Ultrafast Optics and Spectroscopy

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Lecture - 22
Construction of Ultrafast Laser (Continued..)

We are continuing module 6. In this module we are discussing Construction of Ultrafast Laser. In the previous slides we have already understood different elements which are used in the laser oscillator, ultrafast laser oscillator.

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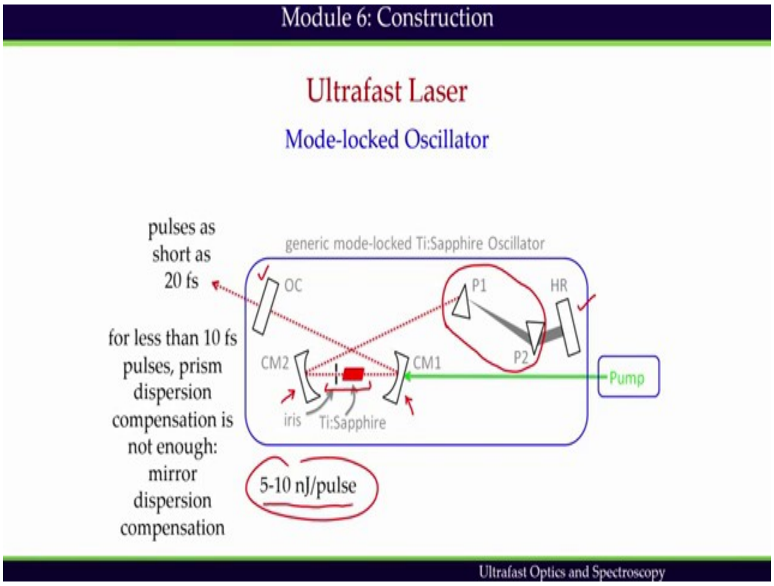

We have dispersion compensate dispersion compensator given by two prisms, high reflector. We have self phase self mode locking done by this aperture and the gain medium and the laser cavity with the help of these two mirrors and the output coupler. So, this kind of laser oscillator this kind of ultrafast oscillator can produce energy in the range 5 to 10 nano Joule per pulse.

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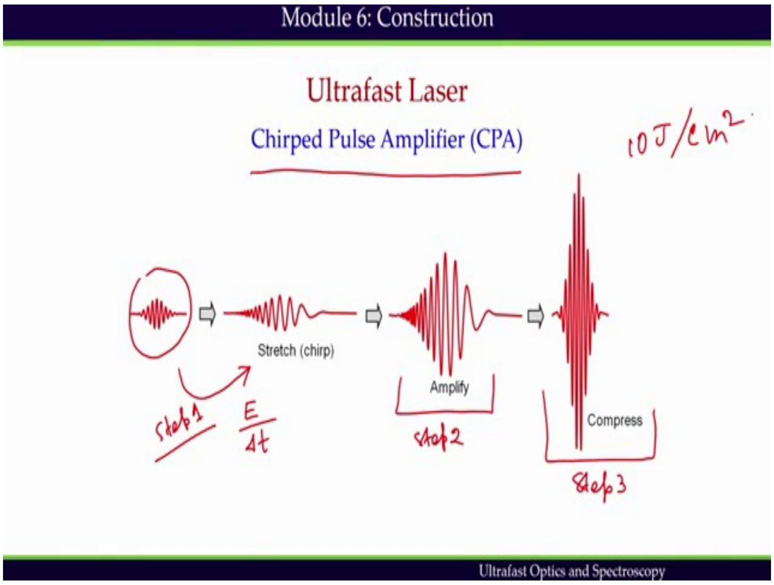

Now, question is if we need more energy what to do? Definitely we have to amplify the pulse. Due to this high peak intensity ultrafast pulses cause local heating at the bulk or surface of the gain medium resulting in thermal fracture, decomposition, melting of the gain medium. The surface damage threshold; however, varies based on thermal diffusion, how quickly the local heat is dissipated over the bulk of the optical element.

Non-linear self focusing on the other hand causes bulk damage when high intensity ultrafast pulse propagates through the optical elements. Therefore, amplification of output beam of the ultrafast laser oscillator is not a straight forward task. How can the deleterious effects of high peak power be avoided during amplification stage? Nearly all high power ultrafast laser systems make use of the technique called Chirped Pulse Amplification: CPA.

What does it mean? It has 3 steps; step 1 the pulse which is coming from the oscillator which is less intense pulse first needs to be stretched. So, that the peak power can be reduced and peak power is defined by defined by energy per pulse E divided by delta t; delta t is the duration of the pulse and we remind duration of the pulse is defined as a full width half max of the intensity profile. So, what we have done?

We have to do step 1 we have to stretch the pulse so, that the peak intensity can be dropped. Then you amplify the pulse and then re-compress the pulse, this is step 2 and this is step 3. So, this is called this scheme is called chirped pulse amplification, CPA scheme can increase the energy of a short pulse while avoiding very high peak powers in the laser amplification process.

This is done by lengthening the duration of the pulse being amplified, by lengthening the pulse in time energy can efficiently be extracted from the laser gain medium, while avoiding damage to the optical amplifier. CPA is particularly important for efficient utilization of solid state laser gain medium with high stored energy density. This scheme can provide energy per pulse as large as 10 Joule per square centimeter.

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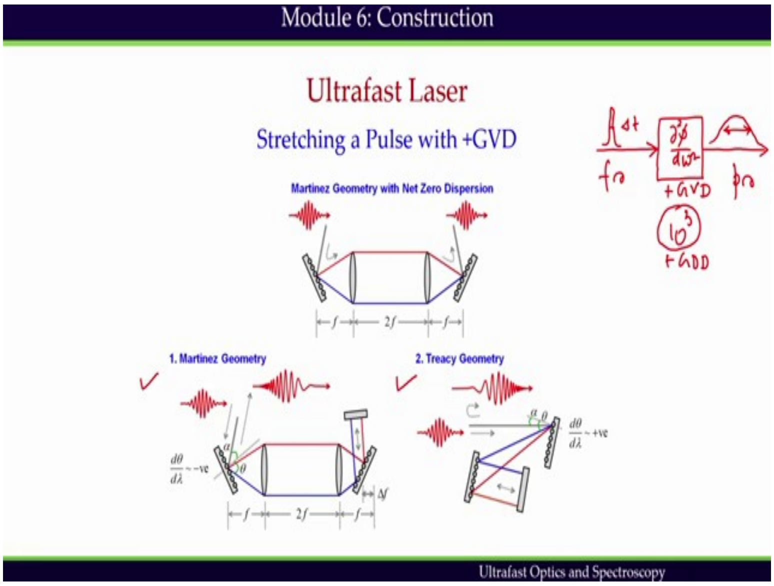

But before injection into the amplifier short pulse needs to be stretched in time by introducing a frequency chirped into the pulse which increases the duration of the pulse by a factor of 10 to the power 3 to 10 to the power 4. The duration of the stretch pulse is determined by the damage threshold of the optics and non-linear distortion of the spatial and temporal profiles of the beam.

As discussed in earlier module a chirped pulse can be obtained simply by propagating a short pulse through optical material such as glass. So, we have already seen that material dispersion and particularly second order spectral phase can actually introduced chirp or broaden the pulse. So, if I have a short pulse it can be broaden like this material dispersion and it is positive GVD which is responsible for this kind of dispersion for this kind of pulse broadening.

However, to increase the duration of the pulse by a factor of 10 to the power 3 to 10 to the power 4 which means if I have femtosecond pulse, I have to get picosecond pulse. So, the broadening has to be 10 to the power 3 times, the dispersion brought about by pulse propagation through simple optical material is not sufficient, because we have seen that only GDD of a material is very small.

So, we need certain kind of optical elements which will introduce a big amount of positive GDD of the order of 10 to the power 3, a factor of 10 to the power 3. In this case a grating pairs is very suitable, a grating pairs provides necessary high dispersion that is required to stretch a pulse by a factor of 10 to the power 3 to 10 to the power of 4. We shall come back to this. So, here we have shown two different arrangements Martinez geometry and Treacy's geometry. These two geometries, if you look at these two geometries we are using grating pairs to introduce the chirp or broadening the pulse.

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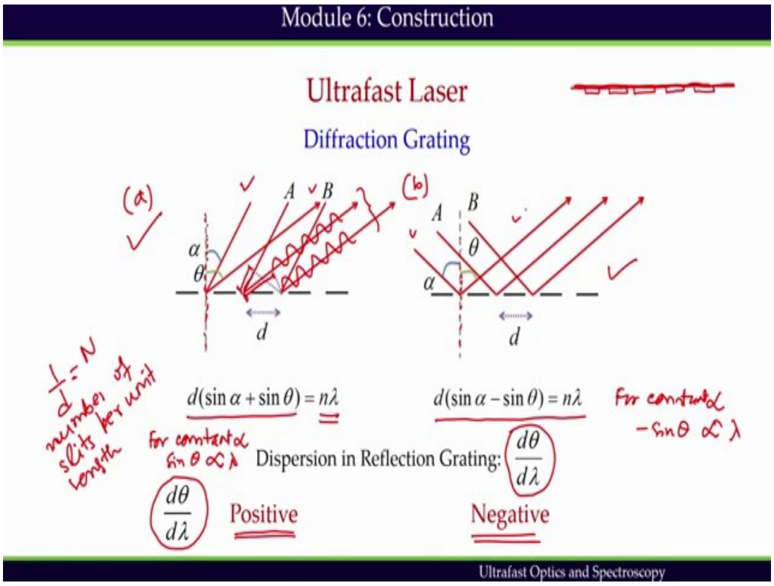

But we will discuss this shortly, before we do that we have to go over the grating equation; need to understand the property of a grating. A diffraction grating is an optical element that possesses an arrangement of a large number of parallel equidistant and closely space slits of same width which are placed side by side. If I have a flat surface we prepare slits like this, we make grooves and the surface becomes grating surface.

Slit sizes are comparable to the wavelength of the light. Diffraction gratings are manufactured by ruling or drawing lines on a well polished thin uniform sheet of glass or reflecting metal surface. The number of grooves which are drawn may vary from 15,000 to 30,000 per inch or even more. The grooves scatter light and acts like opaque substance while undisturbed polish parts behave like slits.

Similar to prism a diffraction grating disperses light composed of different wavelengths into light components by wavelength. Diffraction gratings are usually of two types: transmission grating and reflection grating. As reflection grating find numerous applications in ultrafast laser system, we shall briefly discuss dispersion of reflecting grating. As depicted here there are two different configurations we have shown.

They differ by how the incident beam and the diffracted beam are with respect to the surface normal. So, the first figure; figure number a, we see that with respect to the surface normal this dotted line A the input beam and diffracted beam, they are on the same side. On the other hand in this figure b, input beam and diffracted beam are on the opposite sides with respect to the surface normal of the grating.

Alpha is incident angle and theta is diffraction angle. Now, if you look at A and B this two rays, then we see that in order to have constructive interference after diffraction the beam which is this a beam diffracted A beam and diffracted B beam. In order to have this constructive interference between these two beams, the extra path length traveled by A; that is this distance plus this distance this two.

This extra distance is travelled by A and in order to have this constructive interference after the diffraction, we need to have this extra distance to be n lambda, then only we get this constructive interference. And d sin alpha plus d sin theta is representing this extra distance, distance from here to here and here to here. Similarly, if you look at this geometry we get another equation.

These equations are characteristic equations of grating, here d is spacing between slits and 1 by d is representing N which is the number of slits per unit length and N is order of diffraction, lambda is the wavelength. So, if we considered a constant alpha, if this constant alpha so, for constant alpha for constant alpha we can say that sin theta is proportional to lambda, sin theta is proportional to lambda. So, in this configuration, configuration a we see that theta and alpha are on the same side of the grating normal. And, in that case d theta d lambda this derivative is going to be always positive.

But, on the other hand here for this configuration where configuration b, where alpha and theta are on the opposite side of the grating normal for that for constant alpha, for constant alpha we have minus sin theta which is proportional to lambda. So, this d theta d lambda is going to be negative. So, to remind or to remember whether this d theta d lambda would be positive or negative, we have to just remember that whether the beam incident beam and the diffracted beam are on the same side of the normal, surface normal or they are in the opposite side of the surface normal.

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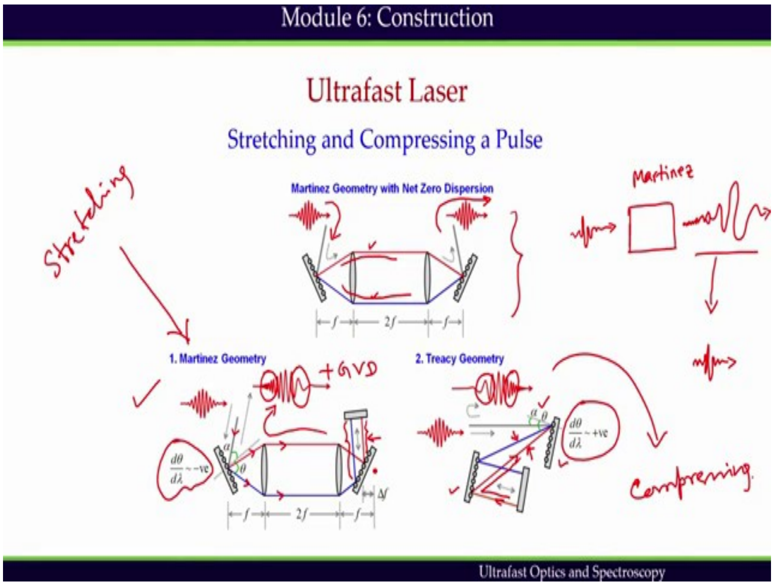

So, this is the feature of a grating and given this information, if we again take a look at the stretcher or compressor in which we use grating, we will be able to understand its action as well. In Martinez geometry, Martinez demonstrated that by placing a telescope between a grating pair the overall dispersion or lengthening of the pulse can be controlled by the effective distance between second grating and the image of the first grating.

Here in the first configuration, we have two lens of focal length f and this two lens are placed 2 f apart to form a telescope. Now, if an object is placed at f, in front of the first lens and images formed at the distance f, behind second lens and that is exactly where two gratings are placed.

So, two gratings are placed at this focal lengths and if you place them the net dispersion remains 0. So, even the pulse a short pulse is entering the this optical arrangement, when they are coming out of it we do not introduce any dispersion. The same pulse will come out because, the this red light and blue light representing lower frequency and higher frequency regime of a pulse.

So, what will happen these lower frequency components and higher frequency components will have the same optical path length, they are traveling the same distance and that is why there is no effective chirp introduced in the pulse. Now, if we push the second grating towards the lens to a distance f minus delta f in this configuration. So, this was the previous focus point where the grating was previously, now we have pushed this grating towards the lens.

And if you do that what happens? Blue ray which means high frequency components travels longer path, here we look at this incident beam and diffracted beams are on the opposite side and that is why d theta d lambda is going to be negative. If it is negative which means higher frequency will bend more will have; so, higher frequency will bend more and lower frequency will bend less. And that is why we get red colour propagating along this direction and blue colour propagating along this direction.

But, if we look at the relative path distance or the path difference we see that the blue light is travelling extra distance as compared to red light. So, and this is introducing positive GVD because, rate component will come out of this cavity first. So, the earlier phase or the earlier time is represented by the low frequency components of the pulse. And later time of the pulse is represented by the high frequency component of the pulse and this is nothing, but positive GVD.

We have introduced positivity GVD that is why we have introduced chirp and we have stretched the pulse. Now, if you look at Treacy's geometry what happens? When a pulse entering a pair of identical parallelly dispersed grating; so, we have two gratings facing each other, but there are parallelly displaced.

Two gratings are parallelly displaced and here alpha and theta are on the same side of the surface normal that is why d theta lambda is going to be positive which means red light now will bend more and blue light will be bend less. And in that case red light is now travelling longer distance, when they are coming out of this arrangement and blue light is travelling shorter distance.

And that is why in the early time of the pulse we get blue components and later time of the pulse is contributed by the interference of the low frequency components. And this is the way we can introduce again a chirp in the pulse. But, now imagine if we consider Martinez geometry and we have a pulse, short pulse going through Martinez configuration that is caused stretcher, then we introduce this chirp.

And then if you send this pulse to the Treacy's geometry we get the reverse of this effect which means we recompress the pulse again. This is why the basis for a perfectly matched stretcher or compressor prior is to introduce right sign and factor for GVD. Stretching and recompression with grating pairs either using Martinez configuration or Treacy's geometry does allow large and reversible stretch factors or compression factors. So, we can use this as stretcher and this configuration as compression.

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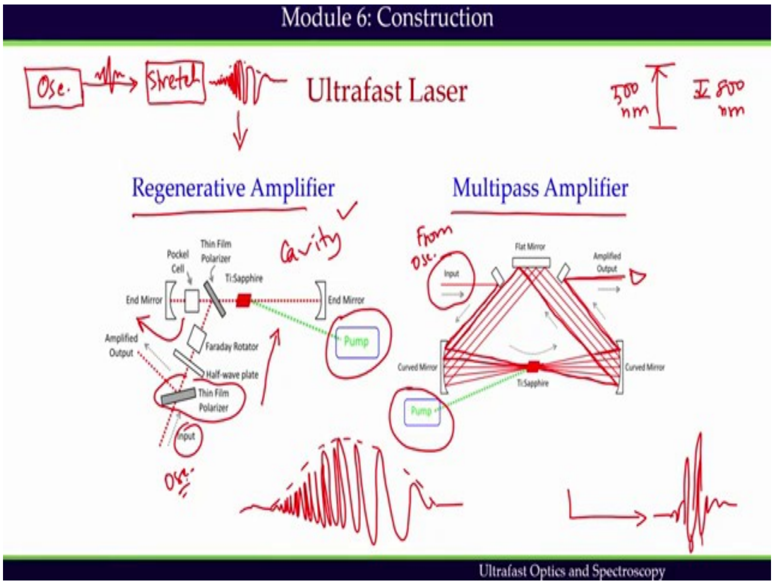

Amplification of chirp pulse is done by titanium doped sapphire, a material having very desirable characteristics, very high damage threshold, high saturation fluence, high thermal conductivity. Therefore, pulses with an energy greater than 1 Joule can be extracted from a relatively small diameter rod, let say 1 centimeter.

Therefore, pulses with an energy greater than 1 Joule can be extracted from a relatively small diameter rod Ti-sapphire rod 1 centimeter 1 by 1 centimeter it could be. It has also brought absorption maximum near 500 nano meter. Absorption maximum which means that if I use of pump laser to create the population inversion, again we can remind that this is a four level system.

So, I need a pump with higher frequency and it will give stimulated emission at lower frequency and that is why it gives stimulated emission at 800 nano meter and pump is used for 500 nano meter. Since, the sapphire host is by refringent this crystal must be cut; so, that both the pump laser and amplifier pulse polarization are along the crystal optic axis.

There are two different types of amplifiers we have, but before amplification we have to remember that we have to we have an oscillator. This oscillator produces low energy pulses, very short low energy pulses and then we have to stretch the pulse. We need a stretcher and once we have stretch the pulse, stretch pulse is always a chirped pulse and then we have to send it to the amplifier.

After amplification we have to again recompress the pulse in the amplifier, we simply amplify a chirped pulse and then we recompress the pulse again. So, in the amplification stage we can use two different kind of amplifiers; regenerative amplifier and multipass amplifier. Regenerative amplifier, the difference between these two amplifiers is in regenerative amplifier we use a cavity, but in multiples amplifier we do not use a cavity.

The low energy chirped pulse is introduced to the cavity in this region amplifier using a time gated polarization device, which is called here such as focal cell and a thin film polarizer. The pulse then makes many round trips to the gain medium at which point the high energy pulse is switched out by a second time gated polarization gating. So, one time gating polarization is used to introduce the pulse, then second time gated polarization rotation is used to take the amplified pulse out from the cavity. On the other hand in the multi-pass amplifier beam passes through the gain medium multiple times without the use of cavity.

So, we have input beam coming this way it is making one trip through the crystal, then is reflected here, its getting reflected. So, the first round trip comes here, getting reflected here is going here then again is coming here and multiple times it undergoes and then it comes out of the cavity like this. In both amplifiers we have to use pump which is used for 500 nano meter excitation to create the population inversion and the seed beam is the input beam coming from the oscillator. So, this comes from an oscillator; so, this input beam comes from an oscillator.

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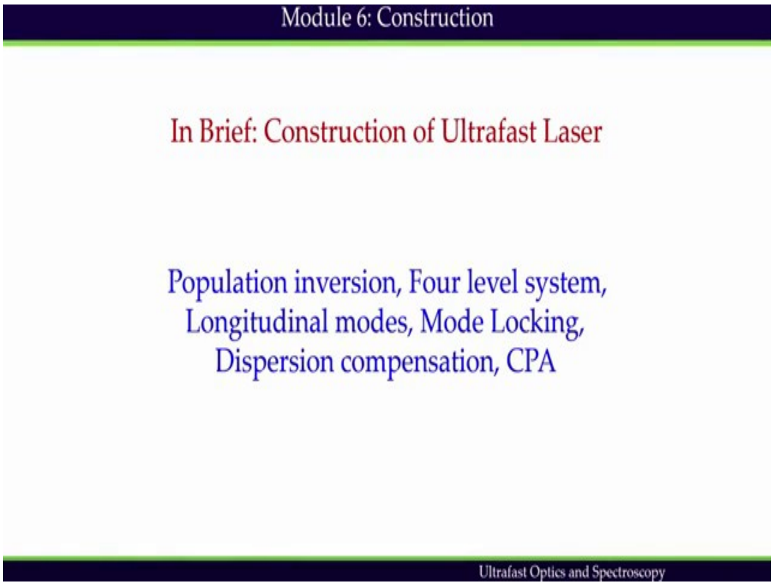

So, with this we have come to the end of this module. In this module we have studied construction of ultrafast laser, different properties of ultrafast pulse propagation have been discussed. And those properties have been used to think about how to build an ultrafast laser. We have discussed population inversion, we have discussed four level system, we have discussed longitudinal modes, mode locking, dispersion compensation and finally, we have discussed the scheme of chirped pulse amplification.

We will meet again for the next module.