Ultrafast Processes in Chemistry

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Lecture No. 28
Cavity Dumping

Today we will do a little bit of discussion of cavity dumping. Now, this is more for the sake of being historically correct and more for the sake of completeness of knowledge. Because most of the time when we do ultra-fast studies we use titanium sapphire lasers and unfortunately, titanium sapphire lasers cannot be cavity dumped. Cavity dumping was a very popular technique when dye lasers were used. It is not a technique by which you produce ultra-short lasers per say.

What you do is you take the pulses out there is some narrowing down of laser pulses also, but more importantly, you can take the pulses out of a particularly you can take it out of dye laser cavity. And this is attractive because as you will see, cavity dumping is a technique in which the laser is always on we are also going to discuss Q-switching after this we have already discussed mode locking. Cavity dumping is like mode locking where the in the sense that the laser is always on.

As you will see in q switching the laser is not always on. And we will talk very briefly about pulse picking which we use in our lab. As I have said earlier also it is a wasteful technique. We throw away most of the energy we use only 1 - 10th of it or 1 - 20th of it. In cavity dumping when we are not taking the pulse out. Actually the power of the laser goes up in that time interval. That is why it is such a good technique it is unfortunate that we cannot use it with the femtosecond lasers we have now. So, in cavity dumping once again we use an acousto optic modulator.

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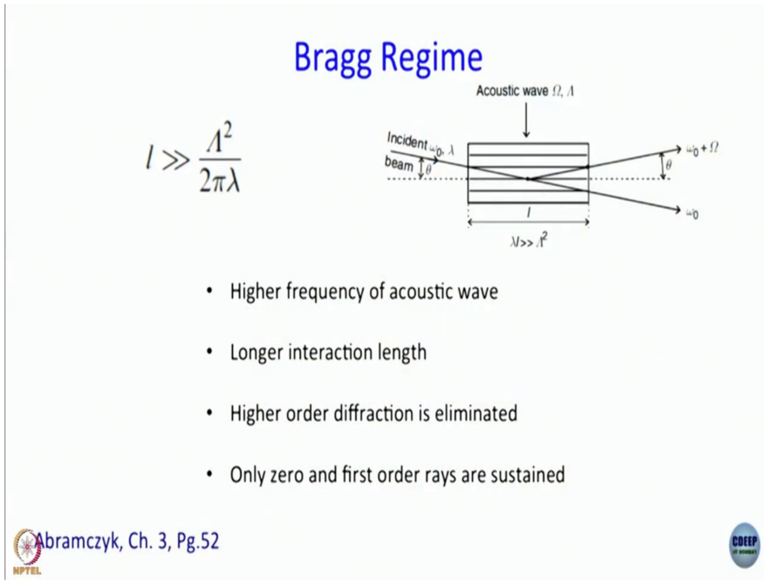

We have talked about mode locking, how you do mode locking using acousto optic modulator, that time we said that we have to use it, use it AOM in Raman Nath regime, where L was much less than lambda square by 2 pi small lambda capital lambda is the wavelength of sound wave, small lambda is the wavelength of light. In case of cavity dumping I think we have discussed it in the previous module as well.

In case of cavity dumping, we have to operate this AOM in the so called Bragg Regime and Bragg Regime means l the thickness of the medium is much greater than capital lambda square by 2 pi lambda. So, essentially you end up using you have to use much higher frequency of acoustic wave so ls to be greater than capital lambda square divided by something. So, capital lambda would better be small, if capital lambda is too small, the corresponding frequency has to be large.

So, we will see what kind of frequency is typically used in this technique. Secondly, it helps if you have a longer interaction length. And here what happens is when you work in this regime, all the higher order diffraction are eliminated, only the zeroth order and first order rays are sustained omega plus or minus capital omega. If you write in angular frequency sometimes it is written as omega zero plus minus capital omega so at for now, this is what we will consider we will consider that here.

When light falls on the Bragg cell, part of it goes straight undeflected, and it does not interact with the media, part of it gets diffracted and it gets frequency moderated by capital omega. This is what we had discussed in the last meeting as well.

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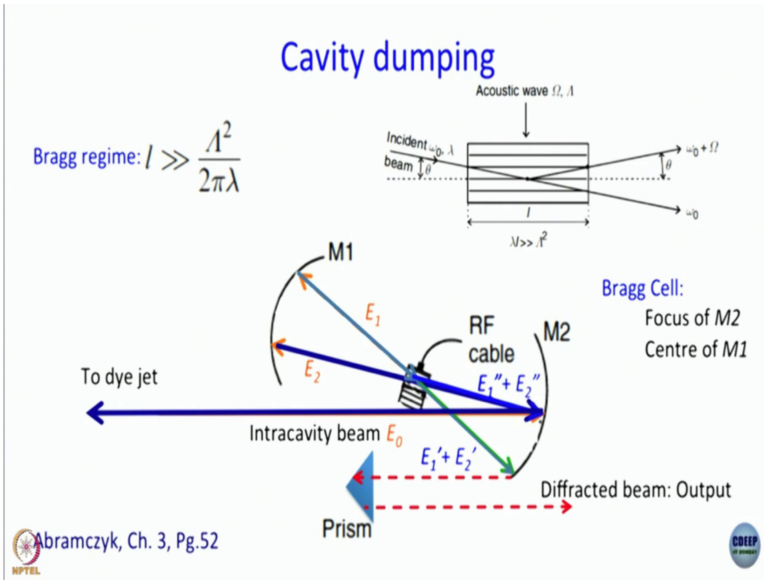

Now, what you do is, in fact, we discussed this as well in the last video, but we went too fast and I think nobody understood anything. So, let us see if you understand it better if you make animations. So this is a part of the laser cavity that we are showing. As we had said earlier, it is important to remember that there is no output coupler here. All mirrors are highly reflecting, and we are showing only 1 end of the cavity. So this is M1, this is M2 and the laser beam goes this way, somewhere here we have the gain media.

And somewhere here we have the other high reflector mirror have you understood the cavity? Have you understood what the cavity is? This is M1, this is M2 what is shown there then the laser comes from M2 this way laser light, this is where the active medium is, and this is where the other reflector is and there might be other mirrors in between, but the crux of the matter is that this is one mirror, the end mirror and M1 is the starting meter, M2 is the other curve mirror that is important for our discussion.

So, this is the simplest cavity that you can think M1, AOM, and M2. Then the gain medium dye jet or whatever it is, say M3 this is a cavity it is a closed cavity or high reflectors. So, you can think that if you pump this gain medium here, there will be a laser. There will be a laser beam in the cavity, but it will never come out. The question is how do we take it out we take it out by cavity dumping and how does that help? So, before showing you the beam path and all.

One thing that I did not say earlier and it is important to say otherwise, it is very difficult to follow what we are saying is that this Bragg cell here is kept at the focus of M2 and at the center of M1, focus of M2. That means any light hitting M2 a parallel beam of light hitting M2. If it is normal to the tangent at the point of hitting, then it will get focused on to the Bragg cell. Since the Bragg cell is at the center of if you draw a line from the center of the Bragg cell to the surface of M1 that will be the radius of curvature of M1.

What happens then? Let us see if we remember any geometrical optics I have a curved mirror, spherical mirror, I draw a ray from the center that ray goes and hits that mirror where does it go afterwards? There is for focus now seeing at the center for a concave mirror usually focal length is half of the radius, is not it? I am saying it is not at F it is 2F. So, this is one of the main reasons why we did not understand last day.

Remember those ray diagrams that we used to draw this is a curved mirror. Something like this comes it will get focused. A ray that comes through the focus will now, from to 2F center, the ray comes and hits the curved mirror. Where does it go? It retraces its path. Why? Because if this is the radius, then the tangent here the radius is perpendicular to the tangent, is not it? So it is like normal incidence. What happens for any mirror in case a normal incidence?

The light it retraces its path, is not it? So for a beam that originates at the center of the mirror, all the rays will retrace their paths. I did not say it in as many words in the last day, but as that is why it was really confusing and also, I showed everything together. Today we are going to show it step by step. Have you understood now what is going to happen if light falls?

So then let me draw this here is the interactivity beam let us see this coming from dye jet gain jet now for M2 the Bragg series that the focus so this is what the path of the light will be now, what I have shown is I have shown the part that goes straight the part that has the part of the beam that has not interacted with the radio frequency. Will this be the only thing or will there be something else? You follow me then what I am saying E0 intracavity beam E0 is the; you can see electric field associated with it.

That falls on M2 get focused on the I am talking about only one ray so it goes through the Bragg cell one part of it goes straight is there another part of it that does not go straight and you can refer to the diagram above we are working within Bragg regime. So, once we get another beam that will get deflected like this what did we say that you will get the zeroth order and the first order beam second third what we use in mode locking Raman Nath regime.

We had omega 0 plus minus capital omega plus minus 2 capital omega plus minus 3 capital omega so on and so forth. Here there is no n omega only omega capital omega. Omega plus or minus capital omega depending on the angle of incidence, here we have written well we will see what we have written. So, let me call this let us say that the electric field associated with this beam that with the first order beam is E1 and let us say the electric field associated with the beam that went through straight is a E2.

Now, let us consider E1 first after hitting M1, where will E1 go it will retrace its path, because the Bragg cell is at exactly the center of M1. So it will retrace its path. And again it is going through the Bragg cell. So part of it will go straight we will call that E1 dash part of it again we will get bend and when it gets bend it will be weighed by the exactly the same angle. So now it will take the path that you would get if you produce this E2 line back to M2. Is that correct?

So we will call this E1 double dash. Have you understood so far now, in the direction of E1 double dash is that the only beam that is there or is there something else what we have said so far is E0 falls on the Bragg cell after reflection in M2 gets divided into 2 parts E2 and E1, then E1 gets reflected by M1 comes back to the Bragg cell the part that goes straight we call it E1 dash, the part that bends we call it E1 double dash.

Now, think into in the, so, what will be the fate of this ray that I have drawn associated with E1 double dash after hitting M2 where will it go? It will go back along the direction of the interactivity beam is it not. So, it will be sent back to the cavity. But we will only E1 double dash sent to the cavity or is there something else that we have not considered yet? Exactly E2 also hits M1 and retraces this path. It goes back to the Bragg cell then what happens a part of it goes straight.

And by the convention that we have used so far, we call it as E2 double dash a part of bends, but before that, well I forgot the sequence of animation. So, now, the field that is sent back to the cavity is E1 dash plus E2, E1 double dash plus E2 double dash understood so, that is what I was talking about a part of it goes back to the cavity. Now, to complete the other part, what will the other part E2 after hitting M1 has come back to the Bragg cell the part that has gone straight we have called it E2 double dash, the part that bends we can call it E2 dash.

So, in this direction, we have a total field of E1 dash plus E2 dash and now see what has happened when the beam came from the dye jet and hit M2, there was only 1 spot, but since Bragg cell has performed deflection, the beams that come back create an additional spot which is associated with the field E1 dash plus E2 dash, where will that go that does not go back into the cavity that is it there so it goes in this direction.

So in whichever direction it goes to keep a prism and the prism access retroreflector you did not even have to keep a prism you can keep 2 mirrors or you can keep this retroreflector that we use whatever it is, conventionally, prisms were used in dye lasers. And this is the beam that comes out. So see even though this laser has no output coupler by using cavity dumper you can take a part of the beam out part of the beam that goes out is of the field associated with it is E1 dash plus E2 dash.

But interestingly for every such cycle E1 double dash plus E2 double dash goes back to the cavity. So, this is what I was saying even while you take the light out the laser beam inside the cavity grows away that is why you get a good power out of the laser have you understood now, so, even if you stop here, I think qualitatively we are good. We understood how it works, but will not stop here will give you a little bit of a feeling of what kind of numbers we can think of.

And how why it is that during cavity dumping, the repetition rate gets modulated does it that it gets cut down in the cavity dumped synchronously mode lock dye laser that I used as a PhD student repetition rate would typically be cut down by a factor of 10 it will go down to 1 - 10th of what the repetition rate was initially. And that was important because he did TCSPC with it so, you could not work with 70, 80 megahertz kind of repetition rate, which is intrinsic of the mode locked output of the pump laser. Now, again, I will ask the question that you did not answer.

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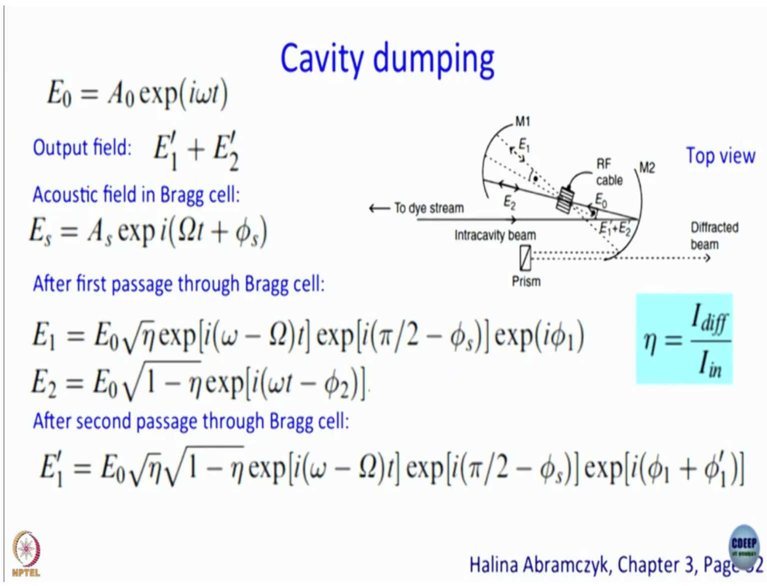

This is what it is and this is the diagram that I had shown you last day. Now, I hope you understand what it means. Now, let us try to see what kind of expressions we get. We want to know what is the expression of E1 dash + E2 dash? So to start with, we will write E0 as A0 e to the power i omega t. Now I want to ask you something. You want to say something about E0 or A0? What does it look like? Looks like it is a constant.

Is it really a constant do not forget what kind of laser we are talking about you are talking about a synchronously pumped, mode locked laser cavity dumping is only take the thing out even if I did not do cavity dumping, it is mode lock nevertheless. So, E0 is actually a pulse is you know A0 is an electric field associated with the pulse. So it actually has a little more complicated structure A0 is not just a constant here that also is something more we know already.

The expression of pulses that you get out of mode lock systems. So, that is the real expression here we are writing this only because otherwise expressions become too large and you will see the implication of it once we are done with this discussion all output field is E1 dash + E2 dash. So, question is what is the E1 dash what is E2 dash? Let us see if we can figure that out. To start with that let us first consider that this might look a little scary because you know we are chemists after all we are not very good mathematicians perhaps.

But this much of will not even try to solve it will tell you how it begins and then we will tell you where it ends. Now, in the Bragg cell also there is this periodic field that you have, because you have applied a sound wave let us say Es s for sound equal to As e to the power i capital omega t + phi s what is capital omega? What is omega in this kind of expression? When I write for the light is E0 equal to A0 it is for i omega t.

What is it omega angular frequency of light, when I write it for sound Es equal to As e to the power of i capital omega t plus phi s capital omega is the angular frequency of sound. That is what that is all and what is phi s, is a phase of sound wave. So, you might remember those of you who worked with the pulse picker particularly you play around with the phase did not you? So, that it is that phase. There are discussions in which they are not considered phase I am going to share some paper with you.

They have actually simple expressions, but phase is a very real thing. We even have a knob to control it. So that is why we will keep it for now. So, after the first pass is E0 will light with associated field A0 passes to the Bragg cell the first time then what happens? It gets split into E1 and E2. So, E1 turns out to be E0 multiplied by square root of eta multiplied by e to the power i omega minus capital omega t this could have been omega plus capital omega t also multiplied by e to the power i pi by 2 - phi s multiplied by e to the power i phi 1.

Of course, you can write this expression in several different ways, is not it? Because it is a product of some 3 exponential functions so you can add up everything you we can group them differently, this is how it is done in the book. So, we will go by this, let us see what every factor means, easier

E0 have talked about already. What is eta? Eta is the ratio of intensity of the diffracted beam divided by intensity of the input beam so, this is ratio of intensities.

This here, we are talking about field E1, what is the relationship between electric field and intensity? Electric field intensity, what is the ratio? Which one is the square of which one intensity is square of electric field? So, therefore, it is not difficult to understand that electric field a square root of intensity. That is where the square root comes from. Square root of eta, have no problem I hope what is the next factor e to the power i omega minus capital omega into t?

Where does this come from? Because you have a light wave with angular frequency small omega you have sound wave with angular frequency capital omega, they are interacting? E1 is the diffracted beam did not forget. So, in diffracted beam, you are going to have an interaction between the 2 that is where that omega minus capital omega comes from next one is something that will take axiomatically where does this pi by 2 come from all of a sudden?

Does anybody know? There is no Pi so far? Out of the blue wherever I got it from? Well, this comes because the interaction is between light wave and sound wave? What kind of kind of wave is light? Light electromagnet is fine, I am only talking about the electronic electric part transverse wave and what kind of wave is Soundwave? Longitudinal. So, whenever there is an interaction between longitudinal and transverse wave that pi by 2 term comes in.

So, these are all very well-known from physical optics. And then this phi we have kept and then last one, it will e to the power i phi 1 that you have to consider. Again, for a simplistic picture, you can set it to be 0 experimentally you can play around and make all the phi is 0 if there is no phase difference between anything, whereas, you can try and do that, but this is the general expression. The point is this; your light is traveling through some glass quartz.

So, some phase difference will come in that is why that is the e to the power i phi 1 comes then what about E2 now knowing the expression of E1, let us try to guess what the expression of E2 will be E0 will be there then will we have eta or will we have something else remember E2 is the electric field associated with the light that has gone through straight no interaction with sound the capital omega comes later I only took out that root over eta, you are right.

Well your answer is the correct answer to the next question that I was going to ask. It is that the e to the power i omega t that is what we will get will not get capital omega then but can we come back to the correct answer of the question I have asked. What about root eta? Will it be root eta will it be something else? No refraction but see eta has to be in some form or the other, because after all E0 it is getting split into the diffracted beam.

The beam is getting split into the diffracted beam and not refrecting the intensity of diffracted beam is i diff as we have written what is the intensity of the beam that has gone through straight i n - i diff. So, what is 1 - eta is i in minus i diff divided by i in. So, here eta we are going to have square root of 1 - eta and then we have e to the power i omega t– phi 2 the phase difference will come.

But this is what have we considered so far. This is a Bragg cell E0 has hit M2 gone to the Bragg cell one part has gone straight one part has been defracted, we have not got to you E1 dash yet, is not it? We have to consider E1 dash. To do that what we have to consider is there is another path in the other direction. So, E1 is to both hit M1 and come back. So this is E1 hits the mirror comes back goes to the Bragg cell again E2 hits M1 comes back goes to the Bragg cell again.

And now for the sake of brevity, we are not going to try to work out what is the expression of the field for light that goes back. Let us see if we can get E1 dash you underestimate what is the light that goes out E1, is not it? So after the second passage, what will E1 dash be E1 dash is which one the beam that that goes straight or gets diffracted, no E1 originated from diffraction that is okay but that was the first passage towards M1 while going towards M2, E1 dash is the part of E1 that goes straight.

So, now see whatever was the original expression for E1 that will be there, but then something like eta or square root of 1 - eta has to come what will come here square root of eta or square root of 1 – eta it is going straight it is not being defracted this time square root of 1 – eta will come here this is what will happen and you can have some additional phase difference that comes in that is how you get this scary expression. So, people who work in optics or physics students are known for them it is very easy when they did not have to do it.

So, slowly look at it, they understand everything but then we might not. So it is better to go a little slower. Similarly, you can work out yourself into E2 dash. Now, we have something we like we have symmetry, we have 2 expressions E1 dash and E2 dash which look more or less the same. So, that is why see earlier it was multiplied by square root of 1 - eta already. So, now it is multiplied by square root of eta. The next part of the math is not difficult just manipulation, you do it and this is the final result I am going to show you.

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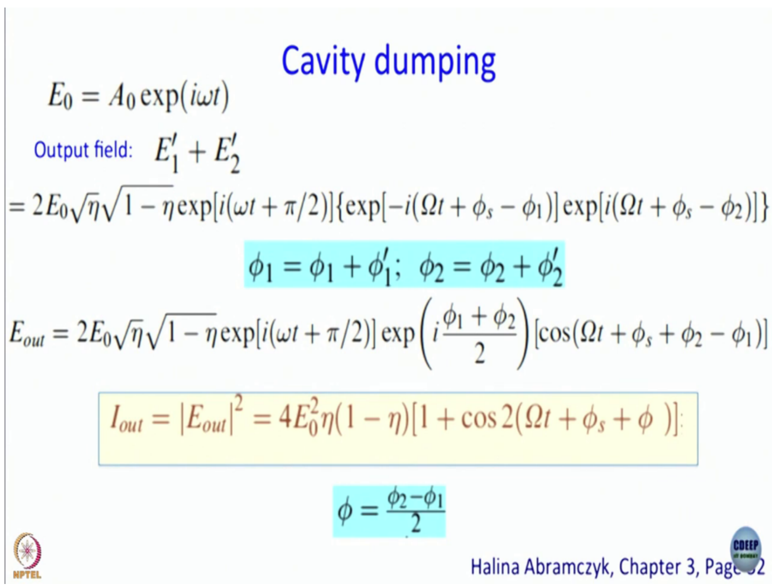

Well we get an expression for E1 dash + E2 double dash sorry E1 + E2 dash. But then finally, what we care about is intensity? Mod square of the intensity is going to be the intensity of the output beam. This is the expression we get for that intensity of the output, we stop here, and we continue from here in the next module.