Optical Spectroscopy and Microscopy : Fundamentals of Optical Measurements and Instrumentation

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Lecture - 32

Hello and welcome to the lecture series on the Optical Spectroscopy and Microscopy. In the last lecture we were talking about different kinds of modes, transverse modes and the longitudinal modes that exist in the lasers. And the whole idea of doing this is to understand how some of these properties are critical in determining our ability to generate short pulses, short laser pulses.

So in this continued effort, what you are going to see is now in this class how we can actually generate this laser pulses and eventually we will try it back to the different modes that we talked about and then see what we can say about their role in the pulse lasers, okay. So now here for the generation of the pulse lasers, it starts from our very first or very initial lectures.

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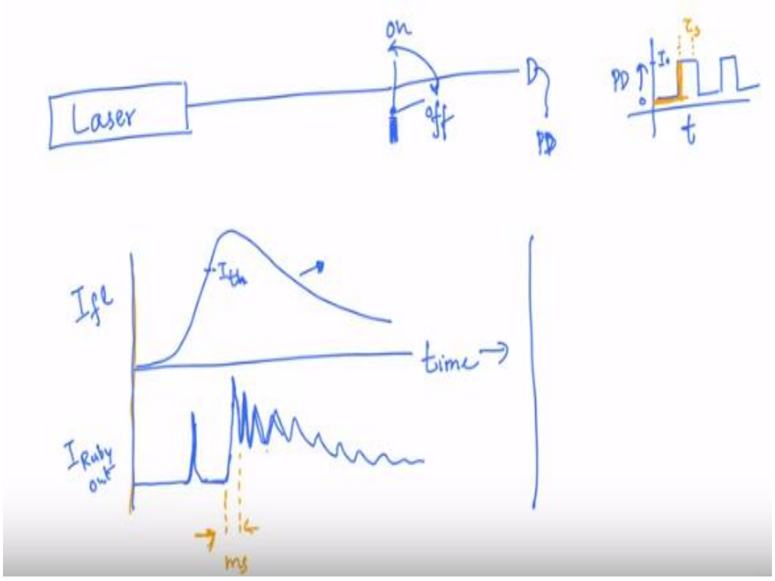

Where we ask the question okay, now I have a laser and I am going to actually put in a mechanical shutter that can actually oscillate between an on state and an off state, okay. This is on and this is off. When it is off, the light can go through and when the shutter is on, the light cannot go through, alright? So it can actually go between these two states. And if by doing this, and I am going to put in a photodiode.

And then if I plot the intensity or the output of photodiode okay, so intensity measured by the photodiode which is the PD out as a function of time, you will see that the light goes between some state I with light being there and then to the baseline state 0, where there is no light, okay. Now the question that we asked is, can I keep increasing, I mean, clearly this period alright, so let us use a different set of colors here.

Clearly this period here corresponds to tau s which is a shutter open period okay. So the question that we were asking is, can I arbitrarily bring this light pulse bring down this tau s such that I generate very short pulse or is there any limitation to it. We know that this can be dealt with through the uncertainty principle and then we said hey, it boils down to the bandwidth of the light that we are actually having to start with.

If you have a higher bandwidth or if you want to go down in pulse then we have to increase the bandwidth, energy content of the light that is, we are dealing with. And so then when we looked at the He Ne laser, then He Ne laser’s bandwidth by itself, we saw that we can actually easily go to about a microsecond or so.

And it turns out the pulse lasers once, I mean pulse light from the lasers, were actually originally thought of getting generated by looking at the output closely in an oscilloscope something similar to this. So the thing dates back to Ruby laser’s output and it is been and the analysis of the output.

Now if you actually look at the first paper that describes the Ruby laser, or the spiking in the Ruby laser, you see this very typical phenomena being documented nicely where you have the time in this axis. I am going to be plotting here intensity of the flash lamp and intensity of the Ruby output, okay. So now you know that the flash lamp actually is acting like a pump.

So the pump profile, the profile of the pump lasts for let us say that here few hundreds of a milliseconds or so. Now if you actually look at the laser light output of the Ruby lasers, then what you see is that you see output just like measured by a photodiode.

You would see an instrumental artifact because of the light being turned on to the electrical coupling and all that stuff.

But the main important thing is that the light, the Ruby light output takes some time, okay? And that is the time where probably let us say, the threshold for lasing has been reached. At that point you start seeing the laser output but instead of following the time profile of the laser lamp or the pulse lamp, what do you see is a fine structure that emerges inside of this overall lamp profile.

And these clearly are in millisecond range, sub I mean millisecond range suggesting so the laser output here itself, I mean invoking a huge reel of studies on why is this transient behavior happening. In fact, you can actually do this very analytically. And the way you do that is actually writing down the population equations just the way we have done it for looking at the two state three state lasers and their descriptions.

Now what we do is what we did there is we actually solved for the steady state, okay. Now what we need to do here is that we do not want to do solve it for the steady state, but we actually want to look at the time evolution itself. And when you look at the time evolution, there are good reasons for us to predict that this kind of a transient spiking to be seen in this lasers. The origins of that comes from the fact, now if you look at the population dynamics, okay.

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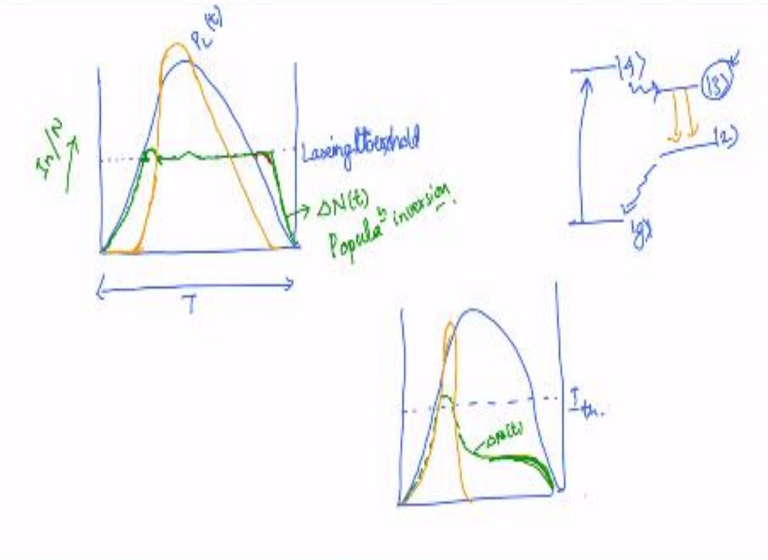

So we were going to plot here the population of, actually population inversion as a function of the pump laser, okay. So now and let us say the pump laser intensity so this whole thing is the time profile of the pulse pump laser. Let us say this pump light flashlight here this is a function of T. So now let us say our threshold for lasing is somewhere right about here. So this is the lasing threshold.

Remember, this is determined by the balance between the gain and the loss I mean gain due to the lasing medium and then the loss suffered by this stimulated emission light in the cavity. If there is a balance that is achieved then in any point above that if the population inversion crosses above that threshold, you are going to have lasing. And if it falls below, then you are not going to have lasing, okay.

So now in the same graph what I am going to do is that I am going to use my description right of this the population description of the my system and then plot out the number of the or the population inversion as a function of time. I can solve it, because it is a set of differential equation, which we can actually solve it. And then when you solve it, you solve it for delta n of t.

Now if you plot that delta n of t here along this graph, what do you see is that as the time as the flashlight is turned on, your population inversion starts to build up, right? That is no surprise, actually. So it starts to build up and it builds, it builds up and then at this point, it starts to, there is a small bump and then what you see is state that is right about here and about at the threshold level before actually it falls back okay.

So now this green here is our delta N of t which is the population inversion. Remember if you do not have a population inversion there is no gain to the stimulated emission, no gain in intensity of the stimulation emission. But why is that coming back down? So what is happening is while you are measuring this right it is so then so this is just it could be the intensity or the number if you are measuring the population inversion.

So what is happening is until this point until this point here, so what we have done is that we have plotted the population inversion. And I just told you that it is going to go up with a little bump and then comes a steady reach a steady I mean, reach a steady value around the threshold and then before the it starts to fall off again at around the right after the flash lamp intensity right, where the flash lamp starts to, the profile of the flash lamp starts to fall down.

Now why is this not going beyond because we are continuously exciting it should go up, but what is happening is at this point, since it reaches the threshold, you will see the lasing right, there is no lasing until this point. Once it starts to reach, crosses the threshold, you start to see the rise of the lasing and its stimulated emission. So it depends on the intensity of the number of photons that are present there and then who can extract.

Now it is so as a result, the slope right, the rate of increase is going to be larger because as the new photons new stimulated emission emitted photons are coming into the cavity, each one of them are going to extract more of this energy. As a result, quickly the slope, okay slope depends on the intensity of the stimulated emitting photons. So since for each passing round it increases, the slope increases and it exceeds, I mean it is larger than the pump profile increase itself.

So quickly it crosses even though it starts late it actually crosses the pump profile at some point. And from that point onwards, you are actually starting to deplete actually the light, the population inversion. And but then it is been constantly being supplied by the pump profile. So what you have is that once it crosses back again that is it starts to deplete continuously.

And then it falls before the lamb profile could fall because it extracted and now it is only maintaining at the level of the, maintaining the population just about at the level of the threshold. So now this behavior clearly you see gives rise to pulsing or pulsing that is shorter than the lamp profile itself, okay. So the lamp profile did not have this, the lamp profile was much longer.

However, what you have done is that what you have, what the stimulated emission has done is that it has actually constructed, it has restricted because of the nonlinear dependence of the intensity and it is on the population inversion, it actually restricts the profile to be smaller than that of the pump laser profile. So because of this, what you have generated is a pulsed laser output, okay?

And this assumes that in our lasing media, when we talked about four level lasers, let us say for example, the only rate that matters here is I mean it has long enough lifetime and all that stuff. Only rate that matters is only the driven by the stimulated emission process and then the optical pumping process and so on. However, if for some reason, okay, so this is our lasing and this our pumping rate.

So now what we are saying is these are ideal, okay. The rates of 4 to 3 and 2 to 3 g are very ideal. And that says in that case that is this is what you will see. However for some reason, if the lifetime of and of course the lifetime of this is larger. So if the lifetime of this process when the state is smaller, then what you see is that there is a self-imposed restriction of the time profile apart from that determined by the dynamics of the extraction of the population inversion from the because of the stimulated emission.

So here we assume that the lifetime is long enough that the depletion caused by the population inversion is purely because of the stimulated emission extracting the energy. But if you include the finite lifetime then the same graph what is going to happen is that we will do it again so that is our I threshold. Now what you will see is that the pump profile of course the population inversion follows the pump profile exactly the same.

However, when it when the population comes down, it cannot I mean, since the state three cannot stay there for long enough period of time, what is going to happen is that you would see a further decline. In the decline it immediately brings down I mean, where the I mean or in the population inversion before population inversion. As a result, if you have to plot the emission profile.

So you have this emission profile going up, however and exceeding the pump. But then however because of the I mean depletion, bringing it down below the threshold, it is going to fall back down. And sorry that is population okay. The population inversion is going to look pretty much like this.

I mean not population inversion, but the population difference between the 3 and 2 will look again in the green curve pretty much like this below the threshold and it cannot lase. As a result it cannot lase. So now this is another way nice way of restricting the time profile the temporal profile of the laser light that we actually generate. So using this, if you actually ask, can we actually reason out what is happening in the Ruby laser?

Then it is pretty simple, right? Because what you are actually seeing is that process. The process wherein you have excited the excited and created the population inversion. But remember here, the delta n we are talking about is between the, it is a three level system, the Ruby laser is a three level system. So it is between the excited state and the ground state.

So as a result, the moment you start extracting the light energy, okay and the intensity that is coming out from it is going to be extracting or depleting more of the population, more of the population in the excited state and bringing back into the ground state. So the delta n actually falls down much more rapidly. And as a result, you have a decline before the intensity of the stimulated emission here itself in this region.

The decline in this region I am talking about. This decline itself is coming, it is letting the population inversion to recover because of the pump and then doing this up and down motion given while the overall amplitude is driven by the flash lamp profile by itself. Now that allowed people to think of ways of generating pulsed laser light. At that point, we are talking about microseconds of laser pulse milliseconds and microseconds of laser pulse.

But now what do you what people wanted to generate are the light pulses that are much shorter. In fact, in the lab as we will go to during the practical session, we will see what we have is a femtosecond laser system wherein the pulses of light start and end within about 100 femtoseconds. Now how do we generate them? And what are all the process? I mean, as you can see, that we could in principle generate by cleverly playing around with the population inversion itself. That is one way.

And there are also other ways of actually generating these pulses, laser pulses. So what we are going to ask is, how are we going to generate these laser pulses and what limitations do they possess and in this regard, I will be talking to you about, I mean there are many different ways of generating this. But in this regard I will be talking about two specific ways.

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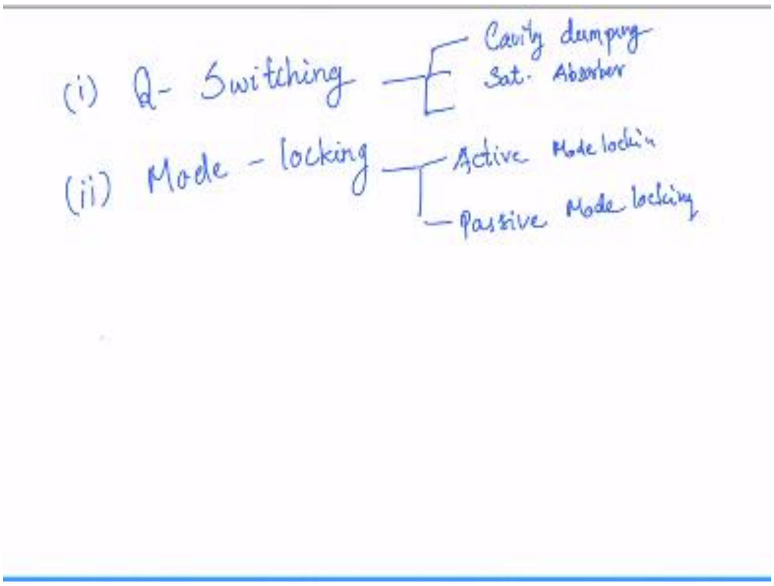

One is called as Q-switching and the other we call it as mode-locking. Of course, there are many ways of achieving this Q-switching and typically we will be talking about methods like cavity dumping and saturable absorber and so on. And here we have active mode-locking and then passive mode-locking. So we will be talking about these four different things of four different ways of achieving these pulses from the laser lights.

So let us look at the operation principles of Q-switching itself. So in order to generate this laser pulses people argued now we know that the dynamics, by modulating the dynamics of the population we can actually modulate the laser output itself. So can I in a controlled manner, modulate this dynamics such that I can extract out maximum amount of energy, pack in a big punch of energy in a short period of time, in a brief period of time.

That way I can actually generate not just a brief pulse, but a brief and an intense pulse. So the first of that method is, as I told you is about Q-switching. So let us look at Q-switching.

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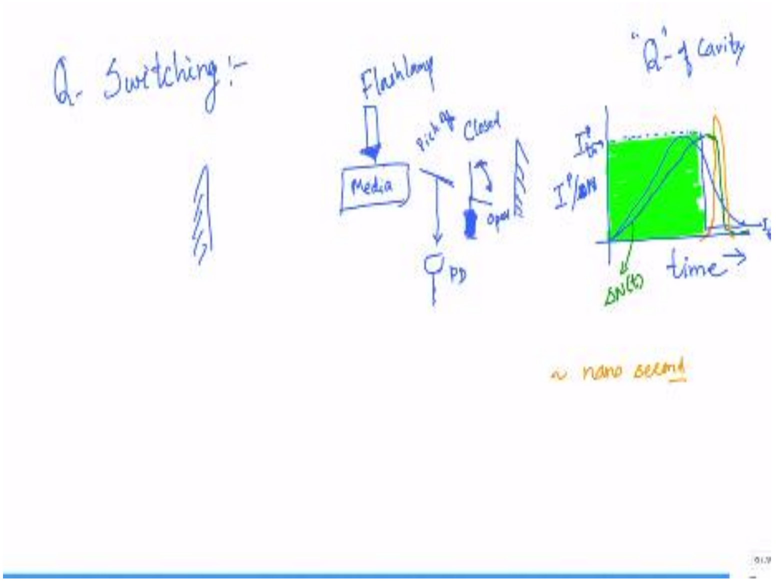

So what is going to happen here is that we are going to have the laser cavity just like usual. And you have a media and let us say this is being pumped by a flash lamp, I mean good. So in order to be clear about this, I am going to just draw a big arrow. So to represent flash lamp is going to drive in, is going to bring in more and more of energy into the system.

However, what we will see is that inside this cavity if suppose I am going to operate a small shutter, okay? Now the shutter is such that it is going to prevent again the same way. So this is the closed state and this is the open state. The shutter can oscillate between these two, okay. And what I am going to do is this which is so this is my, right before this I am also going to have a small mirror or a small glass plate.

It is a transparent plate that also has a small reflection coming from here putting on to my photodiode, okay. So now what I am trying to do here is that I am actually blocking the laser cavity, which means it effectively blocks the lasing, start of the lasing, and then I am going to keep pumping the media constantly until I build up a population inversion that is pretty high I mean as much as I can build up.

I mean I can as until the point of flash lamp what the flash lamp can allow, the intensity of the flash lamp can allow. And then going to suddenly turn this cavity to the open state. You can think of this as in a closed state, the cavity is having a very high loss, okay. The loss coefficient the gamma is very high. As a result sorry the loss coefficient is very high. As a result, the threshold for operation is pretty high.

Until that threshold is reached is never going to operate. So you can represent this in this nice way. So you can think of the Q or the Q factor of the cavity right Q factor of the cavity, which is a measure of how lossy it is being changed from I mean being modulated by the shutter. And when we look at the I threshold as a result of this Q factor, what you will see is that to start with it is very high, okay?

And this entire region we can think of this entire region is the region where the shutter is in the closed state, okay. This entire region where the shutter is in the closed state. I am sorry and we are going to open the shutter later here, okay. So this is what we are going to do. This is a function of time.

But what we are, when we do that and then of course if you say that the pump because of the flash lamp being flashed lamp being turned on the pump profile, if you are to draw here, it would look, let us say it looks something similar to the following, alright. So now what is what do we want to actually ask is that what happens to the so this in this axis, what are there are quite a few factors, so let us re-label them.

So what we are actually doing is Q of cavity is being modulated. And this is my I threshold, okay. So I am plotting in this axis, intensity of the pump beam. This represents I threshold. I can plot I am plotting this same axis I pump beam and then delta n, are the actually the number n itself. So and then the delta n is the function of t, what is going to happen?

Because it is the profile, lamp profile and then we are having a high loss, what is going to happen is that it is going to continuously increase until this point, okay. So increase until this point. The moment, so you can sense this, how? Because what you can do is you can actually watch when the population inversion keeps going up in the population or the excited state keeps going up.

You know that the spontaneous fluorescence, the spontaneous emission, the fluorescence coming out from this media is going to keep going up. Now the mirror that we have put up like here, it is called the pickoff mirror is going to send in a small portion of this light into this light beam into the photodiode.

Now you can actually see how much has the fluorescence gone up and at a point where you have pre decided and said that okay, this much of the fluorescence would correspond to a threshold that I would like where the cavity would have mean that the population would have built to that level, you what we do is that we turn the shutter to the open position and then the Q of the cavity suddenly falls.

Which means I mean, when the there is a less loss in the cavity and the threshold of the cavity suddenly falls. Now this is our new threshold. So what you see here is that there is a huge buildup or a huge excess of population inversion that has built up at this point in time and as a result right after this okay, you start to see the laser emission. But because of this, but this laser emission is going to happen until a point where okay, this by the same convention we have to we should have plotted our population inversion in green.

So N (t). So this population inversion is first thing you notice is that it starts to flat out and it is not going up anymore. Its exponential rise is going to flatten out because of quite a few reasons. One, the pump itself is falling down. Second, its, the laser emission has started. As a result, what you see is that it will start to extract more of this light. And then at this point the pump profile has also fallen down.

So what do you see is that a sudden decline, which is the rate of that decline is given by the slope, the speed at which the emission profile raises and going down here. As a result, if you look at the emission profile, the emission builds up reaches a high point. After this it cannot sustain because the population inversion starts to rapidly fall down. And this follows rapidly.

At this point, it is below the threshold and it dies down. So what you have done is you have really by timing the loss, I mean timing the change in loss of the cavity, you have shrunk the laser emission profile over I mean the entire stimulated emission of the region where it at which it can happen to a very small timescale, okay. Now such kind of switching right by monitoring I mean by altering the cavity loss is called a Q-switching.

And you can generate quite easily nanoseconds of pulses I mean micro to nanoseconds of pulses, nanosecond pulses using this technique. And we will in the next class what we will see is we will see the various methods I mean various techniques one uses, the practical techniques one uses to actually generate such kind of laser pulses. Okay. Thank you.