Optical Spectroscopy and Microscopy
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Lecture – 1
Fundamentals of Optical Measurement and Instrumentation

Hello and welcome to the optics and optical spectroscopy and microscopy course, and in this lecture what we are going to see is that how we are going to develop the essential framework for understanding a generic optical instrument that we most probably would be using to investigate a live system or in many biological system or in any other soft condensed matter system for that matter. So, this would be an idolized equipment you can think of, a schematic of equipment, then we are going to parts out this equipment into 3 different parts and see what is there in insides of these 3 different parts.

The idea here is that the entire course what we will be doing is that we will develop us a conceptual model of what an optical equipment would be, that would be most probably used to prove a living system or a soft condensed matter system or for that matter any physical or chemical study that somebody would like to use and then what we will do is that this optical equipment we will dissect out into different parts a layout now and then for each of these parts we will go inside and investigate what are the fundamental principles from ground up we will go.

Then see what are the fundamental principles on which this equipment is operating on and what we can understand such that when we develop a new technology based on optical methodology that that we are studying in the course, how we can leverage the various technical advantage and the overcome the limitations, okay, so that kind of the spirit of the course and which we will be moving forward. So let us start by asking if I take an optical instrument and then try to open up and see what would be there in an instrument, what do I expect to see?

Typically, so this is common for a spectrometer or a microscope, mostly these are the things that we will be talking about, but this is so general that, I am willing to bet that any of the equipment that you see in the lab lying around or in your office lying around, you would be able to categorize this equipment and other parts in one of these main divisions.

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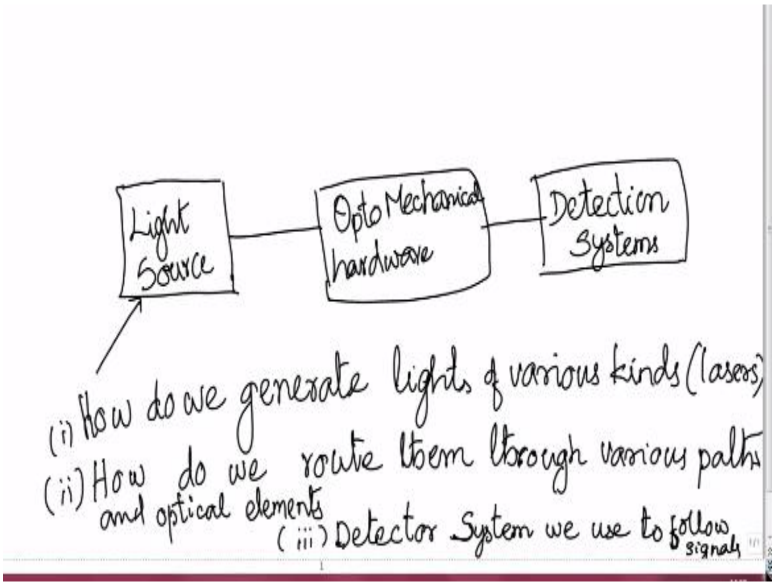

So, if you open up an equipment, my hypothesis as a claim here is that you would see a light source and then opto mechanical hardware, for routing the light and then you will see detection systems okay. So in our course, what we will do is that we will follow this structure of first understanding what is there in this light source? How do we generate lights of various kinds, really we will be here talking mostly about lasers of different kinds and then once we generate the light, how do we route them through various paths and optical elements to impart some character to the light.

Then third is once this thus generated and routed light interacts with the matter or gets into the matter that we want to probe or study, that the kind of detectors we use or detector systems we use to probe and follow the signals that are generate from the system of study, alright. So, in order to do this in the course, it turns out that we need to start from understanding how the light itself is interacting with the matter.

The promise of the courses is we are going to probe the matter with using light and understand how it interacts with the matter in the process, we try to unravel the principles of the dynamics that might be happening in the inside of this matter. So, the first process in doing so is to understand the light matter interaction itself. The idea here is if we will start developing or looking into the formalisms that are existing to understand the description of the light and matter of interaction and how does the light interact with the matter.

In doing so, what we will see is that we will be able to appreciate and discover how the operating principles of one of the prominently used light sources are the lasers that will be constantly using in all of our equipment, at least that is part of this course. So, as well, we would be able to understand some of the signals that are generated because of this light matter interaction, right. So it is of very important for us to pay attention to this, the formalism, and this boils down to describing the matter per se in terms of quantum mechanical states and operators.

If you ask me, do I need to know quantum mechanics to understand what is going to happen? You do not need to, but the idea here is that I do not assume that you would know, but if you know it, it is better, but the point is just because you do not know, should not preclude you to follow this course. The idea here is to provide you the basics and give you the directions to follow to understand and appreciate these principles.

Fundamental principles with the hope that tomorrow when you are encountering with a problem that is not necessarily taught in the course, but something similar, you would be able to apply that and then use your understanding and apply your understanding there to appreciate what could be happening there. So, let us start by looking at the light matter interaction itself. For this, what we are going to do is as I said, we are going to go into a little bit of quantum mechanics.

In fact even before that, I am going to motivate you to tell you a little bit about why we even need to go into that, alright, and what are the main differences and then again this is not a full-fledged quantum mechanics course, but I am just going to give you the glimpse or the essence of what we need for this course to understand how we can describe the interaction of the light with the matter, good. So, let us start by looking at this formalisms itself.

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(i) Absoluteness of size (Absolute Size)

(ii) Principle of superposition.

<u>Uncertainity Principle</u>:-

$$\Delta x \cdot \Delta p \geq \frac{h}{4\pi}$$

$\downarrow$

(high posi^n accuracy) $\Rightarrow$ low accuracy of momentum

Mainly as many of you might know, the quantum mechanics per se was developed largely by Schrodinger and Heisenberg in two independent manner during the early days and then later Dirac came up with a more generalized approach and then showed how the Schrodinger’s approach and Heisenberg’s approach both of them are really a special case or so to say a subset of his more general treatment, and the notations and the language that we will be using is more close to Dirac’s in this course.

Though I would have really, really stripped down a lot of the details to keep it brief and at the same time be informative, alright. So, first let us look into how to develop this idea of quantum mechanics and what are the basis? I think if you were to in one line summarize what triggered or what formed the basis of his entire formalism, then I would say two major principles. One is called the absoluteness of size, it's also called as absolute size, right, as against relative size. Second is the principle of superposition.

So, these are the founding stones so to speak of directs formalism. So, let us look at these 2 to understand what went into his theory. So, the first thing that he realized is that when you want to make a measurement like what we are doing, I mean such as the one that we are planning to do in terms of trying to understand what happens to a system and we are shining a light on to that. What he realized is that the way we probe the system, invariably interacts and causes and disturbs the very system that we are trying to probe.

Now, this is true uniformly across all scales of the matter, but even though it is true all throughout, it becomes particularly significant when the sizes of the objects that we are dealing with are comparable to that of the interaction energies itself okay. Let us simplify a little bit. So, in classical mechanics, the mechanics that we tend to take it for granted in every day, I mean in a day to day life that we deal with, we implicitly assume for every object that we try to study, we can always find a smaller object with which we can probe the system or the object that we are studying.

If you are studying a smaller object, then you can find even more smaller object with which you can interact. That is the nature of implicit assumption that we make, why do we make this? We make this because we neglect the interaction or neglect the disturbance that this measurement process or the interaction process itself is bringing about to the system that we are studying. So, if I am trying to investigate how a cannon ball is moving around in the outside world, I kind of assume the way in proving that, right, is in the light photon or using any other means is not disturbing its trajectory.

That cannon ball is going on in its own trajectory and just by me observing, I am not disturbing that trajectory at all, right? That is an assumption, and that assumption is pretty good and valid when we are dealing with sizes of that megascales. However, that is not true and that is the statement that Dirac made and that is an assumption that he made, that is not true at all scales. We cannot keep on extending it all throughout to the micro cause.

So he said, at some level, this has to fail and certainly it fails when it comes to the level of atomics and subatomic particles and objects that we are investigating in which scale where the disturbance caused by the interaction itself is non-negligible. So, when that happens, we say that we have reached the absolute size limit, we are not able to find any more particles to investigate the system without disturbing that. Quantum mechanics deals invariably with systems of that kind.

One of the major consequences of that is that what we are taken in classical mechanics has granted the causality, alright. So, that is not granted anymore at all because as you can see the causal nature of this entire thing assumes that you are not disturbing the system. The moment the interaction disturbs the system, there is no predictability You cannot predict the trajectory while you are disturbing your probe, trying to probe particularly that the very act of you probing disrupt the system.

So, that is one and immediate consequence to that is a statement of principle called, I would like to call as uncertainty principle. This tells you that because of this nature of the quantum mechanics, the thing that you have taken for granted, that is, the measurements are known with infinite accuracy with very high certainty, I call it as deterministic, they are not deterministic anymore, they can only assign a probability of you getting a particular value for a measurement when you are investigating a system.

So, that probabilistic nature brings in one of very key principles that I am just going to make use of to illustrate the point that the quantum mechanics that we have stepped down is not a very simple academic exercise, I mean for that matter, it is not even an esoteric exercise. It in fact is very much integral to this entire course, alright. So one of the first statement of the principle that I am going to make use of here is that of telling you how accurate your measurements of position and momentum could be, right?

When you are trying to make a prediction about a trajectory, what you are trying to do is that you are trying to make measurement of the position of the particle as well as how fast it is moving at that position, right. So, if you know that with an infinite accuracy, then you say that you know the trajectory in a very deterministic manner, but the fact when you go into this micro cause or microscopic particles and objects and when we are trying to probe this, this very deterministic nature breaks down and it becomes very probabilistic.

As a result, several properties, new properties that comes in, one of them being this uncertainty. That is, if I were to measure my position and then represent the uncertainty associated with that position as delta x, then my uncertainty associated with the momentum as delta p, then what this principle states is that the product of this 2 uncertainty has a limit. The limit is given by Planck's constant by 4 pi.

So, what it tells you is that no matter whatever the capacity of the equipment that you get, it is not limited by your equipment or instrument, but no matter howsoever an accurate or precise system that you try to get, the accuracy with which you know a position depends heavily on how well if you are trying to make the measurements simultaneously, the position the momentum is tightly linked to how well you know the momentum too. The product of those 2 has a limit, I mean, it has a lower limit of h by 4 pi, it cannot be any better than this.

So, if you want to decrease this, right, in which case you know this position really, really accurately high position accuracy, then what it tells you is that high position accuracy implies low accuracy of momentum, right, because only then this can be a constant here, I mean the lower limit can be constant there. So, now why am I saying this? Remember, I told you that I am going to use this to illustrate the point that it is not an esoteric exercise, it is a very much needed, very much related to what we are doing, alright.

So, part of this course is about microscopy, right. In microscopy, one of the important aspect is our ability to tell apart how close or how far two objects in space are, okay.

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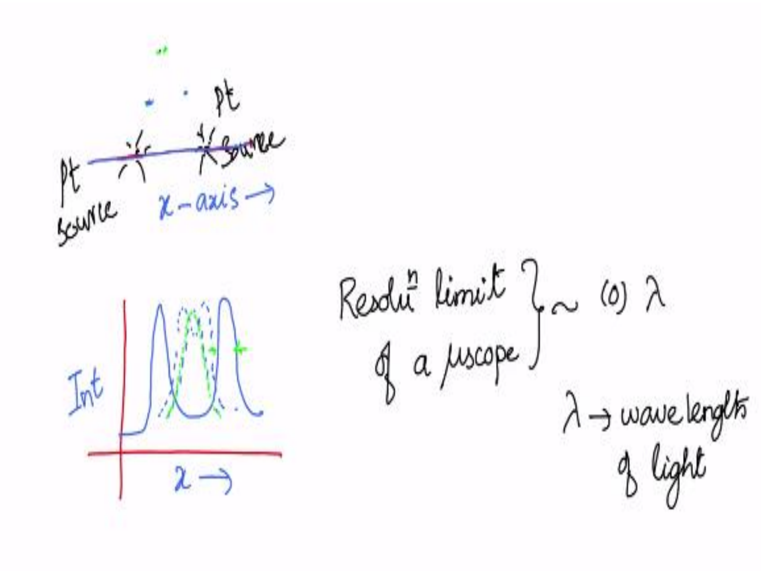

So, let us assume a point object here, it has hardly any dimension, and then another point object here, right. So, often what do you like to ask is can I tell this distance apart by looking into the microscope and you say that you would be able to tell these two things apart if your resolution is at least this or lesser than that, meaning lesser here means the objects that are even smaller, I mean separated by smaller distance can be still resolved. So, now, this has been classically told us these are the point sources and this has been classically equated to the wavelength of light, I mean of the order of the wavelength of light.

The idea that being there for a long period of time given, so let me draw it out nicely for you here. So we have a point source, another point source. What we are asking is that since it is a bright object, right, emitting light and if you had to take capture an image of that and then run a line profile that is to say, I m going to draw a line across these 2 objects, and then ask how does my intensity right, the intensity varies as a function of space, my x axis grows up like this, so what you will see is that this is my intensity.

So, you would see the light going up, coming back down and going up. So, you could imagine that when you bring this two point objects closer and closer, there will be a point at which this would be somewhere in between, there will be a point at which they both would look or give rise to one little peak her, not anymore 2 separate peaks. Now, clearly you can see this depends on how wide these peaks are to start with, right, how wide of a peak I get when I actually image this point objected itself.

So, inherently, conventionally not inherently, traditionally this has been called as a resolution limit of a microscope, okay. We will look at this in a much more detail when we get into the microscopes and all that stuff much later in the course, but it is sufficient to say now here, when we have to point sources and then we are looking at the line profile, the profile being a line that is drawn across an image of these 2 objects, and then asking how the intensity changes as a function of x axis and what I have done is that I have brought these 2 two points, right, closer and closer, right.

Next, the dotted lines are from points that are of this origin and then the green lines are of that origin, right. So, let us say this is my green, blue dotted lines would correspond to this distances, right? So now, I would say that it is customary to call as a resolution limit and we say that the particles are resolved whenever we are able to find that the intensity has fallen down to 1 over e between those 2 peaks, alright, thanks to Abbe, this limit has been shown as, I am going to just restrict to, of the order lambda, where lambda is the wavelength of light.

Now, what I am going to tell you is that this very principle of there being a fundamental limit with which we can resolve things, and there is a fundamental limit to tell apart 2 things closely spaced in space using no matter howsoever higher magnifying microscope that we use, draws such basis right in from the uncertainty principle that I described before. Let us look at that little bit more closely, and where is that coming from?

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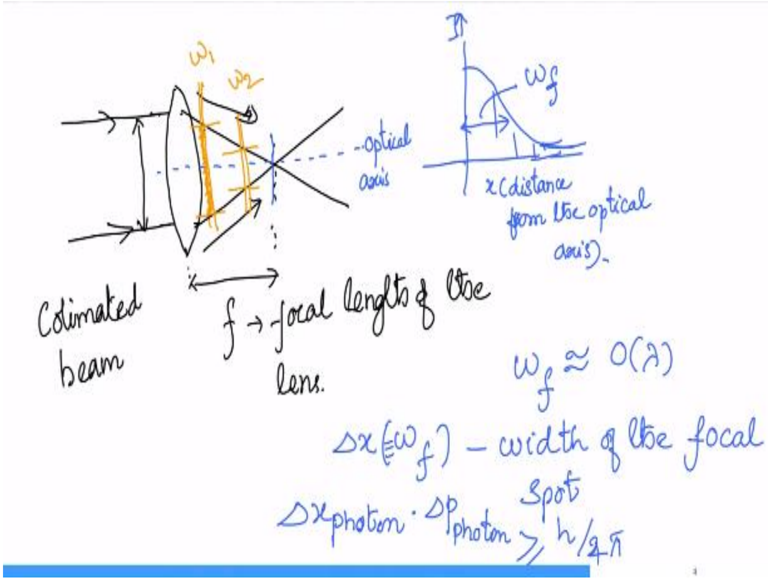

So, ultimately, what we are actually asking is that we are taking a lens and passing a beam of light, and when you pass the beam of light, and these are parallel rays that I have drawn is called as a beam of light that has these kind of rays, you call it as collimated beam, clearly the reason being that if you extend, if you let the beam pass through a long distance, very very long distance ideally, the collimated beams maintains its width alright in space, no matter how much ever distance it propagates.

Such kind of beams are called as collimated beam, and then when you take the collimated beam from simple high school physics, we know that when you pass through a lens it focuses at a distance, yeah the focal length of the lens. So what we want to ask is if a light consisting of photons had to be focused, then what we are trying to say is that the rays that the lines that we draw here represents the boundaries within which you have a higher probability of locating that photon.

Now, that boundary is as we travel along in this direction, we see that boundary is reducing, we say that the light is getting focused. When that happens, what we are actually doing is that our ability to localize a photon to our particular space increases progressively, right? Initially, your ability to localize the photon if I were to slice up this region, right, let us take a different color, so, let us say the orange, and if I were to slice up this regions in 10 sheets, then what I am actually stating is that initially if it were to be so dim a light, there is a one photon.

Then what we are trying to say here is that that one photon could be present anywhere within this shaded region, but as we progress forward towards the focal length, the focal point yes, then what we are seeing is that, that distance has reduced from that to this, right, some w1 to w2. Like that, we can keep on going forward and in geometry optics, we take it for granted, it can be focused to an infinitesimally small spot without any finite dimensions, but that is not true.

In reality no matter however big or however high focal length of lens that you have, however good the lens that you have, when you focus what you will see is that at the focus the light occupies a definite width, definite extent, it is not a no extent object. It has a finite extent like the way we did it previously to draw the profile, we could draw the profile here and that could take depending on the incoming a beam of light, it could be a Gaussian or any profile, but the key is it would have a finite width.

So, this is my distance from the center, this is my distance from the optical axis. So this is my optical axis. What I am doing here is I am plotting the intensity as a function of distance x, distance from the optical axis okay. Now, as you can see it is very high at the center and then it drops down. Now, what it tells us is that you have a very high probability of locating the photon in this place, but that it is not only present here, there is also a final probability of locating here, here, and so on, and I mean if it had to be Gaussian, it goes to 0 only at infinity.

That is that is to say your ability to localize the photon are to form a tightest spot of focus, right, where let us call this as our omega f. Now, there is a lower limit to omega f, right, that is what it says, I mean no matter how hard you try to focus with the best of the lenses that you have, you still end up having a finite width and that width is of the order of lambda okay. Now, why is that? Now if you look at this diagram and all along I have been talking about localizing the photon in space, right. So, I am actually trying to follow the position of the photon, so that is x.

So, my uncertainty of localizing the photon in space is given by delta x, which in our case is basically omega f, right. This is the width of the focal spot, then once we had transposed this into the idea of uncertainty in position, then we know the relationship, right. The delta x of this photon, we are trying to minimize this right. We are trying to minimize it, so that it becomes sharper and sharper, because the omega f becomes smaller and smaller, this has a limit, what is that limit?

We know that delta x photon times delta p photon has a limit, right, given by uncertainty principle has to be greater, the best can be equal to that of h by 4 pi. What does it mean? It means the more and more you try to localize the photon, the more and more you try to focus it sharp, your uncertainty in momentum has to increase okay. So, now if that is the case, can I actually write down an expression for p, so that I can actually estimate how small a spot can I found?

Like if I can actually get, I mean if there is a limit to delta x, if I can write down an expression for delta x in terms of properties of the light photon, right, then I may be able to see if there is a limit to it and how does that compare to the conventional or a traditional resolution limit that we know of? If I were able to show that these two are same or equal or have the same order, then my argument here is that you have a basis for what has been taught or what has been told to you as a resolution limit given by Abbe, right, of microscope coming directly from various different wave optics and other equations.

Now here, we can trace down to the fundamental principles of quantum mechanics predicting what that limit would be, okay. In the next class, we will write down the p, the momentum of the photon and then calculate the delta p, plug into this equation and then write down an expression for x, delta x, which is I mean clearly the lower, I mean the minimum that you can actually go to, because it is constrained by means it tells you a limit, right?

So, it gives you a limit. So you will get limit on delta x and see how does that compare with the conventional resolution limit, okay. Thank you. We will see you in the next class.