Optical Fiber Sensors
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture 28
Phase modulated sensors - 8

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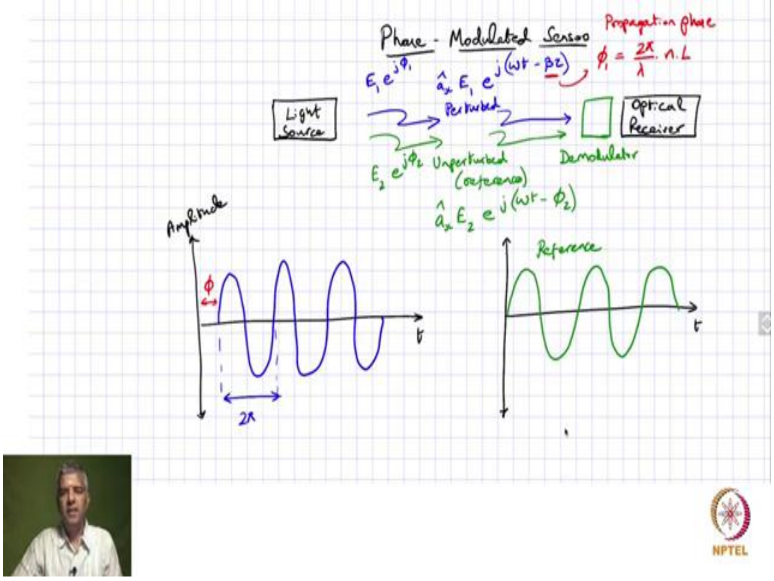
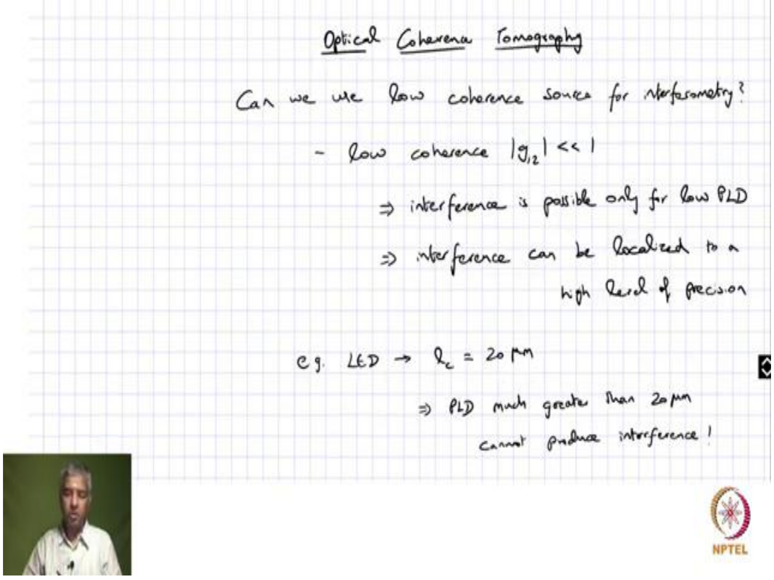
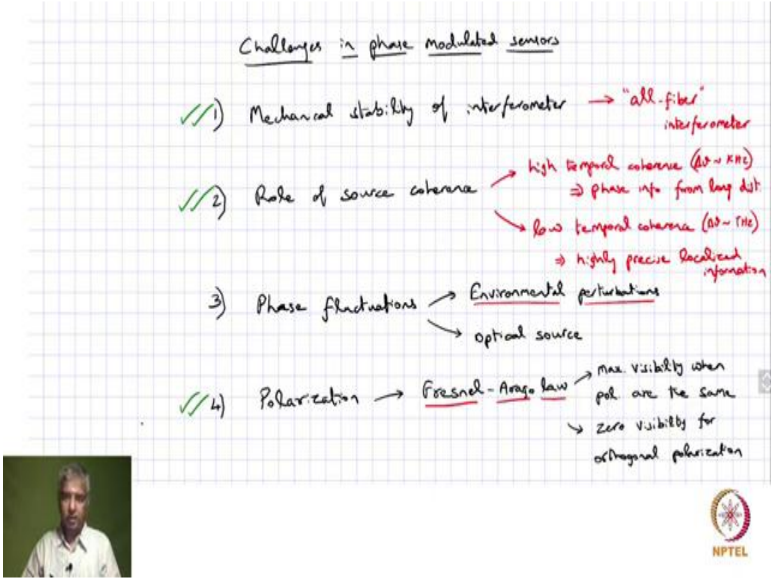



Optical Coherence Tomography

Can we use low coherence source for interferometry?

- low coherence $|g_{12}| << 1$
  $\Rightarrow$ interference is possible only for low PLD
  $\Rightarrow$ interference can be localized to a high level of precision

e.g. LED $\rightarrow$ $l_c = 20\ \mu m$
  $\Rightarrow$ PLD much greater than $20\ \mu m$ cannot produce interference!



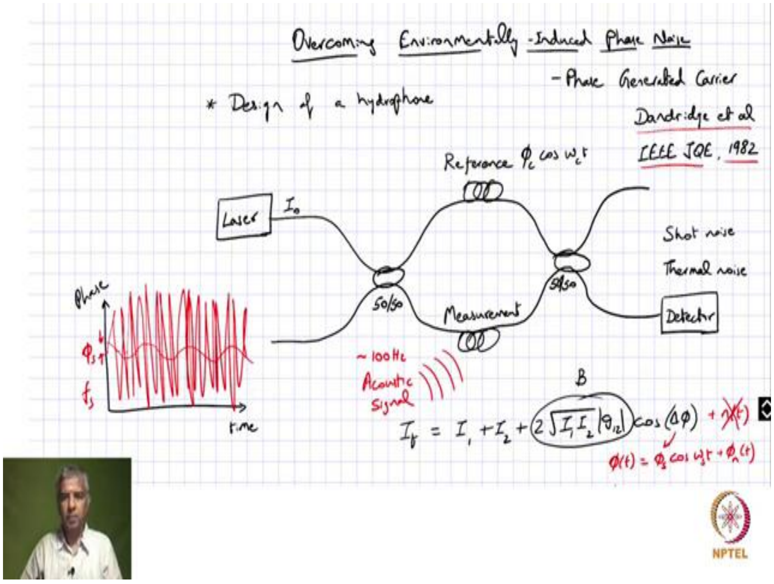
Challenges in phase modulated sensors

✓✓ 1) Mechanical stability of interferometer → "all-fiber" interferometer

✓✓ 2) Role of source coherence
- → high temporal coherence ($\Delta\nu \sim$ kHz) ⇒ phase info from long dist.
- → low temporal coherence ($\Delta\nu \sim$ THz) ⇒ highly precise localized information

3) Phase fluctuations
- → Environmental perturbations
- → optical source

✓✓ 4) Polarization → Fresnel - Arago law
- → max. visibility when pol. are the same
- → zero visibility for orthogonal polarization



Overcoming Environmentally-Induced Phase Noise

- Phase Generated Carrier

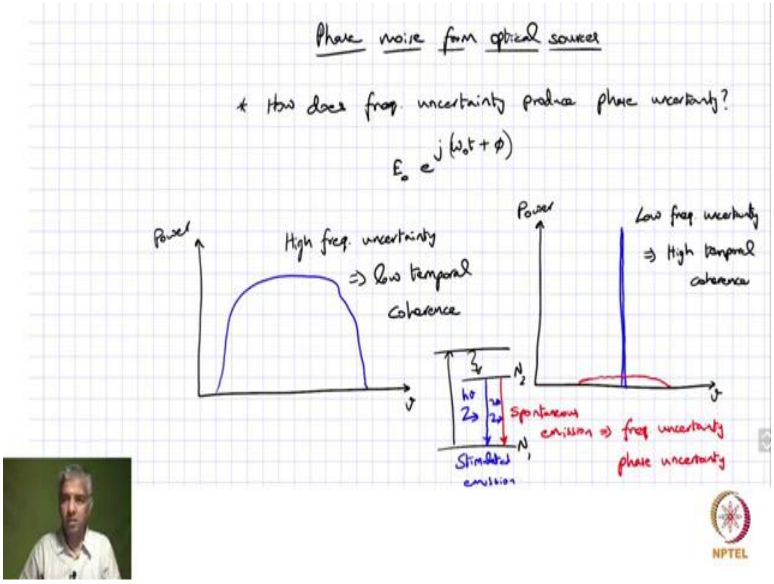
Dandridge et al

IEEE JQE, 1982

* Design of a hydrophone

$$I_f = I_1 + I_2 + \overset{B}{\boxed{2\sqrt{I_1 I_2}\,|\gamma_{12}|}}\cos(\Delta\phi) + \cancel{\eta(t)}$$

$$\phi(t) = \phi_s \cos \omega_s t + \phi_n(t)$$



Phase noise from optical sources

* How does freq. uncertainty produce phase uncertainty?

$$E_0\, e^{j(\omega_0 t + \phi)}$$

We have been looking at phase modulated sensors for the past several lectures. We started with the basic principles of phase modulated sensors and then we went on to look at specific configurations. We realized that if you want to read phase using an optical receiver you need to have a demodulation arrangement.

So, typically an interferometer, so we started with looking at examples of using a Michelson interferometer, we looked at this specific example of optical coherence tomography and then went on to look at the challenges in phase modulated sensors and as part of that we introduced this other application which is the case of an hydrophone and we looked at what are they, how are phase measurements done in an hydrophone.

How do we overcome some of those challenges there? And then of course, finally we got around to defining that the fundamental limitation as far as any phase measurement is concerned is actually the phase noise from the optical source itself. So, that is where we are.

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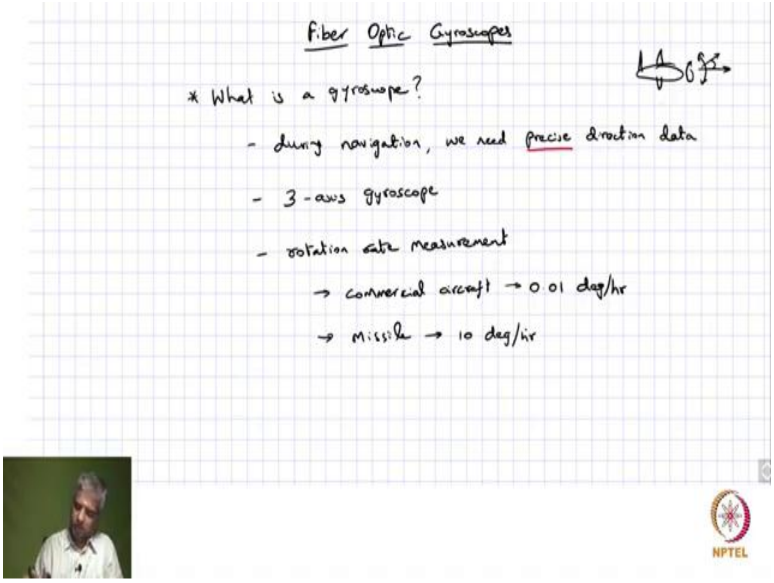

Fiber Optic Gyroscopes

* What is a gyroscope?

  - during navigation, we need precise direction data
  - 3-axis gyroscope
  - rotation rate measurement
    - → commercial aircraft → 0.01 deg/hr
    - → missile → 10 deg/hr

Now, in today's lecture what we will consider is yet another example of a phase modulated sensor, this is one of the, probably the most popular and most widely used application, so this is called an fiber optic gyroscope. So, let us actually look at what is a gyroscope in the first place? So, what is a gyroscope? So, if you are let us say doing some navigation, let us say you are the pilot of an airplane.

So, let us actually try to draw an airplane, if you can believe that is representing an airplane. Now, if you are a pilot you want to know what is the exact direction that you are taking? So, you have basically, you are looking at going in a particular direction and you need to know what is the azimuthal direction and also what is the angular direction. This is what we call as elevation. And you also need to know if you are actually undergoing any rotation in that sense.

So, basically what we are talking about is if you are going down a direction, a particular direction, you want to know whether what is your position in this axis and your position in this axis and you want to know whether you are rotating this way or this way. So, you essentially need three-dimensional direction information. So, what is a gyroscope?

During navigation we need precise direction data, what is the precise direction that you are taking. And of course, like we talked about what we typically need is a 3 axis gyroscope, the gyroscope is one that provides that directional data and so you need you need fairly, precise information, so what is the kind of precision that we are talking about typically.

So, you need to essentially do rotation rate measurements typically expressed in like degree per second or degree per hour type of units, and so for example, if you are looking at a commercial aircraft, so if you want to fly from one place to another, the typical precision that you need in your direction information is in the order of 0.01 degree per hour.

So, if you are talking about going from Chennai to Delhi, for example, so you would need to have that sort of precision in your direction, so that you can take a very specific flight path and get your destination. If you are off by 0.01, 0.02 degrees, you may be actually you know going to a neighboring town rather than your actual destination itself.

So, that is the kind of accuracy or the precision that you need for such applications. Of course, if you talk about doing space navigation, so you are going to some other planet and so on you might need precision that is order of magnitude better than that like 0.01, 0.001 one degree per hour type of thing.

On the other hand if you are looking at taking a very short flight, let us say for, if you are looking at a missile, if you are designing something for a missile, this could be as bad as 10 degree per hour just because of the fact that you are taking this relatively short trip, so for that you do not typically need that high level of precision.

But all said and done any of these navigational applications you need a gyroscope and then the question is how do you build a gyroscope.

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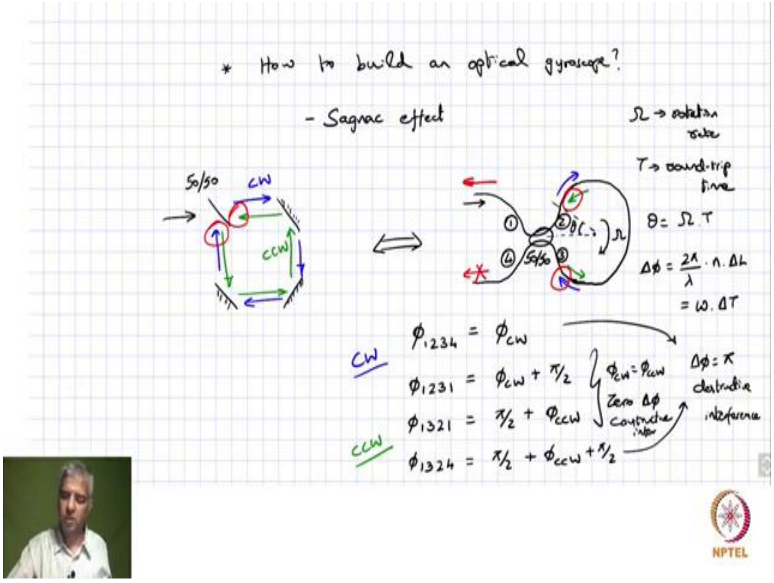


* How to build an optical gyroscope?

- Sagnac effect

$\Omega \rightarrow$ rotation rate

$T \rightarrow$ round-trip time

$\theta = \Omega . T$

$\Delta\phi = \frac{2\pi}{\lambda} . n . \Delta L$

$= \omega . \Delta T$

CW

$\phi_{1234} = \phi_{cw}$

$\phi_{1231} = \phi_{cw} + \pi/2$

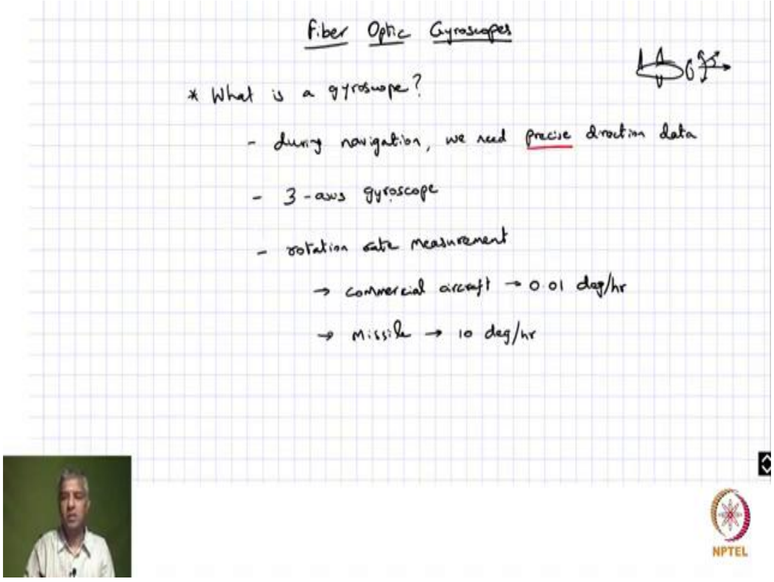
$\phi_{1321} = \pi/2 + \phi_{ccw}$

CCW

$\phi_{1324} = \pi/2 + \phi_{ccw} + \pi/2$

$\phi_{cw} = \phi_{ccw}$
Zero $\Delta\phi$
constructive inter

$\Delta\phi = \pi$
destructive interference



Fiber Optic Gyroscopes

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So, let us actually look into that. So, let us ask the question and specifically we are doing an optical sensor, so we are looking at how to build an optical gyroscope. So, clearly with any of these optical sensors, especially if you are looking at phase modulated sensors you need a demodulation mechanism and that demodulation mechanism as far as sensing rotation rates are concerned is actually provided by what is called a Sagnac effect.

Or in other words the actual apparatus is called as Sagnac interferometer; it is named after a French scientist who first proposed this. So, very simply the interferometer looks like this, you have incoming light, which is let us say split two ways 50-50. So, let me just use two different colors to represent the two ways, so one of the waves is going to go here, and let us say it is going to be reflected by a mirror, it is going to go here.

Let us say it is reflected by another mirror, it is going to go here and it can be folded back here, so I put a mirror here, a mirror here, a mirror here and so on, and it is folded back into the same path. Now, I can have another beam, another wave basically that is going in the clockwise direction, so that is going to come this way and and coming here.

So, essentially what we are looking at is interference of these two waves at this point and we are looking for constructive or destructive interference. So, the beauty of this is let us say the clockwise wave and this is actually the counterclockwise propagating way, they both actually go through the same path, and if they are going through the same path we know that they are actually accumulating the same amount of phase shift.

So, there is no delta phi in this case for any perturbations that you put in here, so suppose you, the refractive index of this medium changes, if there is a change in the refractive index of the medium that is experienced by both the clockwise as well as counterclockwise waves, so you do not, you are not really susceptible to environmental perturbations and all that, so from that perspective this Sagnac interferometet is one of the quietest interferometers that you can see.

Normally at room temperature whatever interference output that you get is going to be remaining the same, so remaining fairly constant. Now now the question is then what is really the use of this and or how do we build a gyroscope with that? A simple idea is if there is a rotation of this entire apparatus, then the reference position where this interference is happening that is moved.

So, if that has moved, then maybe the clockwise wave is going to see a longer path compared to the anti-clockwise wave, so there will be a slight phase shift between the two propagating waves and that phase shift can actually give rise to a change in the output intensity that you are looking at and that is essentially, how this can work as a gyroscope.

And of course, we are talking about, whenever we are talking about rotation measurement, you are talking about one particular axis in this case, the axis of this sheet on which I am writing now that is the axis and in which you are actually getting this rotation information and if you wanted to have a three-dimensional gyroscope like we discussed over here, three axis gyroscope, you need to have a similar gyroscope for each of those axes, a separate gyroscope for each of those axes.

Now, I mentioned that what we will go on to build is a fiber optic gyroscope and so let us actually look at this a little more detail from perspective of how we will realize this in a fiber optic gyroscope. So, like we talked about before you have this interferometer which consists of basically 50-50 splitter like we saw in the case of both the Michelson interferometer and as well as the Mach-Zehnder interferometer you have a light that is coming in and it is undergoing a 50-50 split.

But the key difference here is that you are actually looping this back, so that it, so if you number these ports let us say this is port one, this is port two, port three and port four, so it is actually looped back, so that port 2 and port 3 are connected. So, you have a configuration like this. So, what is happening here? So, similar like what we are seeing over here in this bulk form, you have basically a clockwise propagating wave and you also have a counterclockwise propagating wave which comes over here.

And essentially we are looking at interference of these two components. So, let us now actually spend a minute understanding how this interference is going to work out? So, of course, if you want to understand the interference, you want to now look at the phase that each of these waves are undergoing in this apparatus and then see if there is any relative phase shift.

So, let us actually look at the phase accumulated while going through this path that is 1, 2, 3, 4. So, it is starting from here, it s going to port 2, it is going through the loop coming to port 3 and then finally it is exiting in port 4. So, let us look at this phase.

Now, mind you, the reason, one of the key reasons why we are going through a fiber optic arrangement as opposed to this free space arrangement is the fact that in a free space arrangement you need to actually align these mirrors so that you can make sure that the two counter propagating waves are interfering in a stable manner.

If the mirror alignment changes, especially you are having this mounted on an airplane and during landing or takeoff it is going through a lot of perturbations and that might actually make this alignment go off, so the performance, that might actually affect the performance of the gyroscope, whereas here you do not have any alignment requirement at all, because in the optical fiber everything is, the light is confined within the optical fiber so everything is automatically aligned here.

So, that is one of the huge advantages of using an optical fiber sensor, like we already saw in some of the other application that holds good in this application as well. So, let us look at phi 1, 2, 3, 4 and for that we need to understand how this coupler works. The couplers work in such a way that when you go from 1 to 2, there is hardly any phase shift, but whenever it actually, the wave actually has to get coupled into the other fiber that is whenever it crosses the coupler there is a phase shift of pi by 2.

That actually comes from couple mode theory, we are not going to the specifics of that, if you want you can go back and look at couple mode theory and see how that phase shift happens, but let us just take that as a fact, so through port let us say negligible phase shift, let us say 0 phase shift, whereas the cross port, it actually, whenever it goes across there is a pi by 2 phase shift.

So, in this case when it is going from 1 to 2 there is no phase shift and then it, that becomes a clockwise wave, so this is, there is a phase shift corresponding to the clockwise propagation, so you have a phi cw. And then it comes back here and there is no phase shift at all. So, that is, I mean it because from 3 to 4 once again it is a through port, so there is a negligible phase shift so we are going to neglect that.

Now, let us look at the other clockwise propagating component, the other part that is possible which is you start with 1 go to 2 go to 3, but you go back to 1. If you consider that, that is going to go through 1 to 2, 0 phase shift, 2 to 3 is phi cw, and then 3 to 1 it is going across, so that is going to incur a pi by 2 phase shift.

Now, let us move on to the counter clockwise beam. So, for the counter clockwise beam what we have is phi, you are starting with 1, but then you are going to 3 to set up the counterclockwise wave and then you are going to 2, and then let us say you are ending up with 1. If we look at that from 1 to 3 you are going through pi by 2 phase shift and then you are going through the counterclockwise path in the same fiber.

So, you have a c phi ccw and what can you say about phi ccw, that is going to be the same as phi cw, provided everything is static, even if there is a perturbation both of them experience, so phi cc, phi cw and phi ccw are going to be the same and then of course, you are at 2 and then going back to 1 there is a negligible phase shift, so that is about all we have.

And then finally let us look at this other possibility where 1, you are going to from 1 to 3 and then you are going around in counterclockwise direction going to 2, and then you are going to 4, you are ending up at 4. In this case you have pi by 2 plus phi ccw and then going from 2 to 4 you are once again crossing, so you have a pi by 2 phase shift.

So, what do we see when we analyze all of this? We see that if you are starting from 1 and you are ending up at 1, you actually if c, phi cw is phi ccw, then there is 0 phase shift, 0 delta phi, so when it is 0 delta phi what can you say, you are essentially having constructive interference, going through this port, 1 port. Now, if you look at the other case, which is these two cases, where you started from 1, but you are ending up at 4, port 4.

For those two cases once again we say phi cw plus, phi cw is equal to phi ccw, but in this case you are delta phi, what is it, this is 0 here and this is, there is a pi phase shift here, so delta phi equals to pi. So, that means this is actually corresponding to destructive interference. So, without any perturbation, in this case we are looking at rotation as a perturbation, without any rotation if everything is static, then what we see is it is actually going through constructive interference at port 1.

So, your output is going to be at, so whatever you sent in the same power is going to come out, and of course, this one is not present, this basically destructive, it cancels in that direction, so there is no light going in that direction, so all the light that you sent in is actually coming back towards you. So, that is how, in fact, this is an interesting aspect, so there are some who use this effect to make a mirror.

So, you have essentially whatever light going in, it is going to go through that and come back, so you it essentially acts like a mirror, and of course, there are some technical aspects, there is some limitations to that, but overall you can possibly use this as what is called a fiber loop mirror. But let us just come back to what we wanted to look at. What we want to look at is what happens when, let us say this is the axis of this loop over here, what happens when there is say a certain rotation?

Let us say rotation at a rate omega, capital omega that is corresponding to the rotation rate, omega corresponds to the rotation rate, which is what we want to measure in this case. So, when, what happens when there is a rotation? Well, when there is a rotation you can basically say I started with this reference, but I am going to exaggerate now, because of this rotation rate what you have is this coupler, which is where the interference is happening that has moved over an angle theta.

Because this rotation has happened even while this propagation of the wave is happening around this round trip, so if you say t is the round trip time, if t is the round trip time, then you can say that theta is going to correspond to omega times t. Now, it has moved a certain angle theta that means if you consider your counter propagating wave that was set off when the coupler was at this position, so it starts from here, it goes around the loop and by the time it comes to this position, this loop has, this reference has changed.

So, that means this actually path is relatively short compared to the other path where the wave is actually the count, sorry, the clockwise propagating wave is already set off and then it goes, but before it goes through this round trip time, this position has moved, so now it is actually have to travel a longer distance.

So, because of this you have a phase shift, because phase shift when you look at it is corresponding to 2 pi over lambda multiplied by refractive index of the medium multiplied by any path length difference that you have, a physical path length difference that you have. So, what is creating this physical path length difference that is actually because of this movement of this reference over here and that is creating this critical path length difference.

Of course, you can rearrange it, you can basically say delta l is, it can be written as c into delta t, if you are talking about propagation time is t, so delta t corresponds to the difference in the propagation time between the two parts, and then this lambda over n can be written as c over f, so if you do this then you can basically show that this corresponds to omega times delta t, where omega is the angular frequency of the light that is propagating.

And delta t corresponds to the difference in the time for the round trip time for the clockwise and counterclockwise, which is because of this omega. So, now we need to see how to quantify this delta t and how to associate that to this capital omega and from that we can basically say that, what you are measuring is a delta phi, but that measurement would correspond to a certain rotation rate. So, that is what we are going to see next.