Ultrafast Processes in Chemistry
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Lecture No. 31
Stretching and Compressing Ultrashort Laser Pulses

In the last module, we stopped with a very brief discussion of chirped pulse amplification. As you know, for many applications like pump probe, which is one of the more simple applications of lasers, we cannot work with the output of a titanium sapphire oscillator because the pulse energy of nanojoules is tact too low. So, we have to find a way of amplifying the pulse and the way it is done is called chirped pulse amplification. We are going to try to discuss chirp pulse amplification in the next 2 or 3 modules. This is the scheme of chirped pulse amplification.

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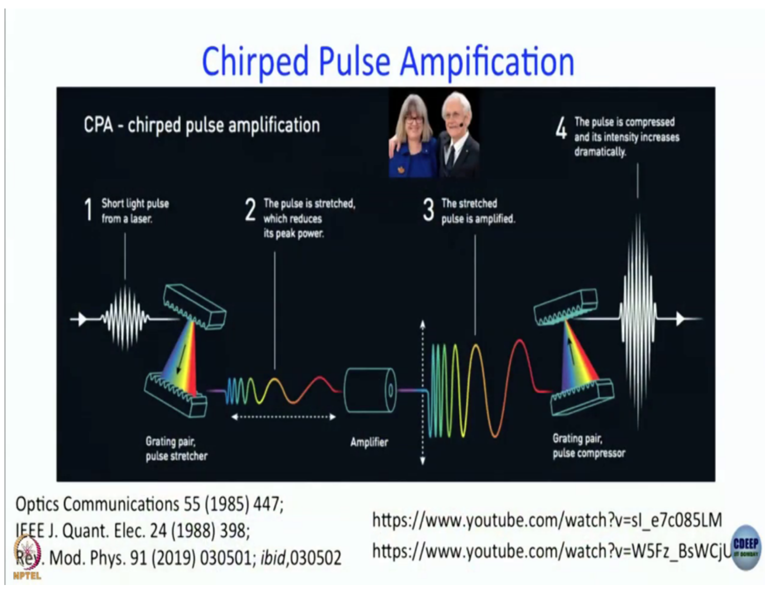

I think this was the last slide more or less of the last module anyway. So there we said that last year Nobel Prize in Physics was in 2 parts 1 for optical tweezers. The second one was for Gerard Mauro and Donna Strickland's work on chirped pulse amplification. So, I strongly recommend you to read these or see these videos or do both the YouTube videos that are listed here they are the noble lectures of Mauro and Strickland.

This optics communications paper is one of the original one of the very few original papers of these 2 Nobel laureates published together on this technique. And well these 2 actually optics communications and IEEE in Journal of quantum electronics these are 2 papers which reported for the first time their work in this field and these 2 papers on reviews of modern physics published earlier this year, they contain they are basically the paper form of the Nobel lecture they delivered last year.

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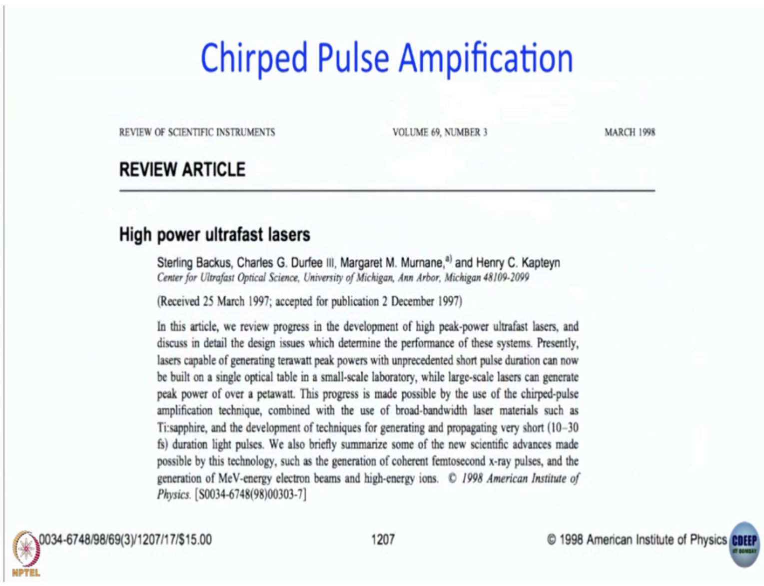

So, two and one more paper that you should read is this one. on the chirped pulse amplification, this is very nice review by or high power ultra-fast lasers by Kapteyn, Murnane and other workers. It was published way back in 1998 in review of scientific instruments, but it provides a good idea of what we are going to discuss now. In fact, it provides a good idea of what we are going to discuss now, and also things that we are not going to discuss.

So, what we will do is we will keep it very qualitative we will try to draw pictures and show how things happen and try to develop a physical insight rather than stressing too much on the math rather stressing the math at all in the next 2, 3 modules, but there is actually a lot of calculation a lot of physics a lot of optics that is required you do not have to study all but you should be aware that it is not just hit and go trial and error, nothing like that a lot of design a lot of theory has gone into this kind of work.

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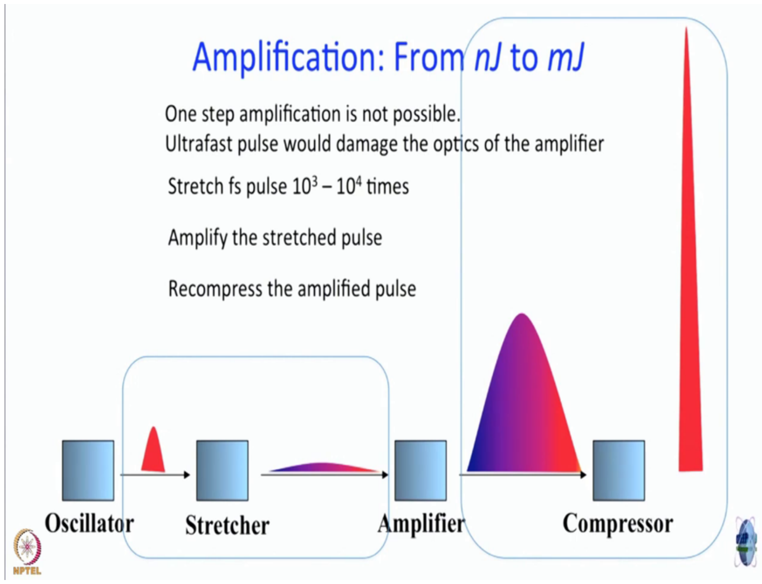

So, when we say we want to amplify from nanojoule to millijoule, we can think very simplistically that we have an oscillator which we have discussed in one of the earlier modules titanium sapphire oscillator or some other oscillator that gives you femtosecond pulses, we are going to maybe feed it into something like an amplifier, which will give us the desired ultra-short but amplified pulse. But it is not so easily done.

It is also easily done because in the amplifier typically what would want what one will try to do as we are going to discuss later in the next module, definitely not this one is the way you try to do it is you try to feed the output of an oscillator into a gain medium another the Ti sapphire crystal, which is pumped by a green laser. Now, if you are going to put in the ultra-short pulse, then as you yourself have calculated few weeks ago, a lot of energy goes into the system in a very small amount of time.

And then, we have talked about thermal lensing. It is intense part of the beam that gets focused. So, in a very short amount of time, a lot of energy impinges on a very small region of space. So, if you try to do direct amplification like what is sort of shown in the scheme, then it is very highly unlikely that you are not going to cause damage to the optics and when I say optics, the piece of optics that I have in my mind more than anything else is the Ti sapphire crystal in the amplifier itself there is going to burn.

So, you have to somehow find a way of spreading out the energy of the oscillator before you can feed it into the amplifier. So, the way it is done following the method of the Nobel laureates is that you have the output of an oscillator. First of all, try and stretch it and we know already; what is an easy way of stretching a pulse because it was already there remember when we discussed the titanium sapphire laser? We had said that when you produce an ultrashort pulse by thermal lensing, the good thing is that thermal lensing gives you an ultrashort pulse.

The bad thing is since you have a spatial variation of refractive index, it acts as a lens. You also have something called chirping different wavelengths travel at different speeds and that causes a broadening of pulses. So that is something that is already there. And so far we have seen it as a hindrance. The beauty of chirped amplification is that this apparent hindrance has been made use of converted to an advantage and it has been used in amplification.

So, first of all in a stretcher what you do is you produce a chiped pulse. So, now see if you look at a few these are all schematic but this if you look at this ultra-short pulse on the oscillator, and if you look at this stretched pulse output of a stretcher, even visually, what is the difference that you see, it can be a little confusing because I have drawn this in red. But here you can see that this part is blue and this part is red. And x axis is time, which means what I have done is I have made red light travel a shorter distance somehow.

So it leads and the blue light trails, there is one aspect. What is another aspect? You see the other obvious relationship between the unchirped pulse and the chirped pulse. Typically this would be some terms of femtosecond and the chirped pulse would be something like 200 picosecond. Will you agree with me if I say that the area under this pulse and this pulse should be the same, well what is the number of photons is it not.

So, number of photons is the same, it is just that I spread it out over a longer time, then what happens that then in a very small amount of time a lot of energy does not impinge on the crystal. So, if I can stretch the pulse by introducing chirp, then the resultant chirp pulse, which is long is not going to damage the crystal so much. So, what you do is you feed this into an amplifier and then the amplified pulse is also chirped.

Now, the areas are of course, not the same, this area is many times more than the area under this curve, but the property that is conserved is the chirping see the leading edge is still red, the trailing edge is still blue. And then when this chirp pulse is compressed, then you get the desired ultra-short chirp free pulse. This is the scheme of things. So, our job in the next 2 or 3 modules is to understand how this is done.

So, to start with in this module, we are trying to discuss how stretching and compressing is done. Actual amplification will come in the next module. So, if I have a pulse of light, and I want different colors in the pulse to spread out, what is easiest way of doing it forget about time? If I want to, I have a mixture of colors, of course, by now you know that the pulse can see so many modes that are locked together. So, that is why an ultrashort pulse is always broadband pulse shorter the pulse border is the band.

And then that transform limiting factor is there my question is, what happens or how do you make this different how to separate these different colors from each other, forget about time let us talk in space that is very easy is it not, use a grating, then different colors will go different ways. And then if I put a mirror in such a way that path length of red is more than that of blue, or path length of blue is more than that of red, then my job is done. So there are several designs that one can think of. I will start with this pulse stretcher or pulse compressor using a single grating, a concave mirror and a plain mirror.

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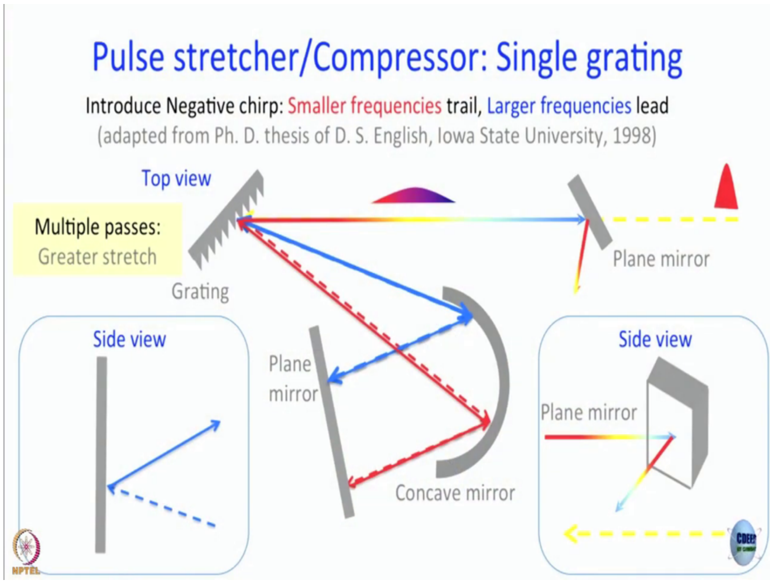

This is the design of the laser that I had used as a post doc long ago, but more or less this design is still used in many places. And as we will see in the next few minutes, it does get more complicated from here. So let us say we have this and then this pulse goes in this part is very simple the ray drawn in red and ray drawn in blue and see this angle of grating is also important whether you put it this way or that way by selecting the parameters the generally in this kind of a setup what you do is you introduce a negative chirp. Negative chirp means smaller frequencies lesser energies trail.

And larger frequencies lead that means, blue has a shorter path length and it has a longer pathway and it will just look at the length of the arrows that is achieved already. But the problem now is that it is dispersed in space it will be difficult to handle you have to somehow get it back and make a beam. How do you do that? You do that with the help of the plane mirrors. So, the way it is placed is that this grating is at the focus of the concave mirror this point in the focal plane of the concave mirror.

So, now what will be the fate of this diverging beam which is spatially dispersed after hitting the concave mirror. The blue as well as the red both the beams have come from the focus of the concave mirrors. So, what will be the path after hitting the concave mirror? Point from of focus after hitting concave mirror what happened to them rays from a focus sorry rays from the focal point, there we go parallel beam the only difference between this parallel beams.

And the parallel beams that we usually study is that in the usual parallel beams, the color is same throughout here it is not the case this is what will happen then you put in this plane mirror, now, how do you put the plane mirror that is simple you can put it like this normal incident if you do it in normal incidents the good thing is that the rays will retrace their paths, and then they will get focused on the grating again and it will go out in the same direction as the incoming beam.

People do that, but then there is a problem, is how do you separate the outgoing beam from the incoming beam. So, you have to use in that case something called an optical isolator we will not discuss optical isolator now, because there is an easier way of circumventing this problem and the ways this what you see here is the top view is it top view? Now, let us see the side view are you ever looking from here, now, we look from this side.

How do the beams hit the plane mirror like this? Like this, the 2 beams hit like this so, what will be the direction of the beams that come out like this? Of course, it is not so easy maybe this is easier that I can make these 2 fingers parallel it will hit like this and go like this? This is how they will go. So if you look from the top what will happen? Looking from the top, this is input, this is output. It looks like the same direction, is not it? But the good thing is they are vertically separated so you do not need any of the optical isolator.

So they come back from the top you think that it is retracing his path was actually it is not all. I hope you understand the color code the stretched beam is chirped. So that is what is shown in gradation of colors, red trailing, blue leading. And again, if you take a side view in this region, then it is like this you see the incoming beam, incoming beam is lower, outgoing chirp beam is higher. Now, it is very, simple matter to take the beam out? I put a mirror like this and the mirror that does not block the path of the incoming beam.

So, put a mirror here and the chirped stretch beam can go in whatever direction you need it to go. So, this is the design of a pulsed stretcher using a single grating. Do you have any question? Simple now, let me ask something, what kind of chirped is this, this is negative chirp. Suppose my input beam a same input beam is a positively chirped beam and then what will happen? Here the discussion is that the input beam is an unchirped ultrashort pulse.

I am saying the input is not an ultrashort unchirped pulse, it is a chirped pulse with positive chirp then what will happen provided the amount of chirping induced is exactly equal in magnitude to the amount of chirping that was there in the incoming beam. So, in the same design, one could make a compressor. It all depends on what is going in, but it is easier said than done. It is very easy for me to draw this and say that this is what it is going to happen stretching, you can still do it.

But the moment you try to compress then you have to be very careful that you should compensate exactly for the amount of chirping induced in the stretcher that is where very intricate and careful calculation comes in because if you compensate too less, then there is still be some chirp left and if you compensate too much then we will then what will happen then again you have a chirp pulse is it not, it is just a positive chirp will change to negative chirp it is understood.

So, you have in the stretcher let us say blue is going fast blue is leading and red is trailing. Now, I put in a compressor which will make you go through a bigger path distance that path distance has to exactly compensate for the lead it had taken on red. If it the compensation is too little, you will still have some chirp left. If you overcompensate then it will now turn head on now red will lead and blue will follow and you will still not have an ultrashort pulse. In fact, sometimes it happens.

And it all depends on what kind of application you are working on. If you need a very short output for our kind of experiments, we are happy with the 50 femtosecond pulse, but there are applications where you might need a 10 femtosecond pulse there it is not so easy to get an exact compensation by using a stretcher compressor combined. In that case, you will see in those experiments, you will see a block diagram of their apparatus.

You will see they use additional prism pairs outside the cavity to compensate for whatever residual chirp is there of course, because you will have to know what amount of chirp is there, then only you can compensate for it sometimes just what is there in the box is not sufficient you might have to do a little more. So, this is the simplest possible design I can think of. Suppose you want a greater, what kind of path difference will we need? I have a 10 femtosecond pulse.

I want to make it 200 picoseconds 200 picoseconds translates to what length 100 said that we all remember 1 nanosecond, 1 foot, 1 nanosecond is equivalent to 30 centimeter. So, point 2 nanosecond is equivalent to what kind of 0.2 into 30 which is that 6 centimeter. So see it is not very small. If you really want it 200 picosecond pulse this one round trip may not be enough want to part difference between this blue and red beam? You want the path difference of 6 centimeters. So that means your stretcher has to be really very long? Only if these beams travel at least a couple of meters.

Can you think about having a path difference of 6 centimeter is not it? So then the stretcher has to be really very long. And usually space is always a premium so many times what you do is you introduce additional optics, by which you make multiple passes and each pass introduces some additional chirp. So multiple passes are often required to get a pulse stretching your desired extent, so with that, we will close this module. And we will come back in the next one and start from this side.