**Optical Fiber Sensors**
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**Lecture No. 02**
**Different types of Optical Sensors**

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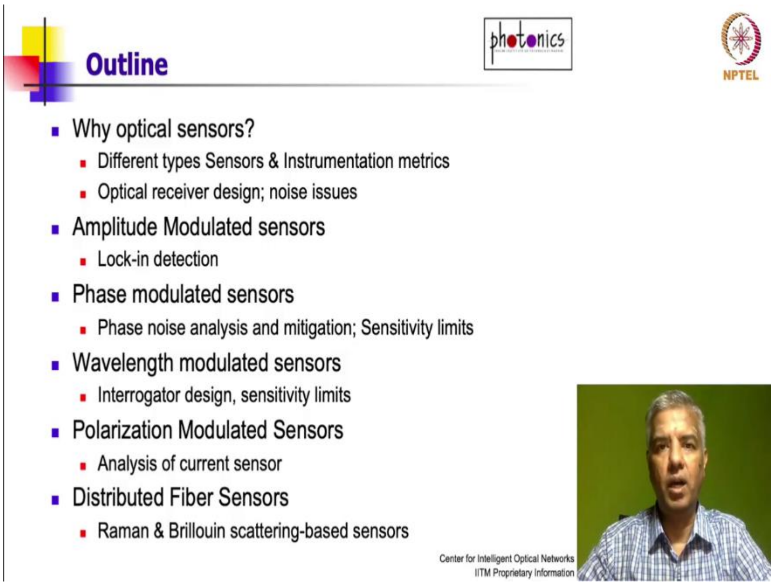


So far, we have been talking about different sensors, what is the need for sensors, just giving perspective of what are the different properties of light that we could potentially exploit and how to pick up different physical parameters, like strain, pressure, temperature, and so on, using this properties of light. So, now it is time to go on to see few examples of these sensors. So, let me just go ahead and try to give you a feel for how to do sensing based on these parameters.

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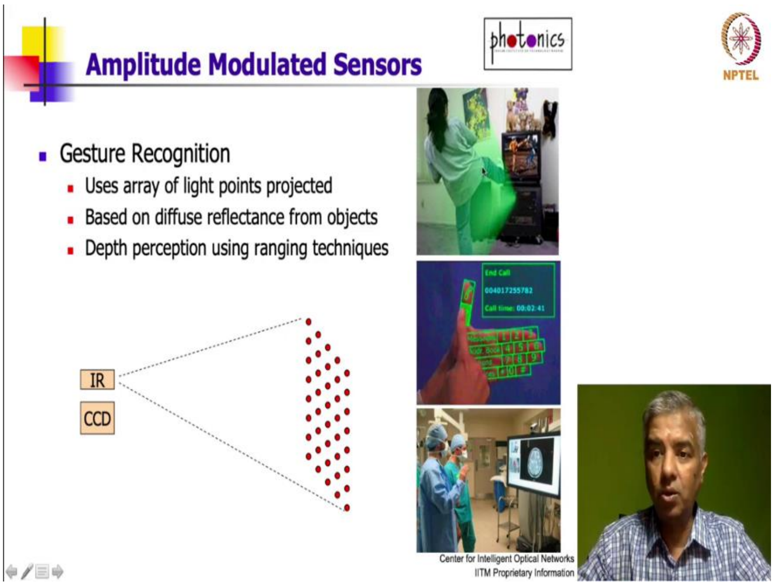


So, let us first consider amplitude modulators, sensors. And, you would see in the common literature that these are either called amplitude modulators sensors, or intensity modulated sensors, both are typically the same amplitude, you are referring to the electric field amplitude, but that the magnitude of the electric field amplitude, square of that is what intensity is. So, you can even look at it as intensity modulated sensors.

So, what do you see here? You see a kid that is playing with the television, it seems like and clearly this, this is a video game that is running over here. So, how is this person able to communicate with this television console, or if you want to think about more serious thing, this is actually a hospital in an operating theatre, and very sterile environment that we need to keep, and this person is seem to be referring to something on the screen over here, and trying to understand what is going on maybe in the middle of surgery and so on.

So, what exactly is going on, in these type of applications? How is an optical sensor useful in these type of applications? Well, these are applications that are called gesture recognition. So, what is gesture recognition? Basically, I do this gesture, and then the computer should be able to say, this is what this person is trying to gesture, and then based on that computer might take an action, in this case, if the kid is actually throwing up, throwing a punch or throwing a kick, then the computer should recognize that and project an image which is mimicking that action.

So, how does it sense this? Well, this is actually a very good example of intensity modulators sensor on amplitude modulators sensor, what exactly is happening here, you have somewhere over this console, you have an infrared source, so infrared source is something that we cannot see, with our bare eyes or eyes or was able to see only the visible radiation that is from 400 to 700 nanometers. But, if you go to the near infrared radiation, something in the order of 900 or 1300 nanometers, you would not be able to see that.

So, imagine there is a source of light like this, and it is able to project a pattern of dots in the far field, if you are able to do that, and if you have an object in between the source and the pattern of dots, then the object is going to scatter only a few of these dots and other dots are just going to go to the background and basically this there may be negligible scatter from the background.

But whatever is scattered from the object is going to be captured using a CCD array. And the CCD array may be programmed to see this image of dots, the silhouette of these dots and based on that, it will be able to sort of figure out the periphery of the object that is scattering light from here. So, you can imagine, if you want to have very fine features, these dots could be much closer, and then you will be able to make out even smallest of gestures.

So, this is quite useful, because whenever you are making a gesture from, let us say, from here, you are waving your hand from here, then I am actually scattering a different set of points with respect to this. So, and if I can continuously track that movement, then I know that I am making a gesture from one side to the other side. So, that is essentially what is happening and that is how these people are able to communicate with the machine.

So, in the real world, today, we are actually trying to break down the man machine interface and try to make it easier for somebody to actually interact with machines and gesture recognition is really at the forefront of this revolution of how this interface is going to happen. So, in the future, you can imagine that there will be a lot more machines, which respond to gestures from other human beings.

So, this is actually, there is a Microsoft is a company that has come up with a product as called a Microsoft Kinect system, which is used in this Xbox video gaming console. But I believe there are plans from Microsoft to incorporate this in into their regular operating system. So, the future operating systems have gesture recognition as part of it. So, maybe you do not need a mouse or a keyboard even that you could potentially communicate with the machine in a rather easier manner. And that is actually enabled through optical sensors, in this case, an amplitude modulators sensor. So, let us move on to another type of sensor. Now I will go to how a phase modulators sensor might work.

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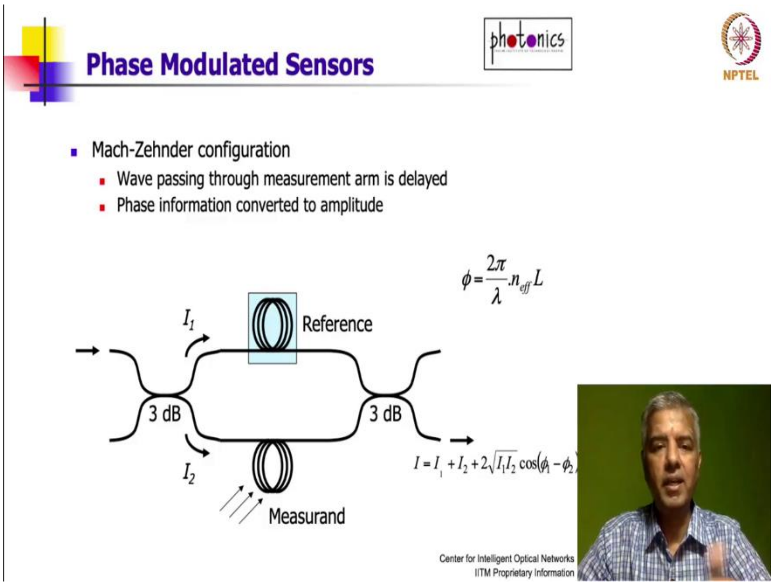


A phase modulated sensor to see how it works, I know consider this diagram over here, you have light coming in to this, what is called this 3 dB power splitter, it splits the light into two equal parts. And then it is going to go through some length of fiber and then it comes to another 3 dB splitter. Here, you have mixing of this, these two intensities, and then the fields corresponding to these two light waves. And then you have a combined product over here, here as well as here, but just let us focus our attention to what is coming out here.

Now what is going to come out here is going to be based on the phase that it accumulates acids propagating through the structure. So, we know that face when you are looking at it is corresponding to 2 pi over lambda multiplied by lambda is the wavelength of your incoming light source. An effective is the refractive index of this waveguide effective refractive index of this waveguide. And L could be the total length that it is traversing.

So, if you look at the combined product, so the field from both these arms are they are going to beat with each other and so, one of them can be looked upon as a reference arm and other one could be the measurement arm. I will tell you why, that terminology is important. But when you look at the total intensity that comes into it, it corresponds to the intensity of the individual arms, and then you have a beat component, the beat component, and the key part here is that the beat component is going to have a sinusoidal dependence on the relative phase difference between the two arms, the light propagating in the two arms.

And from this perspective, let us say we are interested in the phase that you can get, this is a phase that you want to measure, and so if you are looking at the output intensity, output intensity is going to fluctuate, but you do not know whether it is fluctuating because of the, what you want to measure or because of what is happening in the other arm.

So, suppose you keeping this other arm in a controlled environment, so we call that reference environment. So, it is a fairly well controlled environment. So, exactly how much is the phase that is accumulated over here, and that does not change as a function of time, then any intensity change, because of this component, is going to be because of this change in phi 2 that is actually what we call as the measurement arm.

So, this is actually an example of phase modulated sensor. And you are not going to be able to do this without this arrangement, because of the fact that you may ask the question. Why cannot I just take this light here and put it through a detector? In that case, what you would be measuring is the intensity, the photodiode that you might use to pick up the light, it is not sensitive to phase by itself. So, the photodiode is actually color blind, it does not pick-up phase. And also, it does not pick-up polarization.

So, all it can pick up is changes in intensity. So, what you need to do is to convert any phase change here into a corresponding intensity change. And that is why this entire setup, which is called a Mach-Zehnder configuration, that Mach-Zehnder configuration is very important. And it is essentially an interferometer. So, what does interferometer do? It converts phase changes into intensities changes, so that you can pick up with regular optical receivers. So, where is this useful?

Well, this could be useful in a variety of applications. One such application that is very popular is called a hydrophone. So, you typically incorporate sensors, say underwater, and you want to track if there are any, for example, enemy ships that are coming in or towards you. So, since any moving object, any motorized moving object is going to emit certain acoustic signals, those acoustic signals can come and this fiber coil could be exposed to those acoustic signals, in which case, it will impart some pressure on this fiber. And due to the pressure, both the refractive index as well as the length are changing ever so slightly.

Just imagine, this is actually divided by wavelength, which is in the order of 1 micron. So, even if there is a change of the order of 10 power minus 6 in either of these quantities, you are going to have a fairly huge change in phase. So, this is actually a very, very sensitive measurement. So, you can essentially, in this case, pick up acoustic signals, underwater acoustic signals, that is what hydrophone is, with very high sensitivity. So, that is one possible example of a face modulated sensor.

Now, another example is what we discussed previously, in the case of an airplane, we talked about the need for inertial navigation system. And what we are really using there is actually a gyroscope. And in this case, it is an optical fiber gyroscope. So, what is that principle all about, that is (())(14:07) once again, another phase modulated sensor.

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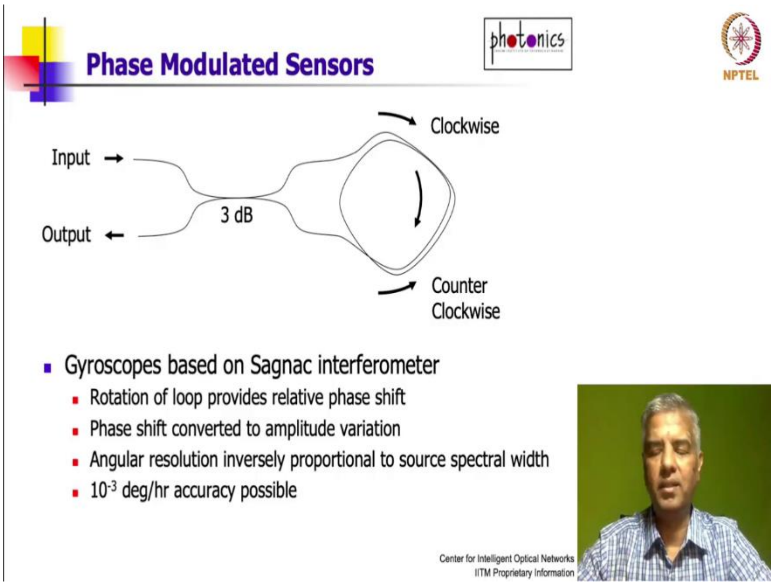


But in this case, what you do is you send the light through a splitter, but instead of going into two separate arms, you actually coil the fiber and bring it back to the same splitter. So, essentially what you are doing is light can come in here and one part of it can go clockwise, and the other part of it will go counterclockwise. So, the path that they are traveling in this case are both the same, and because of that, when they come back and when you look at the output, they essentially cancel each other. So, the phase differences between them is 0, and so, all the light is just going there, there is no output over here.

But suppose you have this coil fixed with rotating object, if there is a rotation over here, then that actually introduce a relative path length difference between the clockwise and counter clockwise light beams and any relative phase path length difference between the two waves is going to create a phase difference at this point. And correspondingly, there will be a change in the intensity of the output. So, and that intensity is going to be proportional to the rate at which the rotation happens. So, this is actually a very nice way of picking up rotation.

And this is typically not very sensitive to anything else, because any other normal change in the strain or temperature of this fiber, both the waves are actually experiencing that so they will cancel. So, it is actually a very quiet interferometer, the quietest interferometer that you can find out there. And, it is called a Sagnac interferometer.

But, if, it would not change for anything other than just rotation. And so, it is a very, very sensitive measurement of rotation, how sensitive it is, you are talking about 10 power minus 3 degree per hour type of accuracy is possible. So, that is actually very, very small number, so it can give you a very high accuracy in terms of the navigation that you want to accomplish.

So, that is like once again, another phase modulated sensor, I am not really talking about the challenges involved here that I will reserve for future lectures. But this is just to give you an idea of how to use phase changes in light for sensing parameters, in this case, we are sensing rotation. So, let us move on to one more type of sensor. Let us look at how polarization, the light polarization can be used to sense some physical parameter.

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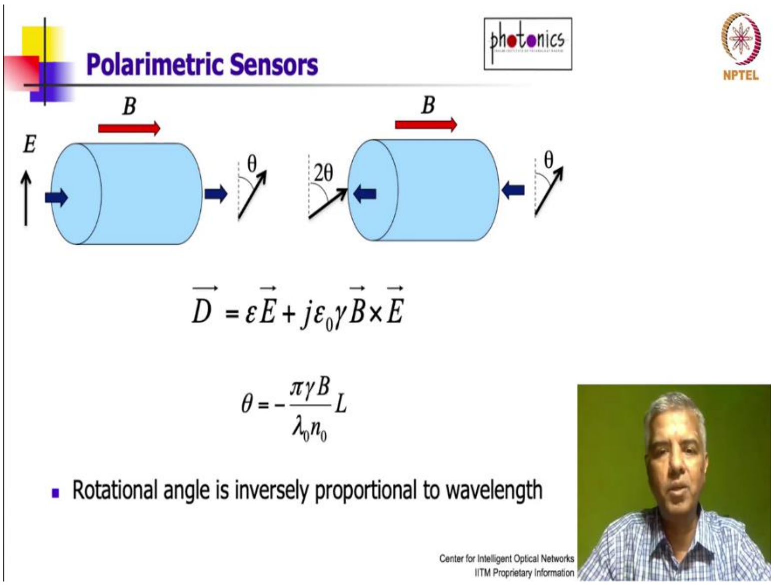


So, let us go into what are called polarimetric sensors. To explain this, I will have to explain something that is called the Faraday Effect. So, what is the Faraday Effect? Well, you can come in with light with a particular polarization linear polarization, let us say and it can go through this material which has, what is called a very relatively large magneto gyration coefficient. So, what does that mean?

In the presence of axial magnetic field, this material will deflect the light polarization, so it will deflect it through an angle and specific way it works is that the response to the incoming polarization is in the fact of epsilon E, which is the normal response to the permittivity and then it has this other component where you have curl of the magnetic flux density and the electric field intensity and that is through this mediated through this gamma, which is the magneto gyration coefficient.

So, some materials exhibit this stronger than other materials. So, but if you are using one of those materials, it will essentially take this incoming polarization and it will rotate it by an angle theta and theta can be quantified using this expression is essentially dependent on the magneto gyration coefficient multiplied by the magnitude of the magnetic flux density that you are applying as well as the length of this crystal. So, longer length means you can have larger amount of rotation.

The interesting part of this is it is a non-reciprocal effect. So, what do I mean by a non-reciprocal effect? Reciprocity refers to the case where if you flip the input and the output, you essentially get the same result. Meaning if I came in with this polarization and this is a reciprocal effect, it goes through a rotation data let us say, if I come back with this data, it will go back to the original polarization, so that will be a completely reciprocal effect.

Now, this Faraday Effect is actually not reciprocal, I can get an idea why it may not be reciprocal, because it is actually a vector multiplication of the B with the E field. So, when you are coming from the reverse direction, you are actually the imagine that the magnetic flux is actually against you. So, the sine of B changes, and correspondingly sine of theta also changes. So instead of going back to this original polarization, you will end up actually getting two times the rotation that you have over here. So, this is actually what is called the Faraday Effect.

And if you can make theta, for example 45 degrees, if you design this crystal, so that the theta equal to 45 degrees, you will see that the light that is coming in the reverse direction will go through a rotation of 90 degrees, meaning if you go in with vertical polarization, whatever is coming out is horizontal polarization. So, if you put a polarizer oriented vertically, you can extinguish that light. And that is actually the principle for optical isolators, so you will be able to extinguish back reflected light in optical isolators, because of this Faraday Effect. But we are planning to use this for a sensor. So, let us actually see how it can be used for a sensing application.

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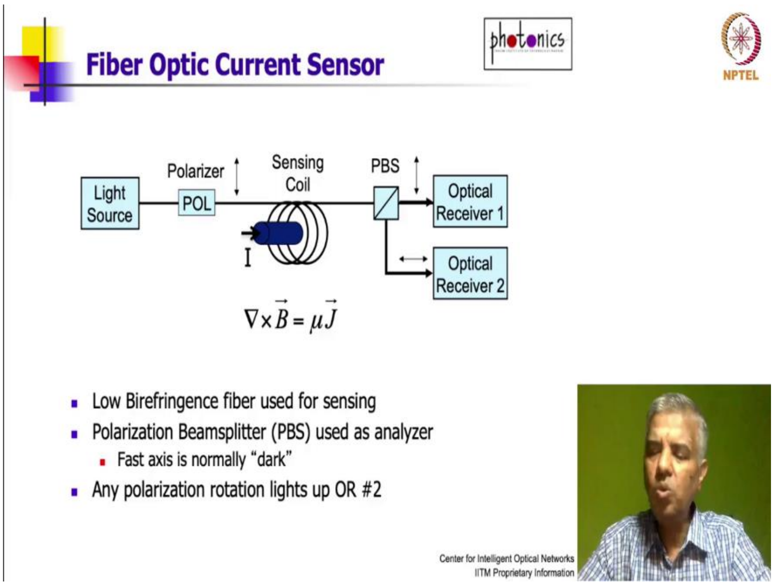


To see that, let us actually consider a light source and, and let it go through a polarizer so that what is coming out of the polarizer is actually vertically polarized, and then it goes through a certain length of fiber. And then what you have on the other side is actually a analyzer. Analyzer, it is basically, in this case is called a polarization beam splitter. So, it works such that it will allow the light in a vertically polarized light in this direction, and the horizontally polarized light will be deflected, this line should be actually the reverse diagonal. So, there is a small typo there. But nevertheless, it deflects, essentially, horizontal polarized light over here.

So, if you have, essentially, the polarization maintained in this fiber coil, then all the light would have ended up here, and there would not be any light in optical receiver 2. But that can change if you introduce a current carrying conductor through the axis of this coil, so what happens over here, when you have a current carrying wire that is inserted through the middle of this coil, we know that, Biot Savart law and Amperes law tells you that whenever there is a current going through this conductor, there is going to be concentric, generation of this magnetic flux around it. So, that magnetic flux now is oriented along the axis of the fiber.

And remember, the Faraday effect that we saw, just saw which means that if you have a magnetic flux along the axis of the fiber, and there is a certain polarization that is traveling in through the fiber. This, the presence of this magnetic flux will cause a deflection of the polarization. So, the output polarization will have a small component in that will essentially register itself an optical receiver 2.

So initially, without any current all the light is going over here, but with a certain amount of current, you will have a certain light intensity that is coming in this port, and if you increase the current through which you are increasing your magnetic flux density, then it will increase theta. Basically, that is what we saw over here. So, the theta is proportional to the magnetic flux density. So, with larger magnetic flux density, which is dependent on the current you have a larger data and hence you will essentially have more light in this port compared to this port.

And so, this could be used as, what is called a fiber optic current sensor. So, this is actually a very popular device, very popular device in the power industry to measure current with very high linearity, we are talking about the linearity in 0.1 amp when you are measuring something, the order of fraction of an amp to even kilo amps of current, it gives you a very, very linear response. So, that is the power of this, this particular technology. And, that is actually an example of a polarimetric sensor.

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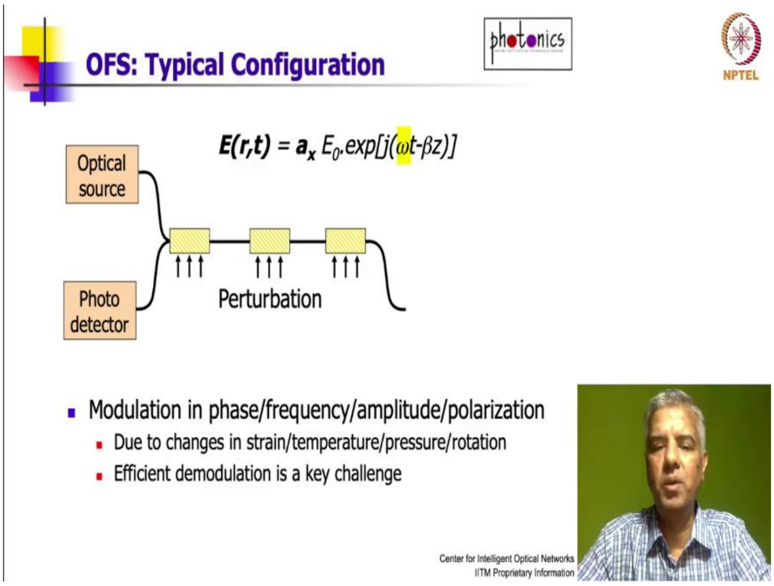


Now, let us move on to the last type of sensor that we want to talk about, which is a wavelength modulated sensor. So far, if you look at what we had been talking about, we talked about changes in amplitude, changes in phase, changes in polarization, now, it is time to consider changes in frequency. And I have highlighted this and for a good reason, frequency modulated sensors are going to be one of the most rugged sensors that you will find. Why do I say that?

Well, if you consider amplitude modulated sensor, just like this one, you can, if you are trying to pick up perturbation over here, let us say, it changes the amplitude of light, but before it reaches the photon detector that might get corrupted during this propagation, maybe it can get perturbed at some other point, and that is also changing the amplitude and so on. So, it can get corrupted, same thing you can say about the face or the polarization.

But, when you consider frequency modulation, once you have encoded the information that you want in frequency, there is very little that can corrupt that information. Meaning for example, if I take a light source, let us say a laser pointer, a green laser point, it is emitting at 532 nanometers, you measure across the room, and you measure as 532 nanometers. Now you shoot the same green laser to the moon, and you measure from the moon, what that wavelength is, and that wavelength will still be 532 nanometers.

Meaning, it is that information about, that the wavelength is not changing upon propagation over very long distances, it is not corrupted in the process of propagating over long distances. So, from that perspective, wavelength encoded sensors are quite different and they are quite rugged as well, then more impervious to noise, if you may want to call that. So, let us actually see how a wavelength encoded sensor would work.

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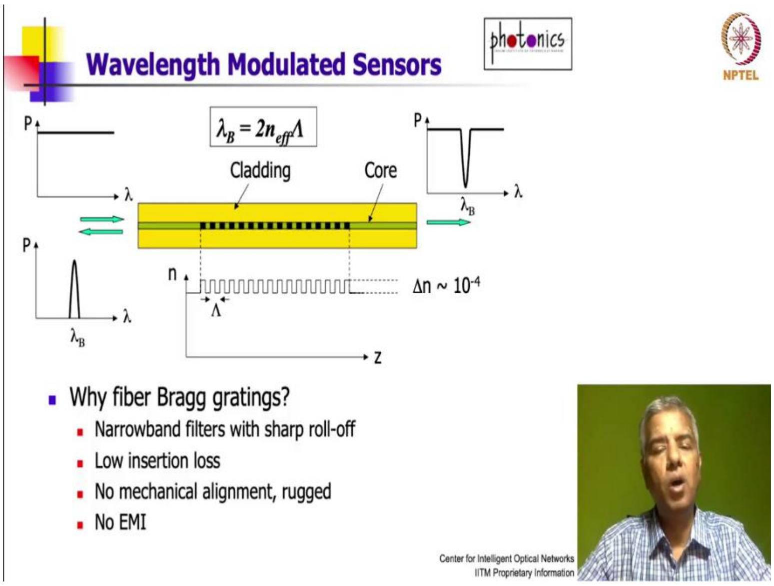


One example of a wavelength modulated sensor is, what we call a fiber Bragg grating. And what is a fiber bragg grating, we are looking at, say the core of the optical fiber, which is surrounded by the cladding, if you modify the refractive index of the core in a periodic manner, and that is what we are shown over here, let us say this direction is Z and this is the refractive index, the core of refractive index is normally unmodulated is like this, but if you manage to create a density variation like this, so that the refractive index is periodically change with a period capital lambda, then you can go back to Bragg diffraction theory.

And, what Bragg diffraction theory tells you is, this will coherently cause interference for in the, for light in the opposite direction. And that light, whose wavelength is lambda B is going to be reflected from this point. And lambda B is given by 2 times in effective which is the effective refractive index of the light that is propagating through this guide, multiplied by period. So, if you change the period, you can change the wavelength or the color at which it is reflected. So, let us just see what exactly happens. So, you can put in broadband light into this fiber into this fiber Bragg grating.

And then what you get at the output, you have one color missing, where did the missing color go? The missing color actually got reflected, so it got reflected and just that particular color which is defined by the Bragg wavelength, and just a little bit around that is what is going to be reflected. So, why are fiber Bragg gratings? It is all fiber device, so very low insertion laws, there is no alignment required and more importantly from a sensing perspective, there is negligible electromagnetic interference for this type of thing. So, how can this work like wavelength modulated sensor?

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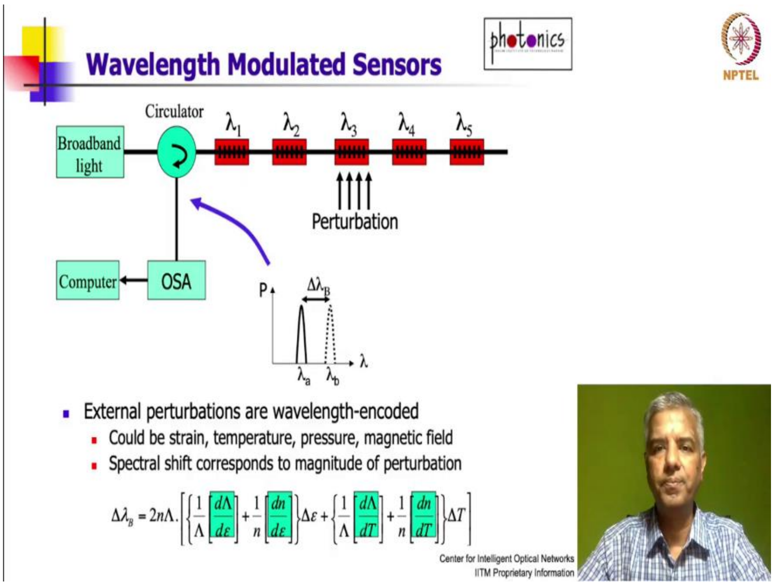


So, to understand this, let us consider this sort of schematic you have broadband light, which is going through this device called a circulator. Circulator essentially directs light from port 1 to port 2, but any light coming from port 2 would not go back to port 1, instead it will go to another port, which is port 3. So, when we have grating in this fiber, and broadband light goes and is incident on the grating, only one particular color of light is going to be picked that corresponds to a Bragg wavelength. And if you see what is coming over here, using an optical spectrum analyzer, you will see that the power is actually high at a particular wavelength compared to other wavelengths.

Now, how it works like a sensor is through this, if you subject this to some perturbation, let us say you are straining the fiber, if you are just pulling the fiber, then what happens is it will essentially change the period physically it will change the period, but it will also through what is called a strain optic effect change the refractive index of the fiber as well. So, both of these contribute to a change in the Bragg wavelength, so, the color is going to change and by carefully calibrating this change in color, you can basically solve the inverse problem which is saying, whenever there is whenever you see so much change in the in the Bragg wavelength, you say that, there must have been so much perturbation at this particular point.

And However, this is where it gets a little tricky, you will find that it is not just strain that can change the Bragg wavelength, even temperature can change that how, whenever you heat this grating, there is thermal expansion coefficient, which is increasing your period. And then there is actually what is called a thermo optic effect where it changes the refractive index also.

So, that is what is actually highlighted over here, this is a thermal expansion coefficient and the thermo optic coefficient, both of these also causes through the change in temperature, it causes a change in the Bragg wavelength, so whenever you see a change in Bragg wavelength, you do not know whether it is because of change in strain, or it is because of change in temperature. So, you need to be a little careful about that.

And these are, issues that we will talk about at a later point. But the key takeaway point is that this is actually a wavelength modulated sensor, because now we are looking at changes in wavelength to understand the strength of the perturbation. And the interesting thing is it can be extended to multiple positions are multiple regions of interest; you could concatenate multiple sensors.

And this is simply done by having slightly different period for all these Bragg gratings that are inscribed in this fiber. And so, each, each location corresponds to a slightly different color. This is like color coding that you want to, that you are accomplishing using this this is like color coding of a male or say that Dabbawalla's, they are not, they are quite famous for the way they handle all the dabbas is by color coding them and making sure that different colors are corresponding to different destinations and they do a very efficient job of sorting it out.

So similar to that, you have color coding of all these locations. So, if you see some Bragg wavelength change around, let us say green color, then that green is the color of the reflecting reflection at this particular point. So, that the perturbation would correspond to this. Whereas, if you encoded this location with red color, any change around the red color can be attributed to perturbation in this location and so on. So, you can actually have what is called a quasi-distributed sensing that you can accomplish, in this case using wavelength correlated sensors.