Optical Fiber Sensors
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Lecture 21
Phase Modulated Sensors - I

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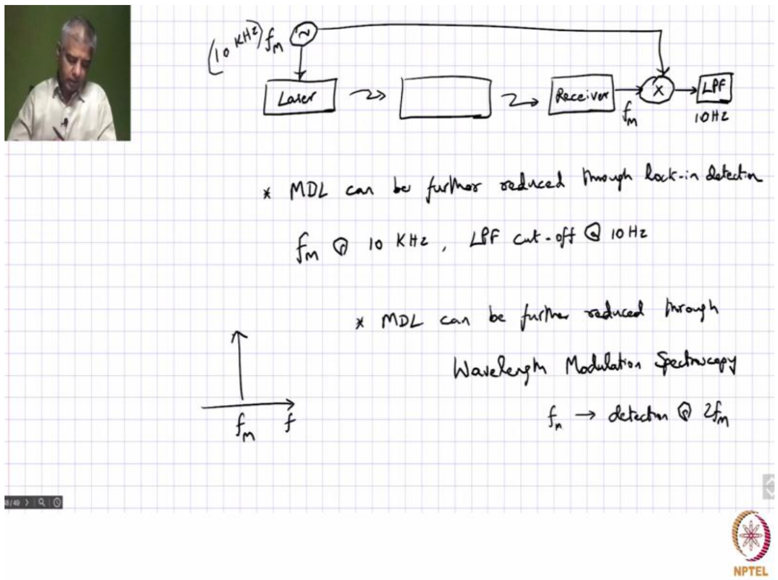

Hello, everyone, in our last lecture, we looked at an example of performing Gas spectroscopy on an extracted sample.

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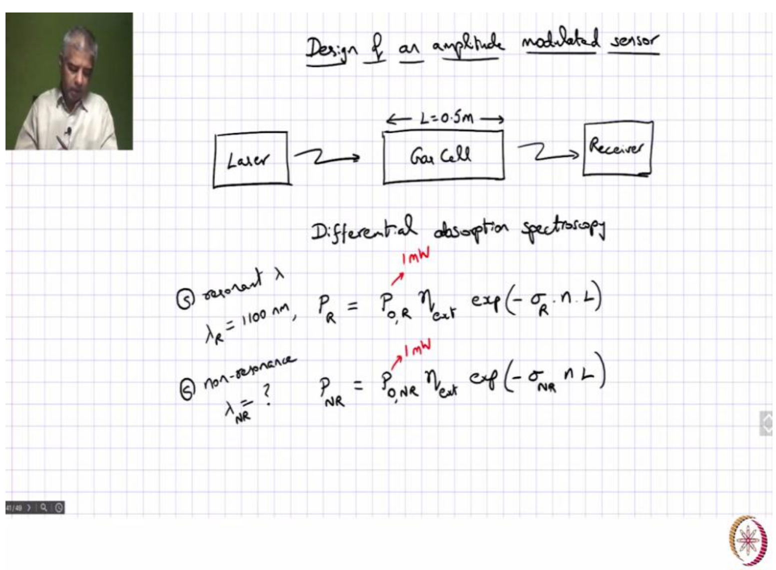

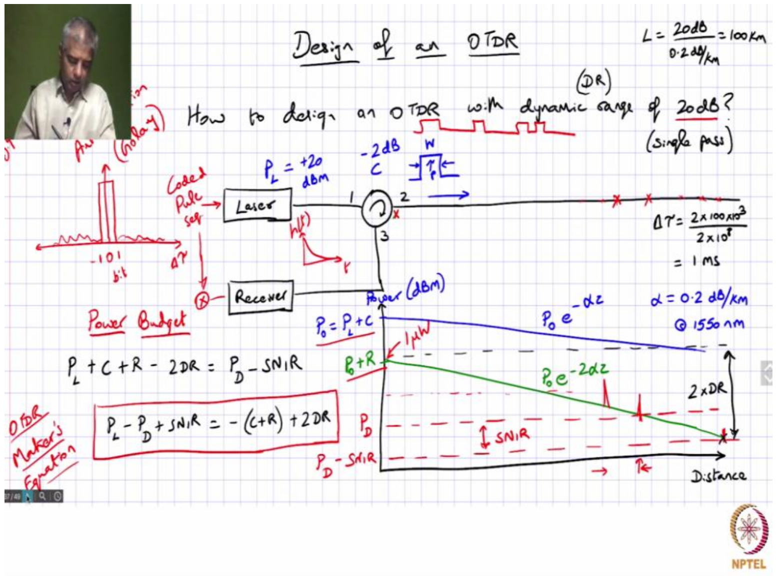

So we were considering the case of doing spectroscopy on an on a gas cell and which consists of nitric oxide. And we were trying to pick up the minimum detectable, detectable limit as far as nitric oxide is concerned. And, of course, if you want to extend this to long distances, we could potentially marry this concept with the OTDR concepts that we discussed previously, we can actually send the light over long distances, the optical fiber and find a way of interacting with the gas.

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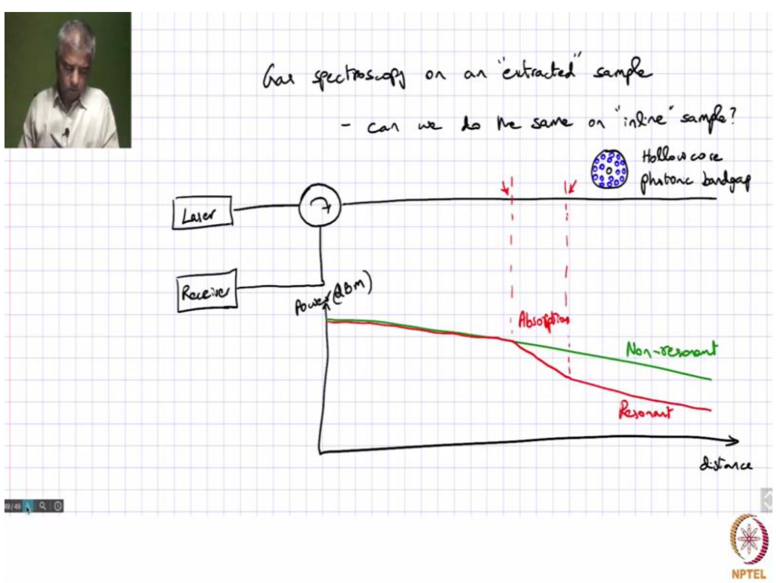

So, for example, we can possibly do something like this. So far, we have been looking at an extracted sample. So we looked at the case example of gas spectroscopy on an extracted sample, but the question is, can we do the same on an inline sample. And let us say, we want to actually do this over a long distance, let us say along the oil or gas pipeline, and we want to actually look at if there is any gas that is leaking from a pipeline. So, you want to do this all along the length of the pipeline. So what we saw previously was, if you wanted to do that, you could possibly use OTDR principles.

So we saw that we could take a laser, send the light through a circulator, and then send it through a long length of fiber. And whatever backscattered light is, whatever backscatter light there is, we can actually capture it using an optical receiver. And we can, from looking at this backscattered light as a function of time. We said we could possibly figure out if there is any absorption that is happening.

Let us say, over this region, there is some absorption happening, corresponding to, let us say, nitric oxide, of course, there is a question as to how can you have absorption events detected using optical fiber. Now, normally we talk about optical fiber we talk about the fiber with the core and a cladding and core has a higher refractive index than the cladding. But recently, there is been a lot of interest in what are called Hollow Core Photonic Bandgap Fibers.

So, these are Hollow Core Photonic Bandgap Fibers. So, essentially, you have a periodic arrangement of holes in the cladding region of the fiber. So, because of that, it actually helps to confine light in the center part which is actually, which could potentially be a hollow core itself. And so, you could, you could possibly have some way of letting the, the gas come in, so you have gas percolating inside the core of the fiber.

And then if you send the appropriate radiation you could actually see absorption. So, what we are talking about is if we look at the backscattered light power as a function of distance, if you send light at some background wavelength, then you would just have this linear line especially if you are expressing power in terms of let us say a log scale. So, what we saw previously was we could actually have this linear line, but if you change the wavelength, you could potentially capture this absorption at a resonant wavelength what we saw was correspond to 1.1 micron.

At the resonant wavelength, you could you will probably have something that looks like this, at this point, up to this point this losses background losses will be the same, but at this point, it will take a different slope because of the extra absorption that is happening within this region and then it will go parallel with the other line. So, based on that, you can actually figure out what is the concentration of nitric oxide within that particular region.

Now, of course, we know using OTDR principles, we could potentially get spatial resolution of meter and this can be available across even 10 kilometers sort of distance. So, essentially we can say that, we can roll the fiber out and we can actually figure out what are the constituent gases in that environment by doing the corresponding spectroscopy and married with this Optical Time Domain Reflectometry principle.

So, a lot of exciting possibilities when you consider such amplitude modulated sensors. So, I wanted to just give you just a background. So, this is just to make sure we are clear about this, this is the non-resonant reference wavelength and this is your resonant wavelength. And you can accomplish this gas spectroscopy using this Optical Time Domain Reflectometer principle.

So, far we have been looking at amplitude modulated sensors. So, I think we covered enough about that there are of course, like I said several other examples of amplitude modulators sensors, but then you will typically have the same issues. So, you looking at changes in amplitude the challenges that you typically face like there are some background changes and you also have noise as a very important aspect of your detection. So, how do you pick out the amplitude modulated signal which consists of whatever measurement you want to do in the presence of noise.

So, we talked about averaging, filtering, locking detection and when it comes to gas spectroscopy, absorption spectroscopy, we also talked about doing that with either differential absorption measurements or wavelength modulation spectroscopy also. So, there could be a variety of these tools that you could use for any given application and try to meet the requirement. So, now, let us actually move on to something else. Let us actually move on to what are called the different class of sensors, optical sensors.

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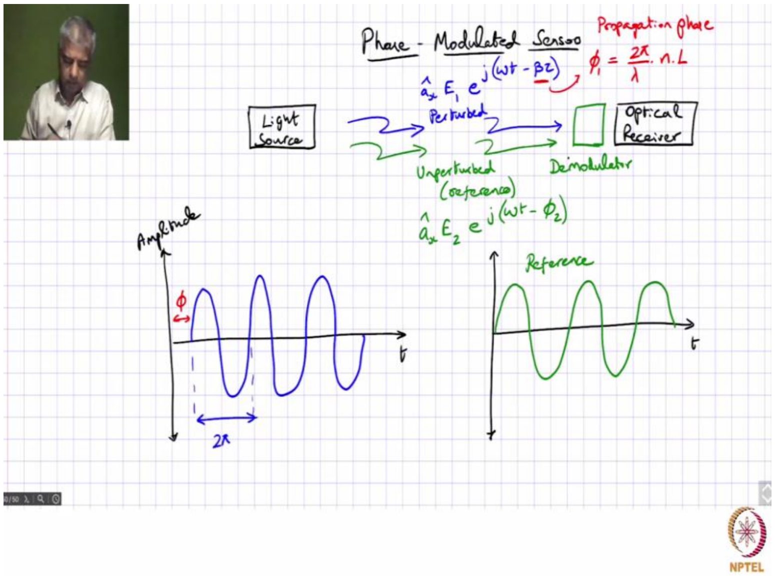

Phase modulated sensing sensors. So, how do you use the principle of phase modulation due to external perturbations, and how do you sense those perturbations? So that is what we are looking at. Now, when we talk about phase, what we are, let us just go back to our original picture. So you have this light source, that is generating some, some light, which can be expressed in terms of its polarization, let us say it is propagating along z direction and it is got a polarized component along the x direction.

Let us say E1 e power j omega t minus beta z, that is what is showing up in the phase term. So that that characterizes this wave, which we may model as a plane wave that is that is propagating along the z direction. Now, when we talk about phase, we are talking about this e power j whatever term. And, and of course, that has got two components; one is omega t, which corresponds to the phase evolution with respect to time meaning, you can just sit at one particular location and you can keep observing this wave.

And the wave will actually go through this phase shift with respect to time and so, it will go through its positive and negative cycles correspondingly. So, that is one thing, but that does not typically convey much information, we will look at, it will probably convey some information when we actually look at it as frequency modulators sensors, which is the other class of sensors that we will look at, at a later point.

But, when we talk about phase modulated sensors, we are primarily interested in this component, this beta z component, which we can actually represent by phase phi which is given by 2 phi over lambda multiplied by the refractive index multiplied by over a certain length propagation over z, let us call this length as L. So, phase is the propagation. So, this is we have to be, we want to be clear, this is the propagation phase and that is typically what is what we are interested in what is the modulation in the propagation phase because of certain perturbations that may be happening in this medium.

And when it comes to actually detecting this phase, there are certain challenges, well, what are those challenges? Well, if you look at your conventional optical receiver, which is considered of a semiconductor photodiode with all the other electronics around it, that photodiode is not sensitive to phase changes, it is only sensitive to intensity changes or amplitude changes. So, that is actually a serious issue.

So, so what we need is, we need to have another box over here which we call as a demodulator. And what does the demodulator do? The demodulator converts phase changes into amplitude changes. So, what exactly are we talking about? Let us actually do a pictorial representation of this. So, typically, let us say we are looking at it as a function of time, the amplitude of this wave that is going to the receiver, then we say that there is actually a sinusoidal waveform that is incident on the photodiode.

Now, of course, we know that for this wave over just this one cycle, what is the phase change that you incur? That corresponds to 2 pi. But the phase that we are interested in is possibly this phase change that has happened due to propagation. So then the question is, how do I pick up this phase change? And how do I do the demodulation? Well to do the demodulation, what you probably have to do one of the common ways of doing the demodulation is to take another wave.

Hopefully at the same frequency and so that you call us your reference. So you are talking about another wave, possibly from the same light source itself but it is not, let us say, it is unperturbed. So this is actually unperturbed. whereas here we are talking about this perturbed light source. So this unperturbed light source is what you call us a reference. So, if you have an unperturbed reference, that has not actually gone through this phase modulation, that perturbed wave is actually going through.

Then, of course, you can possibly get, convert this phase modulation to intensity modulation. So we will look into that a little more detail. But before we get to that, let us just say, let us just make sure we are representing all our waves correctly, mathematically. So let us say this unperturbed wave is also the same polarization, maybe a different amplitude and same frequency. And, but it is actually going through some other phase phi 2. That is actually the reference phase. So, so what will happen? At how do we do the phase demodulation? So let us look at that aspect.

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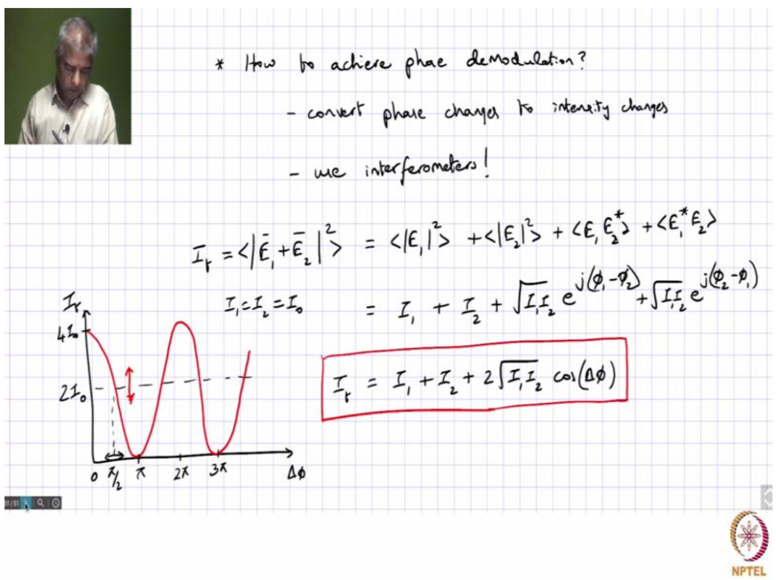

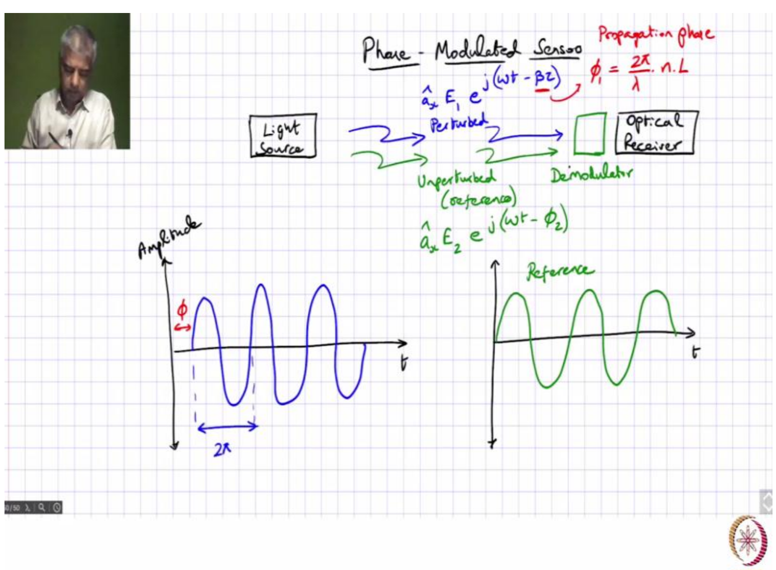

So, the question is, how to achieve phase demodulation? So let us look at that. Well, essentially, what do we mean by phase demodulation, it is such that whatever phase changes we wanted to detect, we are converting to intensity modulation. So, what we are trying to do is convert phase changes to intensity changes. So that is what we are trying to do. And what is a good way of doing it? Well, one of the common ways of doing it as far as optics is concerned, is actually use interferometers.

So that is actually a very nice way of converting phase changes to intensity changes. So let us actually go into specifics of interferometers and then see how, so what are the typical issues when you are trying to build an interferometer and what are you limited by in terms of picking up the phase changes. But before we do that, let us actually look at the meeting of these 2 waves. So, let us just say you are looking at the meeting of these 2 waves at the detector.

So you are actually having a certain intensity at the receiver which corresponds to the fields of the both, both these waves the that is the perturbed wave when the unperturbed reference wave, let us actually say that we are actually looking at them as their phasers basically. So, what do I mean by a phaser, I can actually represent this wave as I can drop the polarization and, and also the frequency dependence and I can just call this e power j phi 1 and similarly, I can refer to this e power j phi 2.

Of course, we said it is a negative value and all that, let us not pay attention to the actual sign and all that but, let us say they are 2 different waves represented by their phasers. So, it is actually a phaser addition that we are looking at and the intensity corresponds to mod of that in square and it is typically a time averaged detection that we are doing. So, that so, if you expand that out, you basically say that this corresponds to E1 square E2 square time average plus you have E1 E2 conjugate time average of that plus E1 conjugate E2. So, those are the beating of the of the 2 waves.

Now, of course, this by definition would correspond to I1 and this by definition would correspond to I2 and you have the magnitudes fall out E1 in E2, so, E1 magnitude will be root I1, E2 will be root I2. So, you have root of I1, I2 and then the conjugate of the complex quantities the especially the phase, so, this will be e power j phi 1 minus phi 2 plus root I1 I2 e power j phi 2 minus phi 1. And of course, we can take the root as common and basically when you, this is like e power j theta plus e power minus j theta.

So, then we know it corresponds to 2 times cos of theta. So, we can just write this out as I1 plus I2 plus 2 root I1 I2 then cos of delta phi, delta phi corresponds to phi 1 minus phi 2. So, that is the total intensity that you get at the after mixing these 2 waves. So, that is that is the process that we call as interference. So, if we say phi 2 is deterministic, so, phi 2 is the reference. So, if you have somehow figured out a way of preserving your reference and not actually expose it to the external perturbation, then phi 2 is constant is deterministic whereas phi1 now is going to be changing with respect to any perturbations that it experiences.

So, by we know everything else, we know I1, we know I2 and so on. And then we know phi 2 and then the remaining part is phi 1, and so, any change in phi 1 is going to cause a change in the total intensity. So, you are essentially demodulated this, this wave the phase changes converted to intensity changes. Now, let us look at some specific examples and see how this is accomplished. Now, of course, let us let us actually look at this, before we do that, let us actually look at this function how it is going to look.

So if you are plotting the total intensity as a function of delta phi, let us actually consider the case where I1 equal to I2 equal to I naught, some constant value, then what we are going to have here is 2 times I naught, and then it is a cosine function, it is going to go through some maximum and then some minimum and so on. So, what is the maximum value correspond to that is when delta phi equal to 0.

So that will be basically, if it is I1 equal to I2 equal to I naught, then that will correspond to four times I naught. And minimum value would correspond to a delta phi equals to pi, in which case this is minus so you basically have 2 I naught, this is going to be minus 2 I naught and this is 2 I naught, so it is going to perfectly cancel, it is pi and then it is going to be maximum goes to 4 pi, when it is 2 pi and then 3 by and all that. So that is what we expect as far as this interferometer is concerned.

And this is important so if you want to make sensitive, device, you want to make a very high sensitivity optical sensor, then you may want to bias it at a point like this, where this is pi by 2, it is typically what is called the Quadrature point. Why? Because any small change in phase around here will correspond to a large change in terms of intensity, so it is most sensitive over there.

So, if you bias around here, and then you do your measurement, then so, how do you bias well, the references in, is under your control. So, you could possibly change the reference phase a little bit you can do some phase shift and make sure that to start with before the perturbation happens, you have you have an intensity at the middle point and then from there on, if any changes in the due to the perturbation will give a corresponding change in intensity.

So that is actually one of the key aspects of building a phase modulated sensor. So, now, let us look at a very specific example of this. And for a minute, I told you that we typically do the demodulation in an interferometer, we did not in the previous example, we did not actually mentioned anything about what is the optical structure that gives us the total wave. So let us actually look at that optical structure.

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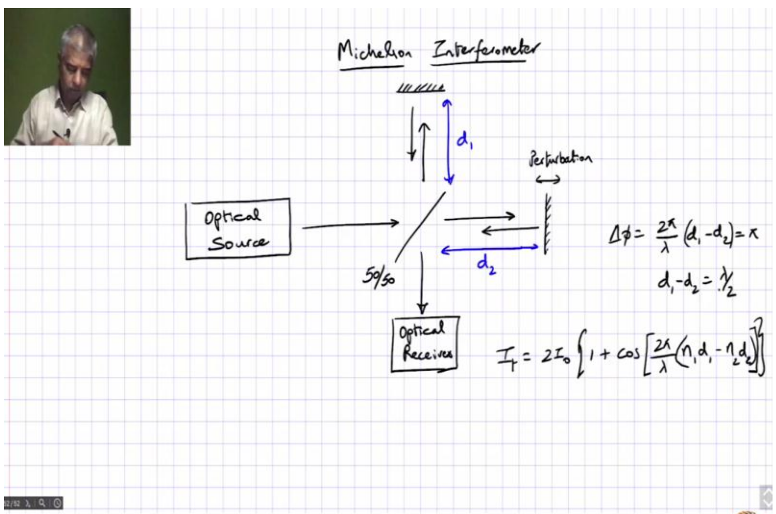

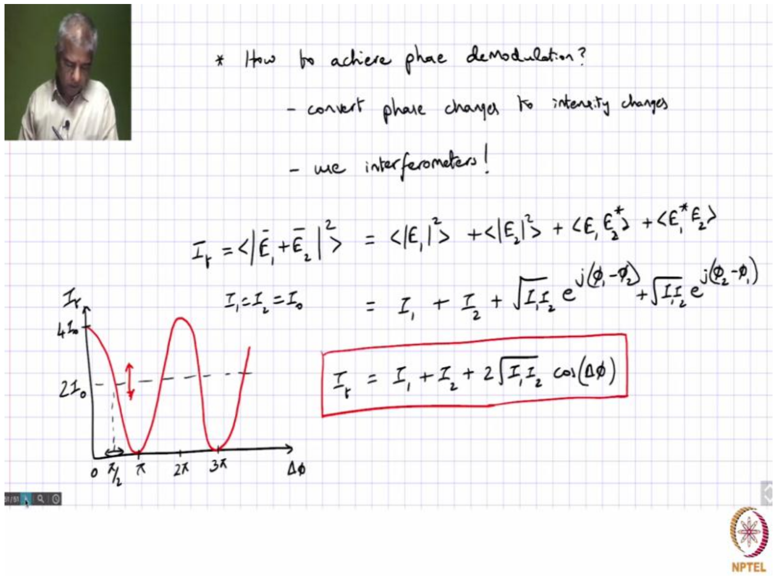

So one example of that is Michelson interferometer. So, what does the Michelson interferometer consists of? Well, you will have an optical source that goes off and then you have a beam splitter that sense part of the light in this direction and the other part actually goes in this direction. Let us say you have you put a mirror over here and then you put another mirror over here, that just bounces the light back in the same path.

So, the mirror will bounce it back like this. And they both will come together. Of course, part of the light will go this way, but we are not interested in that, we, let us say we are looking at this light. So, this we put it through to an optical receiver. And let us say the path length over here, this corresponds to d1 and path length here corresponds to d2, so let us say that is the round trip path length, so that correspond to d1 and d2.

And then in this case, if we were to write the total intensity expression for the total intensity, you will go as It equals let us just say this is actually a 50-50 splitter that means that 50 percent of the light is going this way, 50 percent of the light is going this way, then if you look at the total intensity over here, that will correspond to 2 times I naught 1 plus cos of 2 pi over lambda multiplied by n, where n is actually the refractive index.

So, in general, you can actually write it as n1 could be the refractive index in path 1 multiplied by d1 and minus n2 multiplied by d2. So, you can essentially what we are checking here is the intensity changes due to changes in the path length, the optical path length, even if there is a change in the refractive index that will actually give rise to changes in the intensity over here. So, that is the typical output that we expect.

So, for example, one simple example is if the mirror is sort of like jittering around, if this is moving around like this, let us say this is actually the reference path. So, you have kept it rock solid, it is not perturbed, but this is actually going through some perturbation, maybe some vibration of the mirror, then that will change d2 let us say n1 and n2 are equal to 1 it corresponds to a path length or path medium that we can consider as air and then if you changing d2, any small changes in the perturbation will give a corresponding change in the optical receiver.

So, how sensitive is that well, we can say that we are picking up changes, if it goes over pi, if delta phi equals 2 pi, so we are talking about delta phi equal to 2 pi over lambda n1, well we said we will consider this as air. So, n1 equal to n2 equal to n, so, let us just drop that. So, d1 minus d2 equals to pi. So, if you are looking at pi phase shifts so d1 minus d2 will correspond to lambda by 2.

So, if d1is fixed and d2 is equal to d1 initially and at that condition even if you move by lambda by 2, the lambda that we are using typically is in the order of a micron. So, now, even if it moves by half a micron, you have a huge change in the intensity from maximum to minimum. So, this is actually a highly, highly sensitive way of picking up changes in the location. So, even if it is submicron changes, you can actually pick it up nicely. So, let us actually look at the details later.