Optical Fiber Sensors
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Lecture 23
Phase Modulated Sensors - 3

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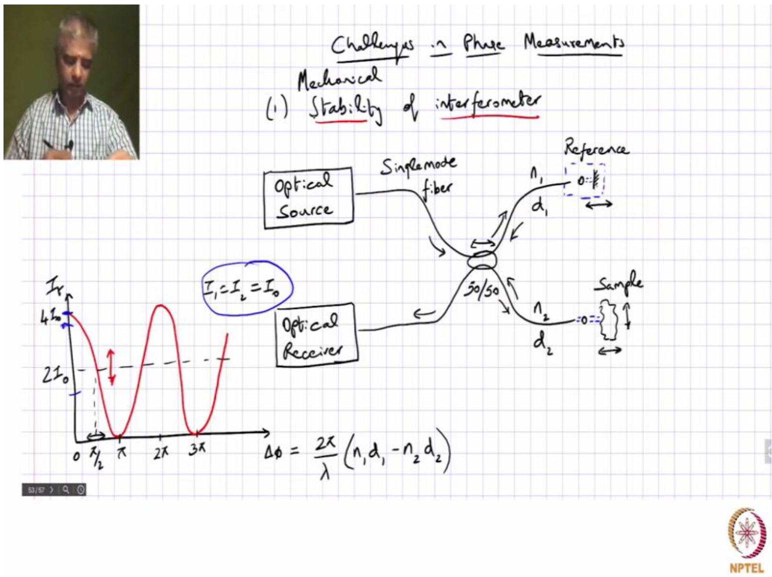

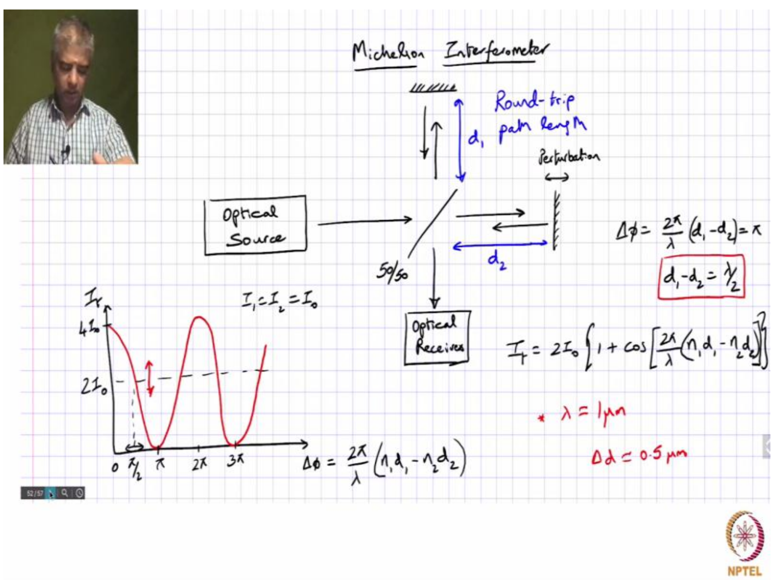

Hello, the last lecture we started talking about challenges in phase measurements. This is in relevance to phase modulated sensors, which we have been discussing over the last few lectures. And one of the challenges that we identified is actually the stability of the interferometer, the you can call it the structural or mechanical stability of the interferometer. So, we were trying to figure out, how do you realize an interferometer that does not require a lot of alignment.

So, as we saw previously, if it is a free space interferometer, then there is a lot of alignment requirements precise alignment requirements, whereas, if you go to a fiber based interferometer, then you could potentially save yourself valuable time and also in terms of getting a good measurement capability set up, this sort of arrangement would actually help you in that in that sense.

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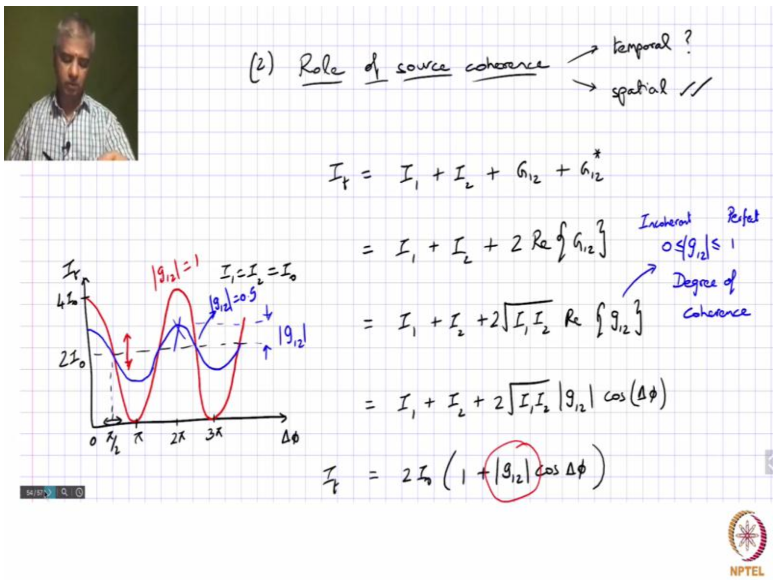

And then of course, we said, there is a question is to what type of source that you use. So, we started talking about the role of source coherence. And then we said, well, coherence could be either define in terms of spatial coherence or temporal coherence. And, of course, in a single mode fiber, you do not really have to worry about spatial coherence, because you are starting with the fundamental mode and you remain with the mode through the interference process.

But there is still a question with respect to temporal coherence, and then we started defining the beating of the 2 waves in terms of the mutual coherence function, which is what we call us g12 and n and its conjugate and then we were able to get an expression of the interference the total intensity in terms of the degree of coherence. So, then we said well, if you had g12 the magnitude of g12 determine the visibility of the fringes that you will get as you change your path length delay or change your phase difference between the 2 arms.

And then we said, if you had high coherence, for example, perfectly coherent light, that is when you get this best fringe visibility. So, you go to maximum and which corresponds to 4 times I naught, if I1 equal to I2 equal to I naught, and then you go to a minimum which is 0 perfect cancellation, when the phase difference is pi and that is valid only when g12 equals to 1.

And we looked at the fact that if g12 is not equal to 1 that is basically this case, magnitude of g12 is like 0.5 or something like that, then you did not necessarily get very good fringe visibility and you were limited by that. But then we said, what is this temporal coherence mean really? So, we said, how do we define what are the characteristics of the source that determines temporal coherence that determines this value of g12.

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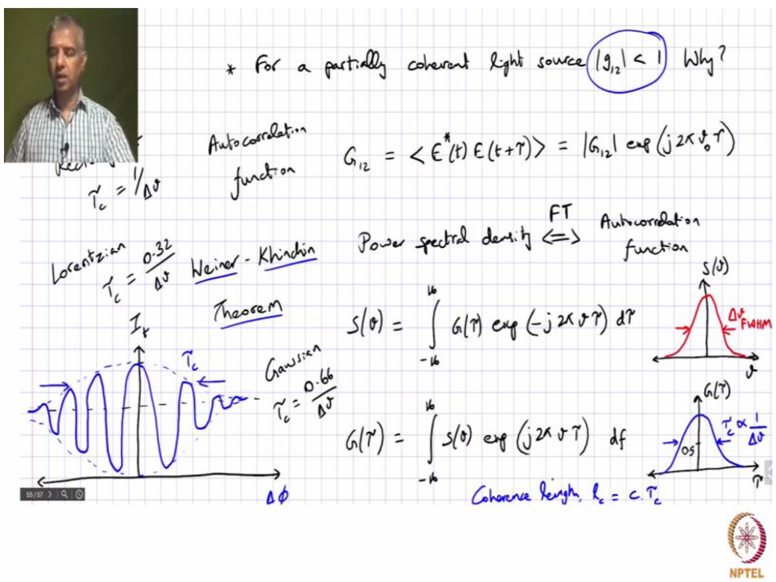

Then we went a little deeper and then, we started looking at partially coherent light sources and what are the properties of partially coherent light sources, we understood that what we are actually measuring in a Michelson interferometer corresponds to an autocorrelation function. And then we went on to say that the autocorrelation function is nothing but a Fourier transform pair with respect to the power spectral density. So, for a given autocorrelation function, you can actually define the power spectral density or vice versa through this Wiener Khinchin theorem.

And then we went on to say that, if you know the power spectral density, you can figure out the autocorrelation function, or vice versa. And more importantly, we realize that for a given source with a certain source line with defined by delta nu, when you look at the coherence time, that is going to be inversely proportional to the source line width. And what that means is the coherence is actually or the interference is actually a valid only for certain values of phase delay, which can be also represented in terms of the coherence length.

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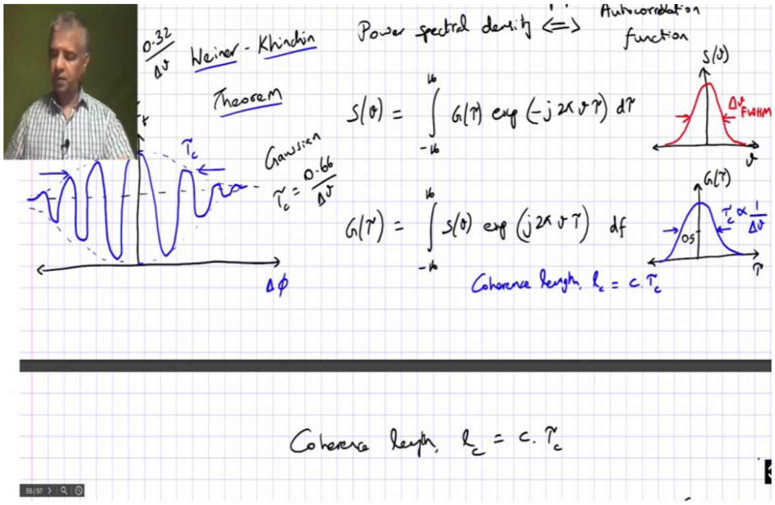

So, we said the coherence length is nothing but c times coherent, I mean, the velocity of light in free space multiplied by coherence time. And that means, you will, you are going to lose your fringes, or you are going to lose the ability to produce interference of light, you are going to lose the ability to use the interferometer to behave like a phase modulated sensor, if you are essentially going if you have a path length difference that is greater than the coherence length, and essentially the corresponding phase in that that is actually defined.

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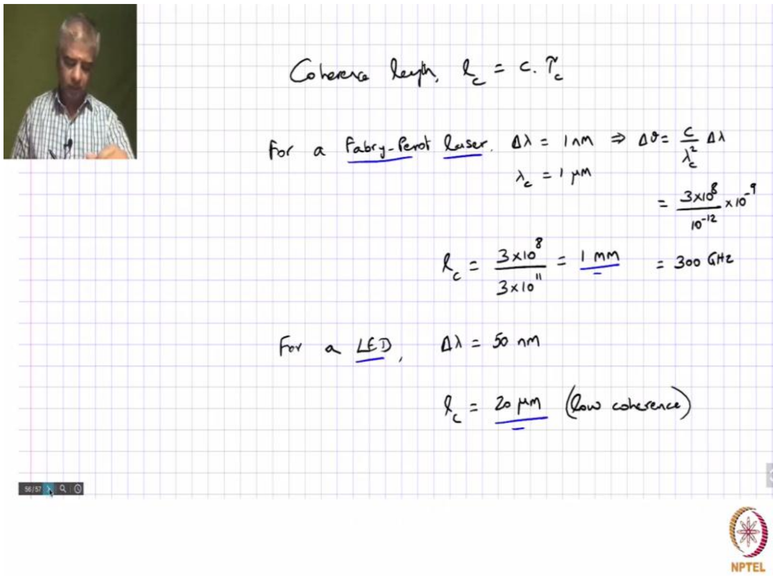

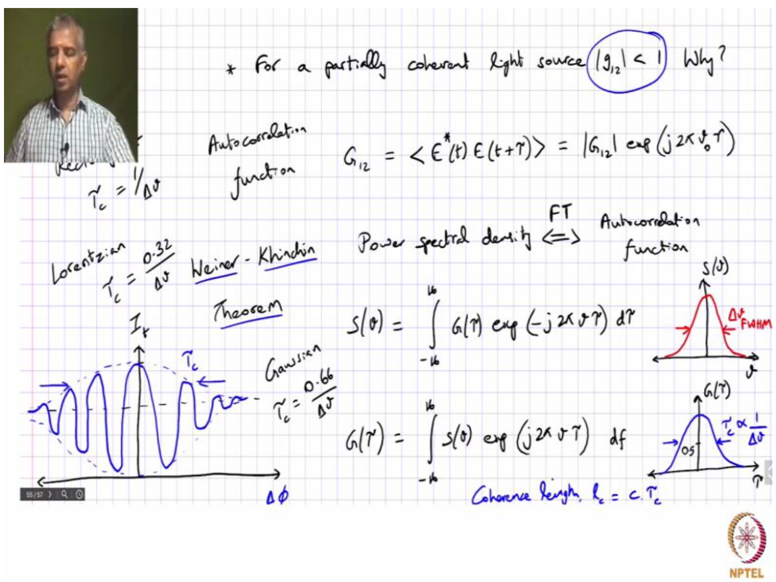

So that is where we were and then of course, we took some examples of a Fabry Perot laser, and we said Fabry Perot laser as a coherence length of 1 millimeter if you take Fabry Perot laser with spectral with a 1 nanometer, and we said, in contrast, if you use a broadband light source like an LED, then the coherence length is 20 micron. So, now the question becomes, I mean, it is clear that, longer the coherence length, more will be the delay path length difference between the 2 arms, where you can achieve significant interference.

And that actually means that, you need to have high coherence, especially, let us say, I mean, we are talking about this example of a LIGO, in a LIGO the, the path lengths, the individual path lengths in the 2 arms are in the order of kilometers. So, if you have something the order of kilometers getting millimeter accuracy in terms of position is going to be extremely difficult. So, you certainly need highly coherent laser, so that the pattern difference even if it is in the order of a meter over, over kilometers, you can still tolerate that.

So that essentially tells you that you need to use a laser, whose line width is something in the order of kilo hertz, even lesser if it can be allowed. So, that is one extreme of an application where you need highly, highly coherent light. And the same example or similar example we were mentioning, when we want to go to, pick up information from long distances, say 10s of kilometers, we said we could use what is called a phase OTDR.

Previously, we looked at OTDR from the perspective of picking up Rayleigh scattering, we were interested primarily in the amplitude or the intensity of the Rayleigh scattered light, but now you can actually look at the phase of the Rayleigh scattered light and you can possibly, detect perturbations that are happening several kilometers away.

And once again, in those sort of situations, it would help if you, had a path length if you had a laser that supported such large path length differences, and once again, in those applications, we are talking about highly temporally coherent laser or a laser with very narrow spectral width in the order of kilo hertz, if we can manage that. Now, that actually brings up the question. Do you have any application for low coherence? Sources, do you always prefer high coherence sources or low current sources useful at all?

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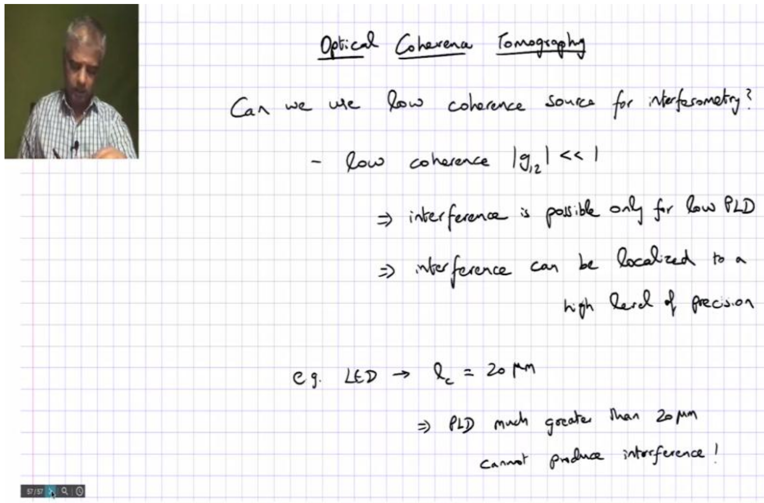

So let us examine that a little deeper today. So, we are going to look at Optical Coherence Tomography. So, what is optical coherence tomography? Well, we start with a question that can we use low coherence source for interferometry and implied in that question is can we use low coherence source for phase modulated sensing and the, and what do we what do we mean by low coherence?

So, low coherence corresponds to the fact that your degree of coherence is far less than 1 something that is closer to 0. So, what is the use of that and what does it mean to have a low coherence source? So, clearly means that the interference is possible only for low path length difference. So, we said lc is equal to 20 micron for LED, so, it supports only some, interference ranges or path length of 20 micro meters.

So, that is that is clearly one way of looking at it, but the other way the positive side of this is that it also implies that interference can be localized. So, you are essentially saying that, you might have a case where the perturbation exists over a deeper region of a material, but you are only looking at, a very small region like in this case with that 20 micron region, that is where the interference fringes are produced.

So, you are essentially examining only that region if you are picking up the fringes. So, you can always also say that interference can be localized to high level of precision. So, that is actually a fairly, useful thing to do, if you could, if you could localize like, so, let us take the example of

LED, which has coherence length of 20 micro meter. So, what does 20 micro meter mean that PLD much greater than 20 micro meter cannot produce interference. And, so, how can we make use of something like this. So, let us actually draw a typical schematic once again of a Michelson interferometer and then examine this.

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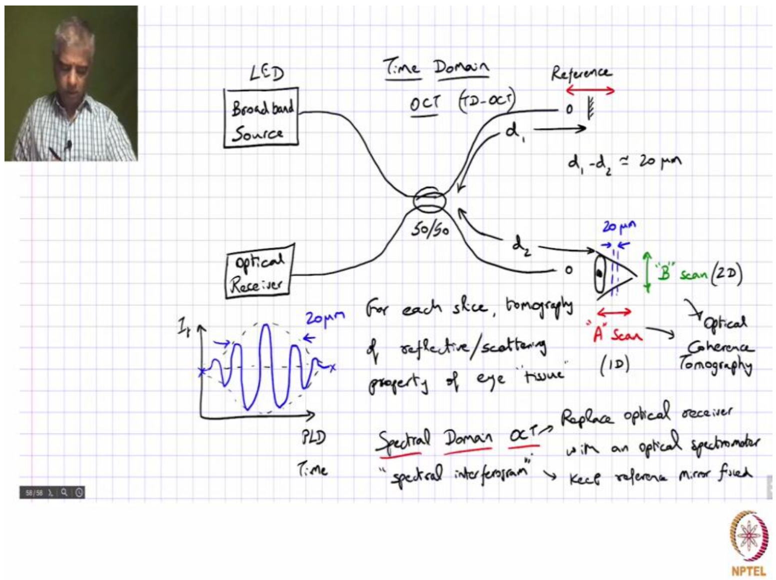

So, so, I start with as usual an optical source, I am looking at a fiber coupled optical source so, you send it through a coupler, and as we did before, we use reference arm, use one arm of this 50-50, split light as a reference arm, and then you bring the other arm over here. And then you can actually, we said we could put a sample over here and then do some measurements.

And of course, what is helping us do those measurements is the indifference component that we can pick up using our optical receiver. So now the question is, where can you use optical coherence tomography, I think this method was actually proposed almost 30 years ago almost 1991. And it really made the world turn around and take notice and it is one of those technologies that had such profound impact that it is commonly used in certain applications, specifically, now Tomology.

So what are we talking about? Well, you could have a some issues with respect to eye. So how do you normally pick up any defects in the eye? Well, you go to the ophthalmologist and ophthalmologist actually makes you sit in front of some viewing, some scope and makes your eye open. In some cases, they usually do dilation of the eye as well. And then they basically try to see if there are any changes, that is happening in the eye.

Now, if there are any issues like that change the color of the, the cornea or something within that, then it will easily show up and when they look at it, but what if for example, something like a cataract forms, and then you are not able to see any discoloration or maybe cataract is a bad example. But I am saying if there are any other infection, which does not change the color of the eye, but it is nevertheless present it, it changes the property of the eye material, in terms of just say, the refractive index of the material of the tissue has changed.

In those cases, it is not going to be easy to pick up what is happening. In those cases, it helps to actually do a scan layer by layer by layer of the eye. And that is where actually optical coherence tomography becomes prominent. So let us actually take a closer look at that. So let us say this is our eye. And, and we what we want to do here is actually look at what is happening layer by layer.

So and we want to do this with very high precision, let us say, in the present case, we can possibly do this over 20 micro meters. And this is a perfect application for, low coherence radiation. So in fact, I can basically say, instead of just any generic optical source, I would say this is a broadband light source, like an LED. If you use a LED with the coherence length of 20 microns.

What that means is for path length differences within 20 micron only we will be able to pick up interference. Outside of that, our optical receiver does not recognize that though these 2 waves are coming from the same source, so they it does not actually produce the interference fringe. So, only for path length differences, when we are talking about path length differences, we are saying, let us call this d1 and let us call this d2.

So, for d1 minus d2 is in the order of 20 microns, 1d over that region, it is going to be able to produce an interference fringe. So you can say that if you are looking at this as a function of path length difference. So you would, like we talked about before, if you are the looking at the total intensity, total intensity is going to be something like this and 1d over path length differences in the order of 20, 20 micron, you are going to have this interference fringes.

And if it is larger than 20 micron, or lesser than 20 micron, you are essentially not going to have, so that corresponds to these points over here, and you are not going to have any interference fringe. So then whatever fringe you are seeing corresponds to the optical property of that light, that scattered back. And the optical property as in the refractive index of the medium is primarily what we are looking at.

And so if there is any change in the refractive index of the medium, or if there is any change in the amount of light that is reflected scattered back, you are going to be able to see that in terms of these interference fringes. So what you do is you want to actually scan layer by layer. So what you essentially have to do in this case is you move your mirror, as you move your mirror, you are actually that is an exaggeration, you are scanning across this depth of the eye.

And that is what we call as A scan and then so that actually gives you depth information. And then the other thing that you can do is you can actually move this qualimeter with respect to the eye, and that actually provides a scan in this direction, which is what we call as a B scan. So, you can do the A scan to do depth information, and let us say you fix at a particular distance, and you basically scan across the transverse direction across the eye. And then you can you can actually get information in the transverse direction.

So you basically take slices of these images, of the eye and that together is you do a tomography. Tomography is basically taking all these slices and stitching them together to get a 3 dimensional view because B scan is giving you a 2D and A scan is giving you a 1D that is along the depth, so you can get a 3D tomography that is done. And this is made possible by using the coherence property of light.

So this is called that is why it is called optical coherence tomography based on the low coherence of light, you are essentially doing this tomography. And whenever you are doing this moving of the mirror, you are essentially doing it with respect to time delay, what you are essentially doing is actually the path length difference and the path length difference is, when you are detecting the receiver, this actually shows up as this change with respect to the interference fringe with respect to time as you scan this region.

So, this is actually what you call as a time domain OCT. So, time domain OCT you move the reference mirror to essentially get A scan done. Then that actually brings up the question is there a way you can achieve the same information, without having to move the mirror. And so happens that is actually possible using what is called spectral domain OCT. So, before we look into that, I do want to make sure you understand that what we are essentially achieving here is for each slice that we are doing, we are doing a tomography of have reflective or scattering property of the eye tissue.

So, you are essentially looking at the tomography of the reflective and scattering property of the eye tissue. And, like we talked about, that is what you are essentially getting with this achieving this A scan and B scan, but the same thing can be achieved using spectral domain OCT as well. So, that is the other type of OCT that you can realize.

So, what we are essentially doing is in the spectral domain OCT we are, replace the article optical receiver which is actually capturing intensity as a function of time, replace that with an optical spectrometer. So, even as we so you keep, so the key thing is keep reference mirror fixed. So, it is not, there are no moving parts as far as a spectral domain OCT is concerned, but you just keep the reference some fixed and then what you realize is that for different wavelengths, you know that the path length difference is I mean your phase is defined with respect to 2 pi over lambda.

So, that means different wavelengths are essentially going to see interference from different regions or different depths across this eye. So, if you are actually looking at spectrogram so, that is essentially what you are doing you are you are getting this spectrogram or in specifically you call this as a spectral interferogram, if you have a spectral interferogram then with that, you can actually each spectral component is representative of one particular depth along the eye.

So with that, you should be able to actually get the entire, so if you have enough spectral width, let us say, from your source, so you are able to get enough spectral components in your spectrometer, then you can actually say, for this wavelength, I am actually looking at this part of the eye, for this wavelength, I am looking at this part of the eye and so on. I mean, I am just explaining that in a coarse manner.

But nevertheless, it is essentially you can think of it as if you do inverse Fourier transform of that, from the spectrum you go to the time domain, that corresponds to different delays, which means that it corresponds to different depths along the eye, so, that is actually a very powerful method of doing optical coherence tomography, like I said, without having to move any move the reference mirror.

And so it is not so alignment sensitive, in fact, you can just have a fiber which is in, whose facet is coated with a mirror, that itself is fine for a reference. And the only moment you have to do is you still have to do the B scan, because you do need to get information across the eye. So that is the only information that you have to do.

But in doing that, you are actually saving a lot of time because in when you do the A scan, B scan, it both of them take a lot of time and that is actually in means that you the speed at which you are getting this measurement done, getting this image done, is not very high, but with this spectral domain OCT, you potentially have a way of speeding up this entire tomography by order of magnitude. So, that is actually a very nice way of using a low coherence source for an application.

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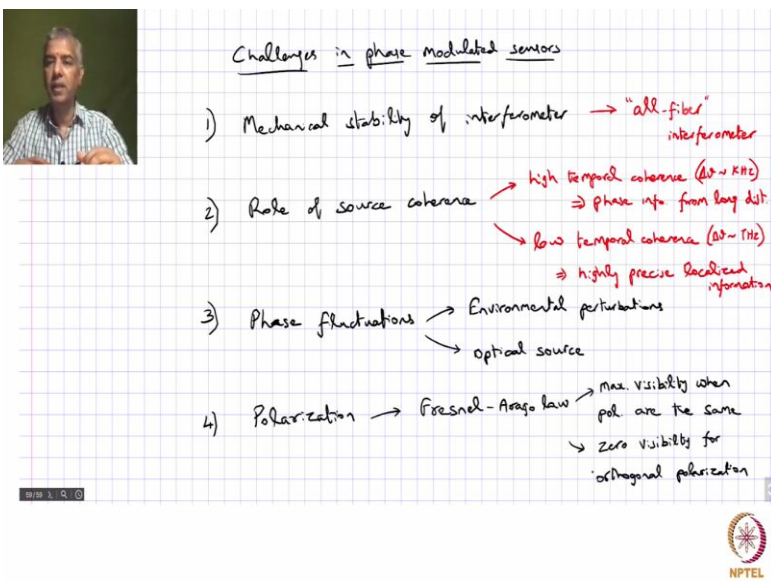

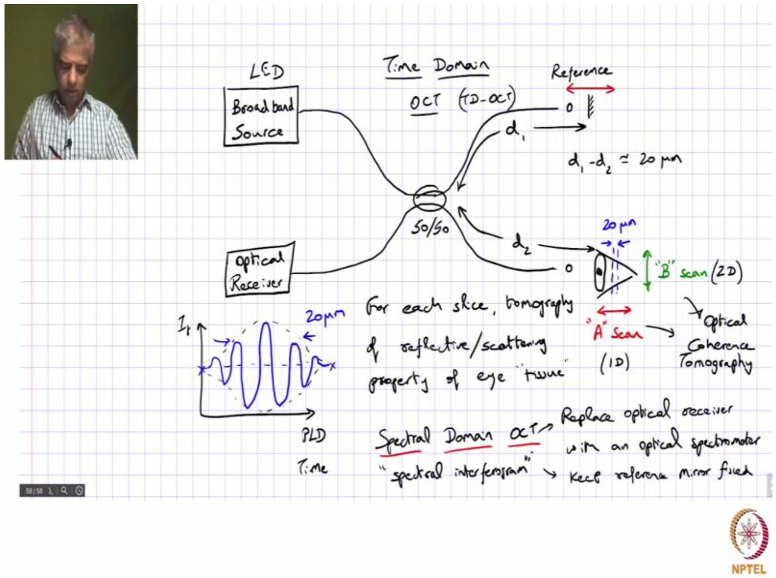

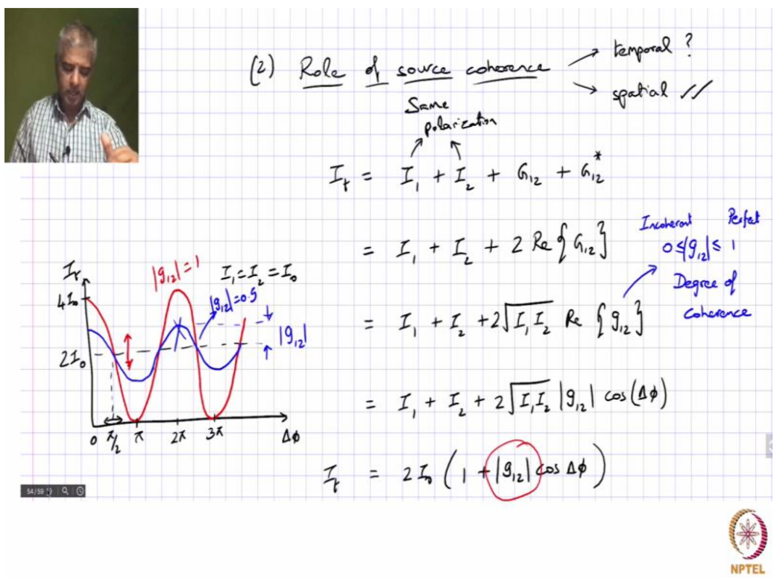

So, now, we can now go back and look at where we started, we started looking at challenges in phase modulated sensors. So, the first one that we looked at is the mechanical stability of interferometer. So, and what were we able to do, we are able to say that, that could be addressed by and all fiber interferometer. So, that was solution we looked at. And second what we have just looked at is the role of source coherence and with respect to this, what we understood was narrow line with sources with high temporal coherence, implied that you could do, you could pick up phase information from long distances, that is what high temporal coherence had enabled us to do.

Whereas, when you talk about low temporal coherence, here, you are looking at delta nu the order of kilo hertz. Here, you are looking at delta nu in the order of terahertz, if you are talking about something the order of 10s of nanometers, you are essentially looking at terahertz type of spectral width. So, we saw that is quite useful for highly precise, localized information.

So that is what we saw so far. But there are other challenges. One of the other challenges that we normally face with phase modulated sensors is that you are typically having to deal with noise. That is a common sort of enemy for all our measurements with the noise. So, what is noise as well as phase modulators sensors goes that is actually corresponds to phase fluctuations that you have to deal with. And where are these fluctuations coming from?

Well, these could come from just environmental perturbations, just changes in the room temperature, just changes in the room pressure for example, those sort of things can possibly give rise to the phase fluctuations or you could actually get that from the, sources from the optical source itself. So, what do I mean by that, essentially, when you talk about line width of a light source, that line width is representing spread in frequency.

But as far as phase measurements are concerned, that is actually corresponding to an uncertainty in defining the phase, if it is a monochromatic source, you do not have any uncertainty in defining the phase of that source. But if you have a polychromatic source, you have a certain uncertainty or you have a level of uncertainty in terms of perfectly defining the phase because polychromatic source consists of multiple sinusoids you may imagine it that way.

And which of these sinusoids are you going to determine, are you going to use as the reference and which of those you are going to pick up the phase for. So, that is actually the challenge. So, larger the spectral width, more will be the phase uncertainty. And that is actually something that may be an issue for certain applications, we looked at examples of that. And, finally, the what we have not talked about is actually the polarization.

What is the role of polarization in doing this phase modulators sensors? So, we clearly understand that phase modulated sensors are based on interference principles. So, what we are essentially looking at when we are doing this interference, we are assuming that both the light sources from these two arms are actually coming at the same polarization.

Because, when you talk about polarization, what is actually important is this, what is called this Fresnel-Arago law, which says that, if it is you get max visibility when the polarization of the two light waves that you are using for your interference are the same and conversely it will be 0 visibility for orthogonal polarization for the two waves. So what do I mean by orthogonal polarization? We are talking about, say if one arm, it is actually vertically polarized light and the other arm is horizontally polarized light. So it is basically bouncing this way as it is coming towards you, as opposed to bouncing this way as it is coming to you.

So, those two are orthogonal polarization states. So, if you are looking at interference of orthogonal polarization states, that interference component is going to be that beat component is going to be 0. So, that actually puts another constraint on, we talked about how this visibility is determined by g12, which corresponded to the degree of coherence, but that what we are now saying is that visibility is also it is controlled by g12 provided both the interfering sources are of the same polarization.

So, the these two are of same polarization, if they are not of the same polarization, then if they are orthogonal polarization, even if you are talking about a perfectly coherent source, highly temporally coherent source, you might not actually see these fringes. So that is what we are saying. And so it is very, very important that we keep the polarization of the interfering sources to be the same and what is the effect of that, we will come back and review that a little deeper.