Optical Spectroscopy and Microscopy : Fundamentals of Optical Measurements and Instrumentation

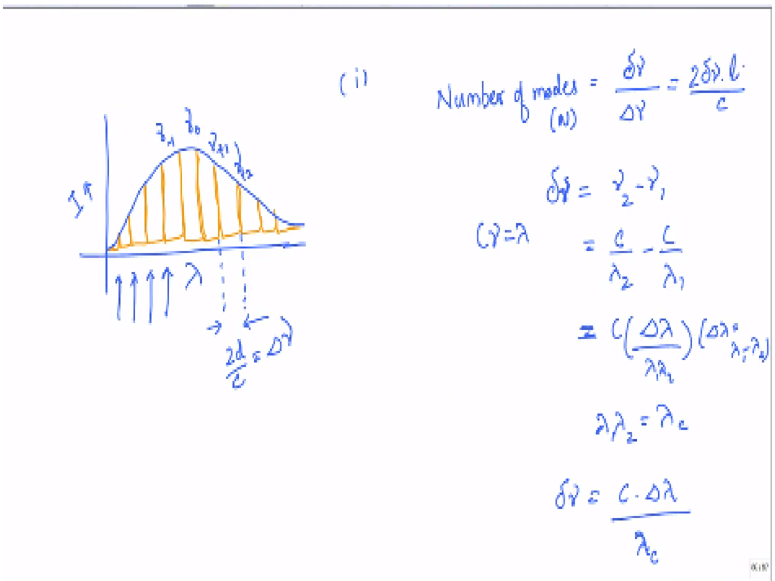
Prof. Balaji Jayaprakash
Centre for Neuroscience
Indian Institute of Science-Bangalore

Lecture - 36

Hello and welcome to the lecture series on the Spectroscopy and Microscopy. We have been looking at generation of the pulse lasers so far and we looked at Q-switching the various ways we can actually generate or implement this Q-switching and then we just piped into mode locking and how we can actually generate this different modes and then still be able to lock in phase these different modes inside a laser.

I had told you that we would look a little bit more deeper into the relationship between the number of modes that you are able to phase lock and the time profile itself. And that is what we are going to do in the beginning today.

(Refer Slide Time: 01:40)



So we said if you look at the gain bandwidth, alright if you look at the gain bandwidth of a laser, and we said that let us say the spectrum of the media is something, the lasing media is something like this. Then the structures that you I mean the because you have put that game media into the cavity, the wavelengths that this lasing medium the cavity can support or the laser can operate on is not the continuous every single wavelength that is present in that entire spectrum.

But there is a discrete set of lines that can be represented. We saw that previously and even in the previous class we have extensively looked into it. So what I said is that one of the ways of thinking about generating this mode lock pulses is to think of saying multiple lasers, okay. Each one of them operating at these different frequencies. So let us say it is a central lambda or a center, I mean center frequency which we can pick one of them.

And I think we have been talking about mu 0 as the central frequency. And then if you go mu plus 1 or mu minus 1, each one of them you can think of as a separate laser operating, except now since they are phase locked, if they are randomly oscillating, then their intensities when you add up, they would not necessarily constructively interfere, but they will cancel out with each other because they are randomly interfering.

And then you may or may not get you may get an average light that is constantly present. But then if you if it were to be possible for us to actually bring them all in phase and do through an acousto-optic modulator or any of that, or any of this device, then we said not only that the central frequency even though we are actually modulating the central frequency, because of the modulation of the greater omega

If the, I mean the capital omega frequency were to match that of your round trip that the mode separation, then what you see is that not only the central frequency but the adjoining modes also get supported and also get picked up in this while you are giving this modulation. So like that, we can actually walk across this entire spectrum starting from mu 0 to mu 1.

And then at that point, then you would be getting mu 0 and mu plus 2 as your side bands, so on and so forth. When you keep doing that, what you end up having is that a bunch of frequencies all phase locked together coming and starting at the place where the AOM is present. So now at the in that case, we could think of the amplitudes being present as a sum of all of these amplitudes together.

So now to know I mean to know how many of these waves are even adding up with each other and then how does this pulse width depends on that number what we are going to do is we are going to first estimate this number n and then sum it all these frequencies assuming that the amplitudes are same, we will sum it over all these frequencies and then see what is the relationship between the time, the envelope period and then the modes.

So it is pretty simple. So first thing that we want to do is we want to know how many number of modes are existing in the cavity. Now that is pretty simple. What we do is that we take the bandwidth of the it is a gain bandwidth. We can, it is delta nu. We have to express this if we are measuring it in lambda, then we actually have to express this in the frequency units. So it is delta nu. So we will talk about that in a minute.

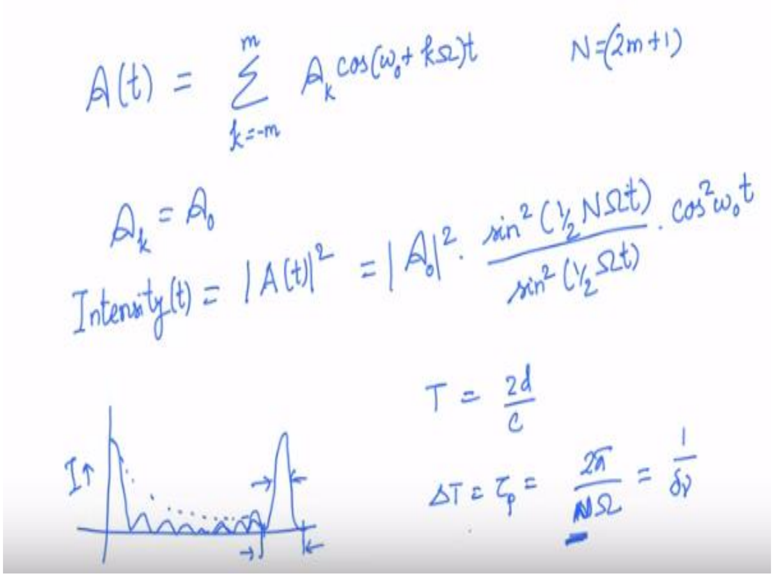
And then we will divide that by the spacing, okay the spacing between the two modes two longitudinal modes. This is nothing but 2d by c, right. This will we will call it as del nu. So which we can write it as, so now this tells you that, that is my entire gain bandwidth and since the spacing is only so much it gives me a way of writing number of modes N as follows.

Now in order to estimate this delta nu because the actual experimental observed one is the spectrum that we observed from the spectrofluorometer. So del nu we typically do that in in terms of lambda in nanometers. So for a visible fluorescence. So del nu we would like to express this in terms of mu 2 minus mu 1, which is basically c is equal to mu lambda. We make use of the fact c is equal to mu lambda.

We want to express it in lambda, okay. And so then we can write it as c by lambda 2 minus c by lambda 1 c times delta lambda by lambda 1 times lambda 2. And please note, the delta lambda that we have defined here is actually we could, what we need is an absolute number so we could actually take it as the bar but nevertheless. So we would replace this lambda 1 times lambda 2 as our central lambda.

So you could write our del nu as c times delta lambda divided by lambda central, okay. Now given that then we can actually we know now there are number of modes in terms of the bandwidth in nanometers and in terms of the cavity length. Actually we have been using l for the cavity length. Yeah c by 2l.

(Refer Slide Time: 10:54)



So then what we do is that the next thing is to say the amplitude the resultant amplitude at any time t is given by of the electric field itself right. So k going between 0 to n and for convenience sake what we are going to do is that we are going to split that n into in symmetric interval about 0. So I am going to say m to m such that our total N is basically I mean is covered by this, okay?

So if we do that, then we could what we could do is that we could write A k this is the index of summation. And for the situation where A k's, all the A k's can be assumed to be equal and then to be the A 0, we can add the sum. And when we add the sum, what we get add and this is amplitude and then what we are actually after is the intensity, is basically the amplitude square, modulus amplitude square, which will be actually t A of t.

So where I am sorry intensity as a function of time we want to express. So that would be A (t) modulus square, which will be given by A naught modulus square times cos square omega naught square k omega t summed over k from minus m to plus m. If you do that and you will get sin omega t an envelope function that is given by half sin square N omega t by sin square omega t.

And a carrier frequency of cos square omega naught t. And what it tells you is that the if you look at the width between the zeros of the function which is basically you want to look at the argument of the sin square term and then see where all it actually 0 the zeros occur and as a function of N. You will see that, so if you plot this function it looks as something like that.

It depends on the how many number of n's we add and so on so forth. But generally, it is a it peaks at regular intervals and the interval itself is given by your the round trip time 2d by c. But then the amplitude per se drops down. And then what we are actually looking at is that the time period between the zeros because that tells you the temporal restriction or the temporal constriction that we have been able to generate or a temporal restricted pulse that we have been able to generate.

And that we can call it as delta T or tau p is basically we have to set this argument to 2 pi divided by N omega which basically is 1 divided by del nu. So what you have got, what you have gotten here is the relationship of the tau p being inversely proportional to del nu the bandwidth for the case where the amplitudes are all equal, okay.

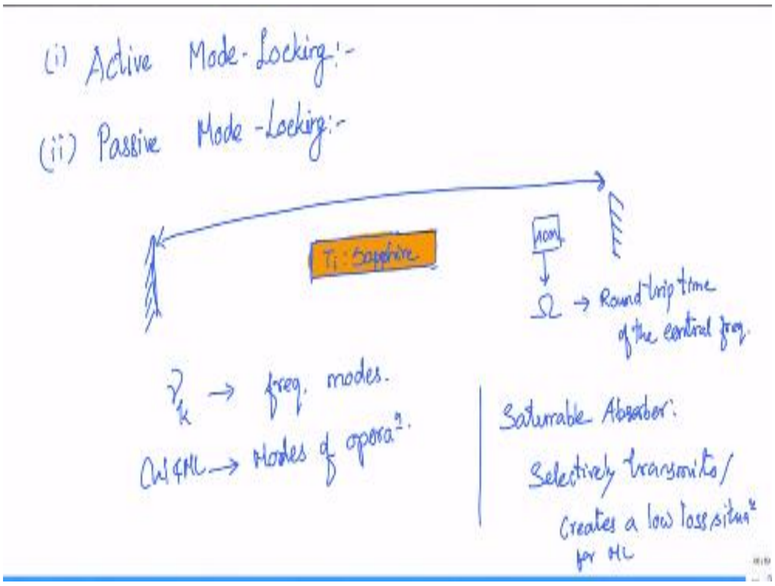
So the higher the number of or we can actually you can actually see from here, the higher the number of these modes, which is wider the bandwidth, then you have the shorter the pulse that you are able to generate. Thus, we this is one of the reasons why when we were actually trying to define what are all the characteristic features of a laser or a laser light we consciously stepped away from defining it as a monochromatic in nature.

Because what we are what we want to ensure here is not necessarily the monochromaticity as you can see from here in the pulse laser particularly the femto, as you bring the pulse width, narrow and narrower, what you see is that the bandwidth the frequency content in that pulse is of that pulse is pretty distributed. And you that the monochromatic argument runs into trouble.

And in fact, what we are actually looking at is that as one way of interpreting this whole scenario is to think of N number of, this N number of lasers, each of them are monochromatic, you can think of that way, all operating in synchrony to generate and give you a pulse, which is of laser or again, it is a laser pulse, which is very time restricted. So then the whole thing comes all in one place.

Because these are all coherent, because that is why you are able to actually make the interference happen because you can phase lock them. And since they are coherent, they can interfere and then they generate a time restricted pulse, alright. So now we just to bring things to perspective. Now how do we actually generate this kind of a pulse in a practical laser, alright?

(Refer Slide Time: 19:56)



There are two ways of generating these pulses. One is called as active mode locking. And clearly the other is called as passive mode mocking. The active mode locking is a scenario where you are actually having the titanium sapphire. I mean I am going to take an example of a titanium sapphire because that is predominantly what we will be using in the course during our lab demonstration, as well as for understanding the or for utilizing that to in our various microscopic studies.

What we will what you can think of is that you have a Ti sapphire rod as a lasing medium, alright. So inside this what you have is an acousto-optic moderator, okay. There are quite a few optics. We will go, eventually we would have gone through when we go through this course, we would have probably gone through each and every one of these elements and then told you why they are existing and so on and so forth.

But the point here is that in this cavity what you will see is that an acousto-optic modulator that is kept inside this cavity and then operated such that the frequency of this operation, right corresponds to the round trip time of the central frequency of operation okay. So clearly the round trip time depends on the length l of the cavity.

So when you when for some reason if the cavity changes then you are going to change the frequency of operation of this AOM to so that it can phase match with the pulses that are being I mean pulses that are being generated in the cavity and then keep it mode locked. Now that is active mode locking. You can also use pockel cells to actually do the similar things where you open up in definite intervals of time.

But interestingly, you do not need to have any active component existing inside this cavity to generate the it turns out you do not need any of this active component to generate this mode locked pulses. But you can use passive devices such as saturable absorbers. Now, we did look at the saturable absorber in a slightly different context in terms of the Q-switching.

So what happened briefly what happened is that, there are substances specifically dice of with a very high cross sections. So what they if you put them inside the cavity, what they do is that they keep absorbing the laser light, thereby not letting any of the light go through until you have reached enough intensity where the population of the excited state and the ground state becomes equal.

Then you create a optically induced transparency or is you saturated the absorption process. So now you can actually use that here in this lasing system to create a mode locked pulse. You select out a mode locked pulse. So as we all know in a lasing cavity, when you are when you introduce any selection element right to the lasing cavity can operate in various different modes.

So the modes can be of because of different frequency, right. These are frequency modes. They can also be of modes of operation CW mode, locked pulsed and so on and so forth. So when you start of a laser, there is a finite probability that the laser starts with the operation of all of them in I mean in a synchronized manner. It is a finite, it is a non-zero probability.

It is a small probability but it is a finite probability that it can actually start of or operate of in that synchronized manner. Now if on top of this, if you actually introduce a sum selection element selection criteria into this cavity such that these phase locked operations are selected against the other.

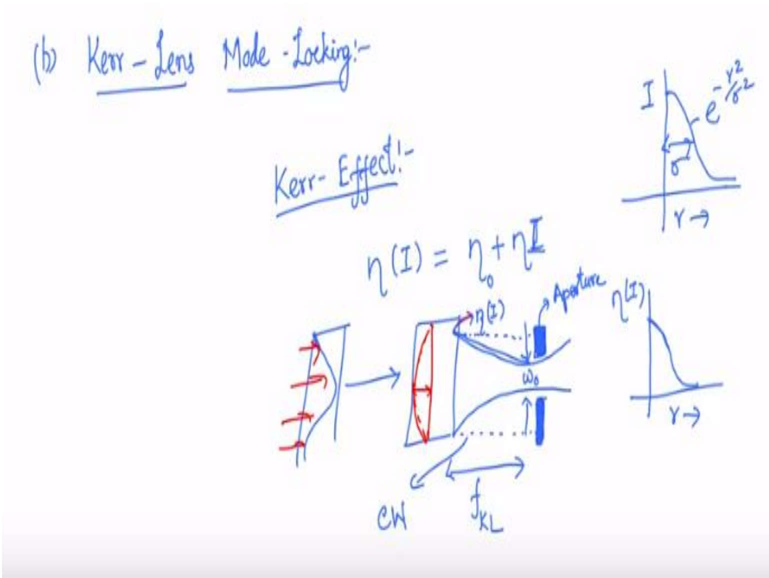
Even a minute selection criteria if you are to give, quickly that advantage translates into this pulse non-linearly extracting out all the energies that are stored in the media into them at the cost thereby dominating the whole laser mode. So now, one such way of introducing this is like, then we are having a different modes. It is called the modes of operation. We will call it as CW and ML.

So what we can actually do is that instead of a AOM, if you have to have a saturable absorber then what the saturable absorber does is that it absorbs all the if you introduce a saturable absorber now the pulsed mode of operation when you look at it right, the intensity here right, this is the intensity that we measure, the instantaneous intensity is very high, while the average intensity is extremely low.

So if there is in the saturable absorber if you carefully choose this saturable absorber such that the high peak intensity can actually cause the saturation really quickly thereby, resulting in the optically induced transparency but that does not last for long because the pulse itself is very short duration. And of course, your lifetime of the saturable absorber should be able to let you do this.

And then when the pulse gets transmitted, there are other CW modes that are existing in the cavity gets absorbed. Thereby, what you have done is that the saturable absorber selectively transmits or creates a low loss situation for the mode locked operation. So it is this I mean, this is one way of actually selecting out the mode locked pulses coming from the titanium sapphire. There is one other mode of making the passive mode locking possible.

(Refer Slide Time: 28:56)



And that is called it is called Kerr lens mode locking. You do that by, this makes use of the idea or an effect called as the optical Kerr effect. So when you look, we had looked at the transfer section of the laser beam. We said that there are different possible modes of this transfer section TM 00, TM 01 and so on and so on.

And we said that the lasers are designed such that they operate dominantly in TM 00 mode for various different reasons. So one of the characteristics of that mode is that when you plot the intensity as a function of any spatial coordinate right. So in this case r what you see is that the intensity I is following a nice little Gaussian distribution with r square by sigma square. So this where that is sigma.

So in this what happens in this what happens is that the intensity is very high at the center, spatial center of the beam and it falls down as we travel away from the beam. So now the optical carrier effect actually utilizes this. It utilizes the fact that the refractive index of the medium is normally independent of intensity. And that is, but then at intensity sufficiently high enough.

Then what it says is it is at that intensity is the it becomes dependent of the intensity itself. Little later in the course, we will actually look at how this effect comes about, but right now you can actually take, we can take it as a fact that the at high enough intensities the refractive index itself becomes a function of as a function of intensity.

So if you take into account this then the we can actually plot out the refractive index of the beam as it travels through the medium which is still is having a uniform refractive index n naught in space. Now when you do that, what we see is that the n of I the nonlinear refractive index for a Gaussian beam would look pretty similar to this, right. So this is n of I expansion of r.

So as a result, the beam of light as it travels through, so if you can, if you have to take a cross section across here, because of its intensity having this Gaussian nature, as the beam of light travels through, what we what we see is that the refractive index that it sees is high here and low here. As a result, the regular medium right, the medium with no I mean it is a with a parallel surfaces and so on and so forth looks to this beam as if it is curved.

If you to better appreciate this if you actually look at the wave front of the or the face front of the beam lights that are coming up from here, then what you see is that the ones that are at the edges suffer larger I mean lesser phase delay while that at the center suffers a larger phase delay effectively acting as if it is a lens. As a result that like a by convex lens, right. That is exactly what happens or a planar convex lens.

And that is exactly what happens in a lens because what you do is that you have created a thicker granted uniform refractive index, but then is a larger path length and the smaller path length. And this is exactly what is happening in a in the other one that the blue line the media with nonlinear refractive index or a intensity dependent refractive index.

What you have seen is that it feels the beam experiences a larger refractive index because of the higher intensity at the center, while lower refractive index on the periphery. As a result, the beam as when it passes through it starts to focus and when it what you can actually do is that we have not talked about the focusing properties yet as of yet but you will see when we talk about it.

The beam gets, the spot of the beam gets constricted. And that is the spot at the center and then expands. Now what you can actually do is that if you know or if you guess what would be the nonlinear element, what will be the element that with a nonlinear refractive index, typically in a titanium sapphire laser, the crystal itself acts like this. Then we can estimate the focal length of the optical Kerr lens.

And at that focal length if you were to have an aperture, now the effect of this would be to select out just that the effect of this aperture, this is the aperture we talk about. The effect of the aperture is to select out just that beam because the regular beam, the CW beam, would not experience this difference, right. Because the intensity is not sufficient enough. So what you see is just a dominant n zero.

Because the peak intensity of the pulsed beam is higher. As a result, what is happening is you are seeing this reflective index. So in effect, what you are doing is that you are blocking out the regular CW beam. While the high intensity beam creates this lens effect from the, I mean creates a phase difference making manifesting as lensing of the beam through the titanium sapphire.

And then when you pass it through an aperture only that is able to make it through, not the other. So this selective transmission make gives an advantage to that mode of operation thereby dominantly creating that mode being the dominantly creating a pulsed laser mode as the output for the lasers. So by opening and constricting this aperture one could actually enhance the ability of the laser to mode lock and or operating in a CW fashion.

Now that brings to the end of different ways of actually generating the pulse lasers. From the next class, what we would, what we will do is that, we would focus on understanding devices and we will do a little bit of a detour from the theoretical approaches and then we go into understanding little bit of the devices. We have dealt quite a bit about the lasers themselves which would be acting as a light sources.

So using that, we would take up one of the device, one device after the other. And then, then and there, we would incorporate or extend our theoretical analysis of the principles governing the extra peripherals that are used in this equipment. I will see you in the next class. Thank you.