Optical Spectroscopy and Microscopy : Fundamentals of Optical Measurements and Instrumentation

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Lecture - 37

Hello and welcome to the course on Optical Spectroscopy and Microscopy. In the previous lectures we were talking about a generation of ultra-short pulses and various different ways of generating the pulse lasers, Q-switching, mode locking etc. And then the methods or the that we adapt to get this different light pulses, right. So one of the methods that we were talking about was the Kerr lens mode locking as a way of passively making a laser cavity oscillate in a pulsed region.

So using these methods often one or a combination of, often using one or a combination of few, it has been possible to generate pulses down to easily to down to about nanoseconds and few picoseconds. But when you have to go to a few sub picoseconds and particularly down to femtoseconds they are sub or around few femtoseconds.

Then these lasers had to be of a particular even for picosecond lasers they have to adapt certain methodologies which would be, which would enable them to generate such short light pulses. Otherwise, which otherwise I mean, if not for them, we would not have been able to generate these pulses. And in this lecture, we would see what these methods are, what is the effect and how do we overcome that effect using these specific methods.

So now let us revisit, we will look the pulse, light pulse itself, and the notion how we have introduced a light pulse. And then let us pick one of the methods mode looking to generate these light pulses. So when we talked about light pulses, particularly the pulse laser, we have to keep in mind, the light pulse is no longer has one unique wavelength, but it has a bandwidth, right and the bandwidth is pretty wide, right.

So compared to a CW laser such as helium, neon or YAG or anything of that kind.

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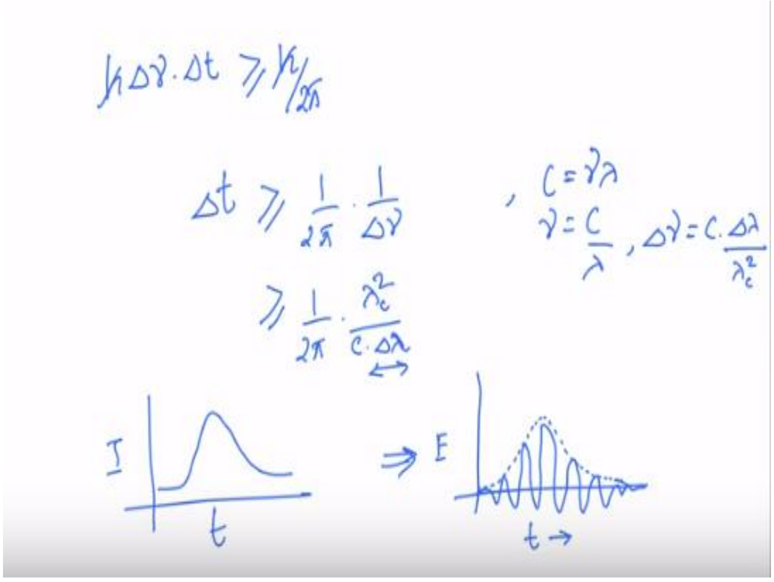

$$h\Delta\nu\cdot\Delta t \geq h/2\pi$$

$$\Delta t \geq \frac{1}{2\pi}\cdot\frac{1}{\Delta\nu} \quad , \; c=\nu\lambda$$

$$\nu=\frac{c}{\lambda}, \; \Delta\nu=\frac{c\cdot\Delta\lambda}{\lambda_c^2}$$

$$\geq \frac{1}{2\pi}\cdot\frac{\lambda_c^2}{c\cdot\underleftrightarrow{\Delta\lambda}}$$

So and we know this that is delta nu delta t has to be greater than or equal to h by right. So given this, then we can actually of course it is kind of convenient to talk in terms of wavelength, rather than the frequency, particularly when you are operating on a visible light region. So we can convert this delta nu in terms of lambda, which is pretty simple. So let us oh it is delta nu.

So we would take off this h and then if you write the delta t the pulse width, the transform limited pulse width it will has to be greater than or equal to 1 over 2 pi times 1 over delta nu. And we know c is equal to mu lambda. Mu is c over lambda and delta nu then is c times delta lambda over lambda c square. Where lambda c is the central lambda. We have seen this previously in the class. So I am going to replace that here.

Replace, use this expression here. So you can see that this would be so increase in the bandwidth measured by the delta lambda you the larger the delta lambda the smaller will be the delta t right. So we knew we know that and we are here talking about few femtoseconds like hundred femtoseconds or so. Then typically we are talking about bandwidth of the order of 10s of nanometers 10, 15, 20 nanometers, alright.

So clearly it is vastly different from the laser light that we are actually getting out from Argon ion or He Ne where the bandwidth we are talking about is 0.001 nanometer and so on, okay. So which means a pulse of light that we actually like to draw as a function of time draw as an intensity and this is the intensity and then we can also talk for this discussion, it is convenient to think in terms of the electric field, okay?

And what you will see is it is not just a envelope like that, but rather it is an oscillating electric field with an envelope, right. So that the dotted line is the envelope and when we are looking at the intensity we are actually looking at the just the intensity and ignoring the fact that the underlying oscillations, ignoring the underlying oscillations in the electric field.

Now why how do we know this and why do we want to talk about this. So now this illustrates the point of how we go about generating this laser I mean laser pulse itself, right.

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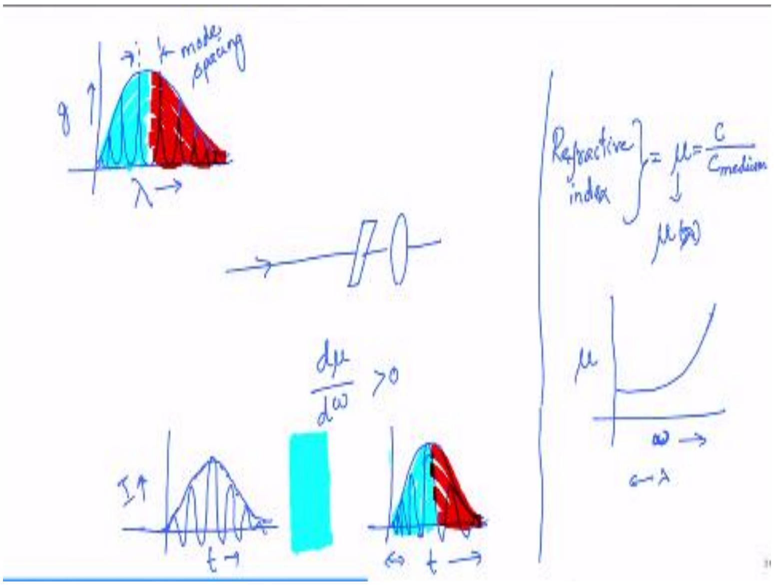

Remember, if you remember from our previous classes, we know that every laser has a gain bandwidth, right? That is, if you were to take the lasing medium, in this case titanium sapphire crystal and then measure its gain, optical gain okay and as a function of the frequency or better lambda. Then what you see is that it has a spectrum, essentially the fluorescence of the crystal, titanium sapphire crystal.

However, because it is kept inside a cavity it is constrained by the cavity, not every single frequency is, it is possible for it to oscillate in every single frequency but rather set wavelengths, okay? With the separation dictated by the this delta lambda is different. This is so this the we can think of that as the gap between the modes right, mode gap is related to the length of the cavity, right.

So you can, so sorry we can actually talk in terms of mode spacing, okay. Given these different frequencies are possible now what you what we said was during the discussion on mode locking is that, you can we can think of the laser, a mode locked laser as a bunch of lasers each operating at one of these peaks of this comb and all operating in phase, in sync.

So when it does that, then what you are what you end up having is a linear sum of all of this like a superposition of all of this individual modes resulting in the pattern, the interference pattern that we have, that I we have seen in the in here, right. So this is the electric field. So when you think of the electric field of these different frequencies right each of these frequencies adding up with each other.

Creating the characteristic envelope and an interval and a frequency content of that envelope, okay. So clearly to generate these pulses we are generating it by through the superposition of multiple basic frequencies that we have utilized. So if such a, if we take such a pulse alright and then ask the question about how is that pulse going to propagate in space?

Then while the envelope per se has we can associate in velocity with respect to that envelope, which tells you how the phase modulation the modulation in the phase is traveling in space, okay. And that phase modulation depends on the how the individual modes and the relative changes in the, I mean the frequencies different frequency modes are experiencing with respect to each other.

Now how it is propagated in space, right? That is what we are actually meaning to say when we say the pulse is traveling. It is actually what is traveling is that there are different oscillation, I mean different waves of slightly different frequencies. Each of them are oscillating in their own frequency, but then when we are adding them up with a definite phase relationship then we can create a shape and then that shape can be propagated in space as well as in time.

So now that tells you if I talk about the pulse, then I need to talk about the propagation of all of this individual frequencies and any disturbance that disturbs any of these frequencies or delays or introduces a relative delay between these frequencies is going to affect the shape of the pulse and hence the pulse width itself.

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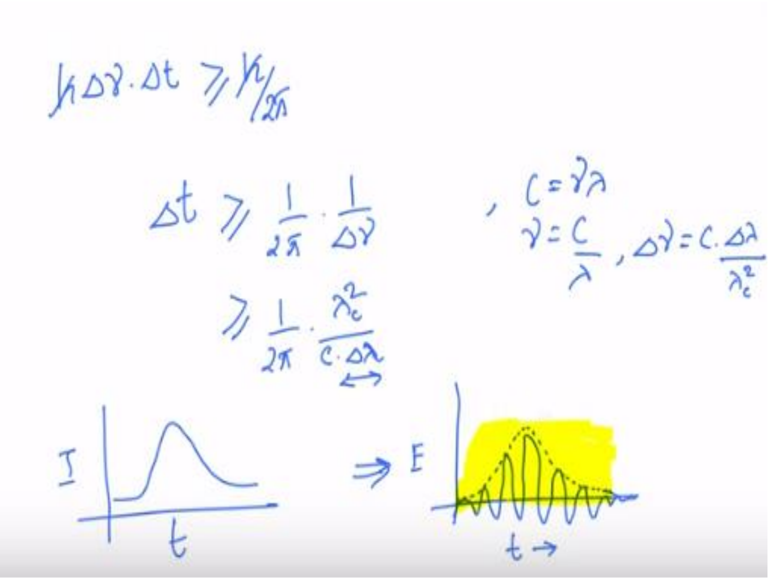

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Okay, so now what we are saying, what I am saying is if we go back then there is no it is not necessary that there is one frequency and in fact it is not. There is no one frequency for this carrier wave, right. But there are it has multiple frequencies. And then depending on how are these frequencies presented inside this pulse, inside this region, right inside this pulse itself, okay.

Depending on how it is presented inside this pulse, you can have a pulse with a positive chirp or a negative chirp. Okay, positive chirp means high frequency components are leading while the low frequency components are lagging and then the while on the other hand the negative would be the exact opposite, okay. All right. So now what we now we have said there is a pulse and in that pulse there are various different frequency components.

Then the next question that comes to our mind is that, hey when we take one such pulse and then put it through a piece of glass or any or a lens or any refracting media, okay or even propagate in air for a longer distances and so on. Now we know this media by themselves are having dispersion property associated with it, which is they have differential speed for different speed for different colors and different frequency of the light components, right.

So then what you will see is that in this pulse, different frequency will be slowed down to different various different extent, right given that we say refractive index is given by mu and is the ratio between the velocity of basically see the velocity of the light in vacuum divided by velocity of the light in a given medium, okay. So higher is the refractive index lesser is the speed of light in that medium.

And this mu is frequency dependent, which means so because of this the path experienced by different colors of light is different. As a result when you are when we are talking about a light pulse traveling through this refract I mean the small elements whose refractive index is different from the refractive index at which the light was traveling until then, it is going to it is going to slow down some of the frequency components.

And the extent to which it will slow down totally depends on the refractive index of that color in that medium. So given this, you can actually see that in the pulse when the pulse travels through a high refractive index medium right, which means the and then the dispersion, which is measured as d nu by well let us call it as d nu by d lambda. And if so as we increase the lambda, okay, so now if you.

Actually, it is usually defined with respect to the angular frequency, so it is easier to do that. So d nu by d omega. So if you plot the refractive index mu as a function of omega for a given medium, it is depending on the shape, you can classify the medium the material in different types. And for the particular case here, what I have plotted is that you can see that the as the angular frequency increases or the lambda decreases, lambda goes in this direction.

Your refractive index okay, the refractive index increases. So higher frequencies have a higher refractive index compared to the lower frequencies. So that is one kind of a medium. One kind of a medium and higher is the angular frequency higher is the refractive index. It is, we are talking here totally about the linear media in linear dispersive medium.

So in such a case, when the light pulse travels through this, so then what you will see is that the higher frequency or lower wavelength light experiences a higher refractive index. As a result you see them slowing down or to say, if you were to actually draw the so now we are talking about medias where d the d nu by d omega right is actually positive.

Meaning as I keep I mean, change in the refractive index increases, I mean it is positive, I mean the refractive index increases with respect to the increasing wavelength. So now in this in such a case, then if I were to plot, if I were to see the pulse before and after it such a pulse traveling through this media.

So then initially it would have started of be even if you were to start with a I mean, with a even distribution of these frequencies of several different frequencies giving rise to oscillation of this, there is an instantaneous frequency within this pulse for the, for this light. So that is pretty uniform inside that pulse.

However, because it is going through this, the fast I mean that the higher wavelength components, that is the modes that are present let us say here let us call let us take this red. I am going to take this. So I am going to so let us say the central frequency is right about here. I am going to call this as my red wavelength, these modes, right? These are all I am going to call this red. While all of these guys oh, I cannot use that blue. So one second.

All of these let us call that as blue wavelength. So now blue wavelength which is of a higher frequency. So now what you will see is that initially they will all be present nice and fine. There is no difference with respect to time. The frequencies could be all uniform, nicely distributed inside the pulse. But once it goes through a glass plate or of some thickness t, because the glass plate is having the dispersion property which is it slows down high frequency more than the lower frequency.

So then the net the result of such a change is that you will see that the pulse is going to be wider because this is the time, this is the intensity here right. So what you will see is that the front end of the pulse right what it was more or less uniform would be containing a slow oscillating okay. So I tried to capture it. So you can see that the instantaneous frequency inside the wave train is higher towards the lagging end.

While the see time is this way. So this is the beginning part of the pulse. And the beginning part of the pulse is more redder in frequency okay while because it is because high frequencies are slowed down more than the red. So what you end up having is that there is a separation of these frequency components thereby widening of the pulsed envelope.

Now this is a very prominent particularly if you I mean clearly it depends on the refractive index of the medium itself, right. And particularly if you look inside a laser cavity, particular femtosecond laser cavity, one of the strong nonlinear, one of the strong material with a very high refractive index is the crystal itself and it is it is of considerable length.

So given that, so you what you will see is that the crystal itself actually introduces a lot of dispersion thereby preventing any pulse that is that could be generated with a sub picosecond duration or even picosecond duration for that matter, okay. So you need to compensate for it, compensate for the spread. The way you do that is through a prism pair compressor unit.

And we are going to look at that prism pair compressor unit, mostly qualitatively and we will later on go into the quantitative aspects of this little bit if time permits. But the qualitatively let us look at this because that is so that we are still in focus with understanding how we generate the femtosecond pulses in the laser.

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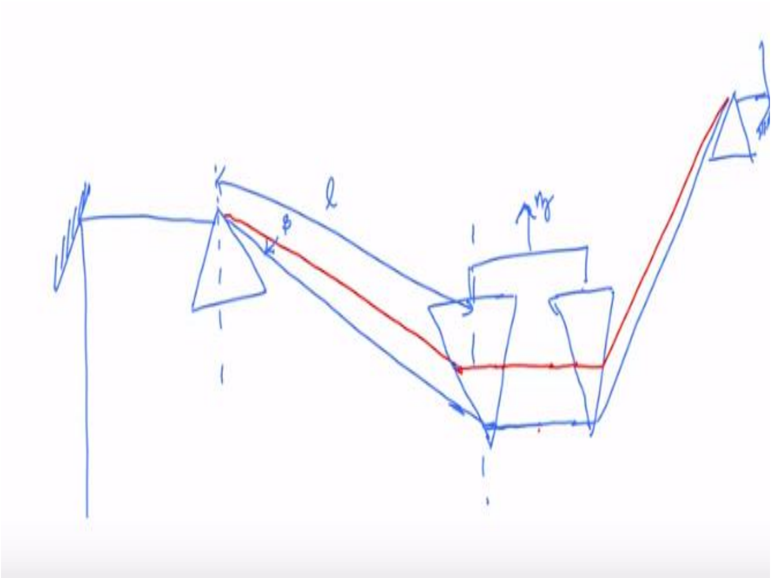

So if you look at that the way you do that is through as I said using a prism pair compressor. So the prism pair compressor essentially is or at least conceptually is set of four prisms. You could actually do that with two prisms but then but even that would be equivalent of even if you do that with two prisms the equivalence is very nicely illustrated and even the two prisms conceptually are really four prisms.

Geometry, so okay. So now what we are doing is so let us input the light into this prism pairs such that after hitting this mirror the light goes in. And because it is entering into a prism, the different frequency components are dispersed in space, right? It is just, they are going to be spread out in space. So you will see that the blue part of the light travels, it means more and travels a longer distance.

While the red part travels a lesser distance, alright. So now let us okay, so that is this is our typical rainbow vibgyor, right? Violet in the bottom and red on the top, right. And this angle, let us call that as beta and this the length be l. So depending on where we keep this prism with respect to the first person, the amount of glass through which the red and the blue lights go through would be very different.

So at this point, if I were to continue with the same line of thought, you will see that the red the path taken by the red is this. But on the other hand the blue light takes a much shorter. Yeah, the blue light through the glass takes a smaller path compared to the red beam of light. However the reverse is true for the propagation of the light in the free space followed by.

Oh, at this point actually it is and then when it goes through the second same thing happens. But now after it comes out from there, so it refocuses in space and then it emerges out as a pulse. It gets reflected by a pick of mirror. So now what you can see is that by altering this length l and where it hits basically how much it is actually moving. How much is given by the z, okay.

The prism pair, the second prism pair is actually moving. The both of them are connected and then they translate with respect to the beginning of this where we have placed that right. So you can alter the l to change what fraction of the blue goes into the red and you can alter the z to alter this z to alter the amount of the difference between the glass path, right. The red here experiences a longer delay compared to this alright.

So now these two are two independent quantities. Now using this or such an arrangement, the claim is that you would be able to put back those frequencies which are present in the pulse and not in correct order. When we do that correct order meaning not uniformly distributed inside the pulse. When we do that, we say that we have compensated the compensated for dispersion.

All I want you to appreciate here is that there are two degrees of freedom. So by changing this length, you can actually make the path taken by the blue light longer than the red light. By changing this z, you can make the you can alter the path taken by the red light being higher than that of the blue light.

So the amount of extra path taken by the red light if you want to adjust you want to increase you want to add in more of this glass, but if you want to alter the light path as indicated by me as indicated by me as blue, if you want to do that, you can actually if you want to increase this you can actually move the increase the distance between this pulse pair and the first prism, the prism pair and then the first prism.

Now with this you would be able to adjust or you would have independently alter the phase difference between different components. Now this was an essential integral part of laser cavity. And once you once we put this into the laser cavity, and then what you do is you start with a pulse, who which has high frequency components in the beginning and low frequency component in towards the end and then run through. What you have is a way of adjusting or compensating for this dispersion.

So now we let us put that inside our laser cavity. I am going to show you a picture of this laser cavity and this is the snapshot of the actual laser cavity present in the lab.

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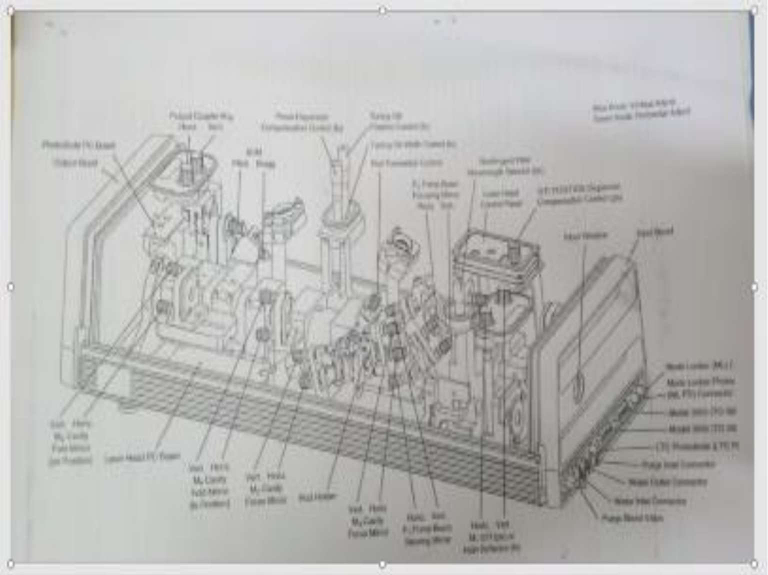

It is from it is the it is a it is called as tsunami laser and it is from a Spectra-Physics company. So here we have this is a picture of a opened version. There are quite a few optical components here, mostly mirrors and some other some few other important components too. So we will see this in real life in the laboratory setting tomorrow.

However, we need to understand the layout or how the light travels through this different mirrors and gets reflected a little bit more in detail and that we will do it in the next lecture.