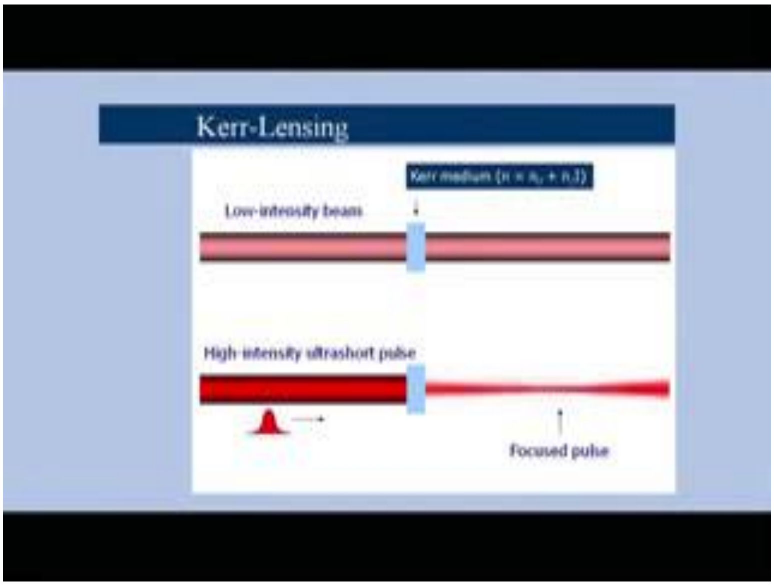


The Kerr-Lensing one we discuss in detail because that is the one which is been used in detail now days. The Kerr medium is our Sapphire crystal that we used in Titanium Sapphire for instance and the high intensity ultra short pulses are the ones which are which survived in this process the focus pulse is going through high intensity profile only the ultra short pulses survive the rest do not.

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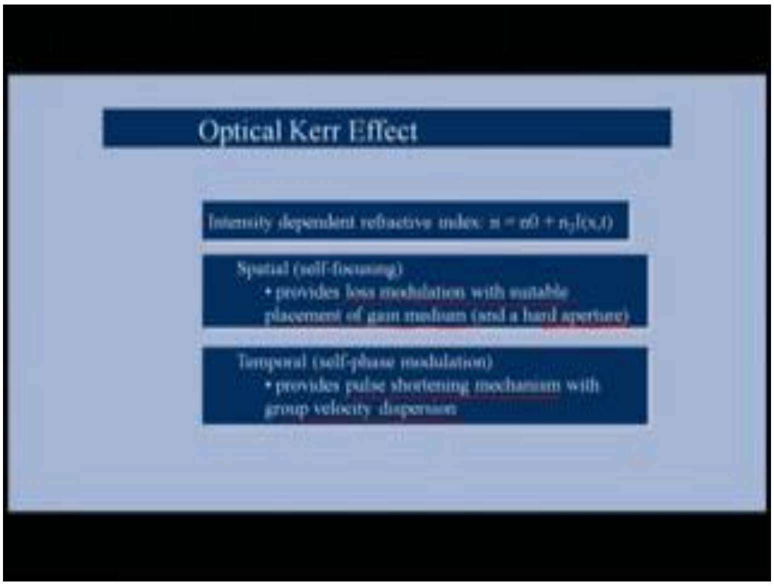


The intensity dependent refractive index one which helps in this process it creates specially self focusing condition as well as the temporally self focusing condition which is due to pulse shortening along due to group velocity dispersion and this is the loss modulation with saturable placement of Kerr medium and a hard aperture which is coming due to the intensity dependent refractive index.

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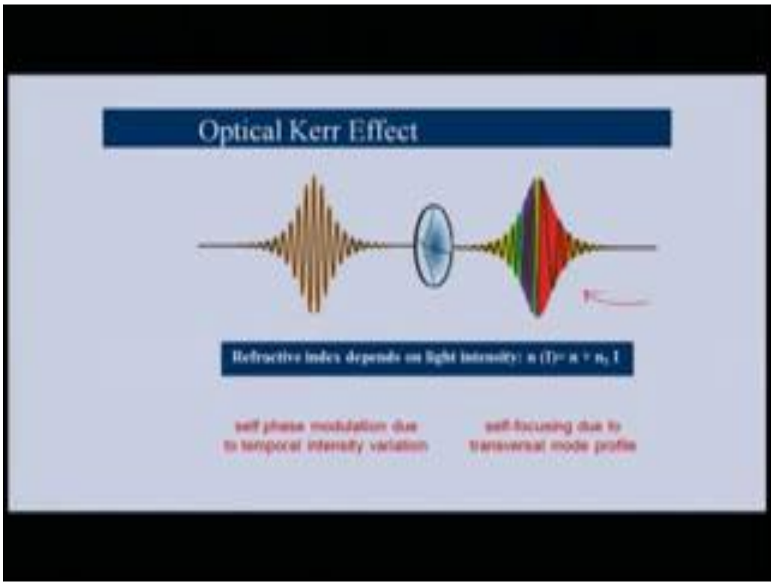

So, here is the cartoon which shows the refractive index depends on the intensity of light; self phase modulation due to temporal intensity; due to transversal mode profile and as it goes through it produces this short pulses which are then stretches which is short of stretch.

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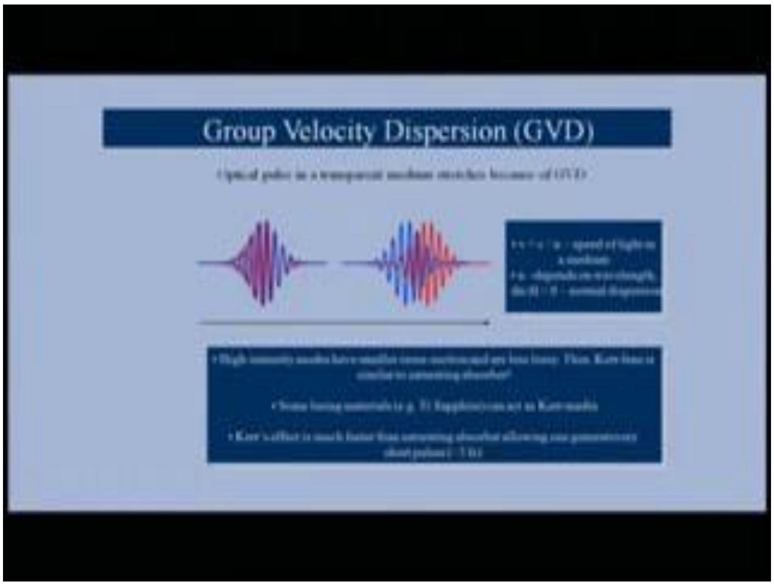


Because the group velocity dispersion which is provided due to this process and one can have it shortened by using other process compensating for the group velocity dispersion because it is a linear process.

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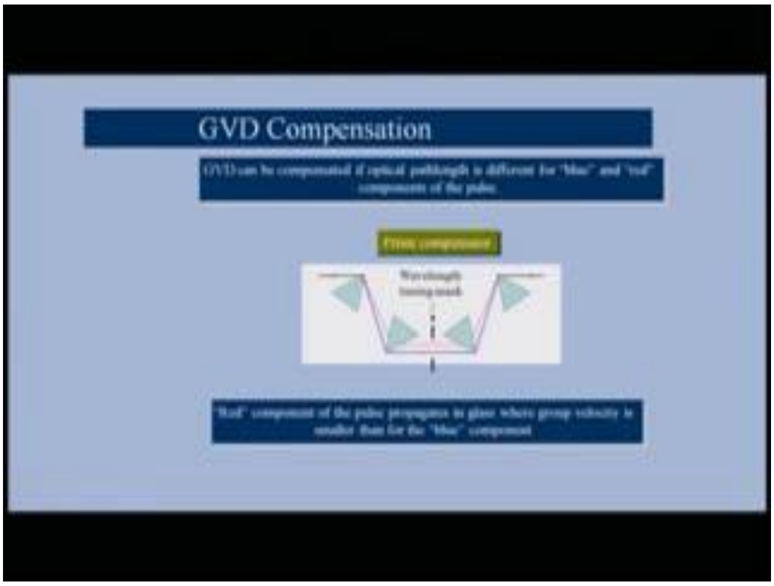

And we can get as short as 6 femtoseconds, 5 femtoseconds in this kind of process. So, the compensator can be simple as a Prism Compensator; can basically go through the wave length tuning mask this is the bandwidth part where we essentially making sure it can be compensated. So, it goes through the prism systems where the amount of linear frequency chirps are compensated by this process.

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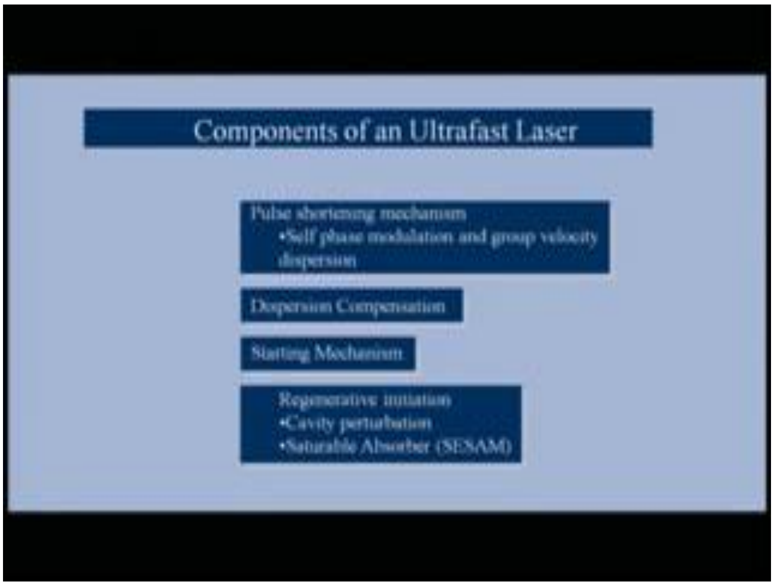


So, these are the components of the ultrafast system; shortening mechanism, dispersion compensation.

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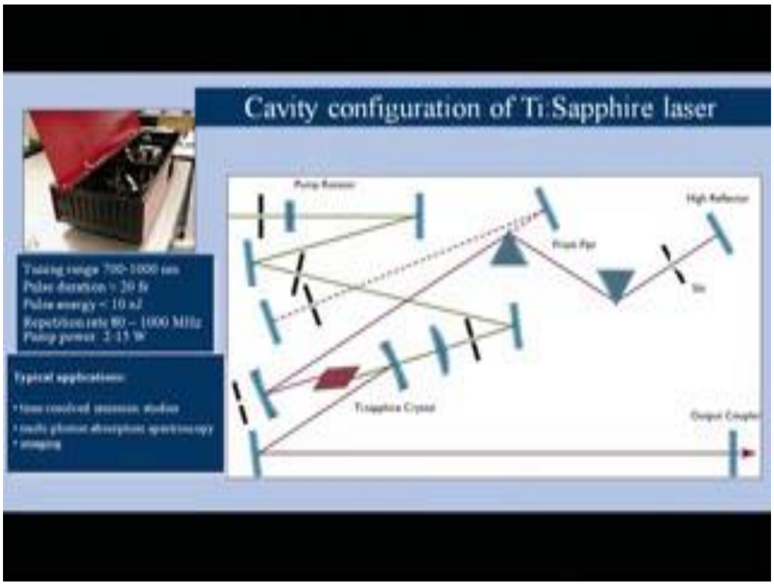

And the starting one was the process that we mentioned; it can also have many other processes like saturable absorber and cavity perturbation and all that. In a Ti Sapphire laser which is one which is most important today is it has a typical cavity as shown here which is inside and oscillator which is then compensated with the help of prism pair the dispersion and it is applied for many different cases.

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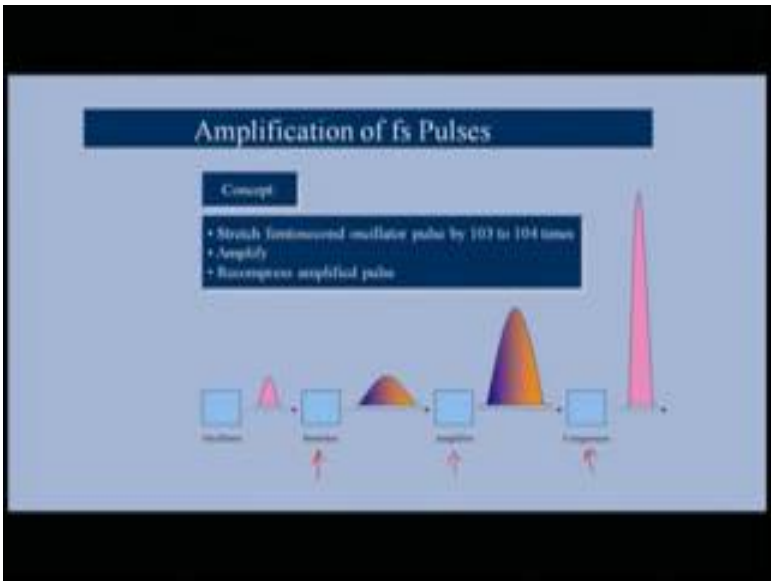


And the output coupler comes through the laser. It can be further amplified by using the (Refer Time: 32:48) of linear gain where it is done is the oscillator is put through a linear stretching device which makes a longer a pulse, it is then put through an amplifier where it is again amplified in this process and then a compressor which again compresses the system of the amplified pulse to get even higher intense pulses.

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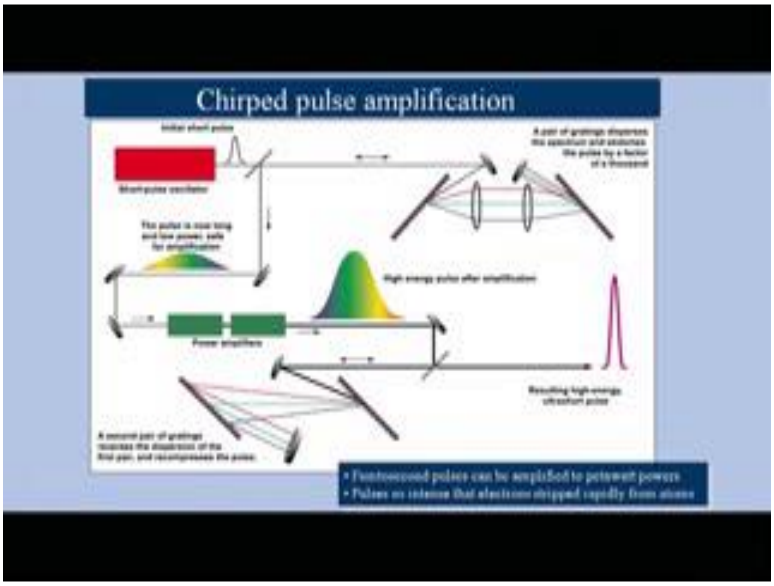


So, here is the typical Chirped Pulse Amplification principle that we have of today. Oscillator which produces the short pulse, initial short pulse which goes through chirping process to stretch it and then the low power safe for amplification goes though amplifiers and then high energy pulses have done to amplifier then second grating pair reverses the dispersion of the first pair. So, this is the first part which lengthens pulse then the second pair is eventually compresses it and it results finally, in a high intensity ultra short pulses.

So, femtosecond pulse can be amplified to petawatt powers. These are so intense that electrons can be rapidly stripped from atoms.

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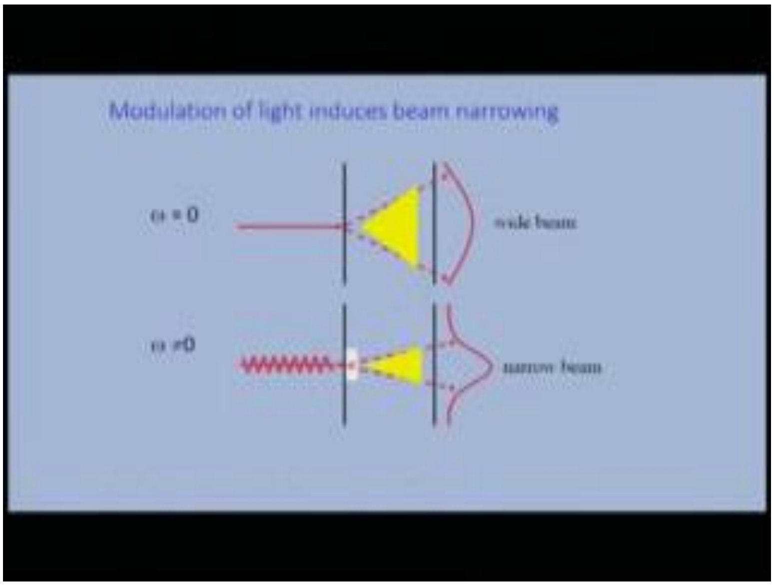


So, we have used principles where we have also use the idea that the modulation of light induces the beam narrowing.

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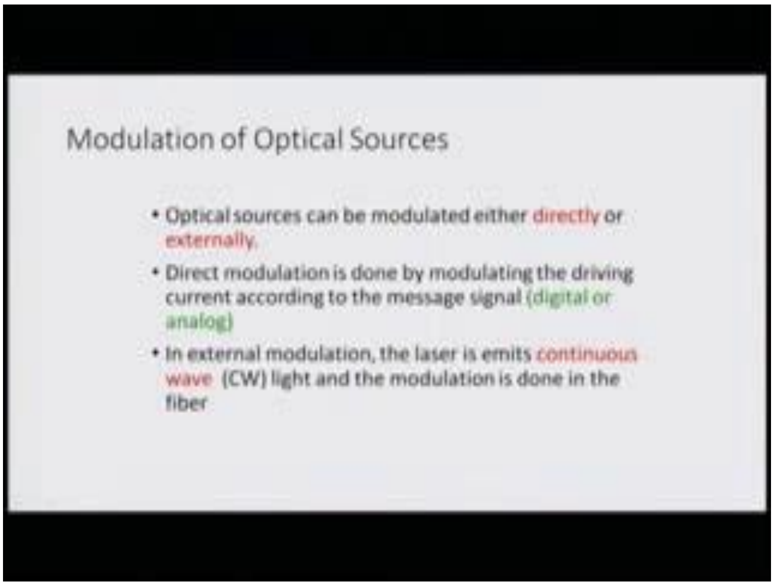


And all these principles were used for mode-locking as just we mentioned. We mention modulation directly or externally by using different principles and typical external modulation was to use the c w laser light and modulation which are also done in fibers and other kinds of optical sources.

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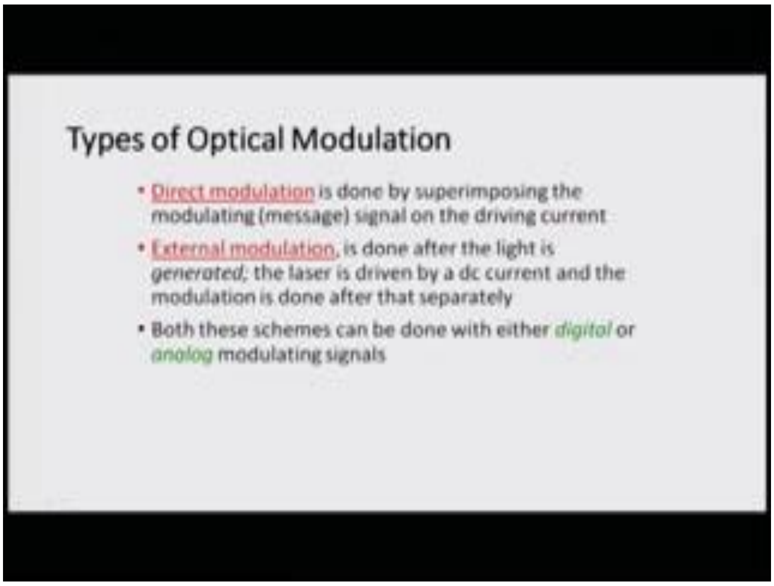


The femtosecond lasers thus amplified can be taken out to petwatt powers which can be so intense that can strip electrons rapidly from atoms. With this I am going to end this lecture because whatever we wanted to do in terms of lasers; in their being a continuous source for the kinds of operation that we are interested or as source we can actually use them for timed measurements or inducing non linear process have all been looked into this lecture.

With this we end this entire look into then lasers and their required ideas behind it and the next lecture on we will be using them for further applications into quantum computing.

Thank you.