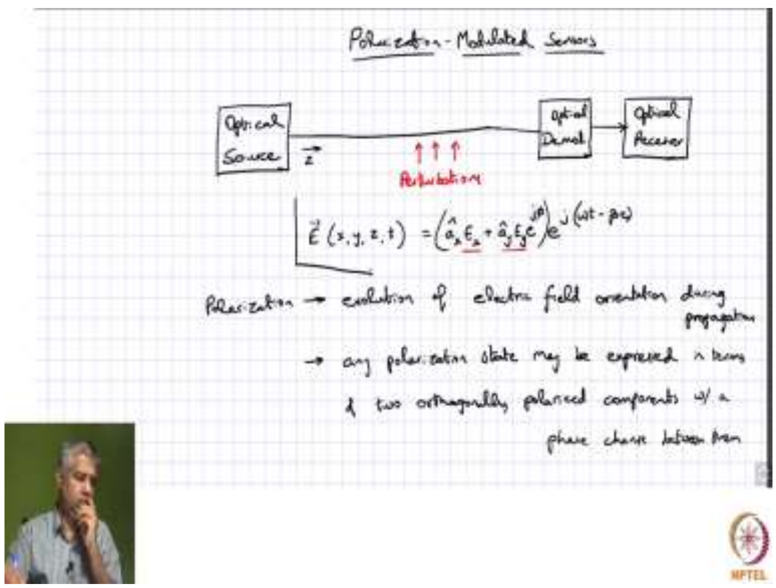
Optical Fiber Sensors
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Polarization Modulated Sensors - 1

Hi, we have been looking at designing optical fiber sensors for various applications using different properties of light. We started looking at amplitude modulated sensors then went on to look at phase modulated sensors. And lately, we have been looking at wavelength modulated sensors. So, now it is time to move on and look at the other characteristic of light that describes light, which is polarization. So, we will look at what is, what can we do by looking at changes in polarization, whether that could be used for picking up certain perturbations, that is what we will discuss in the next couple of lectures.

(Refer Slide Time: 01:10)



So, we are talking about polarization modulated censors. And as usual, we start with the optical source and, of course, we want to look at the output light output using an optical receiver. And let us say we have a fiber optic sensor that we are trying to make. So, when light is propagating through this optical fiber, you can describe that light in terms of different quantities like in specifically in terms of the electric field of, corresponding to the electromagnetic wave.

And previously, we saw that the electric field as a vector that can be expressed in x y, z and there is a spatial coordinates and then time. So, we said it has a certain amplitude, and then you have e power g omega t minus beta z term. So, omega corresponds to the frequency, the angular frequency, and beta z corresponds to the propagation phase. And now, we are ready to look at this other aspect, which is the polarization of the light.

When it comes to polarization of light, let us actually talk about modeling the fundamental mode as a plane electromagnetic wave. And if we do that, then if propagation is along the z direction, let us say this is our z direction, then we are now looking at the wave having, polarization components in the transverse plane that is actually in the x y plane. So, in general instead of just having some common amplitude, you can talk about the amplitude in the x direction and the y direction.

So, we can talk about, let us say, Ax, Ex plus Ay, Ey. And let us just say that, in general there is no rule that the x and y components have to be in phase. So, there could be a difference in phase between the two components. And that is what we are denoting by e power j phi. So, that can potentially describe the polarization of the wave. It could be either oriented in the x direction or in the y direction or somewhere in between, and it might actually have a phase difference relative to each other.

However, in terms of, picking up so how can we use this is a sensor well, whenever we perturb the fiber whenever we expose this to perturbations, this can these perturbations can change the polarization of the light. And so, by monitoring that change in polarization of light, you could possibly say something about the perturbation specifically quantify the perturbations. So, we will come back and look at what type of perturbations that that are quantifiable by looking at changes in polarization.

But what we know is that the optical receiver the photodiode as part of the optical receiver, which is a front end of the optical receiver is not polarization sensitive. So, it cannot actually tell if there is a change in polarization. So, just like we how we deal with this situation with phase modulated and wavelength modulated sensors, even polarization modulators sensors we need an optical demodulator.

So, an optical demodulator which can convert changes in polarization to changes in intensity and then that can be picked up using optical receiver. So, we will look at what this optical demodulator is all about, but let us start looking at polarization what is polarization? Well polarization is can be defined as the evolution of the electric field orientation. So, light is an electromagnetic wave. So, the electric field corresponding to that the orientation of the electric field during propagation is what we are tracking as far as polarization is concerned.

Now, you may ask the question why is it the electric field can I do that to the magnetic field? Sure, you could use either but the convention is that we go with tracking the electric field and we do expect that the magnetic field is oriented in perpendicular to that electric field. So, you can you can of course, do the same with respect to the magnetic field if you want , but we are looking at the evolution of the electric field orientation during propagation.

So, we talk about see if wave is propagating towards you. Now, you can look at the wave as being having a certain electric field and how that electric field is evolving as a function of time is what we are as it propagates is what we are actually tracking. Of course, it could be like this or it could be bouncing like this or it could be bouncing like this or it could be rotating like this assets coming towards you. So, that all these actually constitute different states of polarization.

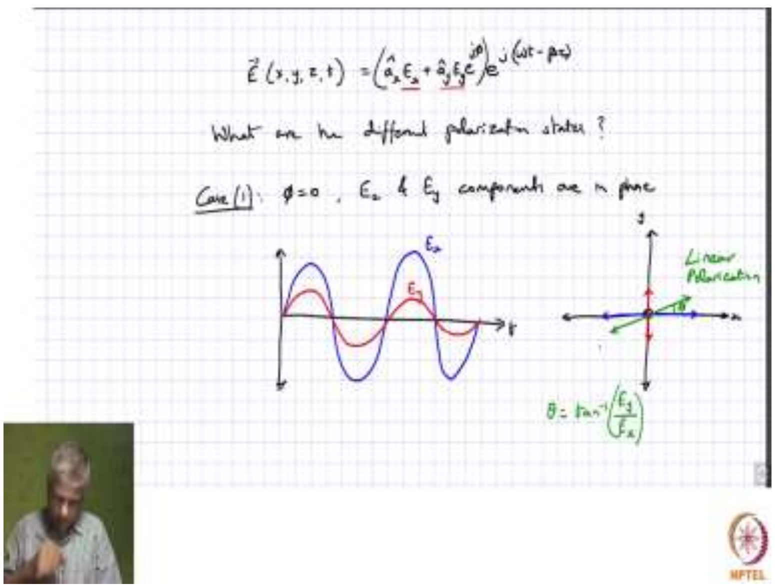
And like I said what we are looking for as far as polarization modulators sensors concern is that these states of polarization are changing and corresponding to a certain perturbation that it is exposed to that the material is exposed. So, the key thought that we are going to rely on and this is something that is probably inherent in the way we have expressed is the fact that any polarization state may be expressed as just express in terms of two orthogonally polarized components.

So, what are we talking about? Well, we are talking about in this case for example, we are expressing in terms of the x component and Y component. So, the ax is actually a linear polarization component along the x direction and ay corresponds to linear polarization component along the y direction. So, we could express any polarization in terms of 2 orthogonal components.

So, we are in this case saying that the two orthogonal components can correspond to these two linearly polarized components along the x and y directions. And of course, it could also have a with a phase change between them. So, in this case, this quantity within the brackets this actually denotes the polarization and it could be any arbitrary polarization state. So, that is the beauty of this any arbitrary polarization state can be expressed in terms of these x and y polarization components.

They are y component maybe, it has got the same frequency and same phase, so but it might have a different amplitude. So, your y component might be something like this, it is evolving something like this. So, this is Ey and this is your Ex component. Now, to look at the actual polarization of this, you want to look at the wave assets coming towards you. So, you define let us say the x y and let us say the z is z is that direction coming towards you. So, this is got to be x and this is got to be y. So, what we are saying now is Ex is actually having a certain amplitude.

(Refer Slide Time: 13:06)



So, Ex you can represent as having this much amplitude. But Ey is not having as much amplitude. So, you say Ey is something like this. So, then when we look at the combination of that, and both are actually in phase. So, when you are looking at the combination of that combination would probably something look like something like this. So, this is actually combined when you are looking at this together they are combined oscillating in orientation, like this assets propagating along this z direction.

So, this is the polarization and this actually describes the line as it is propagating. So, this is actually what you call is linear polarization. And that actually makes an angle data with respect to the x axis, where data can be defined as tan inverse of Ey over Ex. So, of course if you have only x component then Ey equal to 0 then theta equals to 0. And the other case where you have Ey is present and Ex is 0 then that that corresponds to data equals to pi by 2.

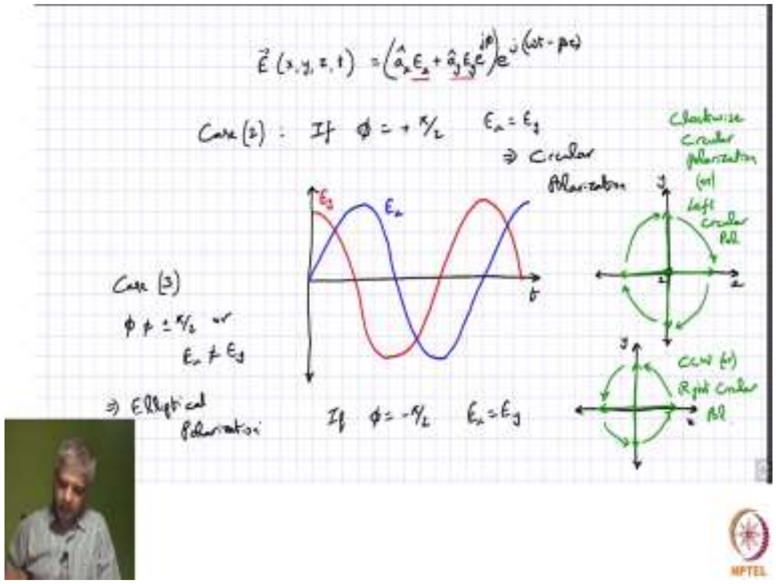
So, that is actually linear polarization, which could have any arbitrary orientation in this transverse plane. Now, let us move on and let us look at case two. So, I would still like to retain this case two is, what if phi equals to, plus or minus pi by 2. Let us actually look at the case of what if phi equals to plus pi by 2. So, in this case, and let us say Ex equal to Ey. Now, in this case, we are saying that Ey is actually leading with respect to Ex.

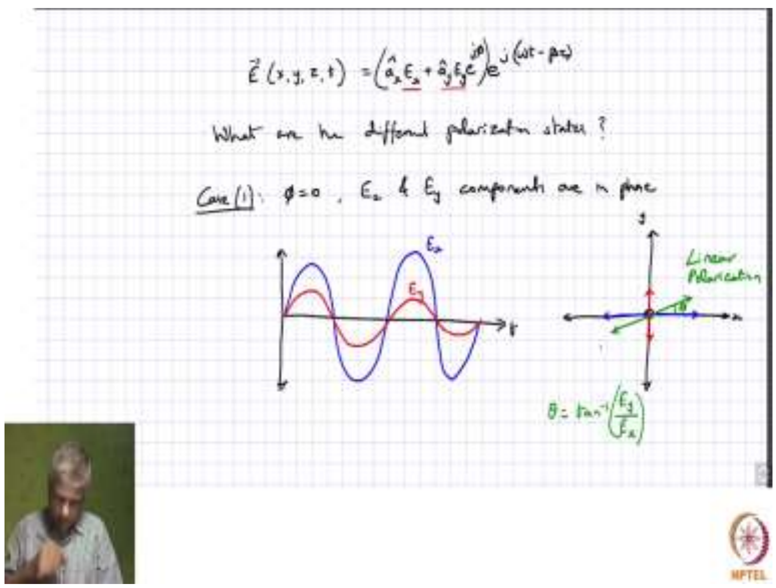
So, if we plot a similar picture with respect to time, so what we are saying is Ey is leading with respect to Ex. So, Ey is something like this and Ex now is going to come like this Ex is going to evolve like this and both are actually we are saying is having equal amplitude. So, this is your Ex, and this is your Ey. So, now let us look at what happens as far as your combined polarization is concerned. So once again, we look at the x y and this is z.

So, if we look at the polarization and that it is holds evolving with respect to time. So, initially the maximum at time equal to 0 the maximum is along the y direction. And or maybe I should draw the combined polarization. So, initially, it is got a maximum at y direction, but after a certain time, y goes to 0 and the x is actually present. So, it goes from basically, here to here. And then after some time, your y goes to maximum x goes to 0.

So, it goes here and then after some time, it goes to maximum of negative x. And then it goes back to the original thing where y is maximum and x is 0. So, this is the this repeats itself as it propagates in space. And of course, with respect to space, you can say that this is repeating itself with a wavelength lambda.

(Refer Slide Time: 18:34)





Now, this actually constitutes what is called clockwise. And it is actually it is defining a circle here. So, it is called clockwise circular polarization. But to define it, you have to use your left hand, so you have your thumb pointing the direction of propagation. And then you are sweeping it in the clockwise direction to define this. So, this is also called left circular polarization. So, this is left circular polarization.

Now if we had started with the case, if y equals to, minus pi by 2 and Ex equal to Ey, you would have essentially seeing something slightly different. In that case, Ex, it would have started with maximum of Ex and then it would have gone it would have started with the maximum of Ex and then it would have gone to a maximum of Ey. Because in this case Ex is this component and then Ey would be lagging Ex.

So, Ex would replace the blue or Ey would replace the blue curve here and so it goes like this and then it goes like this and then it goes like this. So, this is called counter clockwise polarization or in other words, it is also called as right circular polarization. Because what we are using in this case is your right hand. So, you have this thing pointing along the direction of propagation, your thumb pointing along the direction of propagation and you are using your right hand to describe the evolution of the polarization.

So, this is called right circular polarization, but in any case, if we have phi equals to plus pi by 2 or minus pi by 2, but Ex is equal to Ey this is called circular polarization in general because it defines a circle. Now, if Ex is not equal to Ey or if phi is not equal to plus or minus pi by 2 in any of those generic cases, you say case three phi is not equal to plus or minus pi by 2 or Ex is not equal to Ey you will find that this is actually defining ellipse.

So, this is what you would call is elliptical polarization. So, that is actually a neat way of representing these polarization states that is whether you say linear circular or elliptical and that is that representation in a three dimensional way is through what is called Poincare sphere. So, it is named after this famous scientists named Poincare.

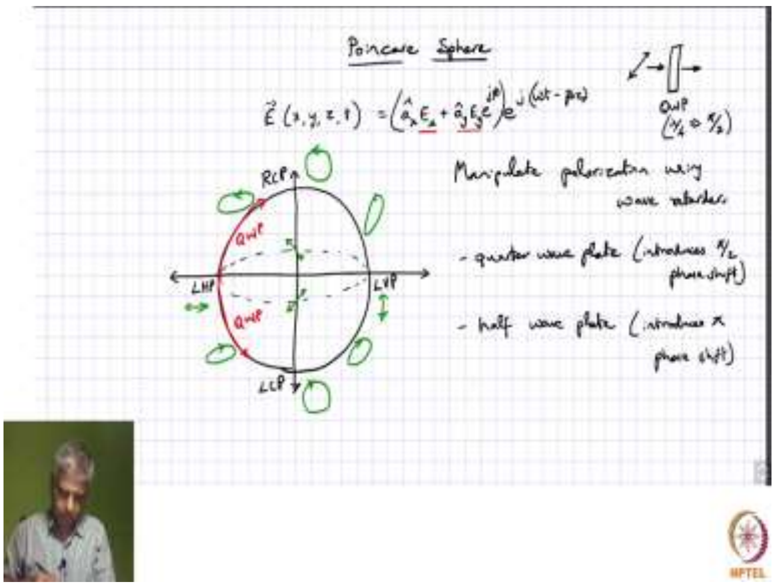
But essentially he found a very nice way of representing this he basically defined one axis like this and so, he basically defined it as a three dimensional sphere all these different, he found that it is actually a convenient way of representing this. Now, of course, I am not drawing it as a three dimensional sphere, but I can explain to you what it essentially means. But essentially this sphere over here which you can probably imagine in terms of three dimensions, you say.

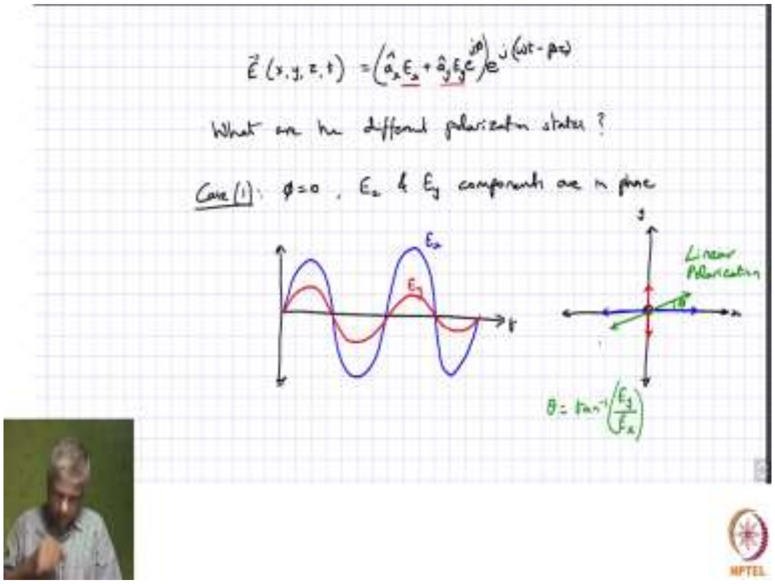
This is if you are looking at the depth of that sphere, that is what it corresponds to the top of the sphere is your right circular polarization and your bottom of your sphere is your left circular polarization and this one is your linear horizontal polarization and this is your linear vertical polarization. So, we know what these polarization states are this vertical polarization corresponds to this, this horizontal polarization corresponds to this.

And your LCP is your otherwise called your clockwise polarization is like this. And your RCP is your counter clockwise polarization state. So, anyway of these polarization states can be and you can imagine anything else in between is going to be elliptical polarization. So, along the equator it will be all these different polarization states.

So, it would it would basically be at this point along the equator it will be linearly polarized but 45 degrees this way and at this point, the other side it will be linearly polarized, but it will be the orthogonal with respect to this polarization. And anything in between is going to be elliptically polarized. So, somewhere over here is going to be more towards the horizontal.

(Refer Slide Time: 25:56)





And it is going to be, left circularly polarized. So, it is going to be something like this. This and over here, it is going to be once again horizontal, but it is going to be a bit close to horizontal, but it is going to be right circularly polarized. So, that is actually the (())(26:20) polarization that we have and over here it is going to be closer to the vertical polarization state.

So, you have an ellipse that is looking like this, but that the upper half corresponds to the upper hemisphere corresponds to right circularly polarization state and the lower hemisphere corresponds to left circularly polarization state. So, you will have the same orientation, but it will be clockwise polarization. So, all the different polarization states can be represented over here. So, why we are doing this why are we interested in this? We are interested in finding how the polarization changes.

And first of all, we are interested in understanding if we could manipulate this polarization so that you can change from one polarization state to another polarization state. So, it turns out that we could manipulate the polarization use. So, you can manipulate the polarization state using what are called wave retarders. So, what is the wave retarder basically, it is a birefringent element when we say birefringence is talking about two different refractive index and two different refractive index between the for the x direction and the y direction.

So, if you have a birefringent material then what happens is you could basically change the phase or retired one component with respect to another component. And one popular in a retarder is what is called a quarter wave plate. So, what is a quarter of a plate do it returns by so, when you go through that material basically it retards whatever incoming polarization a the x and y component of the incoming polarization is retarded by, as the name suggests is lambda by 4 that is in terms of the path length.

But in terms of phase you can say that this lambda by 4 implies that corresponds to pi by 2 change in phase. So, if you start with a linear polarization, let us say we are starting somewhere over here. And if you actually incorporate a phase change of pi by 2, where let us say the along the y direction, it is pi by 2 retarded with respect to x direction, then we are talking about moving from this towards this direction.

So, moving from the equator to the towards the pole. So, this is actually what quarter a plate does it actually moves you from the equator upwards? Or if it is the other way it is minus pi by 2 the if it is plus pi by 2 that means Ey is leading Ex. So, in that case it will go in this direction. But if it is minus pi by 2, it will essentially go in this direction. So, that is what a quarter of a plate does. It essentially introduces pi by 2 phase shift between the two polarization alternate polarization components.

So, that is what a quarter wave plate does it goes moves you away from the equator. But let us look at what a half wave plate does. So, what a half wave plate does is actually introduces pi phase shift between the two alternate components. So, essentially, if you have, Ex and Ey like this, if your Ey is flipped. So, then that actually corresponds to the, polarization is still linear, but it would have this, would have flipped vertically.

So, then that would actually be oriented in this direction. So, in essence, what you are doing is, you are actually causing a rotation in the polarization. So, essentially, what you are doing when you are putting it through the halfway plate, is you are rotating the polarization, you are staying in the equator, but you are rotating your polarization when you are using a halfway plate. So, those are the typical manipulation that you do, as far as the polarization is concerned.

Now, this is actually if you want to achieve a particular polarization state. But if you want to use it as a sensor, then things are different, then what you are really looking for is you start with say, one polarization state like this, and you are trying to track and you are sending it through some material, which is subjected to some perturbation, and then you are trying to see which way this is moving, whether it is moving this way, or, along this or along this along this, you are looking at which way it is moving.

And by looking at which way it is moving, you can actually tell what the polarization what the perturbation has done, the perturbation would have either change the amplitude, if it is changing the amplitude, then it is only moving along the equator. It is just changing its remains or linear, but it is changing along the equator. But if it has changed the phase, between the two polarization components, then it would actually move out of this equator towards the poles.

So, as a sensor, you are actually looking at the inverse problem, you are analyzing the polarization. So, that is what, when you come back here, you look at this, what this optical demodulator does is analyzing the polarization state. And you know what you launched into your fiber at the transmitter, you have a specific, you usually put a polarizer here to ensure that you are launching a very specific polarization state.

And then you analyze, what is the polarization state at the output and based on that without any perturbation, maybe it would be the same polarization that is coming out. But if that, if there was a perturbation that polarization state would change, and correspondingly, this optical demodulator will give a change in the intensity. So, that is how we use it as a optical sensor and we will look at that in a little more detail in the next lecture.