Lecture No. 29
Cavity Dumping (Contd...)

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Cavity dumping

$$I_{out} = |E_{out}|^2 = 4E_0^2\eta(1-\eta)[1 + \cos 2(\Omega t + \phi_s + \phi)]$$

Maximum when $\Omega t + \phi_s + \phi = k$ where k is an integer

Minimum when $\Omega t + \phi_s + \phi = k + \dfrac{1}{2}$

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This is where we had reached in the previous module, intensity of the output beam for a cavity dumped synchronously pumped mode locked laser. I have used several qualifiers, adjectives. Well right now even if you did not understand synchrony pump if you forget it, is but you cannot forget that not only is this cavity dumped, even before cavity dumping it is mode locked. I have said it 3 or 4 times already.

But it is important as you will see, so this is the expression for your intensity, of the output. So, what you see is that this output is modulated by a frequency that is double the frequency of the sound wave used is that is that right? The phi's are just phase difference phases or frequency is given by 2 omega. So, it is modulated at 2 omega 2 capital omega. Now, the question is what does this modulation mean? When is this going to be maximum? When is this going to be minimum cos 2 x.

What is the maximum value of cos function cos theta? + 1, what is the minimum value? - 1 or 0, - 1? - 1 is less than 0 cosine function is not a cos square, it is cos. So, your squares on the other terms 0 square and all but then it is a cosine function. So, when will it be maximum when cos of 2 capital omega t + phi s + phi will be equal to 1 and when is that cosine function equal to 1, only at 0, actually 0 there is a problem.

If it is 0 then it means that capital omega is 0. If it is 0 capital omega is 0 so, that is trivial solution if capital omega is 0 what are we talking about? So, what will be the first number 360. So, what will be the so, basically it has to be an integer is not it because that factor of 2 is there did not forget. So, when k is an integer positive integer that is when it will become maximum. **"Professor – student conversation starts"** When will it be minimum - 1? What is 180? So you are forgetting 2, 2 into 180 it is 360 **"Professor – student conversation ends"**.

So, this nice solution is a minimum when this capital omega t + phi s + phi = k + 1/2. When it is k + 1/2, multiply that by 2. We will take k = 1, 3 by 2 multiplied by 2, how much is it 3. So, all sin tan cos it will be -1. What happens when k = 2, phi by 2 multiplied by 2 it will be. Phi. Since minimum there, so what we get is that, we see that it is a modulated function with maxima and minima.

We will show you in a moment what that function looks like. But now, it is important to remind you once again what E0 is or E0 squared is and that is why we are saying so many times that it is a mode locked laser. See, the intensity that goes in itself is a function of time it is not CW if it is CW, then the curve that you get this function will be something like this oscillation between maximum and minimum. However, do not forget that it is not so simple.

If you think that we have delta function pulses that is the easiest thing to think. Then what will happen, whenever the delta function is there, only in that instant it will be multiplied by the modulation factor, and you will get some value otherwise you would not. And we will see how that leads to a decrease in repetition rate. Without doing too much of math, it is better to show you pictures.
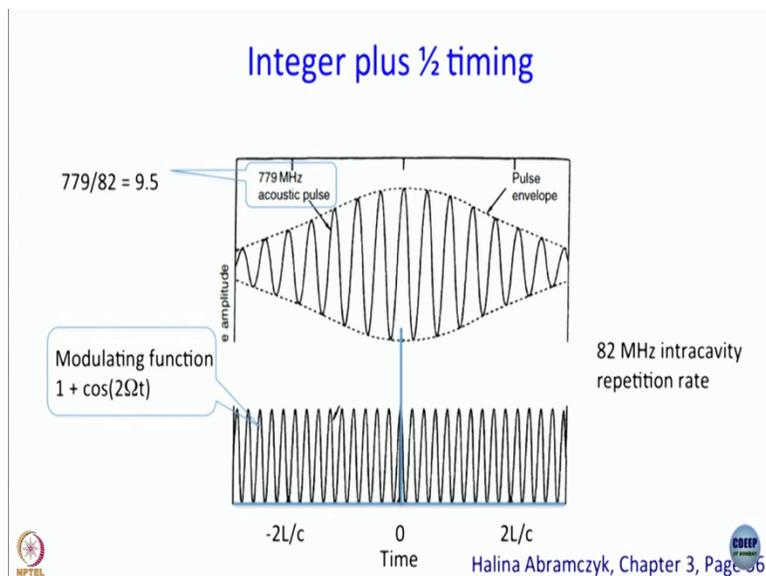
If you did not understand this after reading this book, I suggest that you go back and read the original chapter in by EW Small in topics in fluorescence spectroscopy volume 1, like edited by Lakowich or you go back and read the original paper, I will share the original papers.

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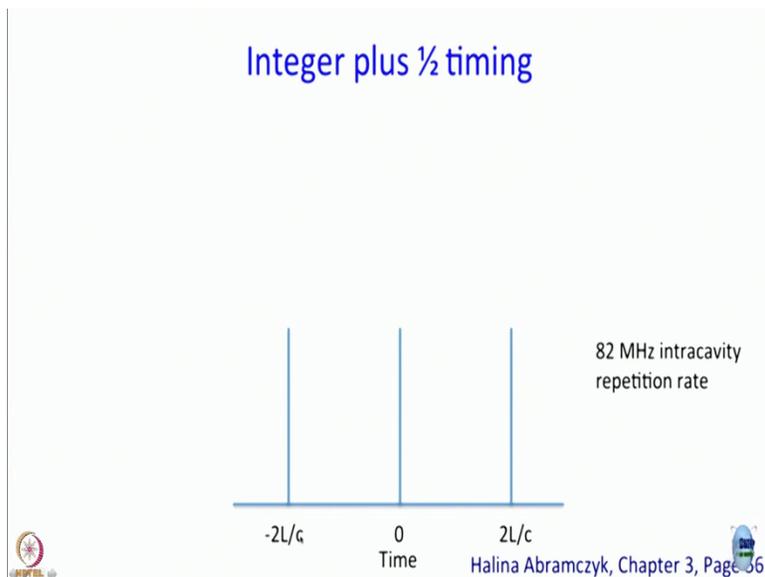
It is interesting to read papers from those era. So the laser that they are discussed was the laser that was used in the EW Small lab actual spectral physics synchronously pumped mode locked cavity dumped dye laser, bromine 60. So there the repetition rate of the intra cavity pulses 82 megahertz because it is pumped by 82 megahertz mode locked ND YAG or ND glass laser. So, you get pulses like this and we know by now that the time between 2 pulses is something like 2L / C round trip time. So, this is the laser pulse within the cavity not coming out.

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Integer plus ½ timing

779/82 = 9.5

779 MHz acoustic pulse

Pulse envelope

Modulating function
$1 + \cos(2\Omega t)$

82 MHz intracavity repetition rate

amplitude

-2L/c   0   2L/c
Time

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And this is the profile of the sound wave that is applied radio frequency that is applied similar 779 megahertz I am sure they wanted to make 800 or 780 but then this numbers worked out to be convenient. And this integer plus halftime is a term coined by I think spectra physics people. Where does this come from integer plus half? Remember what we discussed in the previous slide maxima at K integer minima at k plus half integer plus half.

So, from there it turns out that if you now divide this 779 by 82 megahertz, what do you get? 9.5 is too intelligent I guess it is you get 9.5. So, what is the integer here? 9 + 1/2. So, what happens what this means is again without going into much of math is that every 9 pulse goes out the remaining 8 go back into the cavity. Why does this happen? It happens because you have these modulated pulses. So, we have this omega plus capital omega minus capital omega some people omega zero plus minus capital omega so, these are different frequencies.

So, they are going to also get superimposed with each other. You will have constructive interference, destructive interference so on and so forth. So, that is actually the reason why it happens due to modulation. Now, if this is the pulse, let me show you a figure of the modulating factor remember the modulating factor, what is the modulating factor? What are they modulating factor of intensity? You saw the expression for intensity of output there was a factor of modulation what was that? Eta, we said there is periodic looking at it to remind you, we will go back $1 + \cos$ 2 omega t, remember there is a modulation factor.

So, let me now plot the modulation factor. This here is the modulating function and remember modulating function is multiplied by the intracavity laser intensity to give you the intensity of the output here we are not showing 9 pulses, we are only showing 3 pulses. Look at the first one this blue one is the interactivity pulse and this is modulating factor, you get the final intensity by multiplication of this factor and intensity of this pulse.

What will the product be for this pulse what is the value of moderating function here? Zero. So, anything multiplied by 0 is 0 What about the third one? 0. What about this? there is a maximum? So, what will happen is when you multiply the intensity of the mode lock pulses intra cavity pulses by the modulating factors these 2 vanish only the middle ones survive and gets intensified. That is how repetition rate is cut now is what we were saying all this time.

Do not think that E0 is just a constant. It is not because you are not dealing with a CW laser. Let us think for a moment that we have a CW we did not have, we have this laser with 2 high defectors on the 2 end gain medium. but no mode locking, it is passed by a CW laser, it is pumped via CW laser, and then the laser output would be something like this. You would get a modulated output. But even then it goes down to 0. However here, the intercavity laser itself is pulsed. That is why first of all you get pulsed output and you get an narrow pulse.

Secondly, your reputation rate goes down by how uch the repetition rate will go down is determined by what kind of capital omega you use and timing and will sharpness of pulse intensity of pulse all that is all that can be controlled by controlling the phase ready phases, end of it comes down to turning some knobs for the user, but this is what goes on inside. So, this is how one can produce a cavity dumped output of an already mode to cavity dumped pulse output of an already mode locked laser.

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Pulse picker

- Apply RF to an extra-cavity Bragg cell

- Switch direction of the beam periodically

Now, we will go on to something else and that is something we use in our lab pulse picker. Operational pulse picker is very similar to what we have discussed so far with one exception in a laser where is the mode locker and in mode lock actively mode locked laser or even passively mode locked laser. Where is the mode lock? Inside the cavity exactly what about the pulse picker where is the pulse picker is outside the cavity there is a very major difference?

So here are you use a Bragg cell, like what you use in a cavity dumper, but you use an extra cavity for Bragg cell. What is the problem with that? The problem is you generate 2 beams. Now you decide which one you want the one that has undergone diffraction that is the one that will be modulated, that is where the repetition rate will go down. You choose it but you did not take the other one that is all that part is actually dumped this outside the cavity there is no chance of it to go away back into the cavity and get further amplified.

So, you have an 80 megahertz laser use a pulsed picker to decrease the repetition rate to 8 megahertz. What you do essentially is that you throw away 90% of the energy. It is as you said earlier a wasteful technique. But unfortunately there is no other option if you want to work with femtosecond pulses till date; it has not been possible to cavity dumped Ti sapphire lasers. This is all about pulse picker works roughly.

So, once again, you play around with the phase and all you get the desired output. That is one thing. Let us now move on from the realm of ultra-short pulses to ultra-long pulses. But there is plenty of use of that as well. And when we finish the discussion, we will see that the lesson we learned from dealing with ultra-long well should not say ultra-long, longer than for ultra-short pulses is useful in ultra-short laser technology as well.

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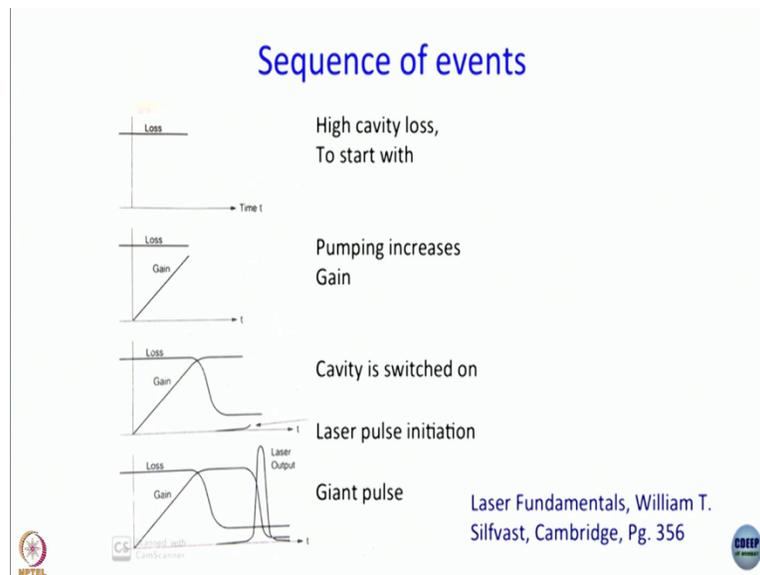
So, when we change this so you did not know what I mean by sequence of events. What we want to talk about now is how Q switching takes place. Q switching is a technique by which one cannot produce femtosecond pulses. One can produce picosecond and nanosecond pulses. But these are called giant pulses, pulses that have a lot of energy. And in fact, you could do something else. As we are going to come back to this again, you could use a Q switch to produce giant pulses which contain mode lock pulses.

So you can produce pulse envelop within which many ultrashort pulses out there. We will come to that later that part is not very difficult to understand, but once we have understood the rest. So the essence of Qs switching is that first of all, you maintain the laser in a very low Q level. Does somebody remember what the meaning of Q is in this context? We are not talking about Q in James Bond movies. Q is for quality factor. And what is quality factor? Is the ratio of gain to loss multiplied by 2pi.

What is the meaning of gain what is the meaning of loss? Gain means how much energy has been built up in the system. Loss means how much energy has exited the system. So, to start with the way Q switching works, the phase switching is that first of all you have a gain medium but you did not have a cavity now, you consider a hypothetical situation where you can magically create a cavity whenever you want.

So, let us say we only have a gain medium and it is being pumped slowly we have turned the pump on pump is becoming stronger and stronger initially what will happen population of the lower energy level is much more than population of the higher energy level. So, there will be absorption they will also know so, to start with, you have a high cavity loss. Then, as you pump gain increases, at a point when gain is nearly equal to loss, that is when you switch the cavity on.

Switch the cavity on means you have again medium here, you are pumping to start with let us say I have blocked the mirrors when I switch the cavity on me, so, I will remove my hands or whatever the shutter is and so, now the mirrors are in place, what will happen when I can switch the cavity on in this case now, stimulated emission will go back and forth in the cavity and there will be a huge increase of gain until there is saturation.

So, that is what happens and the moment that happens, loss will go down significantly because stimulated emission. So, what will happen is the population of the high level will keep on increasing finally, it will saturate and then you will have a steady state that you will reach well, so, this is Q switching, you switch from a low Q cavity to a high Q cavity but then when there is a lot of gain we are talking about a regular cavity here regular cavity means a high reflector and an output coupler.

So, as gain increases and saturates what will happen eventually a threshold lasing threshold will be crossed and light will come out through the output coupler, then what will happen then all of a sudden the moment the light comes out, gain will go down again and then you cannot have any more lasing. So, this is what will happen this is a sequence of events. Start with the loss, high loss cavity then increase gain when it is nearly equal to loss switch on the cavity so that all of a sudden, the loss goes down.

And then soon afterwards you reach a threshold saturation. After which light comes out the moment light comes out gain falls and this is how you see now this is from this point on the x axis this time here, from this point onwards, the buildup of pulse starts. And this is what you get; we do have an animation a little later. This is where this is why it is called a giant pulse, whatever energy has been built up, that is given out very quickly. Now, we are not going to discuss every detail point about this.

There are conditions involving an excited state lifetime, what kind of cavity, what kind of gain what kind of loss, I encourage you to read it from this book. For once we are citing another book, laser fundamentals by Silfvast quite an old actually book was published, I think, in 1998. And then, they have reprints, quite a nice book, but you will appreciate it if you are familiar with a little bit of mathematics and you like optics.

If you did not want to do that this discussion should serve for a qualitative understanding. Have you understood? Is there a question? Can I move on? Now the question is how do you do it? How do you at your will switch on the cavity? You do it by using something called a Pockel cell.

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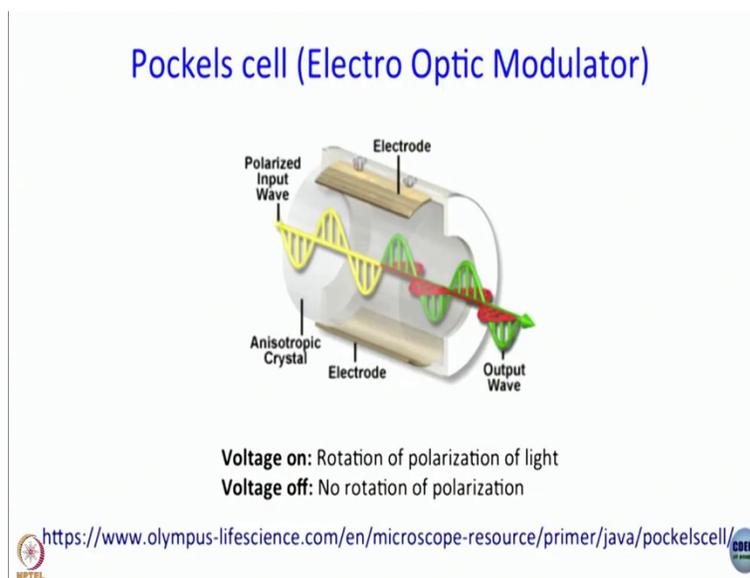
This colorful diagram is from, I think Olympus website, but you would find mode informative sources in many places. To put it very simply, a Pockel cell is a nonlinear optical media where

here you have a window through which light enters and then in a direction perpendicular to the propagation of light, you can apply an electric field. There is something called Pockel's effect we will not discuss it here.

It suffice it will suffice if we know the end result what it means is that when you apply this medium is it is a property of the medium with which you make Pockel cells, it is a nonlinear optical medium. So, when a voltage is applied in a perpendicular direction to the propagation of light, if the light is polarized light application of voltage causes rotation of polarization and now by how much rotation. So, if there is no voltage there is no rotation, if voltage is there then rotation is there.

So, you can for chemists, you can think that this is something like an electric chiral media who know chiral media rotate the molecule rotate the plane of polarization of light. Here also the plane of polarization of light is rotated, but only when you apply an electric field. Now, the question is by how much does it rotate it? Does it rotate by 4 degree or 50 degree, 90 degree or 180 degree? It depends on what kind of voltage you apply for how long.

So, what is shown here is how to produce circularly polarized light, you apply the electric field in such a way that the output is half horizontally polarized light half vertically polarized light with a certain phase difference that is what gives you circularly polarized light. If they are not exactly the same ratio, you get electrically polarized light. If you can convert everything, then you get a 90 degree rotated plane polarized light.

Half of that you can rotate by 45 degrees or whatever you want, that completely depends on the medium and the voltage that you use and then you can apply the voltage for a small amount of time 10s of nanoseconds or microseconds or something. So, suppose you applied it for 10, 9 nanosecond then what will happen? Polarization of the light going through will rotate for this 10 nanosecond only. The moment you the voltage off polarization goes back to its original position. So this is how Pockel cell works.