Optical Fiber Sensors
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Lecture 24
Amplitube modulated sensors - 4

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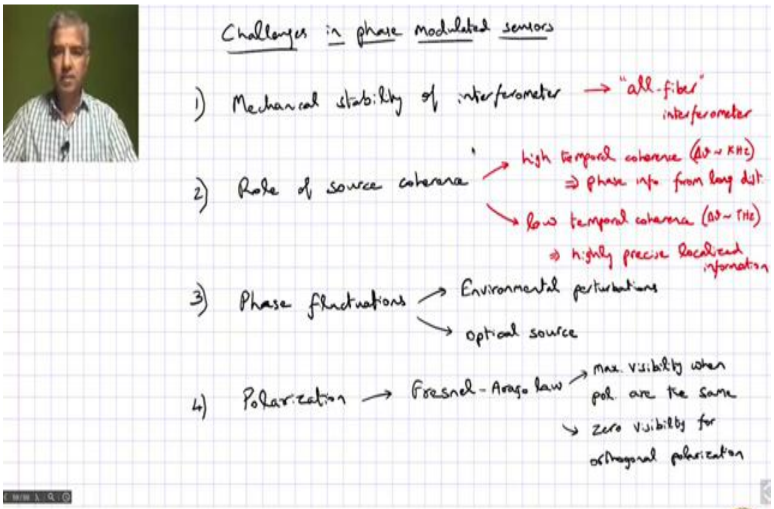

In looking at some of the challenges in phase modulated sensors and in the last couple of lectures we have identified that mechanical stability of the interferometer is one of those challenges and we looked at how going to an all fiber configuration can possibly address that issue. And then we went on to look at the role of source coherence as far as these interferometers are concerned, which is one of the key aspects of phase modulated sensor in terms of demodulating the phase into intensity information we typically use interferometer.

And we looked at the role of source coherence and what we identified was that if we use a source with relatively high temporal coherence, which corresponds to relatively short spectral width, then we could possibly get phase information from over long distances. We talked about the example of a ligo or phase OTDR.

And then we also understood that the other extreme that if we have extremely low temporal coherence, so if we have spectral widths in the order of terahertz as in the case of a light emitting diode then we could potentially get highly precise localized information. So, we looked at those two issues and then we said, okay, of course, we are having to make measurements in the presence of noise.

And so we are going to actually look at what are the possible sources of noise a little later on, but in the meantime we thought we will look at the effect of polarization in these phase modulated sensors. So, let us actually go and look into this a little more deeply and of course, what we said was in such sensors, when you consider polarization, we are having to consider this, what is called this Fresnel Arago law.

And we said at the end of the last session that the Fresnel Arago law is saying that you can get max visibility when the interfering sources have the same polarization and then we said the other extreme is the case where the interference has zero visibility for orthogonal polarization.

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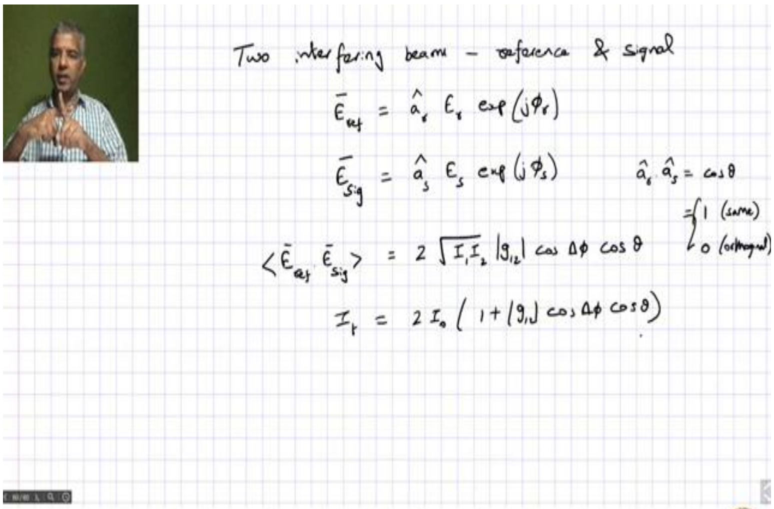

So, let us actually try to put this in perspective let us actually consider two interfering beams, so one is typically a reference and another is the signal, the measurement that we want to get done, so that is actually carrying the phase information that we want to pick up. So, we could potentially represent these in terms of this electric field vectors where we can say the reference electric field corresponds to some vector.

Let us just call that ar, some gen, it is characterized by some polarization ar and then you have basically Er is the amplitude of the field and we are going to have exponential of j phi r that corresponds to the phase of the reference beam. So let us just say we are looking at only the phaser part of it. So, similarly you have E-sig and that can be characterized by some other polarization.

Let us just represent that as as and that has amplitude es and e power j phi s. So, what we are seeing now is when we do a bit of E-reference, E-signal and remind you these are phasors but they are also vectors now because they actually carry the polarization information, so that is going to be given by 2 times root of i1, i2 just as before g12 is the, it corresponds to the degree of coherence and then you have the cos delta phi, where delta phi now corresponds to um phi r minus phi s.

And then we want to actually represent this additional term, which is corresponding to cos theta. So, why do we have cos theta? It is because of the fact that ar dot as, let us say for simplicity both of these are corresponding to some linear polarization, then ar dot as, the dot product of these two unit vectors would corresponding, would correspond to cos theta.

So, what that tells you is when both the polarizations are aligned you have this dot product giving rise to one, so that is the condition that we have been seeing so far, wherein we said It equals to 2 I naught 1 plus g12 cos of delta phi, but now we are saying we have the cos theta term also, so far we have not considered this because we have been assuming that, we are actually having the same polarization.

So, what Fresnel Arago law is telling you is that this essentially equals to 1 if the polarization state are the same, but it is equal to 0 if the polarization states are orthogonal to each other, that is basically ar is actually orthogonal to as, they have a angle of 90 degrees, theta equals to 90 degrees between the two polarization, then that is going to give us 0, which will essentially kill the bth term. So that is what we are looking at. So, the question is how do we ensure that both the polarizations are the same?

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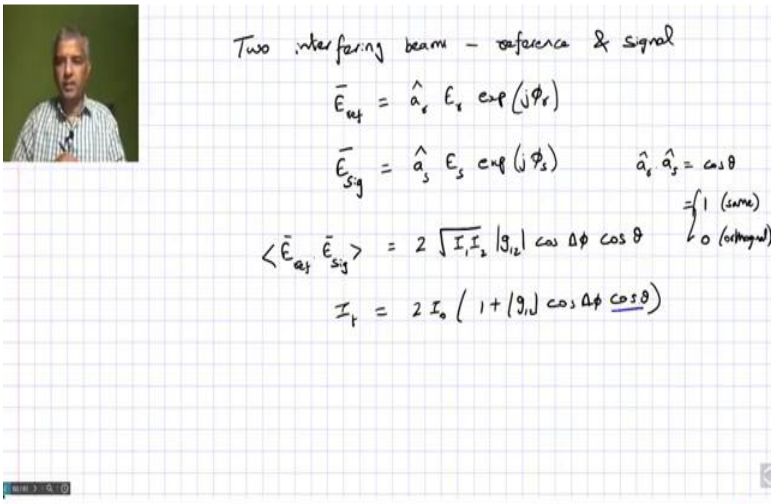

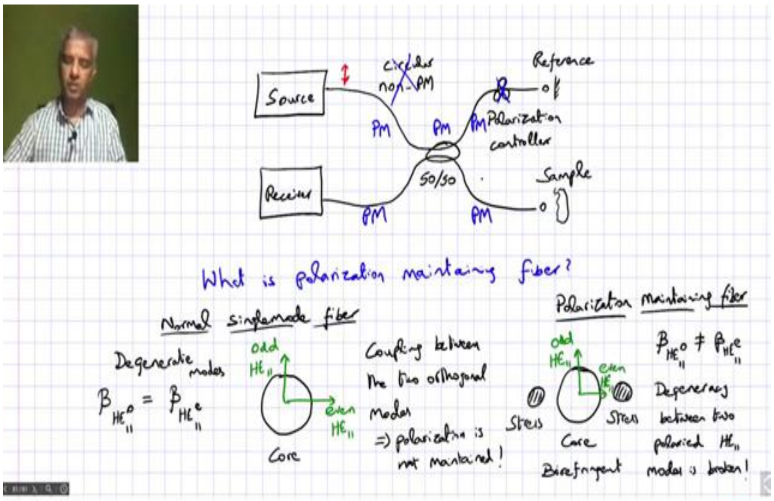

So, let us actually look into that a little more detail, like before let us just assume we are still considering a Michelson interferometer, so we have basically your source, your receiver and then that is connected through an optical fiber. So, similarly you have another optical fiber here, so that is a 50-50 splitter and then of course, you have your reference arm and here is your sample, so this is sample and this is your reference.

Now, what we are saying is normally when you have this fiber, you consider what is called standard single mode fiber would be a non-polarization maintaining fiber. So, even though your source is polarized, typically semiconductor light sources are tm polarized, so even though if your source is polarized, by the time they propagate through this fiber and they go around, there is no guarantee that the polarization is going to remain.

Let us say you start with vertical polarization, by the time it goes through this it might have gone into some elliptical polarization and some maybe even some circular polarization and by the time it comes back there is no guarantee that the polarization of the waves that are coming back are going to be aligned with respect to each other. So, how do you deal with this? That is basically because your typical what do we call circular non-pol pm fiber, circular waveguide, it is not really circular.

It might have some slight ellipticity and it might also have a random orientation of that ellipticity and which means that there is, it is really not a circular waveguide, it will be a perturbation from the circular waveguide and the random orientation of the ellipse can give rise to random birefringence and that means your polarization will evolve as it propagates through the fiber.

So, in such cases how do you deal with this? Well, you have typically what is called polarization controller. The polarization controller would consist of essentially fibers that are wound around in a coil and such that there is some, the fiber one axis on whichever it is wound it is actually having some stress, so that provides some birefringence what is called stress induced birefringence on the fiber.

And you can make it such that you wind with a certain number of turns and that actually behaves like a quarter wave plate, meaning it gives you basically a pi by 2 phase shift, pi by 2 retardation of 1 polarization with respect to the orthogonal polarization and and then you have another paddle, another coil, which is twice as long and that actually acts like a halfway plate, which means that it gives a retardation of pi between the orthogonal components.

And then you have another paddle, which corresponds to a, once again a quarter wave plate. The idea is if you have a combination of a quarter wave plate, halfway plate and a quarter wave plate, this corresponds to three paddles. By changing the orientation of those paddles you can take any polarization and convert it to any other polarization. So, that is the idea.

So, essentially you can use a polarization controller such that it matches this, the polarization from the other arm. How do you know it matches? Well, when it matches that is when you get the maximum visibility for a given light source and a given path length, you get the maximum visibility. So, you look at the visibility of the fringes as a function of path length delay and you try to maximize that visibility by adjusting the polarization controller.

But as we can see it is actually fairly tedious to incorporate, so you would rather replace that with what is called a polarization maintaining fiber. So, you do not want this sort of arrangement, so what you say is instead of using a circular non-pm fiber, can I use a pm fiber all across and if I use a polarization maintaining fiber, for all these fiber lens, then you can maintain the polarization.

If you start with linear polarization and of course, this even this coupler has to be a polarization, maintaining coupler, and then it will retain that polarization all across this entire structure and from that perspective you can say that you will have a good interference, essentially, you are maintaining the polarization, which means the reference and the signal arms actually have the same polarization, which means that cos theta goes to 1 and then you do not have this issue with respect to different polarization.

But what does it mean to have a polarization maintaining fiber? So, let us look at that. So the question is what is polarization maintaining fiber? So to understand this first of all we need to understand how light is actually propagating, how polarized light is propagating in an optical fiber. So, let us actually now look at a non-polarization maintaining fiber and let us see this is basically what you call as a normal or standard single mode fiber.

So, if you have a standard single mode fiber how does polarized light propagate inside that? Well, when we say single mode we are talking about the fundamental mode of the optical fiber which is the LP01 mode. If we were to represent the LP01 mode, let us say we blow up the core of the optical fiber, so we can see this clearly. What it actually consists of is two orthogonally polarized modes, these are the hybrid modes.

So, they correspond to what is called the odd HE11 mode and the even HE11 mode. So these are, so although we call it a single mode fiber, it actually consists of two polarized modes that are typically degenerate. So, what do we mean by degenerate? Well, each of these polarized modes, each of these field configurations will have a certain rate at which it accumulates phase as it is propagating down the fiber, so that is defined through the phase constant.

So, you can say if beta of HE11 odd corresponds to the phase constant for the odd HE11 mode and beta HE11 even corresponds to the phase constant of the even HE11 mode, in a normal single mode fiber these two are equal that means they are what are called degenerate modes. So, when you have degenerate modes you can essentially couple light from one fiber to the other fiber, one polarized mode to the other polarized mode.

So, effect of that is that if you launch polarization along one of those axis, let us say you are launching polarization of vertical axis, there is nothing that prevents it from coupling to the horizontal polarization. So, any small abnormality in the fiber, like we talked about the ellipticity of the fiber, can actually couple can scatter light from this mode, this polarization mode to this polarization mode.

And because of that you are having what is called this random birefringence and through the random birefringence you couple between that, coupling between the two orthogonal modes and whenever that coupling happens you essentially have, the polarization actually change, it could be linearly polarized to start with say vertically newly polarized, but then over a period of time it might actually rotate like this.

And maybe there could even be a retardation of this polarization with respect to this polarization in which case it, rather than being a linearly polarized mode it goes into an elliptically polarized mode and it could even go to a circularly polarized mode. So, you could actually go to all these different polarization modes in a random manner, so you cannot actually predict that you start having linearly polarize here, it is going to be linearly here, it could be some other polarization state.

And that happens because of the coupling between two orthogonal modes, which means that polarization is not maintained in a standard single mode fiber. So that is what is happening in a standard single mode fiber. So, how do you get around this problem, how do you make a polarization maintaining fiber? Well, the answer lies right here.

So it says, if you break the degeneracy between the two orthogonal modes, then you can actually reduce the coupling between, so when it is, when you break the degeneracy the beta values are different and if they are different then the coupling between this mode to this mode is not going to be, happening in an effective manner, so you are essentially able to keep this this polarized mode propagating down the fiber for a longer distance.

So, let us actually put that into a perspective. So, when you talk about polarization maintaining fiber, what we are talking about is the same core. Now, is having two different propagation constants or the phase constant for these two different modes. How? And that that could be ensured by, let us say you have some stress rods in the cladding.

So, like I talked about this is the core of the fiber and these are basically some stress elements in the cladding next to the core that means it is going to actually produce a strain across this direction and there is no strain across this direction. So, now when we look at these two polarized states, the odd HE11 is going to have a different propagation constant compared to the even HE11 mode.

So, essentially what we have done is beta for HE11 odd is not equal to beta for HE11 even. And we have this condition, then what we are saying is when you couple into one way you do not have enough perturbation or in other words you you make the, this wave guide, it is actually a birefringent waveguide, meaning the effective refractive index for that one mode sees the odd HE11 mode sees is different from the effective refractive index that the even HE11 mode sees, so it essentially becomes birefringent.

And in the case of a birefringent fiber, the beta is not going to be equal and that means the degeneracy between the between two polarized HE11 modes is broken and once the degeneracy is broken, then if you coupled into one of those polarized modes, it remains in the same polarization and it is also like, if you couple light into say at 45 degrees, that means it is equally coupling into the odd HE11 mode and even HE11 mode.

Since, there is no crosstalk between them, there is no coupling between them, they remain their respective amplitudes, so as they propagate down the fiber they remain at the same polarization. So, that is what is called a polarization maintaining fiber. And, so that is actually a very popular fiber that could be useful for these sort of applications to make sure that polarization is not as much of an issue. And essentially we can have that cos theta go to one and thereby we are essentially having a proper interference for this phase modulated sensor.

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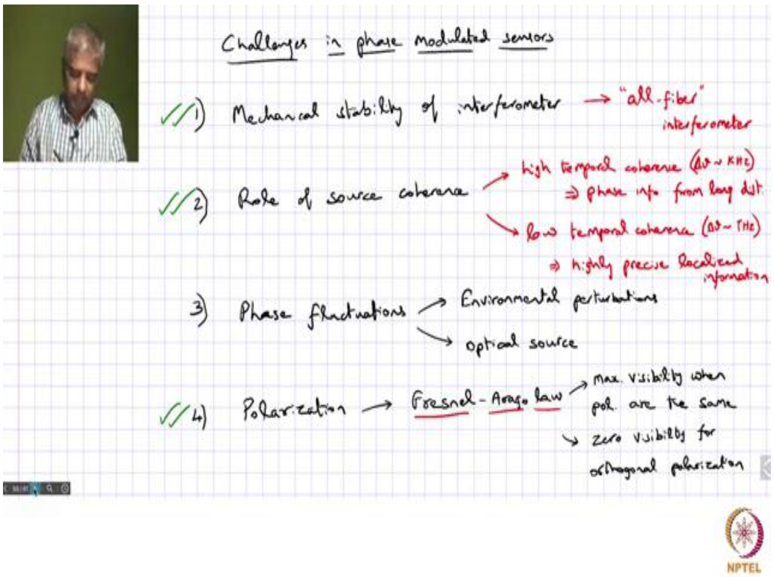

So, we have talked about mechanical stability, we talked about role of source coherence, we talked about polarization and now it is time to understand the phase fluctuations that are happening in a phase modulated sensor and how do you overcome those phase fluctuations. So, let us just go ahead and take a look at that.

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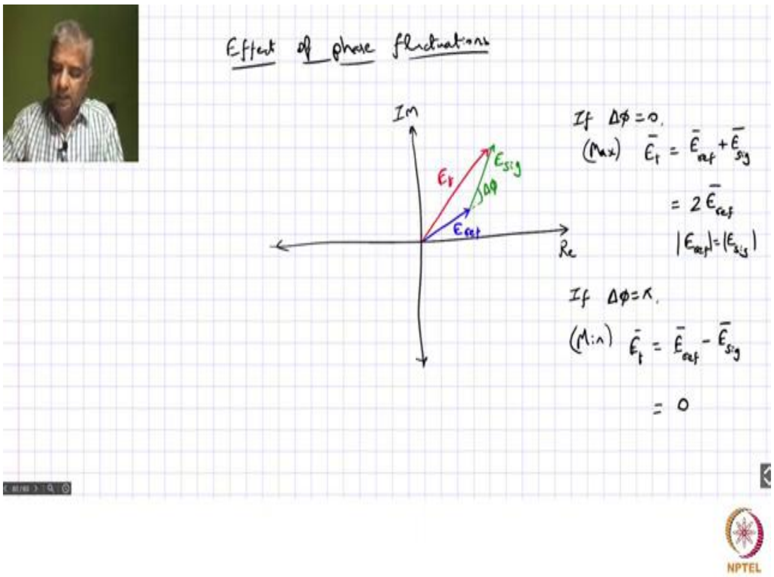

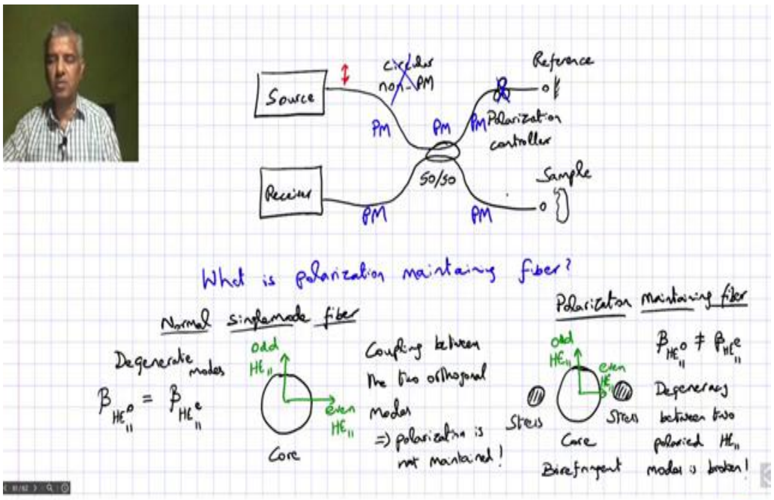

So, to understand this part, so we are looking at effect of phase fluctuations in this polaris, in this phase modulated sensors. So, to understand this let us actually look at the phasor diagram. So, we said we are looking at the, to represent a phasor you would actually take a complex plane and now you can actually represent your reference signal and then the electric field corresponding to the reference signal and the electric field corresponding to the, to your measured signal.

So, let us say the reference signal, the electric field is like this, so we call this E Ref and then if we talk about the signal that you want to measure, let us say that corresponds to E Sig that the phase difference between them is delta phi, so E Sig is actually delta phi away from this, it has got an angle delta phi with respect to the phasor corresponding to E Ref. And then the total field that we get to see at the receiver is a combination of these two.

So, that will correspond to the total field. So, if we have a situation like this, then it is not too difficult to figure out the relative phase because you can say that, I mean, let us look at this, if delta phi equal to 0, then it pretty much lines up along the same direction, so you can say if delta phi equal to 0, then you have Et equals to E Ref plus E Sig.

So, and if E Ref and E Sig are equal then it becomes twice the electric field corresponding to one of those. On the other hand if delta phi equal to pi, then what happens, then Et equals to E Ref minus E Sig, so here is plus, here is minus, so here it becomes 2 times E Ref, if you consider E Ref equals to magnitude of E Ref equal to magnitude of E Sig, if those two phasors are of the same length, then you get two times E Ref.

But on the other hand if delta phi equal to pi and if the magnitude of those two phasors are the same, then it perfectly cancels these two, so then you would get two 0. So, this corresponds to, like what we talked about previously, this corresponds to the maximum condition and this corresponds to the minimum condition, that is constructive interference and this is destructive interference.

So that is great and anything in between, we get a corresponding intensity and then based on the measurement of the intensity you can actually figure out what is your phase of the signal, the measured signal with respect to the reference and everything is great. However, things are not so easy. It is not so easy in a realistic condition. Why? Because each of these signals, each of these quantities, electric field quantities are corrupted by noise.

So, where does the noise come from? If we go back and look at an arrangement like this, this fiber is environmentally susceptible, meaning, if there are changes in temperature or if there are changes in pressure or strain then that changes the refractive index of the fiber and through that you actually change the phase of the light that is propagating through the fiber and the distribution of strain or temperature along the length of the fibers is random in nature.

And that means that the phase that evolves is actually random in nature, it actually ends up changing with respect to time. And, so that is changing and the refractive index here is also changing randomly and because of that you have a random phase noise component. So, how do you represent this over here?

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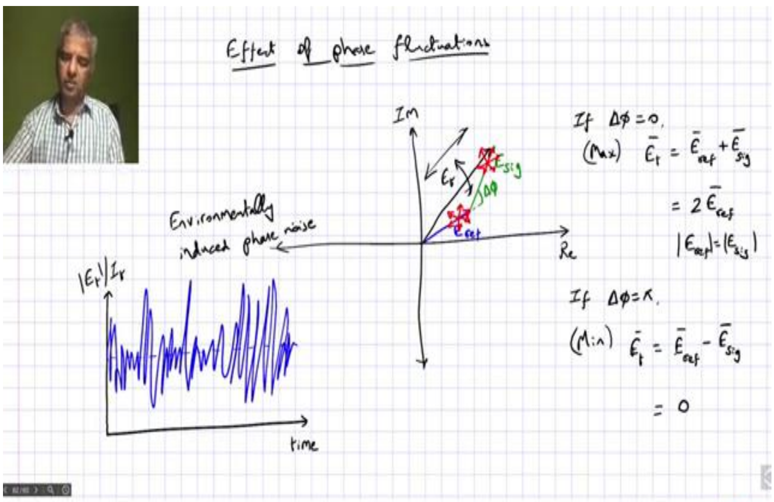

Well, actually to represent that let me erase this vector for now and represent that with a black over here that is corresponding to Et. Now, what we are talking about is this noise that you have in with respect to the reference wave is actually, let us say this component and it is not like a constant amplitude. The amplitude may also change as a function of time.

But more importantly for our application what we are seeing is that the noise actually has got a random phase associated with that because the refractive index is varying in a random manner because of environmental fluctuations. So, you have this varying randomly and similarly, here also you have a random fluctuation in the phase and because of these random fluctuations, now when you look at your as a function of time.

So, basically the Et or you can you can also look at the intensity, which is mod of Et square as a function of time, so it is looking at the magnitude of Et let us say you are expecting for a given delta phi, you are expecting something like this, it should be constant with respect to time if delta phi is actually not varying with respect to time. So, if the intensity is this value, then you can actually say that that corresponds to a certain delta phi.

Your measurement is done, but because of this noise, now how does this look, it is not like this but it is basically like this, like this and and it is essentially all over the place and we are representing this at only one frequency. Remember the phaser representation is typically at only one frequency, but the noise that you have tends to be white noise. And because of that there is no specific frequency here, it is a wide range of frequencies that contribute to this noise and this is actually the problem.

So, how do you now extract this the real intensity that you have, the signal intensity that you have or the beating because of the signal intensity and then how do you extract the corresponding phase, that is actually the typical challenge as far as a phase modulated sensor is concerned, as far as this Michelson interferometer base phase modulation sensor is concerned.

Now, of course you can say that what, I can actually control the reference to some extent, I can actually put it in that particular arm, I can package it such that it is isolated from external pressure or strain and I can also maintain the temperature of that reference. You can do all of that, so we can reduce this noise a little bit, but you still have this noise in the measured signal because that essentially has to interact with the external medium.

And that actually causes this wild fluctuation in the electric field vector and that not only in the phase, but also in terms of the amplitude of this, the magnitude of the electric field, because of this noise and that is typically the problem. So, how do you extract the phase in the presence of this phase noise, which as of now we are talking about environmentally induced phase noise?

But we will actually we will handle this and then we will go on to look at what it means to deal with the source itself, the source itself has some phase uncertainty, how do you deal with that. So, let us look at this first, how do we deal with this first before we go to the source related phase noise.