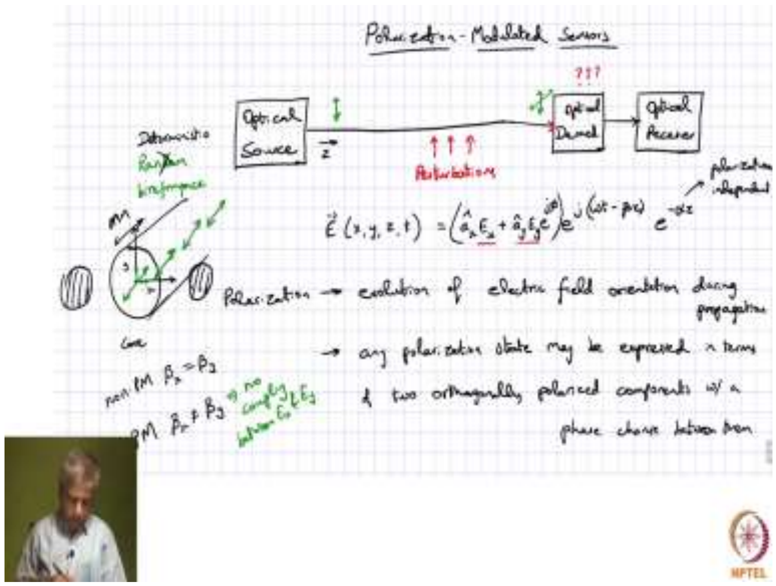
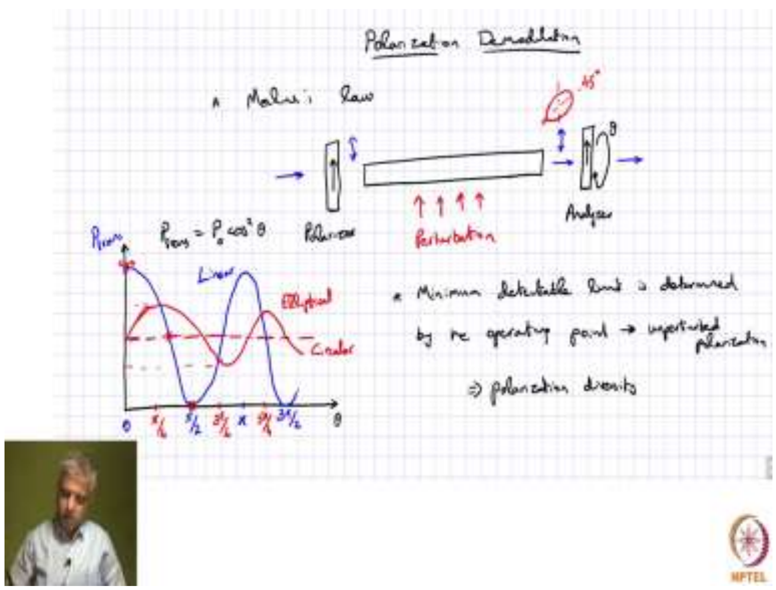
Optical Fiber Sensors
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Polarization Modulated Sensors - 2

(Refer Slide Time: 0:25)





So, we started looking at polarization modulated sensors in the last lecture. So, we talked about using an optical source and so, if it is an optical fiber sensor, you launch that into an optical fiber such that you launch a particular polarization inside that optical fiber and with perturbations the polarization state might change, but since your optical receiver is not sensitive to polarization changes, you need some sort of a demodulation mechanism to convert any polarization change into a change in intensity, which can subsequently be picked up by the optical receiver.

So, today the question is, so what is this demodulator? So, that is what we are going to look at. And so, for polarization demodulation, it is quite helpful to understand Malus law. What Malus Law states is that if you have polarized light, let us say, you have this optical radiation coming in and this polarizer is oriented such that it gives vertical polarization. And if it goes through, some material let us say, initially, this material is not perturbed.

So, the, you would expect that without any external perturbation, whatever, incident polarization is the same polarization, you would get over here. But how do you know that you are getting the same polarization? Well, one way you could possibly do that is just like you had a polarizer. Here, you, you have another polarizer over here, which we call as an analyzer. And let us say it is originally oriented vertically, so it allows vertical polarization to go through.

But you do certain rotation. So, you can basically rotate, suppose you put it on a mount where you can rotate that analyzer, so you can actually go through different angles with respect to the polarizer angle. And what Malus law tells us is, if you do that, if you rotate it over angle data, then you would essentially see the polarization, the intent, the transmitted intensity, that you are looking at over here, that you can call that P transmitted.

The P transmitted would have a maximum at theta equals to 0. And then as you start rotating, it is going to start allowing a smaller component of this light to pass through, so it is going to come down, and it is going to go to a point where it becomes 0. And that corresponds to the point where this is actually oriented at 90 degrees. So, it is orthogonal to this polarization state. So, this is actually something that happens at pi by 2.

And then of course, if you still keep going further, it will go to a maximum and then go to the minimum and so on. So, this is actually at pi and this is 3 pi by 2 and so on. So, you can essentially by analyzing the output radiation that you have here from this medium, you can actually figure out what is the polarization state at the output. Now, so what Malus law tells us is the, this is actually cos square function.

So, Malus law tells us that P transmitted is going to be the incident power P naught multiplied by cos square of theta, where theta is the orientation of the output polarizer, which is what we call as the analyzer. So, it essentially goes through a cos square function. Now, how do we pick up any perturbation? So, if there are some perturbations that this medium is exposed to, then the output polarization is going to change. So, let us say it shifts to some sort of an elliptical polarization.

So, the polarization axis has changed, and then it also the perturbation has introduced some there is some birefringence in this medium, so, it did not introduce a phase shift between the two orthogonal components. So, then you have an elliptical polarization and let us say if this is at 45 degrees, then so, what we expect here is, as you rotate this analyzer, you are going to see maximum at 45 and minimum at 135 and then maximum once again at 225 and so on.

So, you would basically say, at pi by 4, it will go to a maximum at 3 pi by 4, it will go to a minimum and, 5 pi by 4, it will go to a maximum again. So, you would expect something like this, this is your average line, then you would you would essentially go to a maximum here at pi by 4 and then you will go to a minimum at 3 pi by 4 and then a maximum again at 5 pi by 4 and so on. So, this would be the output that you get to see for the perturb case.

And by looking at this we can make out that it is elliptical. So, how can we say it is elliptical because of the fact that your maximum and your minimum is not as high or as low as compared to your linear polarization its minimum should be 0 for linear polarization but because in the elliptical polarization the minimum would still correspond to the intensity in the minor along the minor axis, of the polarization.

So, it would not go to 0. So, by looking at this you can say that this is actually elliptical polarization whereas, the originally started with linear polarization state. So, you can essentially tell that some perturbation has happened which is caused both coupling into the orthogonal polarization straight from the vertical polarization to the horizontal polarization. And also there is a phase shift between that and of course, so, we talked about linear and elliptical.

So, what would happen if it was circular polarization at the output because of this perturbation (())(09:38) to just correspond to just a straight line here because as you rotate across the circular polarization you get a constant intensity. So, you can also tell that if it is clearly polarized you can tell that you can tell that by looking at this transmitted power through the analyzer. So, this analyzer essentially, is what acts like a polarization demodulation mechanism.

So, that is great that we could actually analyze the polarization in relatively simple manner. Of course, we cannot tell which handed polarization it is, right hand or left handed and all of that. So, that is an issue, but not a major issue, because you are just trying to sense the magnitude of the perturbation. So, when you talk about magnitude of the perturbation, you are interested in picking up, you want to understand what is the minimum limit, minimum detectable limit as far as the perturbation is concerned.

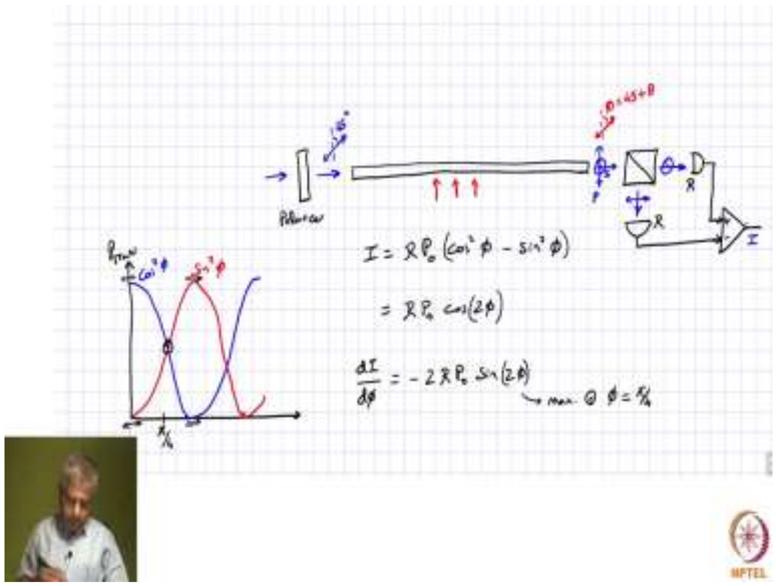
And in this case, you find that the minimum detectable limit is, the case where it is linear, and then it is slightly, maybe tilted or something like that, with respect to so you are starting with this without any perturbation, and then you are slightly moving around here. And we see that it is not very sensitive at that particular point. So, it is its minimum detectable limit is determined by the operating by the operating point which corresponds to the unperturbed polarization.

Now, of course, you can make a couple of arguments about this, you can say that, I can increase my sensitivity by instead of looking at a polarizer, with this, oriented like this, originally, I can, I can look at something where it is cross polarized, so normally, it is dark. So, if it is cross polarized, that would actually correspond to P naught sine square theta form. So, I normally it is dark, but if there is any perturbation, then it becomes some finite intensity will leak through. And based on that, you can possibly tell what is the magnitude of that perturbation.

However, even in that case, what will happen is, as you increase your perturbation, it is eventually going to go to the maximum. So, if you start operating at this point. So, if you can argue that it can start operating at this point, and then you can have some sensitivity here, but even here, it is not ideal. So, you would what you probably want to do is actually, have your bias point somewhere over there. So, that is where you get the maximum sensitivity.

However, if you are just looking at one output like this, that may not actually provide the highest sensitivity. So, the idea is, can you use polarization diversity. So, what is polarization diversity?

(Refer Slide Time: 14:18)



Well, so now once again, you are looking at perturbations to this medium. So, we once again start with a polarizer. So, light actually comes in here, it is launched into this medium, which could now case could be an optical fiber. So, the output of that instead of analyzing just with the regular polarizer, use what is called a polarization beam splitter. So, there is something called a gland, Thomson polarizer, which essentially consists of a birefringent material.

So, we know whenever we go into a birefringent material, especially at an angle with respect to what is called optical access of the birefringent material, you generate what is called the ordinary ray and the extraordinary ray. And then you could essentially have an air gap over here, which reflects one of those rays and let the one transmit, because those two are at two different angles.

So, you can essentially design it such that it is totally internally reflected to the point that if you have, both polarization, let us say this is the, what is called the perpendicular polarization it is because it is perpendicular to these plane of incidence, the plane of incidence is the plane that has both the incident transmitted and reflected ray. So, this is particular perpendicular polarization. And this is what is called parallel polarization.

So, in short, this is yes, this is P. And this is yes. So, if you have orientation such that you are transmitting your, let us say your particular polarization, and you are reflecting your parallel polarization, then you have basically two light beams that you can simultaneously detect. So, you can put at photodiode here and a photodiode here, and you can generate a photo current, and that photo current now, you can actually give it to balance detector, and then you can essentially, take the output so that is basically corresponding to that differential output.

So, what exactly are we doing, we had this power transmitted, drawn as a function of, say that incident polarization. So, you have essentially whatever response you are getting in this sport corresponds to your cos square function. But the response that you get from the orthogonal port, that will correspond to in a sine squared function now. So, this corresponds to a sine square of whatever the input polarization component, whatever that angle, it has got, with respect to the perpendicular angle, and this is actually corresponds to cos square function.

So, in terms of the current that we are getting here, let us say this is current I, if we put down that current I, that will correspond to certain responsibility of these two photodiodes, let us call that R times the power that is incident on it, let us say is P naught, then you have essentially cos square of phi minus sine square of phi. Because in this port you are picking up the cos square component, and in this port you are picking up the sine square component.

So, you are doing a differential detection in which case there is no if you are picking only, the cos square then you have very little sensitivity around this. And if you are building, if you are picking only the sine square, then you have very little sensitivity here those points. But if you are picking up both sine square and cos square wherever this is actually not sensitive this is you can pick up wherever you do not get much light here you get light there and so on.

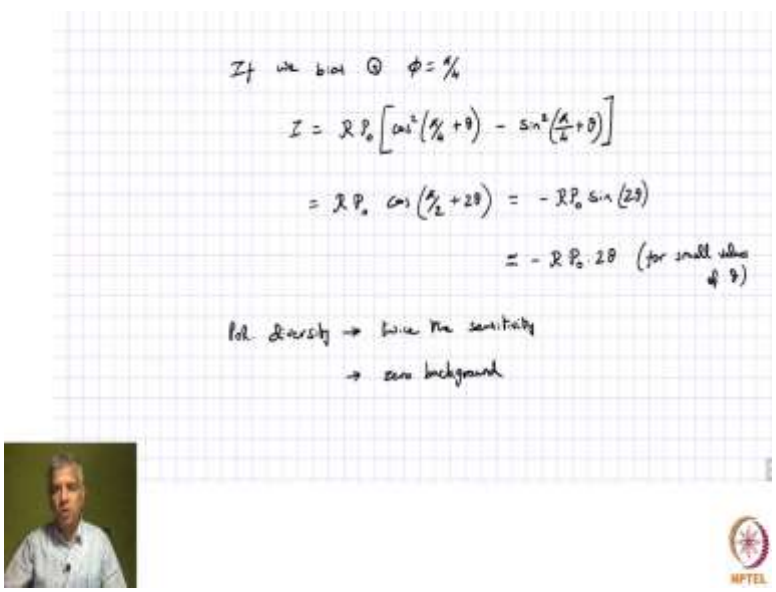
So, you can actually prove that this in this sort of scenario you get the best sensitivity and to do that, you can just basically simplify this. So, that corresponds to R times P naught cos of 2 phi, where phi corresponds to the angle of the incoming polarization. So, let us say the input polarization or the because of the perturbation that output polarization is tilted like that, that phi is what we are tracking now.

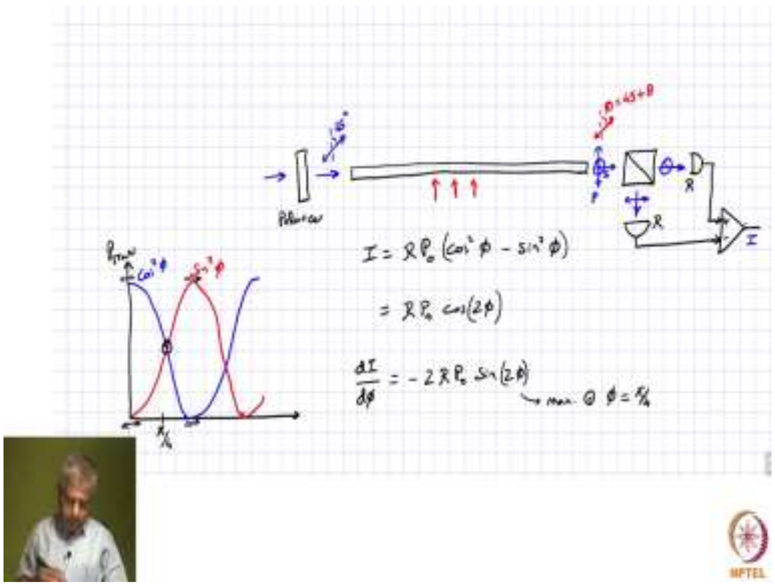
So, that corresponds to this responsibility multiplied by the power that is incident on those detectors multiplied by cos of 2 phi and what we are interested in is what is the minimum change in this rotation angle phi that we can pick up. So, to look at that you basically take a differential dI over d phi, if you do that, then you get minus 2 times R P naught sine of 2 phi. And of course when you look at that where is so, that corresponds to the slope of this response curve here and where is that maximum.

So, this becomes maximum at phi equals to pi by 4 because when phi equals to pi by 4 this term within the prances becomes pi by 2. So, sine pi by 2 equals to 1 so, that is where it becomes maximum. So, what that tells you is something that we intuitively figured out that this point here which corresponds to pi by 4 that is actually the best operating point. So, from a polarizer perspective whatever launch and polarization is concerned you are best off by launching a polarization like this at 45 degrees.

So, that it has got equal components along the two orthogonally polarized directions and then as it propagates, you see because of some perturbations, you might have some small rotation, around this point. So, you are biasing at phi equals to 45 phi and then because of this perturbation you get, say some small theta change in that and that is the change that you are interested in picking up. So, let us just try to write that down mathematically.

(Refer Slide Time: 23:52)





If we bias at phi equals to pi by 4 then I is given by R times P naught cos square of pi by 4 plus theta, that is the theta corresponds to the change in polarization angle as a function of that perturbation minus cos square of, minus sine square of pi by 4 plus theta. And then once again like we did before you would say that is corresponding to cos of twice this argument and we need to cost that twice that argument you get basically, cos of pi by 2 plus 2 theta which is can be written as minus sine theta.

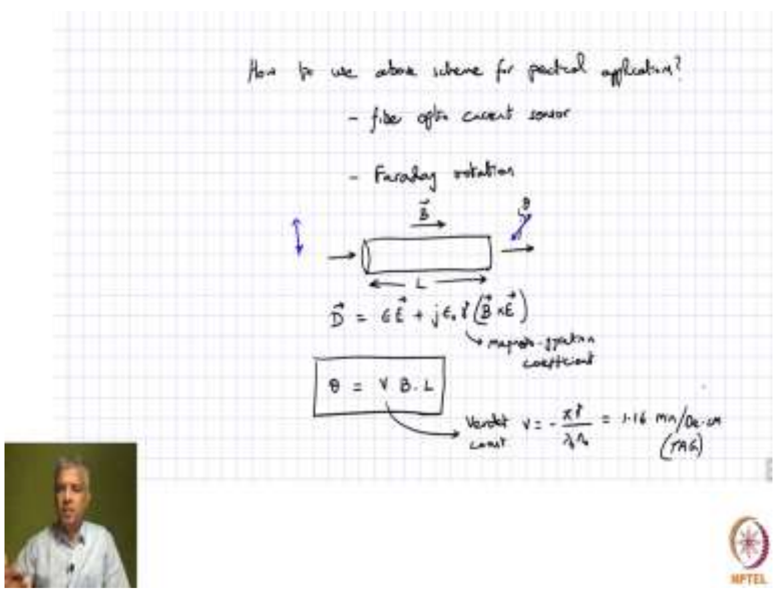
So, this is R times P naught a minus of R times P naught into sine of 2 theta. And for small angles small changes in theta, theta is a deviation from the pi by 4 bias that we have applied first so, far small changes in data sine of 2 theta can be written as 2 theta itself. So, this can be approximated as minus R times P naught 2 times theta. So, this is for small values of theta. So, by going through this polarization diversity now, we can of course, say that if you had only one port that you were looking at you would essentially not get, this this sort of sensitivity.

So, you are better off by going to both the ports and so, essentially you just say because of the polarization diversity you are having or twice the sensitivity like because you have this two theta thing, if you just had only one of these, you would have just a theta term over here. So, you get twice the sensitivity. But the more importantly, in this sort of a scenario, you have 0 background.

So, what do we mean by that? Well, in this sort of scenario, if you are biased over here, you have a very large power that you are measuring and you are within that large power, you are trying to make some look at some very small changes, whereas in this case, and so that large power can give you significant amount of short noise. But in this case, you do not have that background because, essentially you are doing a differential detection over here. So, you do not have when you are looking at I, basically you do not have DC term over here, whatever it is proportional to theta. So, it gives you the signal with high sensitivity with 0 background. So, that is the key point as far as using a polarization diversity scheme is concerned.

So, what we have seen so far is one we can actually do a polarization analysis at the output and that is our demodulation mechanism for picking up changes in polarization and to we said, if you use a polarization diversity scheme, then we can actually do this detection with even more sensitivity and 0 background. So, polarization diversity scheme, which corresponds to looking at both the orthogonal components simultaneously is the way to go as far as picking up polarization changes are concerned. So that is a key way. That is the best way of demodulating your changes in polarization. Now, how can we use this for a practical application?

(Refer Slide Time: 29:32)



So, the question is, how to use above scheme for practical application. And one such practical application where this scheme or this methodology is widely used is what is called fiber optic current sensor. So, for a current sensor essentially you need to be able to pick up relatively small amount of current let us say 0.1 or even less than that 0.01 amperes to something the order of kilo amperes.

So, if you are actually a power generating station you might actually be generating something the order of kilo ampere. So, you need to be able to pick that up with very high linearity. And there are conventional sensors like Hall Effect sensors, which are dependent on the magnetic field that is present because of current flow in a conductor. But those have a lot of calibration issues, whereas, this fiber optic current sensor has been proven to be extremely nice way of picking up current over a very large range like I talked about.

So, how does this fiber optic current sensor work what is the basic principle for this? So, that actually is dependent on what is called Faraday rotation. So, you can essentially use this Faraday basically Faraday Effect to pick up these changes in current. So, how does so, what is a Faraday what is the Faraday affect? Now, if you go through certain material, which are subjected to let us say a magnetic field like this along its axis oriented along its axis.

If you come in with light let us say it is vertically polarized light it can end up changing the polarization state and then under the influence of this magnetic field. So, your output polarization might be tilted with respect to the input polarization through this in under the influence of this magnetic field, and this is actually described by if you look at the displacement vector. So, normally you define the displacement vector as epsilon times E where epsilon corresponds to the permittivity of the material, which is epsilon naught multiplied by the relative permittivity of the material.

But, in addition to that, what you get is actually Magneto gyration effect. So, you get j epsilon naught gamma multiplied by B cross E term where B corresponds to the applied magnetic field cross E corresponds to the, E corresponds to the electric field of your incoming light. So, what that tells you is the response of the material which is characterized by this displacement vector the response of the medium is such that it rotates because this is a curl B cross E that means that it is rotated with respect to the input orientation of the light.

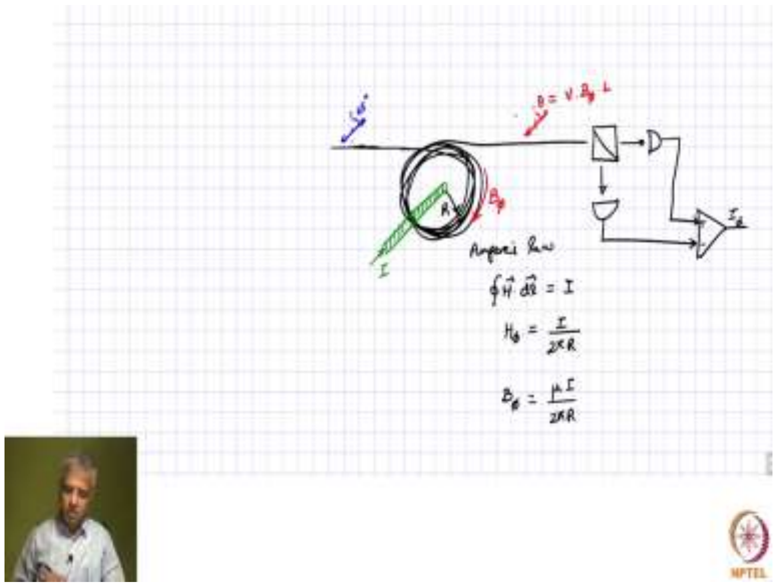
So, you have a certain rotation that is happening and that is actually defined by that response is defined by this gamma which is called the Magneto gyration, gyration is essentially it is like changing the orientation. So, Magneto gyration coefficient, so, there are certain material which have a larger Magneto gyration coefficient than some other material like so, you have TAG material that corresponds to Terbium Aluminum Garnet that actually exhibits with much higher Magneto gyration coefficient compared to for example, glass which is silica.

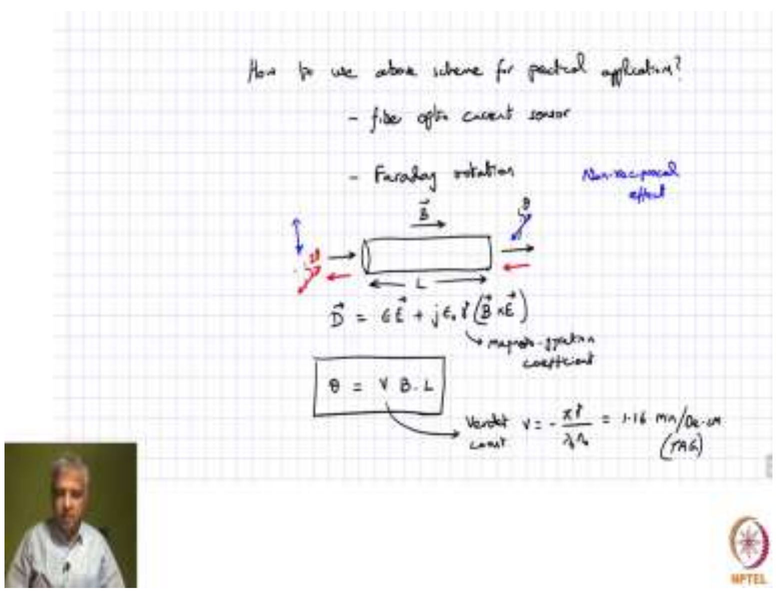
But nevertheless the idea is that because of this Magneto gyration there is a change in the orientation or the input incoming polarization is rotated through an angle theta, which can be defined as in general terms it can it is proportional to the magnitude of the magnetic flux density that we have multiplied by the length of that crystal and the proportionality constant here is this V. Where V is actually a representation of the Magneto gyration coefficient and it is called the Vardet constant.

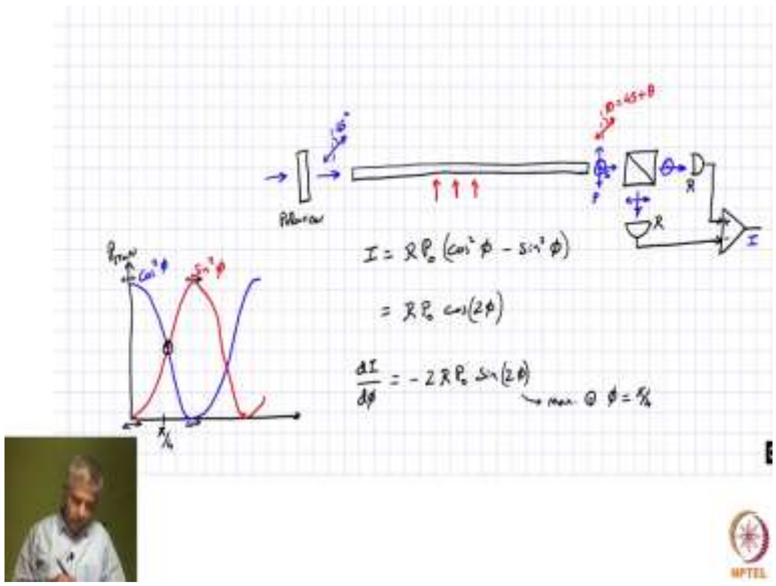
So, the Vardet constant V can be written as minus pi gamma lambda naught divided by lambda naught n naught and this is actually a value that can be like for example, for TAG material, it is 1.16 minutes per Oersted, Oersted is actually unit of magnetic flux density and centimeter corresponds to the length of your crystal. And so, this is actually the angle is expressed in terms of minutes of course you can represent that in terms of degrees or radians as well.

So, that is for particular material like TAG. However, if you want to use this for glass, for glass this is actually two orders of magnitude smaller. So, it will work out to be like 0.01 minute per Oersted centimeter and so on. So, it is actually a much smaller effect in glass. But can we, use glass for picking up this rotation? How can we use this effect in a current sensor? So, let us actually look into that.

(Refer Slide Time: 37:47)







So, what we can actually have is this fiber let us say you are making a coil of this fiber and you are going out like this. Now, I am inserting this current carrying element and let us say a wire and positioning the wire along the axis of this coil and let us say there is a certain current I that is flowing through this conductor we know that because of this current you have a certain magnetic field. So, what is what is going to be the orientation of the magnetic field that is going to be along this along this fiber coil.

So, you develop a magnetic field around it. So, how do you quantify the magnetic field well you go back to amperes law tells you that H dot dl the magnetic field intensity dot product with the line integral, this close line integral that is going to be equal to the current enclosed. So, you can basically do it for this geometry. You basically say this is actually H phi multiplied by if you do a closed loop integral on this, on this fiber path which essentially has let us say a radius R with respect to the center where the current conductors is.

Then you can just say, H phi when the corresponding B phi would be like this so H phi is going to be given by I over 2 pi R. Because that line integral is going to give you 2 pi R term. So, you can take that over here, and you can write this as 2 pi R. So, if you are looking at B phi, that is nothing but mu, mu is the permeability of this medium over here, mu I over 2 pi R. So, the point is, according to the current that is flowing in this wire, you have a magnetic field generated. So what is the big deal?

So, how is this helpful for us? Well, it is helpful because now we are actually looking at the Faraday affect. So, now we can talk about actually launching a polarization like this. So, if light actually goes through this material, imagine that it is actually under the influence of the magnetic field along the axis of this fiber. So, you are subjected to the Magneto gyration effect, the Faraday effect, and because of that, now, you go with an output that is going through an angle theta with respect to the incident polarization angle.

So, theta is given by the Verdit coefficient of silica, which is, which I said is two orders of magnitude lower than that of TAG, B phi, multiplied by length. So, this is an interesting point, the length of these crystals, it is typically in the order of centimeters to get, let us say, 45 degree rotation, like you can possibly have some, 1000 Oersted or something of flux density. And then for that, if you do the calculation, you will find out to get 45 degree rotation, you can do achieve that with just centimeters of fiber I mean centimeters of this material.

But if you want to do the same rotation, if you want to achieve the same rotation in fiber, then, because of Verdit constant is so low you have to compensate that with the L. But that is not too difficult because in a fiber just like we did for this fiber optic gyroscope, we were actually getting a scale factor in terms of the response by the fact that you have a number of turns in your you can make a coil out of your fiber and you have a number of turns in your fiber.

So, similarly you can actually have very long fiber and through that, you can sort of compensate for this fact that this V is relatively small. But nevertheless in terms of detecting this, we do what we did previously. So, we have this polarization beam splitter that is actually picking up this orthogonally polarized components and then you take them into balanced or a differential circuit and then you can get your current I which so, this has to be differentiated with respect to this current here.

So, this is called as ID that corresponds to the current that is detected. So, that essentially, you can say that, depending upon this current you have a magnetic field and that magnetic field rotates this polarization and that polarization changes the power distribution between these 2 detectors. And then you can actually see that power change or measure that power change in terms of the photocurrent and then maybe you can input a transcript and stage beyond this to convert that to a certain voltage and that is how you establish a current sensor.

So, there are some very interesting aspects of this, this is actually highly sensitive to current of course, you can go back to this discussion and say that your probably your best operating point is here. So, instead of having a polarizer just giving you vertical polarization, you, can send in 45 degree polarization. And that that may be your and look for changes in theta with respect to that. So, you start with 45 degrees, and you look for changes with respect to that to get the best sensitivity.

But, yeah, all that you can do to improve that detection, but the basic scheme is based on this Faraday affect. Now, one just leave you with this thought one interesting aspect about Faraday effect is it is a non-reciprocal effect. So, this is actually what is called a non-reciprocal effect. So, what do we mean by that? Now, if you come back with the same polarization in the opposite direction, if it is a reciprocal effect, you would get this, linear polarization output.

But, because it is dependent on the orientation, and the direction of this incoming electric field, if it is coming in the opposite direction, it does not go back to the original stage, instead, it goes through twice this theta. So, you, go one way in forward direction, you get theta, but when you send it back, you get actually twice theta. So, why is this important? Well, it is important because you could get changes in this theta because of lot of random birefringence that you have in the fiber.

But the key point is all those random birefringence because of some external perturbations, you can have by random birefringence and you can have changes in theta, but all those random birefringence would cancel, if you actually put a reflector here and send that light back, it will all cancel out. And, what will be remaining is actually the, this nonreciprocal Faraday affect based rotation and that is what is going to be the thing that you can measure. So, that is actually what is called reflected color reciprocal reflectometer configuration, and that is something that we will look into a little more detail the next lecture.