Optical Spectroscopy and Microscopy : Fundamentals of Optical Measurements and Instrumentation

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Lecture - 30

Hello and welcome to the course on the Optical Spectroscopy and Microscopy. In the last lecture we have been talking about how we can go from the photonic description to the I mean how we can interchangeably go from the photonic description to the wave description and under I mean, how do we establish the equivalence between these two, right.

And then we said okay, and now I am going to use this to actually define coherence in a more practical terms, so that which I can, so that I can measure it in the lab and then see what use does it have. In order to do that I was talking to you about extended light source which is basically nothing, which is basically a simple thing where we have a linearly arranged set of point sources each giving out light okay.

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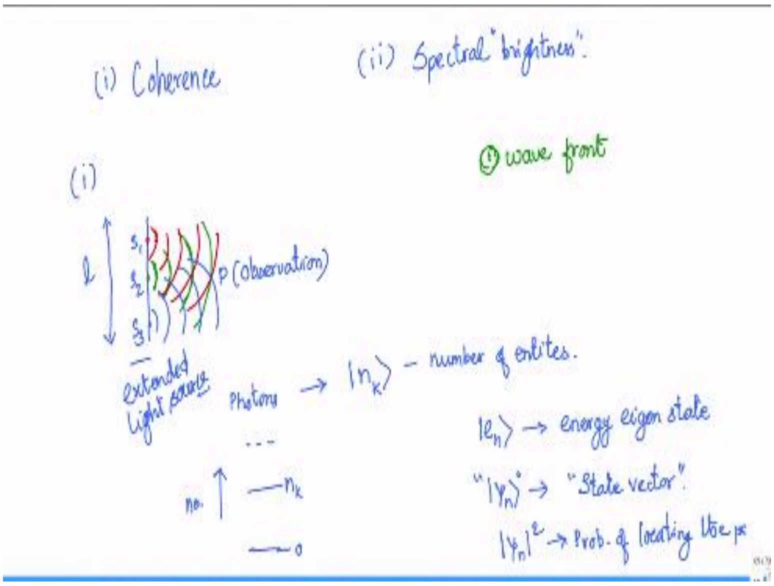

So then if they do that, if you think of extended light source something like this, what we have been seeing, so if you see think of the extended light source, this being the extended light source. Then what we were actually looking for is that at P the point of observation what happens to the intensity or the probability amplitude or the probability of locating the photon.

So in order to do that, I am going to make use of the fact that every source, what we can actually do is that we can actually write down the functions describing the light that is coming out from this source.

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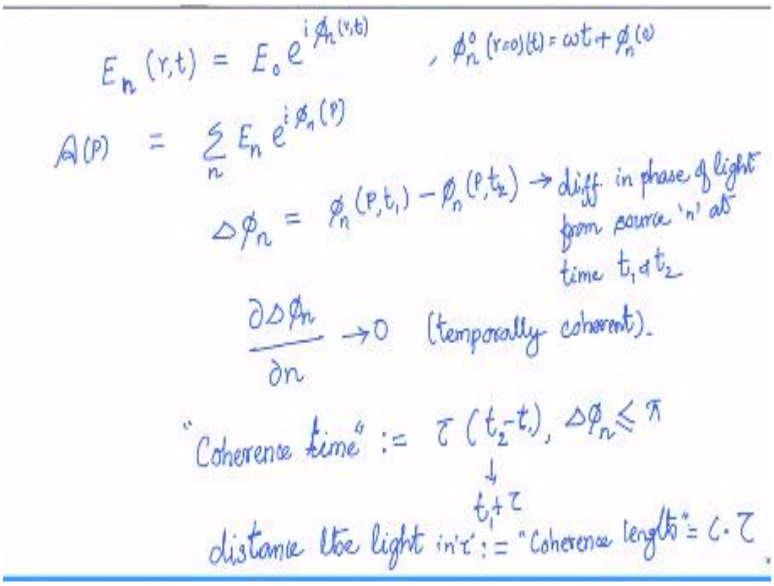

We are going to write down each of the source as basically intensity corresponding to source n, I mean I in the exam the diagram we took three, but in a general case, we can think of the external light source being having n such points. So let us pick a point n and then the intensity of light that is coming from that nth source is given by I n. And this is a function of distance r and time t.

And kind of here neglecting the theta and phi because of symmetric reasons. And r and t can be written as basically I 0 basically the intensity at r equal to zero that is I 0 e to the power i phi n of r, t and the phi n is basically phi n is okay phi n measured at the origin let us say. We call that as let us say phi n of zero, which is basically phi n that r equal to 0 is a function of t, okay.

It can change as a function of t and as given by omega t plus at t equal to 0. This is the starting phase, okay. Phi n is a phase term. So basically we are writing down as a function of the oh I am sorry. I should have written this as an amplitude function. So it is not intensity but it is actually let us call that as E n, okay? So it is not a, it is a complex quantity. The intensity is basically the amplitude square.

So modulus square of the amplitude. So but here for the nth source the I mean the amplitude function takes something like form something like this. So now what we can actually do is that in order to estimate the amplitude at a point P, as we have drawn in the picture, you can think of that as summation of all these individual wave amplitudes okay with their corresponding phases, okay at the point P, okay.

So if you if we do that, then we can actually define something called as a phase difference which is let us pick point source n and the phase difference can be defined here as phase difference in time okay. So we are talking about phi n at point P being measured at time t 1 minus phi n at the same point measured at time t 2. So this again is basically difference in phases of the light arriving at point P at times t 1 and t 2, okay.

So now that we can call it as delta phi n. Clearly that in general could be a function of t. But what we are very much interested is this is basically difference in phase of light from source m at time t 1 and t 2. So now we are interested in a special condition, whereby doh delta phi n by doh n goes to 0. That is to say where in that condition we say the light is temporally coherent. So this condition means it is a temporally coherent.

Now let us look at this little bit more closely. What does it tell you that we change I mean across the different sources we are going to measure this phi n and then we see that the fi n is independent, I mean it is constant, it is a same constant, I mean it is a constant across all the light sources, then we say the light is temporarily coherent. The light, extended light source is temporally coherent.

This is a any condition. So all that we are demanding is that the delta phi n, right, it does not have to be zero by itself, but all that we need is that the delta phi n needs to be constant across the different points in this extended light source. I mean across the lights as are emanating from different points in this extended light source. So if we achieve that, then we say that the light is temporally coherent.

However, the real experimental quantity that you can actually measure is really not this. I mean, because while you are trying to say is that okay is it close to zero but how close to zero can be a measure of how good the temporal coherence it is. But there is a much more precise way of defining it and let us talk about that.

So that being what we are going to say is that this derivative right doh delta phi n by doh n, right, this in turn could be a function of the time interval that we are actually looking at, okay. So if you had to measure this delta phi, right the phase difference between let us say, now I mean and 5 seconds later versus now and 10 seconds later.

And we do that for light emanating from all the sources from the source and then ask, how is that looking like? Is it constant all throughout? Then what we will see is that as we keep extending this time that the time interval across which we are measuring the phase difference, you will see that the temporal coherence falls down, I mean degrades.

So a practical definition here would be of something called as a coherence time which is defined as the time interval tau across which you are measuring the which is basically given by t 2 – t 1 minus t 1 across which you are measuring the phases, okay. The tau for which this delta phi n is lesser than or equal to 5. If so what we are going to do is we are going to keep changing okay.

So this t 2 basically you can think of as t 1. So t 1 + tau and as we keep increasing this tau, we are going to measure the delta phi n. Now for the tau at which the delta phi n exceeds 5 and just that becomes equal to 5 pi, we call that tau being the coherence time, okay. What it means is if you measure this delta phi, the phase difference between two different I mean between two different time points.

As long as those two different as long as the time difference between those two time points is less than the tau, you will see a phase difference of pi or less, okay for any source along that extended point okay. So remember, this is our extended source. And there are different points. All I am doing is I am sitting at p and measuring the phase difference between time now and time tau later.

Now as long that with if I am measuring within any time less than tau, then what it guarantees me the coherence time guarantees me is that the phase difference would be less than pi or at the most be equal to pi. That so that is a very fruitful way of defining coherence time. And the distance the light travels in this time period is called as the coherence length. So is defined as the coherence length, which is given by C times C the velocity of light times tau. And this is directly measurable in the lab.

I mean you can actually measure the coherence length. And it is very useful in turn giving rise to I mean, making you making it possible to measure the coherence time. So if the phase difference is I mean if it is they are extreme, very nicely synchronized. The each of the sources along the extended light the is very nicely synchronized.

We what we see is that we will see this coherence time to be really large and the coherence length to be also very large. Now that is for defining the coherence in the temporal domain or it is called as, we are talking about temporal coherence.

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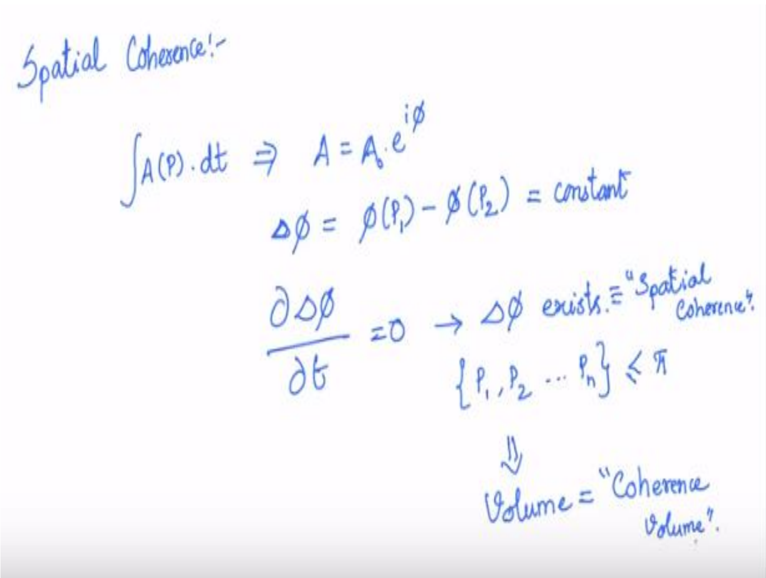

But there is also a spatial coherence which is of great use to us. The spatial coherence is given by this the quantity where what we are going to do is that we are going to sit at the point P exactly like what we have described before. But then we are going to sit at point P and integrate the amplitude okay, integrate the amplitude across time.

Okay when you do that, then what it would imply is that the that amplitude would be given by A that amplitude A integrated amplitude, because we can get rid of the t know is given by A 0 e to the power i phi. So now if the situation is such that when you integrate and then look at the amplitude across different sources clearly. So then you see that you measure this phi the phase, now you measure this phase across two different observation points okay.

The one point that we have measured let us say P, I call it as P 1 and then some other point P 2. If we see that there is if this is equal to a constant there is a constant phase difference across the space okay, that is independent of time. There is no because we have integrated it over and then now we are trying to measure this phase phi across two different points, okay.

Now if it turns out if when you take the difference and they are this is independent of time or in other words, we see that this is equal to 0 then we say that delta phi exists or there is a constant phase difference. It could be this the constant itself could be 0 but the point is it has to be constant with respect to time. If it is because if you measure the phase difference between two different points, right.

Now it is some number, little later it is some other number then it is not a constant phase difference, but then but if you do see that it is constant across different space, then you see that the points okay then basically what you say is that delta phi exists and all the points okay, all the points typically they are spatially continuous but all but all the points where you have measured this phase and found to be constant in time or it is constant in time and it is less than or equal to phi, okay.

You since it is these are points in space and they are contiguous in space, so this defines a volume surrounding the extended source of light and this volume, we call it as coherence volume. Again, if we find that the phase difference of the integrated intensity I mean of the of the amplitude that is averaged across the time of the light at point P 1 and point P 2 to be constant with respect to time, we say that delta phi exist.

And then the light is spatially coherent, okay. Let us call that as spatial coherence. And the measure of the spatial coherence is through this coherence volume or in other words, if there is the coherence were to exist across space over a larger distance, we would see that the volume will be higher. As a result, we say that it is more spatially coherent, the light source is more spatially coherent.

So why are we talking about this coherence? Because what coherence ensures is that either in length or the spatial domain length scale, it gives you a defined length scale on the temporal scale at which the phase of light emanating from a source extended or point source is defined, okay? It is clearly defined and it is constant. So now in this scales, we can talk about interference of the light coming from originating from different sources.

I mean what we did was we took an extended source and then we said okay, it has lot of point source, right? In real life, what we have is you can think of an extended source of light because every light source that you think of has a finite extent. So the one way to think of that is there are multiple light sources and across that extended light source and then we say okay now I am going to talk about the points, the extended light source as a set of point sources.

And then I am going to talk about the relationship spatial and the temporal relationship among these lights coming out from here. And by extension, I mean then I we defined coherence terms of coherence with in these extended light source. By extension, then we can think of this being applicable to any two different light sources, okay.

So the usefulness of that comes from the fact that if I know these quantities for two different light sources, then I can actually predict whether a constructive interference will happen or will not happen. And that is of tremendous importance, because when we want to localize a light photon as we know that is because of combining these two lights on in space or in time, then we need to know at what scales do we expect this coherences to I mean this interference to happen, okay?

We can actually measure these things in a laboratory setting, measure this coherence length and the coherence volume, okay. The way we do that is through interferometry. I am going to reserve that description of interferometry little until a little later in the course where we actually use interferometry to measure little bit, I mean, definitely temporary coherence but in a special case, okay so of pulse lasers.

So until then I am going to reserve this description, but the point here is that you can define I mean, we started out by saying what is special about a light source that is emanating coming from a laser. And what you see what I am stating is that one of the properties that is of very well defined is that the coherence is coherence properties of the laser emission is very different from an incoherent source.

I mean, by definition any other light source if you talk in terms of incandescent light or a flash lamp extra, the coherence properties are very different. The laser lights can have a larger coherence length and coherence volume. Of course, everything has an exception but the what it allows you to for sure I can tell is that you have a defined coherence length and the coherence volume and the extent of this could be different.

But there is a defined coherence length and a coherence volume which is different from that of a incandescent source or any other light source okay. Second important point that I was mentioning, in which the light from the laser emission is different with respect to which the laser emission is different is in terms of spectral brightness, okay.

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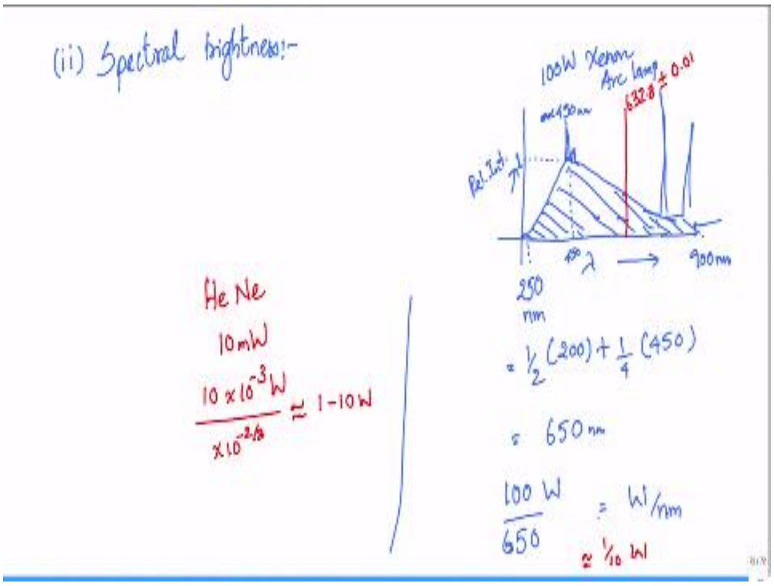

This is capturing the notion that laser lights often are viewed as more intense or powerful, okay. That is a common feeling or common intuition that it provides that arises from arises directly from this characteristics what I am calling it as a spectral brightness.

So when you take like for example, a mercury arc lamp or a xenon arc lamp, their energy that is coming out can range in few tenths of a in fact few it can even, you can even get it to few hundreds of watts of energy like photons. While you have this laser like a helium neon or argon ion for that matter where the output we are talking still I mean particularly if you talk in terms of helium ion, it becomes very striking.

The output we are talking in terms of milliwatts. It is like thousands if you measure the energy with energy density with an energy meter, what you see is that the there is like about I mean four to five order of orders of magnitude difference between what you measure in their energy content per se, in between the helium neon and argon, helium neon and xenon or an mercury arc lamp.

Then why do we get this feeling that the lasers are more brighter? It goes to the fact that when you actually look at the spectrum of the these two light sources the xenon arc lamp if you actually google it google it up you will see the nice spectrum and the spec but the so what I what you will see is a spectrum is the wavelength and then the relative intensity, okay. And it starts it takes a there are you will see sharp peaks here.

But for our purposes, okay, so this it starts from about 250 nanometers and goes all the way up to about 900 nanometers before it is, it drops dead and you do not see much of the energy output coming from this laser. So what you are seeing as a light that is coming from let us say, 100 watt energy that is coming out from a xenon arc lamp is spread over this entire spectrum, okay.

So just for us to estimate for us to make an estimate, what I am going to do is I am going to ignore this pointy structures. I mean by that I am actually transferring more of the photons that are present here or more of the energy that are present here into this area. So if at all anything we are actually going in a conservative fashion right.

So what we are doing is that we are going to see that the entire intensity, entire intensity of the I mean entire energy of that 100 watts lamp is spread over this entire area, okay. And where the peak when you look at it around, it is in the visible region. That is why it is deeply I mean it is pretty wide with slight bluish tinge because of dominant 400 nanometer, approximately 400 nanometer or actually 450 to 480 nanometer light being present.

And we can and if you normalize to that peak, then what we will see is that now that this entire area the photon is distributed over this entire area, I mean the photons are distributed over this entire area. However, if you take a helium neon laser right, so that is we just now saw. I mean, we just now we saw in the previous lectures that the wavelength is 632.8. And we can, 0.08 oh sorry I think it is 0.8 nanometer.

And we can define this with a bandwidth of 1 in 1000 nanometers, right or 0.001. I said 100 I mean 1 in 100 to 1 in 1000. So let us take a conservative estimate of 1 in 100 itself. So it is now you can see all the milliwatt energy is concentrated in that wavelength and that wavelength only while our entire 100 watts is spread over this huge area.

Now to give you I mean clearly you can see as you can see from here, if we were to estimate this area, this is roughly so the peak we can call that as about, if you normalize to the peak, then that is about 1. So we have so this transition happens around 450 nanometer. So this is about a 200 nanometer range and we are going from 0 to 1. So that is about half the times of 200 plus the other area, we are going about 450 nanometers.

So we are getting about 650, it is spread over 650 nanometers region and while on the other hand, so it is spread over the entire 650 nanometer range and then when you are since we are calculating the area normalized to the relative intensity then we are talking about dividing that 100 watts over 650 to get the spectral brightness as watt per nanometer. Now we do that the same thing, right.

The typical He Ne laser can be about 5 to 10 milliwatts, that wavelength, even generate more, but let us take about 10 milliwatts. This is in comparison with He Ne and you take about 10 milliwatts and then say I am going to divide this 10 milliwatts 10 power -3 watts over my wavelength spread is 10 to the power -2 to 3, right. So we can already see that this at 632 or 633 is close to alright, 1 or 10 watts, okay.

Now compare this. So what we have done is we are so the entire 100 watts is divided by 650. So to give you what parameter and that is one unit here, right. So that is the entire area. So now in here if you look at that, I mean this is already less than a watt. But then not the entire that watt is watt per nanometer and not that entire watt is available for the comparison right because we are actually comparing we have to compare oranges to orange.

So we are actually taking a small fraction of that right? It is one hundredth of that right. That corresponds to this main bandwidth. So what we need to do is for comparing, we have to take this watt per nanometer and multiply by the ratio of the peak to this. That is roughly about two times and two or even less than that.

So if you do that, what you will see is that while He Ne gives you about 1 to 10 watt per nanometer in that particular wavelength while your 100 watt bulb gives you about one by so it is 50 by 650 it is a 1 by 10 roughly 1 by 10 to 15 of a watt, okay. So it is because of this reason, you have the perception of I mean you see that lasers tend to be have the brings in the perception of higher power.

It is the power in the spectrum region that very concentrated in the spectrum region and that is huge. I mean, we are talking about two orders of magnitude, larger power in the race as compared to the white light source that we took in this example xenon arc lamp. With that, I would like to conclude this examples about the lasers and laser systems and of and then the special nature of the laser light themselves.

In the next class what we will do is that we will focus on different class of lasers. And these are lasers that does not generate the laser light continuously in time, but they generate the laser light for a brief period of time and brief period of time only. In order to understand that we might need to look into some other some little bit more phenomena and that will be coming in handy.

And how we can actually use that phenomena to for understanding the generation of the what are called as the pulsed light lasers. Until now what we have described are so called the continuous wave lasers because if you plot the laser output or the intensity as a function of time they are steady and continuous.

While on the other hand, if you, the second set of lasers that you are going to or second part of this laser lecture series, what you will see is that we will be talking about pulsed lasers, okay. We will see you in the next class. Thank you.