**Optical Engineering**
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**Lecture - 41**
**Applications of interference**

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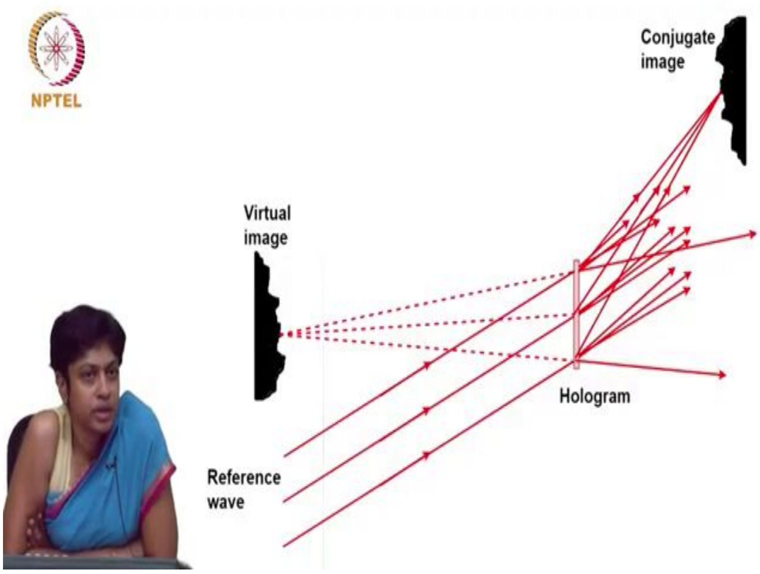


Good morning. So, the last class actually you visited the holography lab right. So, what did you see there, what holograms did you see?

Student: (Refer Time: 00:32) laser.

Was the set up to record also there are only holograms there?

Student: Only reconstruction (Refer Time: 00:41).

Ok.

Student: So, there is a hologram (Refer Time: 00:44).

Ok.

Student: (Refer Time: 00:47) it is like (Refer Time: 00:47) like laser and due to some errors and we can (Refer Time: 00:51) from (Refer Time: 00:54) to see the 3D kind of or (Refer Time: 00:59).

And did he show you if with the broken plate that he was still able to reconstruct the full.

Student: No, there is no broken plate, but he comes and gives (Refer Time: 01:06).

Ok.

Student: (Refer Time: 01:08).

So, I hope the visit you may know brings it because the equations do only so much, but when you see it you. Now one thing is when I started the topic I just one of the reasons I said it was important was it is for example, used to make security features.

Because making an image of something is easy whereas, making a hologram of something is of course, you need to have the technical expertise to do it. And it is much harder to do and that is why many companies will make their stickers with that and use that as in order to show that the product is genuine and comes actually from that company.

But what you can do with holography is not limited to only having some genuine now this is a true brand feature. But you can do a lot of different kinds of measurement on a lot of different experiments which allow you to get information.

So, it is a very powerful sensing technique. So, it is such a vast area you could really spend an entire semester talking about holography but of course we are not going to. We do not even have much of a semester left. So, I just want to show you one application of holography today. So, this is what is shown here is the setup where we are doing the reconstruction alone.

So, you have the previously recorded hologram and then it is illuminated with the reference beam which ideally should be equivalent to the original reference beam and then you will create two images one virtual one real, but these are now 3d images carrying the depth information.

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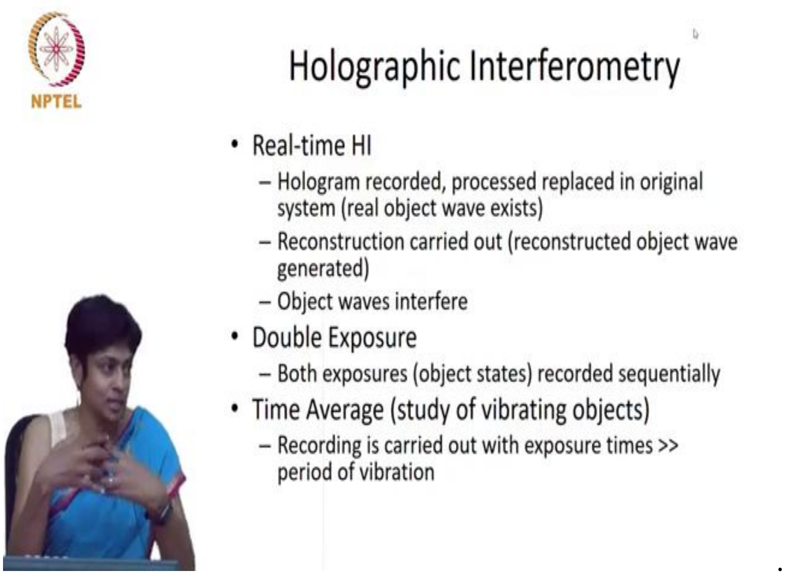


A way to extend this idea is to do what is called holographic interferometry. Now you know holography itself is an interferometric technique you are recording phase or you are capturing that phase information because of the interference of the scattered object wave with the reference wave right.

But here we are now going a step further. So, in holographic interferometry what is the goal? You want to make a hologram of some object, the object that you want to study and you want to see how that object changes over time, how that object changes when you apply some stress to it how that object changes when it is excited by certain frequencies.

So, how are you going to do this in real time? You make first a hologram of the undisturbed object. Then you put that hologram back into your setup. So, now, you have two object beams you do not. It is not the reconstruction setup it is the recording setup, but you have a hologram there. So, you have the object beam from the original object and you have the object beam from the hologram.

Now if you disturb the object you are making a difference in the beam that is coming real time compared to the beam that was recorded. And you will see the interference of these two object beams. Is that clear or should I run through that one more time?

Your goal is to study an object that is not static, something about that object is changing and the change could be a variety; of course, you understand when I say something is changing; something is changing that affects the optical path difference right.

So, maybe your refractive index is changing, path lengths are changing and how could those changes be? It could be straining the object, you could be heating up the object, you could be exciting it with a certain frequency; a variety of different techniques could be used or it is not that they used, the object is experiencing these phenomena and you want to make some measurement of these phenomena.

So, you are putting back, you make a hologram of the undisturbed object, put it back in that original setup. So, the original object beam is still there and then you are looking at the interference of the original object beam and the origin of the undisturbed object beam and it is the interference of these two that you are looking at.

And this is a very powerful technique. Because it also allows you to study very large objects, you can expand a beam to a very large right. We already when we are looking at the Gaussian beam said people did experiment or they sent the Gaussian beam from here to the moon. Now, while you are not measuring that entire diameter on the moon you know that you are talking about a very large beam.

So, if I want to study an object, now what is a very large object I might want to study? Well, there are objects we want to study because we want to ensure that there is no defect in them ok, an aeroplane wing, we need to quickly assess a crack in this aeroplane wing.

Now, I could take a small sensor and go millimeter by millimeter and scan over that and see am I getting a crack. Is there some way to look at that aeroplane wing at one shot and figure out if there is a crack somewhere? So, can fringes give me that information? So, holographic interferometry is used in examples like that.

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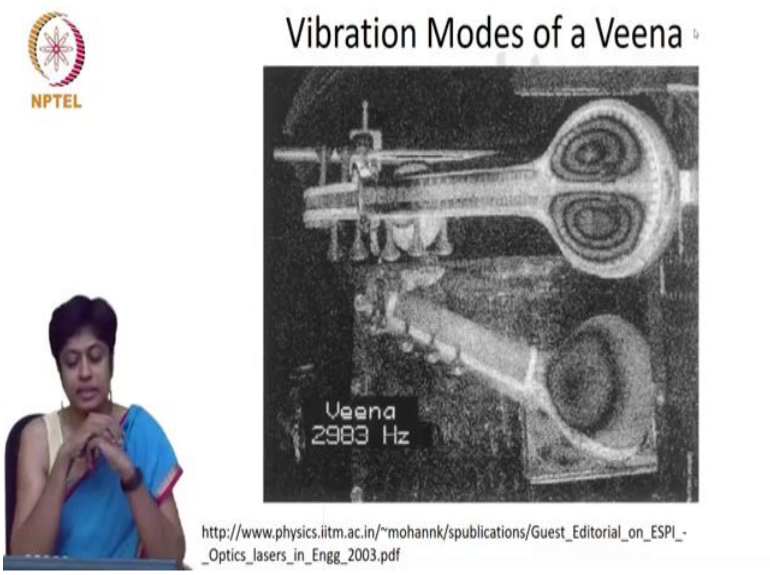


So, let us look at this example. I think I showed you this somewhere in the beginning of the course.

In this example this picture has been taken using holographic interferometry. What are they doing? They are exciting different modes of this musical instrument. So, they had a hologram where the musical instrument is undisturbed and then they put that hologram back into the setup, there is the beam reflecting off the veena, you excite some string of the veena.

So, there is a certain resonance that is happening, that object beam is interfering with the original undisturbed object beam and what you are seeing is the interference pattern. And so, for every mode that the veena has you will see a different set of fringes right. So, it is a way of studying the modes of this musical instrument right. This was work done in the Physics Department of IIT Madras.

But I could say I want to study an aeroplane wing, maybe I set it into vibration or in the case of the aero plane wing maybe I just look at the fringes across the entire wing. Wherever there is a defect the fringes will have some kind of abnormal look to it.

So, you can immediately tell there is something wrong at this place, then you can take a smaller sensor and study that localized area and that will quickly tell you if there is a problem or not.

Whereas, if you took a photograph of the wing, you would not be able to tell; from the photograph externally everything may look ok, there may be a small crack under the paint right. The reflection from that will carry that information whereas, a photograph of that will not carry that information.

So, holographic interferometry is used in a very wide range right. I have just talked about the aeroplane wing as one example. I have shown you modes of a musical instrument as another, but there is really no limit to what you could study ok.

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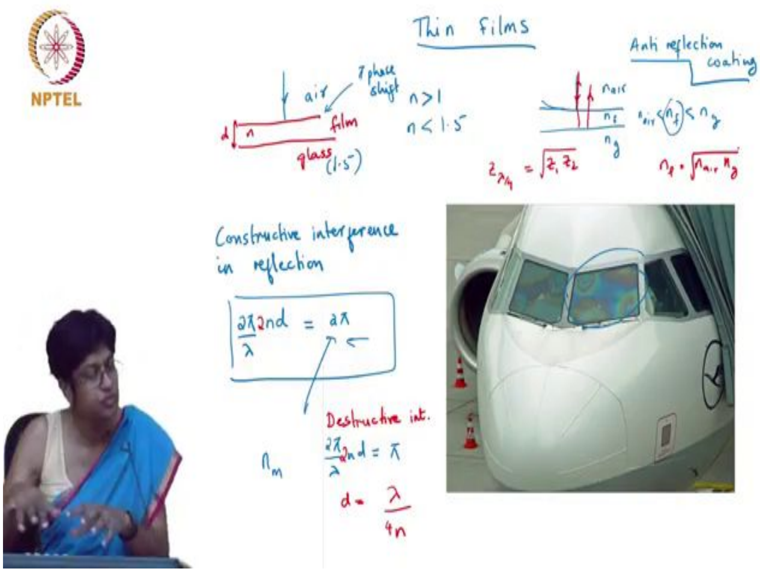


So, we have been looking at once we started wave optics, we looked at interference and then we went into some applications of interference and that is where we started looking at holography.

But I want you to look at some overall applications of interference itself not just limited to holography. So, here is a picture of an aeroplane and you can see a pattern or something over here. What are these patterns that you see here on the windows of this plane, sorry?

Student: Thin film.

So the patterns are thin film?

Student: Yeah maybe.

So, you are seeing because of some film some layer on the window you are able to see these colored patterns, knowing what you now know about interference. Can you think of why we see these different colors like this? What if I were to consider this experimentally what is happening? You are standing outside of this aeroplane looking at this window.

So, the external ambient light sunlight is falling on the window falling everywhere and in fact, you see the aero plane because of the light reflected of this entire aero plane or whatever part of it and it is coming to your eye right or it has been taken by a camera, so through the lens of the camera.

In many parts of the aero plane so in all these regions, you just see the plane as you expect to see it, but in these regions the transparent parts you are seeing are colored light. So, you are seeing these images because of reflection; reflection is happening everywhere but something special is happening in these regions. What do you think is happening that it is causing these different colors to show up?

Student: That means different layers from which the reflected (Refer Time: 11:34).

So, what you are seeing is if I consider that there is a thin layer. So, let us say this is the glass of the window and there is some thin film on that right. Now, it could be that there is some coating on this glass, it could be that it has flown through and it is just landed and it has some kind of it is picked up some dirt along the way right, it could be that they were cleaning it and they have not finished cleaning it and there is some soapy layer on it still there is some coating ok.

To make it easy to understand, let us start with the case where we assume the coating is uniformly thick everywhere. Do you think you would see this then? The fact you are seeing different colors means that it cannot be uniformly thick.

So, you are seeing the image because of reflection. I mean that is normally how we see anything. The light surrounding the ambient light reflects off objects and makes it to our eye or makes it to the camera. That is how we see its reflection, there is no interference happening there.

But in this case this additional pattern we are seeing is not actually it is not that there is a different color there. The reflected light is interfering with some other reflected light and therefore what you are seeing is an interference of these beams of reflected light.

So, if I consider that you had a uniform film, let us say that thickness is d and let us say the refractive index is ok. Again just to make it simple we can start by saying we have normal incidence. That is of course, not the case. You would have light coming in at all angles.

But let us say we have normal incidence. What is the condition that I have constructive interference in reflection? Can you tell me, what is that condition? What is the condition for constructive interference in reflection for a normally incident beam?

Student: $n \times d$ into (Refer Time: 14:12).

Sorry, $n \times d$.

Student: Into integral (Refer Time: 14:15).

So, if I am going to put it in terms of phase, I will say 2 pi by lambda is equal to?

Student: $2\pi$

Ok.

Student: (Refer Time: 14:25).

Now, you have to be a little careful here. Why because what may happen?

Student: (Refer Time: 14:35).

Yes. So, if we assume this is air, this is of course whatever film and we are saying n has a is larger than 1 right and we have whatever this is glass. So, let us say this is 1.5 right, it whenever there is a when you have reflection in a medium which has a lower refractive index, then the next medium you are going to have a pi phase shift. So, in this interface you have a $\pi$ phase shift ok.

Now, I cannot say this is the condition for constructive interference unless I know what is n with respect to 1.5, the refractive index of glass. If n is less than 1.5 that means, I will have another phase shift of pi at that interface. So, the two phase shifts of pi will cancel out and I have this condition right.

If however n is greater than that of glass the refractive index of glass there is no phase shift that happens there. So, I have to take into account that additional phase shift of $\pi$ and I will actually have an odd number of $\pi$ in instead of 2 $\pi$

Yes, you had a question, no question right. So, in this case since we are not sure why the film formed, in this case I cannot say what is exactly the condition for interference, what I can say is that it will depend upon the relative refractive indices between these mediums. What I can also clearly say is wherever I see one color this means, I know this film is not of a uniform thickness. The thickness is varying.

In some places the thickness; let us assume the refractive index is constant. In some places the thickness satisfies the condition for constructive interference for lambda 1 and in other places for lambda 2. The fact we put this here, 2 $\pi$ is a phase change of 2 $\pi$ which corresponds to $\lambda$. If I change $\lambda$ it remains that is a different condition for that wavelength.

So, the different colors in this picture here on that part of the plane means that the film thickness is varying and at different places different wavelengths have a satisfying constructive interference condition and wherever a particular wavelength satisfies it you will get that color reflected back right.

So, it is a contour map of thickness, these fringes are a contour map of thickness. Fringes are always like contour maps but when I have a broad range of wavelengths falling on them then it is very easy telling me that it is a contour map of the varying thickness ok.

You can work out the condition if you have the light coming in at an angle you will have to take the angle into account. And if you are actually putting that thin film on to some surface for again to spectacles will often have thin film. When you go to buy spectacles they may ask you if you want a thin film coating on it right. And when you specifically ask for a thin film coating then the condition is satisfied, sorry.

So, if this is air. So, n air this is n of the film and this is n of glass it n f is chosen so n air is of course less than n f and it is also chosen like this ok.

So, that you have the well known conditions for constructive interference ok. That value of refractive index this value in the case of a thin film you are using it here for an anti reflection coating right that means, you definitely do not want light being reflected back. This simple equation that I have written down here tells you something about the thickness.

So, it is clear, you need to choose a particular thickness of and of course, a film of a particular thickness and a particular refractive index for ensuring that you satisfy this condition.

Now, do you think that I can say I give you a film and I say here is a film that is the material we have and it has a refractive index n m. I give you n m right. Do you think that you will definitely be able to cancel the reflected wave? What condition have I not talked about in this? Think about it? Ok.

We are still in the regime of electromagnetics right. So, you have encountered this kind of thin film or this kind of condition in many other areas of electrical engineering. So, what is the condition over here? You want destructive interference here, not constructive right. So, you want 2 pi by lambda into and to be equal to pi.

Now, in fact sorry that is not even correct. It is not $\frac{2\pi}{\lambda}$ and because the light is going through one beam hitting this surface there is one beam hitting this surface and reflecting and then it carries on and I am just showing it displaced just to make it easy to see and come to know.

So, that distance that actually has been travelled is 2 n d. So there is a 2 here and there is a 2 here all right. So, for destructive interference and when I am doing anti reflection coating that is what I want; I want destructive interference this is the condition; that means, the thickness d has to be $\lambda/4n$ right.

So, I am saying for destructive interference I need a film of quarter lambda thickness. Does this ring any bells at least for the electrical engineers in this class? You have all done electromagnetics you have all done.

Student: (Refer Time: 22:25).

Yes, where did you encounter that in?

Student: Polarization.

In polarization, but not only connected to light you see it in other places. We see quarter wave plates yes, but then that is again an optical application. Where else have you seen?

Student: Transmission lines.

Transmission lines right.

Student: (Refer Time: 22:45)

You use a quarter wave transmission line to reduce reflections in transmission lines, right. Do not look so; are you an electrical engineer or not? No [laughter] ok; then you are forgiven.

Do you now remember the rest of you? No, no idea. So, you meet this condition in several places. So, since you said transmission lines do you, is that the only condition? For the transmission line is the length is the thickness the only condition as there some other condition that? What this lambda by 4 ensures happens between the incident beam and there are two beams, you want destructive interference to happen. What does it mean? You do not want these to add up.

So, the $\frac{\lambda}{4}$ ensures what?

Student: (Refer Time: 23:43). So, the transmitter and the.

Sorry, say the first part again.

Student: Constructive interference is the.

So, the lambda by 4 ensures that you are subtracting beam 2 from beam 1. When you subtract 2 beams the answer is always 0, depending on the magnitude. This lambda by 4 only ensures you are not doing beam 1 + beam 2; it is beam 1 - beam 2. To get empty reflection to get no reflection the result of that subtraction must be 0. How do you ensure that it is 0? The value of that refractive index cannot be arbitrary.

So, I cannot say here is a material here is its refractive index, now you go choose the right thickness; you can choose the right thickness to ensure this subtraction, but if you have not got the right refractive index, you are only reducing the reflection you are not making it go to 0. And the condition and this is the same condition that you will have with a transmission line. In a transmission line you are not talking about refractive indice you are talking about impedances right.

So, in the transmission line you will see the impedance of that quarter wave plate has to be z 1 z 2 root of right where you are inserting this quarter wave transmission line between two transmission lines and you do not want a reflection to come back; that is exactly the same condition you say n f must be n air n g root of. Where is the origin of this, it is not black magic, I am pulling it out of a hat, what ensures how much light gets reflected?

If I want to actually go and solve this I will go write out Maxwell's equations. I will say the wave that is incident has this value, the wave that travels through the film and reflects off the lower surface has this expression. What ensures or what determines how much light is reflected, the boundary conditions and the boundary conditions in this case are going to be determined by the refractive indices.

So, it is that the thickness ensures you have destructive interference, but the actual value of the refractive index is going to ensure that you actually make the destructive interference have a lower value ideally go down to 0 ok, both are important ok. So, people so it is very hard to achieve this because now I am saying I need a specific n m and it is quite hard to achieve this.

So, you will find that in applications where you really need very high levels of anti reflection they will not use one single thin layer coating they will use a stack and they will have $n_1 n_2 n_3 n_4$. And alternating refractive indices will be less than you know low high low high low high and they will be able to achieve perfect 0 reflection from this stack of thin films not from a single thin film ok.

There is a whole science to calculating how many films with refractive indices they may all be lambda by 4 thickness but you need to have different refractive indices ok. So, this is the whole science to that, is that all?

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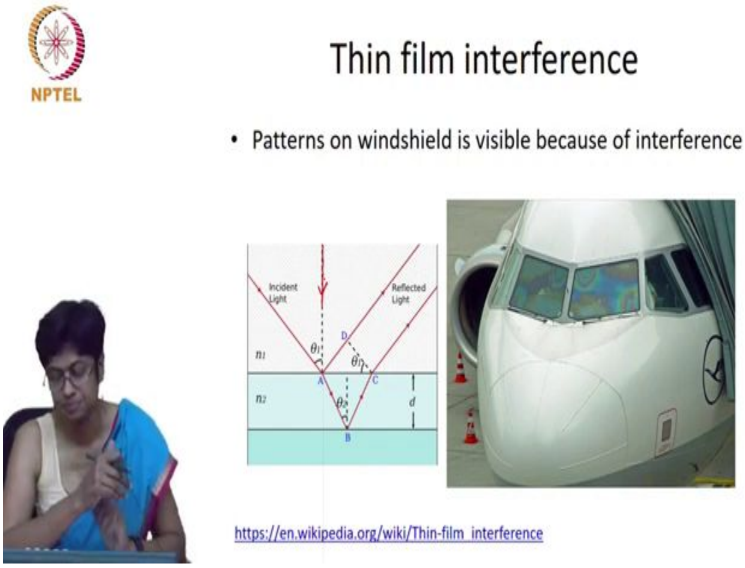


So, this pattern I leave to you as an exercise to work out. What is the condition when you do not have light? I talked about light that is incident normally, what happens if you have light that is incident at an angle; you should see a problem with this because this means I am choosing a thickness and that thickness will work for this angle of incidence, it will not work for another angle of incidence.

So, if in an application you know the light is going to be incident at a particular angle you could calculate the thickness of the film for that angle of incidence. In many cases they will just do normal incidence and for normal incidence you will have the least reflection for all other angles you will have some reflection right or you use this stack to say over a range of angles you are satisfying so that you get a broader coverage, but you cannot do that with a single film ok.

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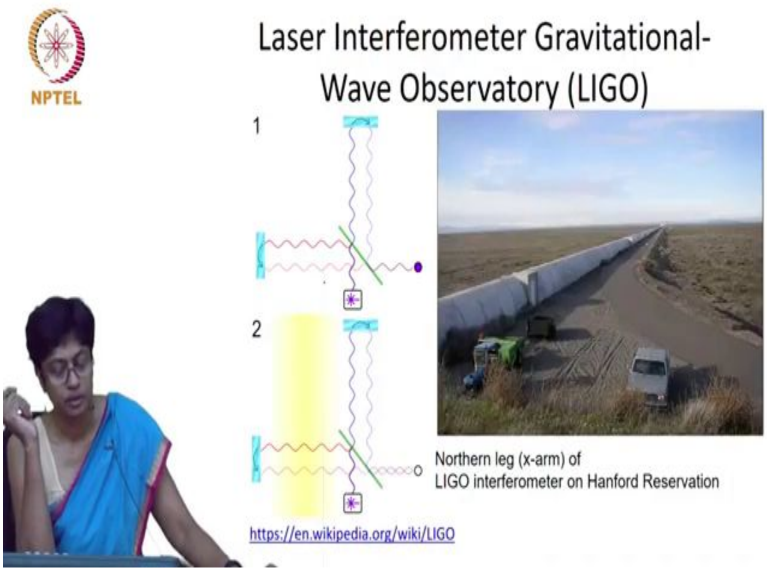


Yeah, maybe I just mentioned I will not go into any detail of it. Hopefully you have all heard of the LIGO. Yes.

Student: If in this case when you are saying uniform thickness, this (Refer Time: 28:29) other than just be angle which will be only for a certain wavelength right and (Refer Time: 28:36).

That is true. So, his.

Student: (Refer Time: 28:37).

Question is when you make a film you are making a film of a uniform thickness. So, you are achieving anti reflection for one wavelength, but again with a single layer that is what you can do, with the stack you can do you know some combination that it will work over a slightly broader range of wavelengths, but with the single film it will work for one wavelength.

Student: (Refer Time: 28:59).

You might note you do not wear glasses, but the people who wear glasses when you buy and they ask you if you want a coating they will ask you what color you want. Because it is anti reflective, you can choose it is anti reflective it one wavelength it will have reflection in another. So, you will have c coatings where you pick up the glasses they have a bluish stitch or they have a slightly brownish stitch.

So, it is cutting off the reflection in one wavelength band, the other wavelengths are reflecting and they combine and give you a color. So, many spectacles have the same colored tinge to them.

Student: So, that is because the complementary color is being.

Exactly.

Student: (Refer Time: 29:40).

Yes, ok. So, one more application is the LIGO interferometer. You ought to know about this because India is going to be getting a LIGO interferometer. It is a Michelson interferometer but it has very long lengths of the arms ok. So, I have been drawing Michelson on this little board here centimeters length. Does anyone know the length of the arm of Michael of the LIGO? Guess.

Student: 6 points.

4 kilometers. So, each arm is 4 kilometers long and the idea is when a gravitational wave passes it will affect one arm differently from the other and from that the way it is affected you will be able to tell something about the gravitational wave. You have to keep the measure difference as in distance in the order of 10 to the power minus 18 meters ok 4 kilometer path length and you are keeping it stable to that accuracy right auto meters.

So, you can see what you are seeing here. It is all enclosed, it is all air conditioned right. So, you can make very accurate measurements with an interferometer in order to increase sensitivity you need to change your path length. Yes, that is what they are doing with this interferometer here ok.

But I just wanted to mention it because it just shows you the all kinds of things from that simple coating on your glasses to measuring a gravitational wave or studying defects on a large object or studying modes of some object that is undergoing vibration all of this and much more you can do with interferometry or holography which is a form of interferometry ok.

So, the rest of the class I will focus on a different application.

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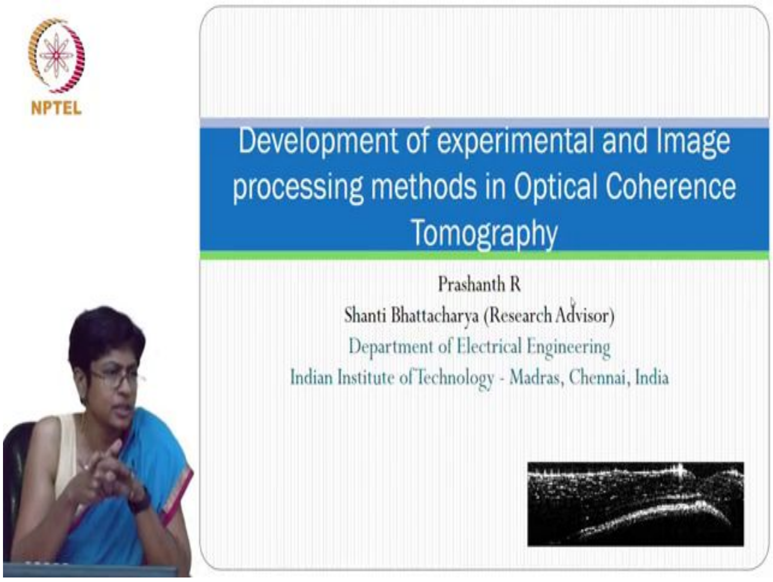


So, this is work that a master student of mine had done. So, we are going to talk about Optical Coherence Tomography. So, when I say tomography, what do you think of? What is tomography? My God! I have to.

Student: (Refer Time: 32:10).

Student: Sections of image.

Sections of image. So, you are creating an image, but you are creating slices somehow of that image. So, optical coherence tomography is a technique to do exactly that creates sections of an image. It has various reductions now it is used a lot. So, we do not need to look at this um.

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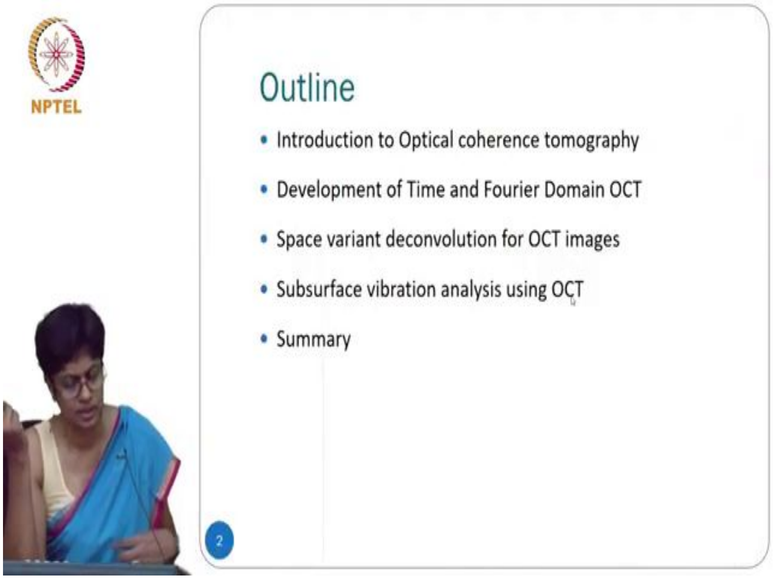


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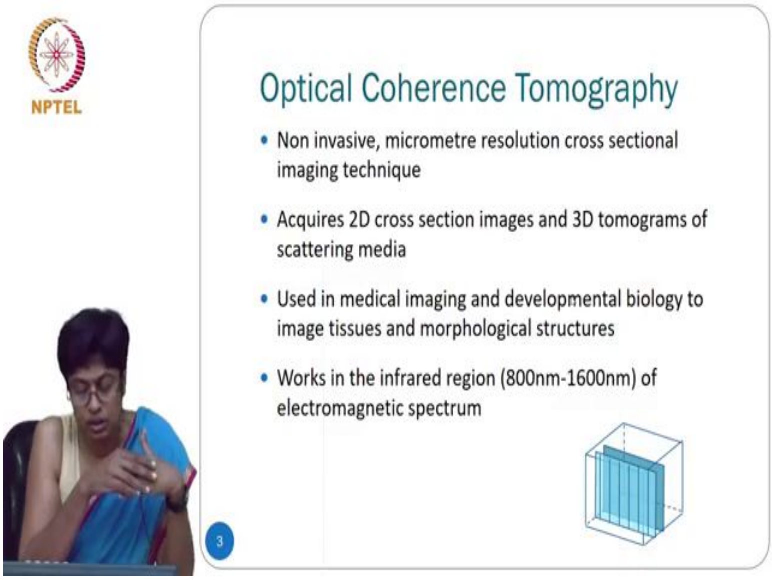


It is used a lot in biomedical imaging. But it can also be used in art restoration. You know you want to look at the different layers in a painting. Earlier, you know how they would do that if you have an old painting and you want to see the different layers. How would they do that?

Student: (Refer Time: 32:55).

So, when you are doing any study of this kind when these are you are trying to get an image you are doing sensing you can do destructive sensing you can do non destructive sensing.

So, earlier they would cut out a bit of the film. So, if they would have the painting they would go to a corner and hide behind the frame and cut off a little bit and use that to study. So, that is destructive ok.

OCT is used for imaging of the eye. Now, they are not going to say ok I need to find out about your eye let me go in and cut out a little bit and say oh you are fine, but no I hole in your eye now because they cut out a little bit. So, clearly when I am doing medical imaging or medical diagnostics if I can avoid an invasive technique yes we do actually do that if you suspect a tumor there will be a surgery and a biopsy to pull out a little bit of tissue to study that.

But they are always trying to research ways that you can look at what is happening inside the body without having to physically go inside the bodies. That is we want a non invasive non non-invasive when you are talking about humans and non destructive when you are talking about some mechanical body ok.

So, OCT is a non invasive technique right we have other non invasive biomedical imaging techniques you have ultrasound right you have MRI right um. I think I do not have that picture here. But if you look at the resolution so what is the problem or why does OCT find a place in all of this.

All the other medical imaging, any medical imaging you will always look at what is the resolution with which I can image, what is the depth with which I can image. I want to go as deep as possible with the best resolution as possible. Some techniques will give you very good resolution but very poor depth; some will give you very good depth not that good resolution right.

So, OCT fix in where it is is not very good in depth but it is better than some other techniques and again it has a fairly better resolution ok and it is completely non invasive. So, in medical imaging the OCT is usually done in this wavelength regime in the infrared and you are creating images 1slice at a time and you can put these slices together and there once you get a

2D slice at a depth within the object of interest and then you create many 2D slices and thereby you have a 3D image.

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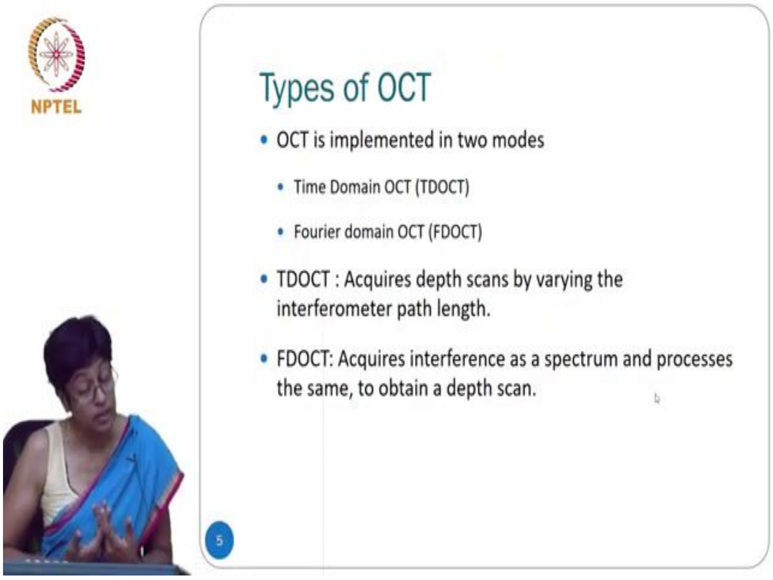


It is; it is really of importance now because if I can create an image of the eye you can also. So, one thing is you can study the retina. So, if there is any damage to the retina you can see that but you could also look at between the eyes so ophthalmology.

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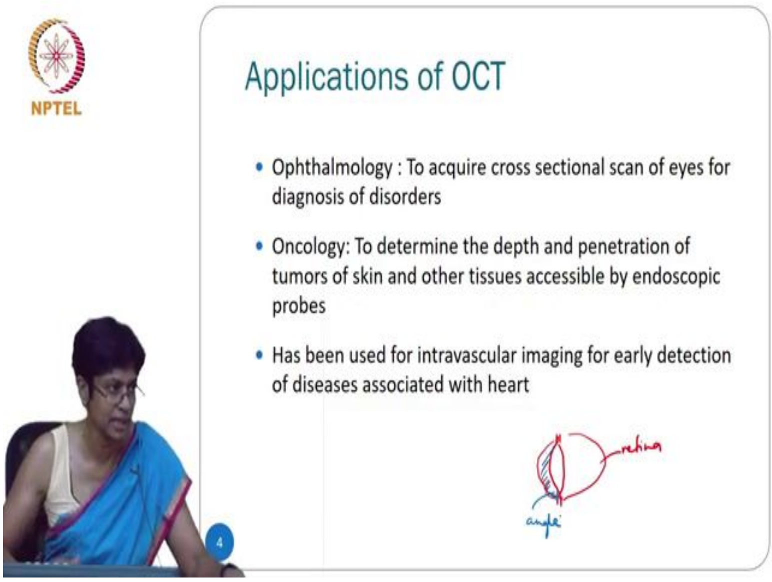

So, if you look at the structure of the eye and clearly I am not going to draw this properly so that is the lens of your eye. Actually you have the cornea right and then you have the retina over here. Very bad eyes clearly this person needs surgery but let us take it as this.

So, I can either image the retina or I can use OCT to image this region right this region and then I measure this angle and it turns out that angle changes when the pressure in your eye changes and that is an early warning sign of diabetes. And you know India has unfortunately got the title of the growing diabetes country in the world you want to make as early a diagnosis as quickly as simply as possible.

So, if you say measuring this angle and seeing the changes of this angle or seeing it vary from what the average is for most Indians you can then make quick and non invasive diagnostic techniques for people ok. So, there is; there is a lot of push for this kind of technology.

The two ways of doing OCT and depending on the time we will see if we cover both. But the idea of OCT at least will come through the first one we call this time domain OCT ok. So, let us look at the set up.

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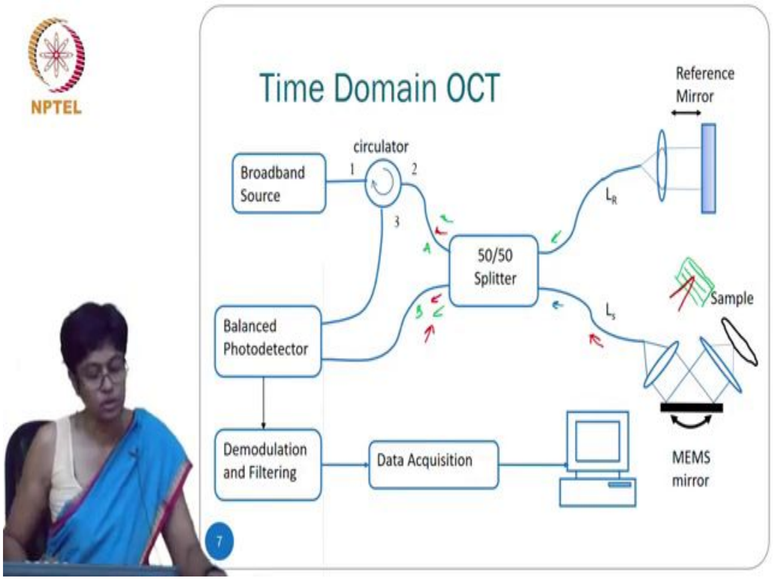



Now, it may not be obvious from this setup, but what you are looking at is a Michelson interferometer ok. This particular setup has been built completely with fibre which is why the arms are not that standard 90 degrees to each other but this is one arm and it leaves the fibre and it gets expanded and hits a reference mirror and this mirror has the ability to move and we will see why that is important.

But it is normally an incident in the mirror. So, it comes back and re-enters the fibre and this splitter is nothing but the beam splitter. The other arm sends light to a sample and again I will explain why it goes through this little set of optics here and this mirror over here. But basically, this is your reference arm and this is your object arm again light reflected off the sample makes its way back and comes here.

Now it comes to the splitter which means everything that comes through this arm gets split. Half of it goes back this way half this way and similarly with this arm. You put a circulator, so a circulator is an optical device that allows light to flow only in one direction. So, because of this circulator the light that comes back here does not go back to the broadband source, you do not want it to go back to the source it will have damaged the source. But instead you send it here.

So, I actually have two interference signals I am measuring: one is coming from I have light from now what did I do right. I have light coming from here and it is going here and here and I have light coming from here and it is going here and here.

So, both these arms A and B carry an interference signal ok. The property of the splitter though is there is a phase difference between these two signals and you will see why or how we can use that. I can in principle take only one of these signals and do everything but this is a slight advantage in using both of them. But one signal alone carries an interference of the reference and the object beam.

Come to this detector and then we do some processing and somehow from this interference pattern we get an image let us see how. It's so important we do not have a laser here, we have a broadband source that immediately means what can you say about it.

Student: (Refer Time: 40:39).

Poor coherence, so what happens and do not forget this mirror can move. Now let us say you set up this experiment such that the mirror reference mirror is in a fixed position and you are getting light from one particular plane in your sample and you are setting up this system such that for that plane the optical path length difference is zero. So, you have the best interference. I can consider this sample just to make it easy. Let us say it consists of layers like this ok.

So, I have set up this such that I get reflection say if I am trying to change this I have reflection from this layer this light is reflecting from all the layers I cannot control that if light is incident on the sample there is a reflection from the top surface from every surface or every disturbance within the medium and from the end of the sample. But I have set up my system such that the path length difference is 0 only for the light reflecting off this one particular layer; it is not 0 for all the other layers right.

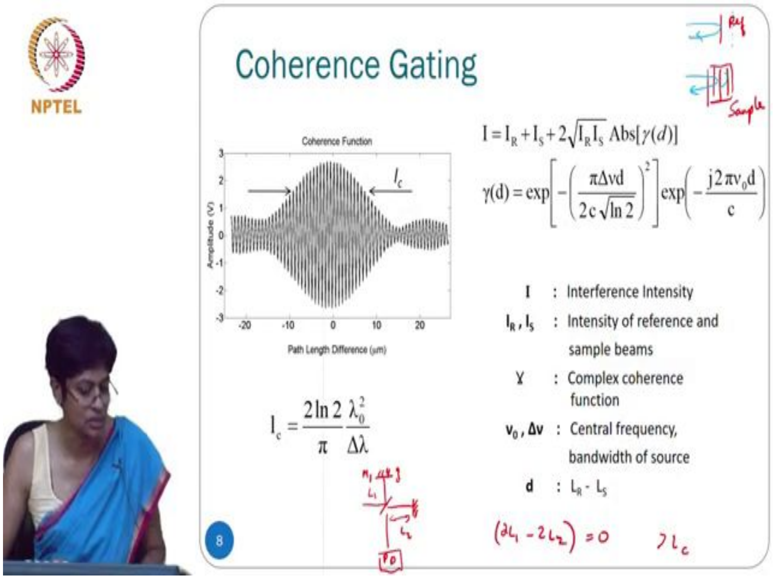
So, this the signal coming back here is a combination of the light reflected back from every layer in the sample. When the interference happens here however, it is going to happen only between the light from the reference mirror and the light coming from the sample which is within the coherence length of the source.

Does that make sense? What happens to the other light? I have light coming back from layer 1, layer 2, layer 3, layer 4. But I have set it up that only layer three has a zero path length difference with the reference mirror. So, what happens to the reflected light from layer 1, layer 2, layer 5, layer 6 so on what happens to that?

Student: That will be (Refer Time: 42:54).

It is just the DC it does not play a role in the cosine term it is just adding a DC to your signal right.

(Refer Slide Time: 43:05)




So, that is what this is talking about. This technique is called coherence gating. Although you have light coming back from a large depth your signal of interest or and the signal that you are going to use is gated by the coherence length of the source you get useful signal only over where the path length difference is matched and that is going to be decided by the coherence length of your source right.

So, if I were to take a simple Michelson interferometer let us draw it here: beam splitter one mirror another mirror and I look at a photo detector here right. We know now that if these two mirrors are perfectly perpendicular to each other on the photodetector I am going to get some intensity. Now let us say I move this mirror one mirror at a particular frequency over a particular distance if the distance goes beyond the path length difference.

So, this is L one let us say this distance this is L2. So, two L1 - 2 L2 is the path length difference assuming everything is in air and neglecting what is happening in the beam splitter. This is a path length difference. Let us say I initially set this up to be 0 my photo detector will have one high value now I move mirror m 1 it is vibrating at a certain frequency if it moves such that l 1 this becomes this difference.

Becomes greater than the coherence length my intensity which was a high will become a 0 and then the mirror moves back again and it is a high then it moves further and it becomes a

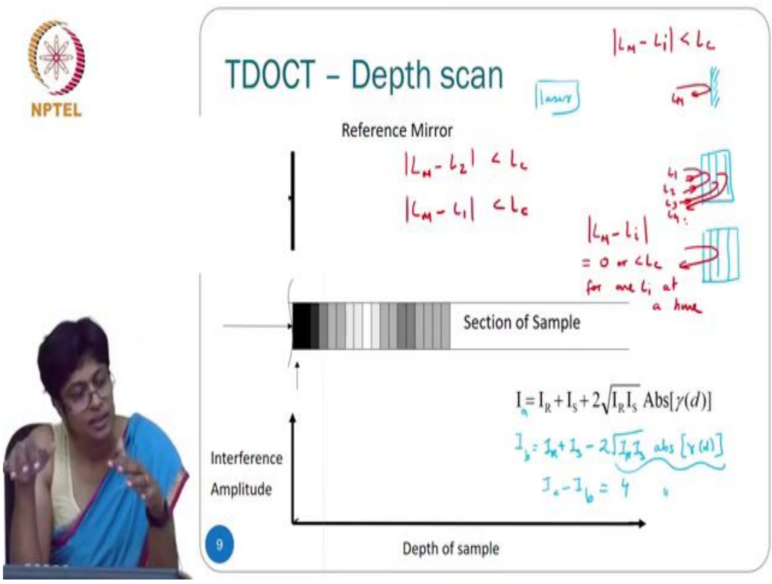
0. But as it moves it is moving from the maximum value to the minimum through a range of values and that is exactly this kind of pattern that you see here this is a pattern as the path length difference varies right.

So, I can use this now to reconstruct right every time the mirror moves to a certain position I am changing where the optical path length is matched in the sample let us let me draw just the sample this is a sample these are the different layers of the sample this is the reference mirror ok.

Now initially it sets up the mirror reference mirror in a position. So, the light coming from here is matched to this position. At this position the path length difference is zero. I get the maximum intensity for this position now the reference mirror let us say it moves over here; that means, the matching condition is now for this layer.

So, if I know if I am able to track where my mirror is and I see a peak there I will say that corresponding location in the sample there is something happening that is causing light to be reflected and using this I am able to reconstruct my image ok.

(Refer Slide Time: 46:47)



So, if you think of this let us say this was a section of your sample and to make it simple we have this thickness is the uniform thickness of course, as real sample tissue will have a lot of scattering centers randomly put.

But just to make it easy to understand we assume each layer is a scattering of one kind right and if it is very dark; that means, it does it scatters very less light if it is very bright it means it scatters a lot of light ok. So, as when I am showing you again only the sample and only the reference mirror on top right not showing you the rest of the Michelson interferometer as the mirror moves you are looking at this interference pattern below this is the interference pattern below it is very poor in the beginning.

Because you have very poor reflection in the beginning it is very bright at this place because you have the maximum reflection at this place and if you are tracking or able to monitor the move length or the location of the mirror. If you know the refractive index of the sample you can tell what the kind of scattering that is happening at different depths at what depth within the sample right.

Simple concept right working purely by the method of coherence gating. Now I had said we get the interference signal from two arms of the splitter and what I am showing you here I can achieve with just one arm of the splitter because that signal itself is an interference signal. But it turns out if I consider arm one as let us call this a that is coming from one arm and the other one is this.

Because I have access to both these signals, what we do is we take the difference between them. So, you get rid of the DC term completely, you actually use 1 a minus 1 b and then you are left with four times this signal. So, you have enhanced the term of importance and got rid of the DC term simultaneously which means you have a better signal to work with ok. So, that is why we use both the signals.

Yeah, you had a question.

Student: (Refer Time: 49:28) one by this is a broadband source required?

Can someone tell why a broadband source is required?

Student: (Refer Time: 49:38).

Sorry.

Student: Since, we have some danger.

That is true that you do not want to send a high power laser through someone's eye, but that is not why there are limits even to a laser as long as it is lower than a certain power you can send it into the eye.

Student: We want to know what kind of (Refer Time: 49:55) eye objective. What are the (Refer Time: 49:56). No, the whole idea rests on what was the previous slide.

Student: Coherence gating.

Coherence gating. Why can you answer your own question?

Student: I did not understand the for density part, didn't know why (Refer Time: 50:12).

Let us say I used a laser. Now I have a sample. I am not drawing the full setup. These are the different layers of the sample; this is the reference mirror ok. Now I have light reflecting off of this and there is light coming of this, there is light coming of this, there is light coming of this, there is light coming of this. If I have a laser each one of these is an interference signal they are all strong.

Because the laser is a long coherence length how do I tell that something happened at this position I cannot tell I have an interference signal from the top of the sample from every scattering point within the sample as well as right at the end of the sample because I have poor coherence what we are saying is. In my sample there are different layers. Yes I have reflection from every the same thing optically the same thing is happening there is light reflecting everywhere.

But I can set it up. So, that only this beam has zero path length difference with that 1 on forget 0 path length difference only this beam the path length difference is less than coherence length. So, in the let us say let us count each of these beams is L1, L2, L3,L4 and so on and this is LM. Let us say the path length to go to the reference mirror and back is LM and the path length to go to the first layer and back is L1 to the second layer L2.

So, in the case of a laser LM - L1 is always less than the coherence length for let us say L i for any layer and in this case L M minus L i is only equal to 0 or less than L c for one L i at a time. Does that make sense? Think about it. It is a very simple concept not that easy to grasp, but can you tell if you understand the difference between this condition?

In the first condition, if I use a source with a long coherence length I am getting an interference signal back from every layer simultaneously. I cannot distinguish layers and the whole purpose of this imaging is to say something happened here therefore there is a scatterer here.

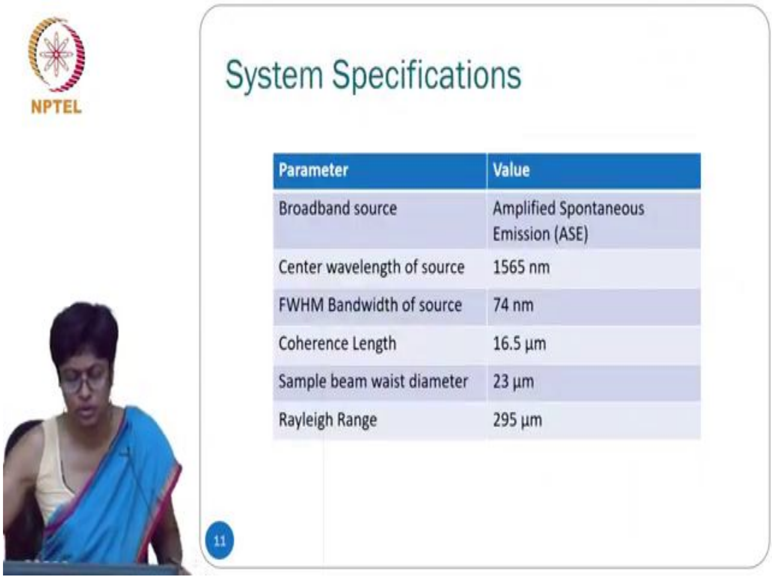
Student: But let us say in this case also it may (Refer Time: 52:59) L M minus L 2 is less than coherence length then L M minus L 1 will also be less than coherence length here.

No, it will not be; it will not be, go and check that it will not be, put numbers and see it will not be.

Student: In this case depending on the bandwidth of the broadband source, we will know how many layers it can (Refer Time: 53:24).

Because yeah, sorry yeah the bandwidth source determines the coherence length right the broader the source the less the coherence length the less the coherence length the higher the resolution of your OCT system. Conventional systems now have like 10 micron you can get a 10 micron coherence sorry resolution because the problem so, you have in this case I do not know if I have that here yeah.

(Refer Slide Time: 53:54)




So, for example, the source we used the bandwidth is 74 nanometers and; that means, we had a coherence length of 16 microns. People use up to 100 nanometers and they may have gone down in coherence length.

Student: Also can here you wrote I b plus IR + I S - $\sqrt{2}$; why is that the case?

That is the condition in the beam splitter. So, this is what happens at the beam splitter there is a phase shift of.

Student: (Refer Time: 54:31).

pi over here between the two arms. So, we have just made use of that fact. Often we just throw away one arm, we do not we just ensure it does not go back to the source we do not use it, but you can also use it in this case.

Student: Is it the same case in micro (Refer Time: 54:47). In interferometry also that last lab does this happen, is there a phase (Refer Time: 54:52)?

Yes, yes it can happen yes.

Student: (Refer Time: 54:55) the one which goes to the (Refer Time: 54:58) and the one which goes to the source (Refer Time: 55:00).

It I want it to depend on the type of splitter that you are using because these phase changes are happening because of the reflections that are happening you know; you know there is a pi effect. So, it depends on the beam splitter, but in the fibre splitter there is definitely a phase change it depends on the type of beam splitter you are using, but yes it can happen.

So, this at least gives you an idea of optical coherence tomography. He asked a very relevant question it seems like if I say LM - l2, If I say this is less than Lc it seems like LM -L1 should be less than Lc too right it seems like that, but that is not the case.

So, go and I want you to think about this right, why is that not the case. Your condition will only be ever satisfied for one small distance because you are moving your mirror also do not forget that. When I say L M remember in your experiment LM is also moving, LM is not constant right that is why in time domain OCT the reference mirror moves. So, every time I have a new LM for that LM you are ensuring that the condition is satisfied for one layer in the sample.

Because I move the mirror to a new position, right. So, go think about it. If you have the basic concept you should be able to reconstruct the working. I would not have time to do the Fourier domain. What the Fourier domain does is it gets rid of the movement of the reference mirror and says well I can just take a Fourier transform of the signal and I can extract the information from there because it is buried in there right.

So, I will not talk about that because I want you to get the idea that we you know we have talked about sources with good in coherence, but here you want the poorer the coherence the better the resolution of the source and in fact, white light interferometry is used in sensing all the time because it allows you to measure very small displacements because of the poor coherence length again.

You only get interference if it is less than the coherence length and because the coherence length is so small you can use that to measure very small displacements because you will not get interference unless you are doing so over a very small displacement ok. So, it is not that coherence is required for interference, but we often exploit poor coherence because it gives us better sensitivity ok. So, I will end with that today.