Ultrafast Processes in Chemistry
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Lecture No. 24
Titanium Sapphire Lasers

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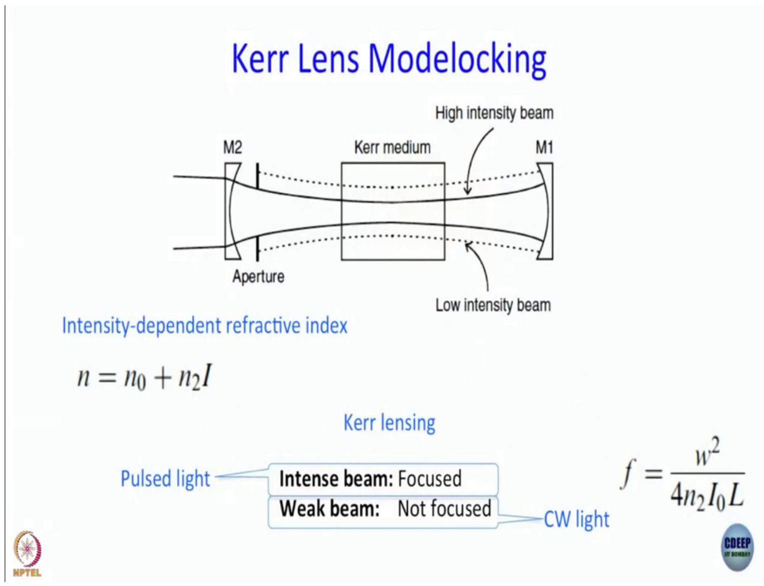

Hi, now, in this module, we are going to learn the basics of ti sapphire laser what is there inside and how to use it. But before that, this is what we have learned and this is where we ended the last module, we talked about kerr lens mode locking. Kerr lens modelocking means, because of the Gaussian distribution of a TEM 00 mode, you have greater intensity at the center of the beam and it falls off as you go towards the edge.

This brings in an intensity dependent refractive index, which sort of acts like a lens it is called a Kerr lens. And since pulse light so, it focuses the intense beam and does not focus beams that are less intense and since pulse light is intrinsically more intense. What this kerr lens does is that it can select pulse light over CW light you can do it actively by putting in an aperture in the path of the beam. But that is not even required the optics usually take care of it.

This is what we said. And this is how pulses are produced. So femtosecond pulses are produced by kerr lens modelocking without us having to do much. In subsequent modules, we are going to talk about active modelocking, where we have to introduce something and get the modelocking done there is we have to use something called acoustic optic device but here that is not even required thermal lensing takes care of it.

And of course, why is it that we get femtosecond pulses and not picosecond pulses by thermal lensing because in femtosecond pulses intensity is much more you are modelocking many more pulse many more modes are locked that is why pulse width is so small. So this is what you can get by Kerr lens modelocking. If you want because pico second pulse the nanosecond pulses, you have to do something. We said that this is the advantage of kerr lens mode locking it produces pulses.

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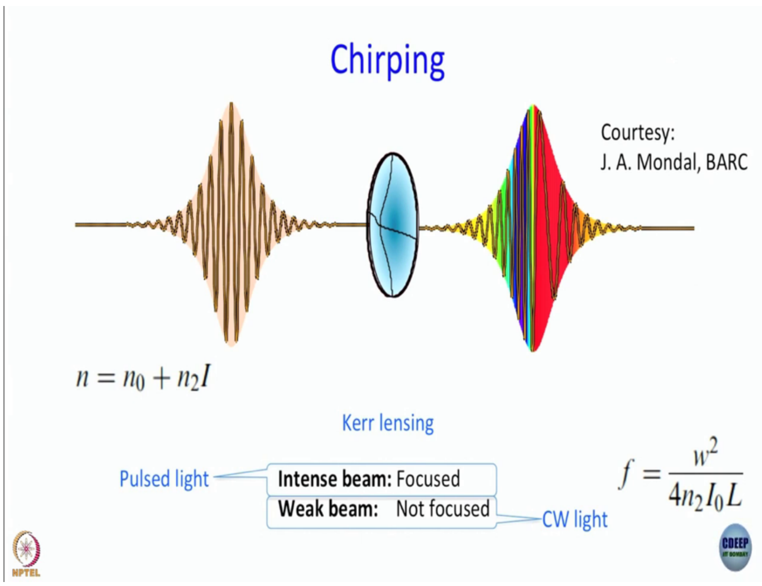

Disadvantage of Kerr lens mode locking is that it also brings in chirp which effectively is going to broaden the pulse. So, before we can think of making a laser, we have to correct for this chirp and how to correct for this chirp? The answer is very simple. Once again go back to this analogy of computation. So, I entered a running race with Tanuja. All of you agreed that Tanuja is going to win, hands down because she is a faster runner. But I do not want that.

I want to reach the end point at the same time as Tanuja, even though I was slower runner. So if I am powerful enough, what will I do? I will make her run more and I will run less. I will take a shortcut and not let her take a shortcut. So, difference in speed has to be compensated for by altering path length, it is that simple. And that is what is done to compensate for chirping.

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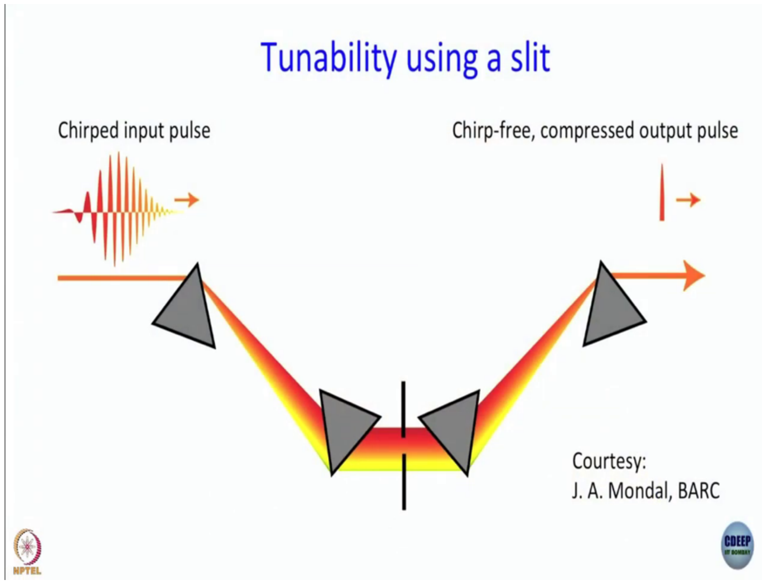

What you have to do is whichever path whichever light is leading, has to go through a longer path. The frequencies that are trailing have to go through a shorter path. And this is done quite easily by using a prism pairs. In fact, it is enough to use 1 prism pair I am going to show you an arrangement using 2 prisms. But what is more common and what we have inside the laser we use is 2 pairs of prism.

And the job of this prism is to do a compensation for what is called group velocity dispersion what is the meaning of group velocity dispersion the separation in time of different frequencies due to different velocities in medium with a finite refractive index that is called group velocity dispersion we are trying to compensate for it. So, what do you do? Say you have a chirp pulse that has gone in you can see the chirp here.

The wavelengths are more here the wavelengths are shorter greater frequency on this side, lesser frequency on this side. So, you make it go through a prism everybody knows what happens when go through the prism it gets dispersed then introduce in the path of the light another prism which is facing opposite and the angles have to be same. Then what will happen is, look at this path. What is this color on the side on the top? Green, red. What is the color at the bottom? Yellow.

So what we are showing here is that red has traveled less and yellow has traveled more then you put this then it will become a collimated beam. And I will show you in a moment why? What is the advantage of using 2 prism pairs, and then it goes to another prism pair. Then again they are brought together and it goes out as a beam. So here the inherent assumption is that the light marked in red is trailing and the light marked in yellow is leading.

So, we have given a bigger path length to the yellow beam, yellow color the color that are used to depict the beam here and I have given a smaller path length to the frequency that I have depicted in red. So, if red was trailing with respect to yellow in this region, then that would be compensated for have you understood? So, this is how GVD dispersion is done. Are we clear? Now, what is the advantage of using 2 prism pair instead of 1? The advantage is you can have tunability.

How do we have tunability? And this is what we have in our tsunami laser when we open it up the next day. We are going to show it. tsunami laser or many other lasers which are tunable what you do is you introduce a slit in this portion that is why you require a collimated beam otherwise it will be very difficult to calibrate. Suppose you have this slit in this region, then this part of the light is going to go through other part will be blocked. So that will be the modal wavelength.

If I move the slit, I made some animation, but I think I have moved it up. But I think you can understand, if I move the slit, the way it is drawn here, vertically, I bring it down, then the light that is depicted in yellow, we will go through to a greater extent, move it up light that is depicted in red will go through to a greater extent, this is how we get tunability and I am going to show the picture of a laser at least today there we will see how we do it.

And when you open it up and see it even better. This is the advantage if you use only 1 prism pair, then it is difficult to get tunability. Then, it is whatever the system gives you the spectral maximum but advantage of using 2 prism pairs is in addition to compensating for GVD, you can have a tunable output.

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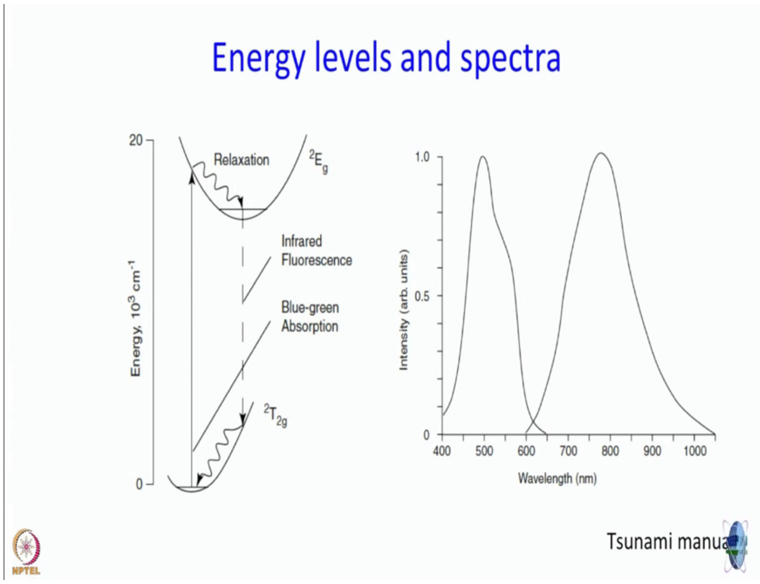

Now, the laser that we use in our laboratory is a titanium Sapphire laser. What is the meaning of a titanium Sapphire laser? Sapphire, I think we discussed earlier what is a Sapphire? What is a Sapphire to a chemist and what is Sapphire to layman? To a layman a sapphire is a precious stone you make a pendant out of it or you wear it on a ring. To a chemist what is sapphire? Aluminum oxide with some doping, so here the doping is titanium. So you can read how it is made.

It is a titanium oxide, aluminum oxide melted together and so on and so forth with particular level of doping aluminum oxide is the matrix, it is a titanium ion that is the actual active ingredient. There can be other depictions of the energy levels, but this is 1 that is there in tsunami manual and this is what describes a system fairly well. Ground state is a doublet T2g excited state is a doublet Eg.

And when you excite I am going to show you this the spectra, excite at say 530 nanometers or so, you can excite there, but then post excitation, there is an ultra-fast relaxation to the 0 vibrational level and this is where the ah emission occurs from. And you can see that the equilibrium bond length will the minimum of the 2 potential any surface not a good idea to bond length right now, but minimum of the potential energy surfaces are not in the same position.

So, when the emission takes place from here, this is where you reach. So, this energy gap is more or less 800 nanometer equivalent that is why you excite using green light and you get what they have called IR light see better in this absorption and emission spectrum. So, you can see absorption spectrum is more or less on 400 nanometer to 650 nanometers, the maximum is somewhere near 500, 550 that region. Emission starts at 600 nanometers, maximum is at about 800 nanometer and it goes all the way up to 1050 nanometers or so.

So, this is what you get to play with, you can excite anywhere here and you can get a emission anywhere here. Usually, one uses 532 nanometer excitation because there is a very robust laser that is already available rubidium L for rubidium YAG laser. That is that technology is so robust that does not make sense to try to pump with anything else and in any case, it more or less matches the absorption maximum so that is your pump laser pumping is CW in this case you do not.

We are going to talk later on about cases where pumping is by pulsed laser, but not in case of a titanium sapphire oscillator, pumping is by CW green laser. And this is where the emission takes place. Now looking at this diagram, the energy level diagram can you tell me what kind of system is it? Is it a 2 level, 3 level or 4 level systems? 4 level system. What kind of output do we expect from 4 level system? Continuously.

So intrinsically, you expect a titanium sapphire laser to give you CW output and it does. Modelocking takes place because of your kerr lens effect and so on so forth. Now with that background, let me show you 1 of the earliest successful designs of a titanium sapphire laser.

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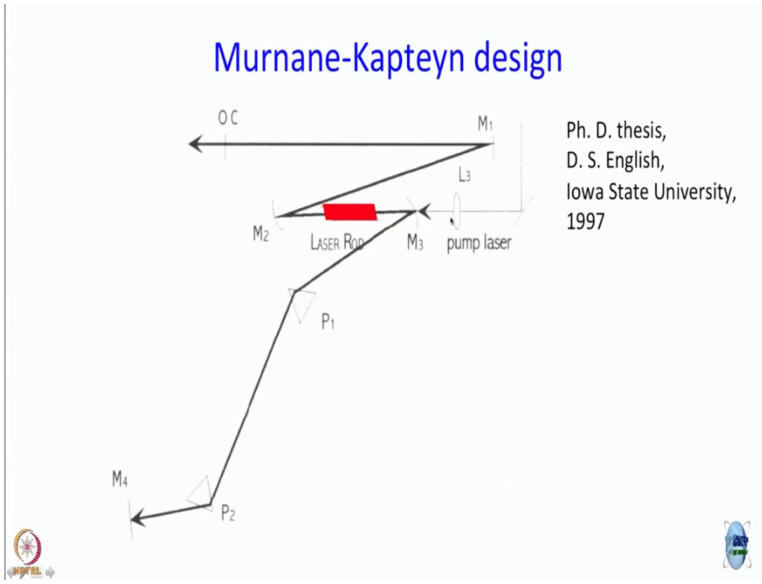

This is called the Murnane Kapteyn design with Kapteyn and Murnane are 2 professors of, I think University of Colorado at Boulder. But they have, for a long time now launched a company which is quite successful. Not so much in India, but across the world is called Kame labs. And claim to fame of Kame labs was this kits that they used to sell at one point of time, where you have everything that you require to build an oscillator and you are supposed to put it together and make a ti sapphire laser yourself that kit is still is available once again on demand.

This is a very simple design, but it takes a bigger space. So, this Kapteyn Murnane laser takes up say 2 feet by 2 feet kind of space on the laser table leaving out the pump laser. So, squarish kind of design. So this is how it works, pump laser comes in. And then you see one thing that will say without going into much detail here is that for solid state lasers, pumping has to be coaxial for di lasers, it is if the axis of lacing is this and you pump like this not so for solid state lasers.

So pumping has to be more or less along the same line. Same axis along with lasing takes place. So that is achieved always. And I want to show you the ray diagram of our ti sapphire laser later it is always used by using 1 meter, that is your dichroic, allows green light to go through does not allow red light to go through. So this M3 mirror that is shown here, it is a dichroic mirror green light go straight through in fact even M2 and red light is reflected.

So this is your pump from 530 nanometer typically for 4 watt, 3 watt or 5 watt whatever it is CW. It is focused on the laser rod the titanium sapphire rod which is shown here as a red trapezium, and then emission from this laser rod is captured by these 2 meters. The concave mirrors I hope you can see and then the focus back onto the rod. So, see we talked about kerr lens modelocking. So this is what sustains modelocked operation, even without using a using your, an aperture.

Because something; the mirrors are aligned in such a way that they are exactly focused where this pulsed beam is supposed to get focused. So anything that is not focusing will not be in the axis of lacing. That is how CW is gotten rid of sometimes there is a little bit of CW contamination you have to play around with the optics and get rid of it. So, now let us go one by one. Let us take M2 to start with, M2 catches this. Focus is it here and then it goes this side.

Goes through a prism pair where you see here in this design, there is only 1 prism pair, what does it mean? You do not have tunability then it goes and hits M4, which is a plain mirror and it hits M4 exactly at right angle. So, then it is sent back it retraces this path is focused here from M2 it goes to M1 again M1 is a plain mirror and then it goes to an output coupler which is partially reflecting mirror through which you get the laser out.

Quite a simple design not very difficult to make provided you have all the distances right. And the reason why Kapteyn Murnane became such a hit is that everything was specified. So just it was like Lego put things together in the right place and you have your laser and always titanium sapphire laser starts operation in CW mode because it is 4 level laser. So you have to bring in some kind of disturbance in the cavity that is what kick starts pulsed operation.

So the way in which I should say that this figure is from; this is from D. S. English who is a professor in somewhere in the US right now, I forgot that where exactly where, and I have used this laser as poster, so what we would do is we would tap a mirror it is an open laser, unlike what we now use. So you go and tap a mirror like this or just disturb the little bit and then modelocking is done.

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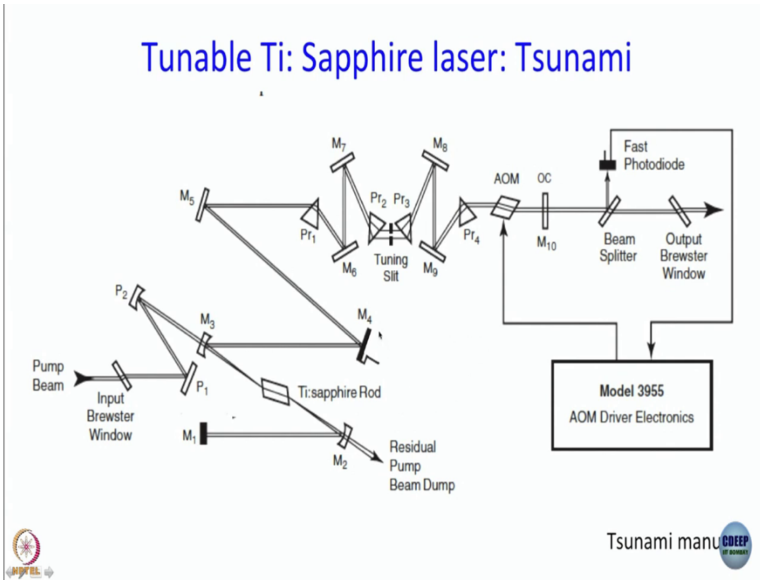

What we have in our lab looks significantly more complicated. In fact, if you look at the manual, it looks even more complicated because other components are included there I have; that is what took a lot of time today. I have to erase all those things that we do not have, let us see if we can understand the optical layout of the spectral physics tsunami laser that we use in our lab. Other lasers from coherent and other places have more or less similar layout but every company has its own design.

So here we will spend a little time on this because we want to understand exactly why? What each component does? So you have the pump beam coming in from here on the left, there is a brewster window when we talk about nonlinear optics we will discuss brewster effect; goes in so this is the entry point of your tsunami lasers, go straight P1 means P for pump. P1 is a green reflecting mirror.

So that, so P1 as you see is a plain mirror, goes to P2 which is a focusing mirror because pump beam also has to be focused at the crystal for optimal operation. P2 is a curved mirror, concave mirror, then see it is going through M3 for the same reason that I discussed when we talked about Kapteyn Murnane design. M3 again is a dichroic mirror allows me to go through reflect slate and see it is more or less coaxial it goes hits Ti sapphire rod.

And then it goes straight I am talking about the pump beam now, pump beam goes through M2, which is again a dichroic mirror and then there is a beam dump. That is where it hits and then it has no further road. From this Ti sapphire rod emission takes place once again similar to Kapteyn Murnane design. You have 2 mirrors, M2 and M3. And here are the high reflector M1 plain mirror the job of plain mirrors is just to send it back, send the beam back and make it retrace its path.

Then from there it goes to M3, M4 which is a plain mirror M5 which is a plain mirror. And then it goes through what we have discussed already 2 pairs of prisms. What is the job of two pairs of prism?, GVD compensation and this here is the tuning slate in the portion where the beam is collinear, so, basically when you change color using a micrometer screw gauge, you move the slit up and down, this is actually vertical, then M8, M9 well this is a prism pair M8 and M9 actually increasing the length between P3 and P4 with Pr3 and Pr4.

Then there is something called acousto optic modulator. Hold on, we will come back to it. And then it goes to your output couplers. And then it goes straight. There is something called beam splitter here and fast photodiode here we will see what they do. But before that, suppose you have a tsunami laser. Here of course, we have not had much problem over the last 12 years that we have had it but suppose your laser is not lacing it has happened once or twice.

How do you get it to lacing and this is true not only for a Ti sapphire laser, any laser whose cavity you have access to, how do you make it lacing. Generally you do not have to do much with the pump beam, but you must ensure that the pump beam is horizontal. In any good alignment, all beams have to be horizontal unless for some design purpose they have to go like this otherwise horizontally it is very important. And here you can see why it has to be horizontal.

If it is anything works horizontal the entire path gets messed up. So horizontally a pump beam is an issue then now Ti sapphire emission is there, it is not lasing you put in a card there, you will see the fluorescence on the card provided your eyes are not as bad as mine. You have to be able to see red nicely. So, you can; there are 2 arms, is not it 1 arm towards M2, 1 arm towards M3. First thing to do is falls on M2 hits M1 and comes back.

You have to ensure that M1 is aligned in such a way that the beam retraces its path. How do you do that? Take a white card and punch a hole in it, hold the card in this beam and make sure that the beam goes through while coming from M2 to M1. Now, when it goes back, let us say this is the hole in the card, this is how the beam goes from M2 to M1 hits M1 comes back. Now, if it is not going to; if it is not tracing its path, it will hit here or here.

So, you can see it on the card then you have to play around with controls of M1. So, that it goes through this then this M1, M2 segment is aligned. You have to do the same thing here. Because fluorescence that is captured by M2 has to retrace its path while going back to the crystal now, of course, you understand the moment you touch M2. Not only is the Ti sapphire rod to M2 alignment changed M1 alignment also get changed.

So, you might have to do it more than once, several times, do the same thing on this side. And then see the beam goes this way and comes back. So once again, you have to take your card with a hole, somewhere here between M3 and M4. Play around with M4 control, and make sure that you are light going in this direction and this direction, travel in the same path. When that is done, take out the card you will see lasing.

This is something that unfortunately, we do not have to do on a daily basis anymore. I am saying unfortunately, because once you do it, you become an expert in alignment. If you do not do it, it is a black box. And if you ever have to do it somewhere, it requires a little bit of practice. Of course now as you are going to the end of this module, things have become toys you cannot do anything. So, maybe that skill is not even required anymore.

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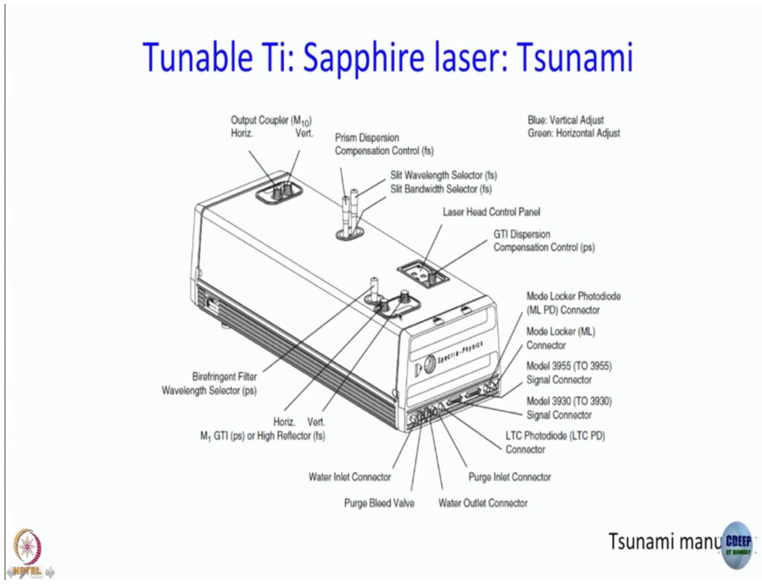

This is what the laser looks like. And again, we are going to go to the lab and see if we have seen it once already. See, what you have is. This is the side through which the pump beam enters, no sorry. This is the side through which the pump beam enters. From outside, you just see some controls. In our laser, we do not even have this birefringent filter wavelength selector. This is a generic diagram. We have these 2 knobs. What are these 2 knobs these are vertical and horizontal controls of the high reflector.

Which one is the high reflector? This one. So this blue and green knob that are there. Green is for Earth horizontal. Blue is for sky vertical. So these are horizontal and vertical controls of the high reflector that is what one usually plays around with. In the other end, we have similar controls for the output coupler. Generally we do not touch it, because the moment you touch both, you are sort of shifting the beam completely. And you are not careful it can get misaligned.

But sometimes we do have to touch the auto coupler because condition of the lamp can change from time to time we do not have this GTI dispersion thing. We do have these 2 micrometer controls here, one for prism dispersion compensation, one for wavelength selection. What are these 2 micrometer controls? One of them changes the distance between the prisms so, they change the distance between the prism you are essentially changing the path difference among the different modes.

The other one moves the slit up and down so by moving the slit up and down to select the wavelength, the modal wavelength, and by playing around with the distance between prisms, that is how you maximize GVD compensation and ensure that you get a good optimal pulse. Now, there are some problems with this tsunami kind of laser. One problem is that the cavity is not sealed. So, if your lab is not absolutely dust free, dust can get in and spoil your optics are regular cleaning are required.

Fortunately, that is not the case in our case and for that is not the case for almost all ultra-fast labs in India. Nobody would invest so much in a laser and keep it in a dirty room. But there is another problem of the cavity being not sealed. The problem is that no matter how much you try you cannot have a room that is absolutely dry the relative humidity we used humidifiers and all but at most we can go down to 40% it is important that we go down to 40%.

But then you can try and use industrial humidifier and go down to till 15% but that is not good for your health nosebleeds have been reported in labs where too much of dryer atmosphere is maintained. So some moisture will be there even if it is 14% and water absorbs in the region of 950 nanometer onwards. So if you are going to tune it, then you do not want moisture in the cavity. So tuning tunable range is severely affected by the presence of moisture.

So in a tsunami kind of laser if you want to go up to say 1000 nanometer output then there is no way other than purging the entire cavity with dry nitrogen. And we have done it a couple of times. And I do not want to do it ever again, the 1 nitrogen cylinder gets over in 1 day, you do one day experiment, the cylinder is always on, and it is an open cavity nitrogen is going out. So it is, first of all, it is cumbersome. And secondly, it is very highly nitrogen intensive; I do not want to do it.

So because of these problems, and also the other issue is the technology is moving in a direction where everything has to become a black box user should not worry about how things are, of course, the purpose, of course, is exactly opposite. But that is how things work. You are a biologist working on 2 photon microscopy you do not really want to know about modes of lasers and how they are coupled and so on and so forth.

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So, this is the state of the art and we have shown this already when we went to the TCSPC lab earlier everything is sealed in the containers advantage of this is that you can have full range of tunability, 690 nanometer to 1050 nanometer at the click of a mouse. Disadvantages anything goes wrong inside this the laser has to go back to the factory because hermetically sealed it cannot be opened anywhere other than the factory where humidity temperature everything well air quality everything is maintained very rigorously.

Question that one should come to one's mind this is actually a laser in which you have the pump laser on one side and you have the ti sapphire laser on the other side. We should have a question when we see this, this here is the laser driver. Why? We have said earlier that you need some kind of a cavity length to have pulsed operation round trip time and so on and so forth. So in such a small thing; how is cavity length maintained.

And that is the diagram I was looking for and unfortunately did not find this morning we will find it I will include it in the presentation and upload. So, what you have there is that you have this Ti sapphire crystal and you have 2 large mirrors and the alignment is such that the light bounces off these mirrors many times. So, even though the separation between the 2 mirrors is not much the effective path length is the same as what it is in tsunami.

That is how compact sealed lasers like MaiTaiwork. So, what we have done today is we have started with principle of modelocking kerr lens for modelocking. And we have given you a little bit of idea about construction of lasers. We have not talked about certain things yet. One is if you remember that diagram, we have not told you what the fast photodiode does. We have not told you what the meaning of AOM.

So, in the next module, we are going to go to the lab open up tsunami and show you after that, we are going to talk about what acousto optic modulator are, how they can produce pulse picker, how they can produce pulsed operation. I told you already that you do not really need the acousto optic modulator in this cavity. Why is it still there? It is still there because there is this technology called regenerative modelock.

And we will discuss that after we have talked about acousto optic modulator. And we will also talk about electro optic modulators like pockel cell can give you not short pulses, but large pulses, but in this context, which are useful in switching the laser pulse out outside the cavity. Once you are done with this discussion, we will talk about how amplification of laser is done. And then we will talk about optical parametric amplification. So, much for today.