Optical Fiber Sensors
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Lecture 32
Wavelength modulated sensors - 1

We have been looking at different phase modulated sensor examples. We started with optical coherence tomography and then went on to design hydrophone and then lately we have been looking at the design of a fiber optic gyroscope. So, all these examples that we have discussed so far, we are typically picking up information, face information, from one particular location.

So, the question is ‘can we possibly extend phase measurements to a distributed area or maybe over several locations if whether that is possible’. So, let us quickly look at that before we go on to talking about wavelength modulated sensors.

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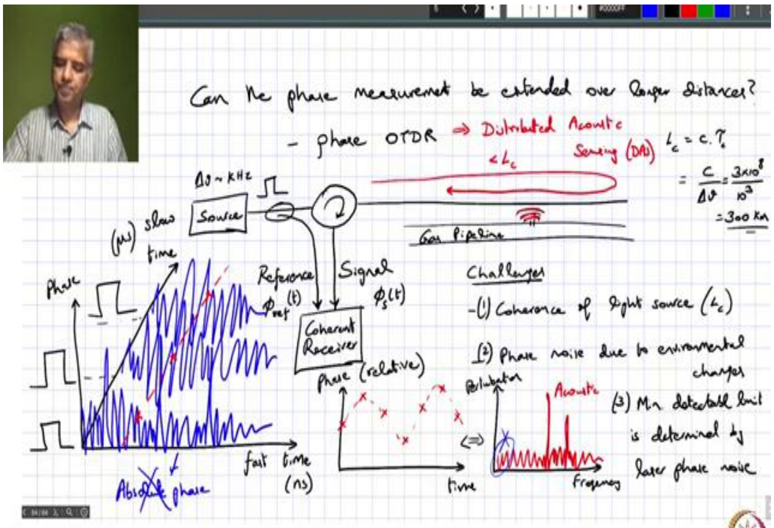

Can the phase measurement be extended over longer distances?

- phase OTDR ⇒ Distributed Acoustic Sensing (DAS)

$L_c = c \cdot \tau_c = \frac{c}{\Delta\nu} = \frac{3\times10^8}{10^3} = 300\text{ km}$

Challenges

-(1) Coherence of light source (L_c)

(2) Phase noise due to environmental changes

(3) Min detectable limit is determined by laser phase noise

So, the question that we are asking is can the phase measurement be extended over longer distances. So, that is the question that we are asking. And the answer for that is – Yes. And how do we do that? Well, we could possibly do that by marrying some of the principles that we talked about, the phase detection principles, with the optical time domain reflectometry.

So, you could possibly do such measurements using what is called a phase optical time domain reflectometer and, so then that is possibly a way of picking up perturbations over much longer distances. So typical examples are, say, for example, you have a oil gas pipeline and you want to find out if there is a leak in this oil or gas pipeline, you can possibly detect that by detecting the acoustics.

When that happen, whenever there is a leak, for example, if you are trying to send gas from one point to another point, if you are trying to transport through a gas pipeline you would want to do that in a highly pressurized manner, typically the pressures could be in the order of tens of bar and in that sort of pressure when gas is sent, if there is a leak in the pipeline because of some defect or some crack that has happened or somebody is intruded and inadvertently created a crack on the pipe, then the gas when it comes out with such high pressure, it is going to make a lot of noise, typically it is at a particular frequency.

So, if you have say an optical fiber installed all along the length of that pipeline, so we are talking about we take a source, typically a narrow line with source, you send it through a circulator over this long length of fiber, which is laid along this gas pipeline. If there is any leak, let us say in this pipeline that is running along this fiber, if there is a leak over here, then there are going to be some acoustic waves that are emitted from that leak point.

And those acoustic waves can happen along anywhere, along the length of the fiber, the length of the gas pipeline could be in the order of tens of kilometres, so this anywhere along that length you should be able to pick up these acoustic waves. So, when this leak happens, its incident on the fiber and those pressure waves essentially cause change in the face of the light, basically the pressure introduces some strain on the fiber and through the strain optic coefficient, for example, it can change the phase of light propagating through the fiber.

So, if you are looking at the back scattered light, which is typically the Rayleigh back scattered light, then you can use a receiver to pick up that light, but typically what we saw in this example of optical time domain reflectometer, the receiver can pick up only changes in the intensity of light. Here we are talking about changes in the face because of this leak that has happened in this gas pipeline.

And of course, a normal receiver is not sensitive to face that is what we have been seeing for several lectures now. So, what do you need to measure face? You need a reference. And where is that reference going to come from? Well, one possible thing that you could do is to tap this light from the source itself and use that as a reference. So this actually is the signal arm, this is the signal which carries this phase information phi s of t, but if you have a reference phase, then you could beat these two signals and then these two waves.

And you know that the beat is going to be proportional to the cosine of phi ref minus phi of phi s. So, then you could convert that to intensity changes and you can pick that up using your optical receiver, so such receivers where you have a reference also coming in and beating in the receiver is called a coherent receiver. So far we have been looking at what is called direct detection, which is only looking at changes in intensity.

But if you use a coherent receiver, you can basically pick up changes in phase. So, this is what we call as a face OTDR and as usual what whatever we have done before that is the same thing that we are going to do, we are going to send a pulse of light and then we are going to try to, even as it is propagating down the fiber, it is going to backscatter some of the, some of that light due to Rayleigh back scattering as we saw before.

And then previously we were looking at the strength of that back scattered light, but now we are looking at the face of that back scattered light and so that is what this phase OTDR or a coherent OTDR is going to do. Now, of course, there are several challenges when you do, when you try to accomplish something like this. So, if you were to look at the common challenges involved in this, one of those challenges is the coherence of a light source.

So, what do I mean by that? So, if these two have to beat and you have to extract the face; then you need to basically have the signal to be coherent with respect to the reference and that is actually, that means your source has to be highly temporally coherent. Why? Because the source would have to go all the way down, maybe i can use a different color, so the source would have to go all the way down and then get back reflected and it has to reach the receiver

So your source after it reaches the, after it comes through that is round trip, it should still be coherent with respect to this. So the round trip length now has to be less than the coherence length of the laser. So that is what we are talking about. We need to have, if you want to extend this to say 10 kilometers, then you need to make sure that your source has a coherence length greater than 10 kilometers, then only you could have you know a coherent beating of these two waves.

So that is a limitation in terms of the distance that you can go, you are going to be able to look at a very high coherence source, which means it is very low spectral width, we know that Lc with corresponds c into tau c and tau c is inversely proportional to delta nu, the spectral width of the source, so if you say the spectral width is say one kilohertz, then this is basically 3 into 10 power 8 divided by 10 power 3.

And that would mean this is about 300, 3 into 10 power 5. So, that is basically 300 kilometer. So you need something, if you want to support this detection over tens of kilometers you need to have a spectral width, so this delta nu should be in the order of kilohertz. So you need a highly coherent light source. So that is one key challenge is finding a source, which can provide such narrow line width.

Then there is of course another significant challenge, which is phase noise due to environmental changes. So, what are we talking about? Well, we already discussed that previously in the context of some of the other sensors, especially when we were talking about the hydrophone, we said the environmental changes can throw the phase away or make the phase fluctuate widely over several 0 to 2 pi or even higher than that.

So, that will cause a serious problem. In fact, when we look at the signal that we are picking up, if you are picking up the, we are trying to get the phase as a function of time as, that is what you normally get as far as the phase OTDR is concerned. The phase is going to be highly, of course, it is going to keep increasing as a function of time because just by propagation it is going to accumulate phase.

But let us say we have a way of correcting for that, but even if you correct for the propagation phase, if you look at the perturbation phase or the phase changes due to perturbation, those phase changes are going to be widely fluctuating with respect to time. So, maybe I can just draw this a little better, so let us say you have all these fluctuations. And so with respect to time and that time corresponds to the propagation time in that fiber.

So, if you are trying to pick up any phase change in an absolute sense that is going to be extremely difficult. So, we are talking about measuring this time in the order of tens of nanoseconds typically, your pulse width could be let us say 10 nanoseconds to support a spatial resolution of one meter and if that is the case, then you are talking about tens, hundreds of nanoseconds, probably you are picking up this information and then it is going to be wildly fluctuating.

So, how can we do a measurement in this sort of environment? Well, you could possibly, one thing you can do is this is what you get for, say one pulse that has launched into the fiber, but let us say after that subsequently you launch another pulse, you wait for all these signals to come back from the farthest end of the fiber and then you launch the next pulse and corresponding to the next pulse you might have once again this while fluctuations here and and and so on and then you launch another pulse.

So corresponding to this next pulse here, let us say this is happening here and this is happening over here, once again you get to see a lot of fluctuations and all of that. So, in real time it does not seem to make much sense, but if you start picking up, let us say at one location, if you start picking up the face, so over here it is this point over here and this point over here and this point over here and then you actually plot that.

So, this is also happening over time, but this is relatively slow time, so this is something the order of microseconds as supposed to this axis which we call as fast time. Fast time is what the response you get for one particular pulse, but slow time is where you are looking at the response over much longer time scale. If you look at that, that might actually convey a slightly different picture.

Especially, if you look at this phase as a function of time, so you might start seeing something that is, suppose if the perturbation, let us say is, this perturbation over here is some acoustic wave at a particular frequency, then you might see some, it will still be noisy, but you might start seeing something that that looks like a waveform, and especially, if you are looking at this in the frequency domain.

So, if you, this is in the time domain, but if you take a periodogram or a Fourier transform and you look at the frequency domain, so this is actually the magnitude of perturbation as a function of frequency, then the corresponding frequency spectrum maybe like this, but maybe that will show some peaks around there, so the most, there will be a lot of noise for sure, but then you might start seeing some peaks over here.

And these peaks would correspond to the acoustics that we are trying to pick up over here. So, essentially, what we are saying is this entire arrangement, because we are picking up these acoustic frequencies in a distributed manner, this type of detection is called distributed acoustic sensing, so, or in short DAS, which is actually becoming very-very important for a lot of applications, not just for these, protecting your oil gas pipelines.

People talk about using this for protecting your border, suppose if you are at the border area and you want to actually keep track of infiltrations, you essentially bury the fiber across the border and whenever somebody walks over there they impart some pressure waves on the ground and that could be actually transferred to the optical fiber. So you could be sitting at a several kilometers away, but you can still hear all these acoustics.

Thanks to this sort of a technology. So, it is a very powerful technology and that is once again another example of a phase modulated sensor. Now you may want to ask the question, so what is the fundamental limitation in doing something like this? So, we talked about the coherence and then the phase noise due to environmental changes, but finally it is the minimum detectable limit is determined by what, by the laser phase noise itself.

Because if the laser itself has a certain level of face noise, then every time you launch this pulse and you wait for this thing to come back, during that time this reference is not stable, that reference is going to be changing as a function of time if the laser itself has a certain face noise. So, that laser phase noise is going to eventually determine, what is the minimum signal that you are going to be able to pick up, the minimum amplitude of this acoustic wave that you are going to be able to pick up?

So, that is actually a key limitation as far as the fundamental limitation as far as phase OTDR is concerned, but nevertheless it is extremely good technology to pick up relative face, so what we are talking about is, this is actually relative phase, you are not trying to pick up absolute face, so it is not very good for absolute phase changes, but if you want to just look at relative phase changes, which mean that you re picking up only the frequency at which this perturbations are happening.

You are not looking at how much strain has it imparted, what is the magnitude of strain, you are interested in more of what is the frequency of the change in strain that you are experiencing, the acoustics. So once again the other way of saying that is around the DC over here it is very noisy, so you cannot pick that up, but if you are going to, say tens of hertz or 100 hertz and so on, in those areas you may be able to pick up reasonably well.

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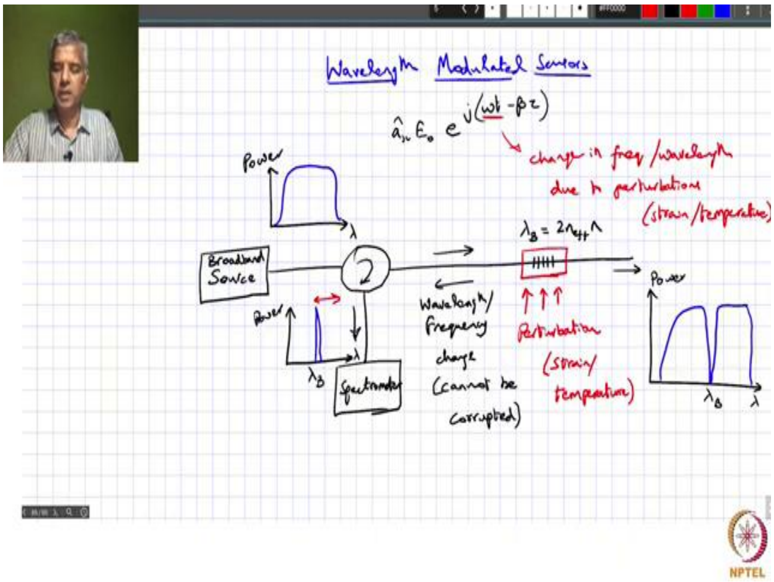

Now, let us switch tracks and let us start looking at wavelength modulated sensors. So, what do we mean by wavelength modulated sensors? So far we have looked at examples of amplitude or intensity modulated sensors where whatever we are trying to measure is actually changes in that quantity is showing up as in change in the intensity of light that we are picking up, that is what we looked at initially.

And the last few weeks we have been looking at the perturbation that we are trying to pick up, how it is encoded in phase that is what we are looking at as far as phase modulated sensor is concerned. Now, what we want to look at is what if the perturbation that you are trying to pick up is encoded in the wavelength or frequency of the light? So, we know that we were talking about light as an electromagnetic wave, has got a certain polarization, certain amplitude and then when we, you have…

So far we have been looking at the propagation phase, but what if this frequency itself is changing because of the perturbation. So, we will look at change in frequency or wavelength due to perturbations, perturbations that we want to measure. So, these are like strain or temperature at a particular point that we want to actually pick up. So, let us see how how this would work in a fiber optic sensor configuration.

And before we go to that, I do want to emphasize something that I had mentioned several weeks ago as to what is the speciality of a wavelength modulated sensor. Whatever we had been looking at this change in intensity or change in phase or we will be looking at change in polarization also, the perturbation happens at a particular point and by the time this signal actually reaches the receiver there is lot of possibility of it getting corrupted by unwanted interferences, unwanted perturbations if you may.

So, you may not actually be able to get the real sense of the measurant that you are trying to pick up. Whereas, if you have encoded this information, the perturbation information in frequency or wavelength, then in a linear medium there is nothing that changes that measureant, basically there is nothing that changes the frequency or wavelength characteristic of the light that is coming back.

So, what are we talking about? Let us just see this in a fiber optic form, so let us say you have a source, and let us say you launched into this sensing fiber, some long length of sensing fiber. If it is subjected to some perturbation, if it is subjected to some perturbation, if that perturbation creates a change in the color of light that we are sending, so this is, basically it goes in and then when the light actually comes back, there is a change in the color of light according to the level of perturbation.

If there is something like that then the back reflected light you can pick up using a receiver, but your normal optical receiver is color blind, like if you take indium gallium arsenide, it is actually sensitive for a wide range of wavelengths from say 0.7 to 0.8 microns all the way up to about 1.6 microns, if you have some signal that you are picking up using the receiver, you cannot tell whether it is because of 0.8 micron or 1.6 micron or anything in between.

Because it just gives you a photo current irrespective of whatever wavelength is incident on the photodiode, so it is in that sense colorblind. So, what you are going to have to do if you want to pick up changes in color? So, what we are talking about is this, due to this perturbation you have change in wavelength or frequency, if you want to pick that up, then you want to use a spectrometer over here.

So, not just a regular detector, but a detector that can detect based on a discrimination of the color of light, so that is what we need. And the nice part about this is once the perturbation happens and then it changes this wavelength of frequency, then this cannot be corrupted, so this cannot be corrupted by any of the normal noise sources, like you can basically stamp on the fiber, you can bend the fiber, twist the fiber, whatever you do, whatever perturbations you do, you can change the intensity of light, you can change the phase of light, but you cannot change the frequency of light that is coming back.

So, that is essentially what we are trying to pick up. Now, this we will do using, so there are different optical phenomena that can provide such changes in wavelength of frequency, so we will probably look at a couple of examples of that. One, very popular example is what is called a fiber Bragg rating. So, what is the fiber Bragg rating? Well, its, if you have a periodic change in the refractive index of the optical fiber, then that will typically reflect one particular color of light.

So, this will reflect, so if you have broadband light source going in, it will actually reflect a one particular color of light and the remaining colors will go through. So, essentially, if you are looking at the light spectrum over here, so this is actually, let us say it is a broadband source, so when you look at the power as a function of wavelength, it might look like this that is what you are sending into the fiber.

Then this grating acts such a way that it actually picks up only one particular color of light, so when you are looking at the back reflected light, which you are extracting using your spectrum analyser, then you are looking at the power as a function of wavelength in, with your spectrometer, you will find that only one particular color that corresponds to, let us say lambda b, that will come over here, and the remaining colors will actually go over here.

So, you will have a broadband source, but it will be missing this one color at lambda b, this is, if you look at the spectrum of the light that is getting transmitted, it will just have a dip over here and then remaining things will show up here. Now, we are interested in this spectral component and specifically we are interested in the fact that whenever there is a perturbation that happens, this lambda b is actually going to change as, with respect to that perturbation.

So, if you have say strain imparted on that grating, then that will actually shift this Bragg wavelength to a longer wavelength and based on the change in color you can actually go back and say so much has happened or so much strain has been imparted at this particular location of the fiber. How do you know the location? Well, you have actually put this grating at a particular location in the fiber.

So, in fact, you can use that to your advantage also, you can concatenate multiple gratings in this fiber, which are picking up perturbations in different locations. We will come back to that later on, but the key point that we want to say is any perturbation due to say strain or temperature will cause a change in the Bragg wavelength and by picking up that change in drag wavelength you are going to be able to figure out the magnitude of strain or temperature.

While saying that, of course, you can imagine there are some limitations of this, of course, what you are seeing is just a change in Bragg wavelength and you do not know whether it is caused by change in strain or change in temperature. So, that is actually one of the classical limitations of this type of a sensor we are working on that inverse problem and you need to figure out what caused it.

And there are some interesting ways of dealing with that situation also, which we will look at possibly in the next few lectures. But before we go to that we want to understand how fiber Bragg grating works, what is the principle behind this Bragg diffraction? And then we also want to look at what determines the spectrum of this fiber Bragg rating and so on. So, that is what we will look at in the next lecture.