# Transducers For Instrumentation

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## Lecture - 16
## Optical Sensors: Distributed

Hello, welcome to the course transducers for instrumentation. In the last lecture we discussed some optical sensors which are based on the interferometric properties of optical waves means the light which was travelling inside the fiber that had some sort of interference with the return light or with some measurement which is affecting this optical waves. Today we will discuss about some distributed sensors. Distributed sensors they are also optical sensors but they differ in the way they work. For example we have a very large structure and we want to measure temperature or the strain across all the length for example we have a kilometer long dam and we are interested in the physical strength of this dam because the amount of water it is holding is too much. So we need to be concerned about the strength how much strength this dam has and there is no kind of degradation in the structure.

So we are interested in the entire length not at a particular point. So it is a one kilometer length one kilometer long dam. We don't want to kind of put thousand sensors every one meter apart and even though we do that there is a possibility that the crack can appear in between that one meter. So it is very difficult to do point measurement for large structures and that is why we use some sort of distributed sensors which are very easy to make using optical fiber.

So today we are going to discuss distributed sensors distributed fiber optic sensors. And as we discussed these distributed sensors is offers the ability to measure temperature or strain at thousands of points. Along a single fiber. And these are very beneficial for monitoring of large structures such as dams, tunnels, pipelines etc. So all these structures are very much large in the length and this sensing systems these sensing systems are based on brilliant on Raman scattering. So, these distributed fiber optic sensing this offers the ability to measure continuously at across the entire length we can measure the temperature or the strain for a very large length such as dams, tunnels and pipelines etc. The property we use in these distributed kind of optical sensor is we shine a very high intensity light into the optical fiber and this optical fiber is very long in length perhaps kilometers or even long. We shine a very high intensity of light into this optical fiber and there is a reflection at every point into the optical fiber because this light is very intense there is a certain amount of light which reflects back across and across the entire length of the optical fiber and this reflected wave by the total time from where we send the light and we receive the light we can estimate at what point this light is being reflected depending upon this time duration we can estimate at what point this particular wave is reflecting that and this is how we do the measurement. The property is we shine a very high intensity light into the fiber and there is a reflection at across all the length of optical fiber. So the property is if an intense light at a known wavelength is shown into a fiber a very small amount of it is scattered back from every location along the optical fiber itself.

So when we are shining a intense light into the optical fiber across its entire length there is a scattering of light and that light comes back to us which we can measure using optical detector. Now this optical wave or the light is made up of photons which has particular wavelength but we have already written here the known wavelength we send with a very high intensity. So the wavelength we know wavelength means the frequency or the energy of photons we know upfront what photon we are sending in when these photons are reflected back from the optical fiber then if the optical fiber at that particular point let's say in the middle of optical fiber there is a zone where the temperature is high it means we have more thermal energy there concentrated in towards the center of this optical fiber when this photon is reflected back from that point this photon receives energy from this temperature which is higher temperature or the thermal energy is higher. So this thermal energy gives rise in the energy of photon when it is reflecting back so what we receive the reflected wave is higher in the energy or higher in the frequency means the wavelength goes down. So we are sending a known wavelength photon into the fiber and we are getting a photon which is higher in the energy it means this photon has received some energy somewhere in the optical fiber.

So depending upon the difference of energy we can find out how much is the temperature at that point into the optical fiber and that point we can calculate based on how much is the round delay of this photon when we are sending and when we are receiving so there is a phase difference between input and what we receive as the output so there is a phase difference so that tells us how far that point is and a difference in energy gives us how much is the temperature rise. So this is how we do the measurement. So this is the property we use and based on these properties when this photon receives energy from temperature we have two cases so this the Raman interaction this is called Raman interaction. So the first is the stoke we call it stoke this is the outcome when the material absorbs energy the material or the optical fiber absorbs energy and emitted photon has a lower energy and the second point is anti-stoke the second outcome is anti-stoke where the material loses energy. And the photon we receive has a higher energy than what we send.

So these are the two cases when we send a known wavelength of light into the optical fiber the returned photon may have higher energy than what we send it means it has received energy from thermal energy in between and the other case is the received photon has less energy it means it has lost some energy somewhere in the middle of optical fiber means some zone has the temperature which is lesser than the normal temperature it means the thermal energy is lost there to that low temperature. So these are the two cases where we have stokes and anti-stokes when we shine this intense light. Now these the structure of this distributed optical fiber is very simple we have a very long optical fiber for example, this is distributed optical fiber sensor. So we have a very long optical fiber it may have turn in between and these distances are very long typically let us say one twenty meter loop this is twenty meter loop and let us say this is hundred meter loop. So this is the optical fiber which we are using now we shine a high intensity light so we use some sort of a lens here to couple all the light into this optical fiber.

So this is the light let us say which comes from here and this is directed into this optical fiber using this lens. This light is actually sent by laser or something which is very high intensity in nature so we have another lens which is coupling this light to this laser we have a laser source. So laser gives you very high intensity of light which goes into this lens and this intense light is coupled to this optical fiber which is very long in length. So as we discussed from each and every point of this optical fiber the photons will be reflected back from this entire length which is very much big let us say kilometers from every point these photons are reflecting back and now we need to read these electrons read these photons means we want to measure how much is the energy of these photons. So we can intercept this path in between where this lens is sending this high intensity light but as well as receiving these small amount of photons which are reflected back we intercept this path in between we are using some sort of beam splitter here let us say this is beam splitter put at 45 degree so this reflected light will be moved towards this let us say here and we have some sort of a grating at this point this light again goes to a lens which couples it to some APD or avalanche photo diode this is the detector which we will discuss next this light is coupled to some sort of APD this is avalanche photo diode which in fact generates an electrical signal this is generally fed to an amplifier which is all electrical amplifier so from this onward all the signals are electrical in nature we have amplifier and then we have certain processing unit and then we have this beam.

So this is the typical structure of distributed fiber optic sensor we are shining a light into the optical fiber using a laser which is very high intensity light source this light is coupled to this optical fiber using lens so when this light goes in this is reflected back across the entire length of optical fiber so photons are coming back as well so we put in between this beam splitter which is so this beam splitter is splitting this incoming and outgoing optical wave and sending these received photons towards the avalanche photo diode or APD this APD is a semiconductor device which detects the photon coming in and generates the equivalent electrical output this electrical output is generally very small in magnitude so we prefer to have a amplifier before processing this signal so this is a electrical amplifier we put after a lunch photo diode this amplifies this amplifier amplifies the signal then we can use some microcontroller sorry our computers to process this data this amplified signal and we can put it on the display so this is how we measure how much is the photon energy compared to what we sent using the lasers so typical stoke and anti-stoke wavelengths are let us say anti-stoke wavelength is typically 1450 nanometer again it depends on what you are sending through this laser and typical stoke signal is 1650 nanometer based on these frequencies we classify the Raman filter which we use in this distributed optical sensors so next we discuss the Bragg grating based sensor which is which is a different phenomena of measuring a measure and using the optical properties of material Bragg grating based sensor is we put a grating in the optical fiber and depending upon the grating what we inscribe on these optical fiber this optical fiber absorbs or reflect certain wavelengths of optical light and depending upon what is the grating size and grating distance that wavelength is different based on this spacing of these Bragg's grating we can detect what wavelength is going to come back or going to be transmitted and this this spacing between the grating is the function of temperature so this is what this is how you can make a temperature sensor using Bragg's grating based optical sensors. So we have Bragg's grating based fiber optic sensor. So this fiber optic fiber Bragg grating or in short we sometime call it FVG is a type of distributed sensor. In this FVG sensor a short segment of optical fiber reflects be passing by. So at the transmitted end what we receive we receive all the wavelengths except the one which is reflected back by the grating.

So you can see here in this graph we are missing this particular wavelength here. This is let us say lambda dash and on the receiving end where on the input side where we are sending this wavelengths we get this reflected wavelength. This is power and this is the reflected one reflected wavelengths and there we do not have other wavelengths only this lambda dash. So this is the reflected wavelength which we receive at the input side and these gratings these are very simple to make on the optical fiber. We photo inscribed these gratings on the optical fiber during the manufacturing process itself.

We can precisely inscribe these gratings and we know the distance very precisely into these gratings. These gratings are simple sensing elements which can be photo inscribed. So this is the property which we call fiber drag grating based sensor. This is the property we want to use now to make a actual sensor. So what we know is we put a grating and based on the spacing of this grating a certain wavelength is reflected back from this grating and this wavelength is corresponding to how much spacing we have in between this grating.

So now using this property now we want to make a sensor. Therefore we are making here a drag grating based sensor. So this particular wavelength is reflected by this grating which has a constant gradient spacing in between. Now this spacing we can subject to the measurement. For example we want to measure the temperature. So when we expose this grating to the outside temperature let's say that temperature is higher there will be a thermal expansion in the optical fiber based on that if there is a thermal expansion the spacing between these grating changes. So earlier let's say this is 100 nanometer when the grating is subject to some temperature which is higher then this 100 nanometer becomes

110 nanometer. So this difference between the earlier spacing and the new spacing the wavelength which is reflected back that wavelength also changes. Earlier let's say we are getting 600 nanometer wavelength reflected now that wavelength will be 650 nanometer. So that reflected wavelength also changes based on the spacing the difference in the spacing of these gratings which is proportional to the outside temperature.

So this is the property we want to use to make a temperature sensor using brag grating based optical sensors. So the construction is again very simple. In this FDG sensor instead of using a laser we generally use a broadband source. We use broadband source because we need to send a wide spectrum into the optical fiber. So this is the optical fiber and here we have let's say 3 dB coupler.

So what 3 dB coupler does it splits the waveform. This is the optical fiber here where we have this grating and we apply the measurement here. This is the measurement zone. This measurement can be anything it can be temperature, it can be pressure or force which changes the spacing between this grating. This is the grating. be passing by. So at the transmitted end what we receive we receive all the wavelengths except the one which is reflected back by the grating. So you can see here in this graph we are missing this particular wavelength here. This is let us say lambda dash and on the receiving end where on the input side where we are sending this wavelengths we get this reflected wavelength. This is power and this is the reflected one reflected wavelengths and there we do not have other wavelengths only this lambda dash. So this is the reflected wavelength which we receive at the input side and these gratings these are very simple to make on the optical fiber. We photo inscribed these gratings on the optical fiber during the manufacturing process itself. We can precisely inscribe these gratings and we know the distance very precisely into these gratings. These gratings are simple sensing elements which can be photo inscribed. So this is the property which we call fiber drag grating based sensor. This is the property we want to use now to make a actual sensor. So what we know is we put a grating and based on the spacing of this grating a certain wavelength is reflected back from this grating and this wavelength is corresponding to how much spacing we have in between this grating. So now using this property now we want to make a sensor. Therefore we are making here a drag grating based sensor. So this particular wavelength is reflected by this grating which has a constant gradient spacing in between. Now this spacing we can subject to the measurement. For example we want to measure the temperature. So when we expose this grating to the outside temperature let's say that temperature is higher there will be a thermal expansion in the optical fiber based on that if there is a thermal expansion the spacing between these grating changes. So earlier let's say this is 100 nanometer when the grating is subject to some temperature which is higher then this 100 nanometer becomes 110 nanometer. So this difference between the earlier spacing and the new spacing the wavelength which is reflected back that wavelength also changes.

Earlier let's say we are getting 600 nanometer wavelength reflected now that wavelength will be 650 nanometer. So that reflected wavelength also changes based on the spacing the difference in the spacing of these gratings which is proportional to the outside temperature. So this is the property we want to use to make a temperature sensor using brag grating based optical sensors. So the construction is again very simple. In this FDG sensor instead of using a laser we generally use a broadband source. We use broadband source because we need to send a wide spectrum into the optical fiber. So this is the optical fiber and here we have let's say 3 dB coupler. So what 3 dB coupler does it splits the waveform. This is the optical fiber here where we have this grating and we apply the measurement here. This is the measurement zone. This measurement can be anything it can be temperature, it can be pressure or force which changes the spacing between this grating. This is the grating. Now this grating will reflect some of the wave which is going this way but some wavelength will be reflected back by this grating. That wave will reach here at 3 dB coupler and this 3 dB coupler will change its path to our detection system. This is optical detector. This can measure which wavelength is reflected back by this sensor and now if we plot the input and output. So we send a input where we have all the wavelengths and at the receiving end at the optical detector we receive the input to optical detector. Let's say before application of temperature the wavelength reflected is lambda dash and when we apply the temperature then there is a change in the grating spacing because of that this wavelength will shift and the new wavelength is let's say lambda double dash. So there is a difference between the reflected wavelength and this difference in the wavelength is dependent on the temperature what we apply in the measurement zone. This is the received signal by optical photo detector.

This is the input and if we measure the optical wave at the far end, at far end it will look something like this. We have this lambda and this is power and at the far end we will receive all the wavelength except this lambda double dash. This particular wavelength is lambda dash and this is lambda double dash. So this is how the Bragg's grating based sensor works. This grating is very particular to a wavelength depending upon its spacing and if the measure end can change the spacing of this grating then the wavelength reflected by this grating is different which is proportional to the measure end. So measure end can be temperature which can thermally expand the optical fiber or it can be force where we are applying a force which can pull this fiber optic sensor and there is a change in the distance between the grating. It can be pressure, it can be multiple other measurements which we can use to make a sensing using of this fiber grating based sensors. Now if we plot the relation between the reflected wavelength and the actual temperature. So this is the temperature and on y axis we have the wavelength shift. This Bragg's grating based sensor gives quite a linear response with the temperature and we can see the wavelength reflected is increasing because when the temperature is increasing that is because when the temperature is rising there is a thermal expansion in fiber the spacing is increasing. It means the grating is now sensitive to the wavelength which are more in length. So that is why we see for the higher temperature the wavelength reflected is higher compared to the lower temperature. So this is the typical output of a Bragg grating based thermal sensor. So this is all about the optical fiber where we discussed interferometric based sensors, distributed sensors and Bragg grating based sensor. Now let us discuss about the source the optical source which is the integral part of this optical fiber optical sensors and the detectors which is also again as important as the optical source.

So before jumping into the optical sources or optical detectors let us review quickly about some semiconductor physics which is involved in working of these optical devices. So let us brush up some of the device physics. So we know that there are three types of material we have one is the insulator and if we plot the band gap of these insulators we have certain conduction band and we have certain valence band. This is conduction band and this is valence band and the energy difference between this conduction band and the valence band which we denote by EG or the band gap.

This is high. This is typically 6 electron volt or even higher. So if we see the band gap of insulator we have conduction band and valence band and the energy difference between these two bands are very much higher if typically 6 electron volt or even higher. So it is not possible for an electron to jump from valence band to the conduction band and if there is no free charge carrier in the conduction band it means the conduction will not happen. If we apply electric field across this material then there is no mobile charge carriers in the conduction band which can conduct. So even if we apply a high electric field there is no current flowing into the material and this material is called insulator. The second case is we have metal. In metal we have this conduction band and valence band they are typically overlapped. This is conduction band and this is valence band and we have some area which is overlapped. This is valence band. So in metal we have these both of these bands are overlapped to each other it means there is no energy difference between valence band and conduction band and the electrons in the valence band can go to the conduction band and they are freely available to move if we apply a electric field. So for a metal if we apply a electric field or the potential electric potential then these charge carriers which are electrons they are free to move and they conduct current. So we when we apply a voltage across a metal it conducts current. So these are two typical cases where insulator the band gap is very high; electrons cannot jump at all. In metal we have no energy band gap it means the electrons are always available no matter what voltage we apply the electrons are available for conduction. The third case which is a special case is semiconductor. Semi means half something like that. So it is a semiconductor it means it can conduct or it cannot conduct depending upon external influences. So we have here conduction band and valence band which are not overlapped. So this is a conduction band and this is valence band and the energy gap is there which is which we call band gap and this band gap now is the order of one electron volt. Typically the band gap between the conduction band and the valence band the band gap is typically one electron volt for semiconductors. Now there is a band gap it means electrons refer to be in the valence band they are all available in the valence band but if they acquire some amount of energy from outside it may be thermal energy it may be the energy they acquire from high electric field.

The energy which is typically in the order of one electron volt if a electron achieves this much of energy it can jump from valence to conduction band and when the electron goes into conduction band this is now available for electrical conduction. If we apply electric potential across semiconductor then this electron can move and it can provide the current. However if the electron does not receive enough energy of the order of one electron volt all these electrons are in the valence band it means the semiconductor whatever voltage we apply it cannot conduct. So depending upon the external factors this material can conduct it can become a metal or like a metal or it can become an insulator close to insulator it can conduct the current or it cannot conduct the current based on the external factors. So this is called semiconductor and typically the band gap of this semiconductor is typically one electron volt. So these semiconductors are of great interest and we make all these optical detectors and optical sources using these semiconductors and even all the electronic devices we use semiconductor material a very known very common material which is semiconductor is silicon we use. So silicon is a semiconductor material very heavily used in electronic circuits. However for optical devices we do not use silicon we use some other materials we will come to that point. So here we have semiconductor where the conduction and valence bands are separated by certain band gap. If we talk about these semiconductor only at T equal to 0 means the temperature is 0 Kelvin so there is no thermal energy.

So there is no thermal energy available to electrons from outside. So if we plot the conduction and valence band the conduction band is typically like this and the valence band is typically like this. At T equal to 0 all the electrons are in the valence band and conduction band is completely empty it has available state which electron can fill up but currently all these states are empty. So I am drawing it by open symbol which means that these states are available to occupy but they are empty at T equal to 0. When we increase the temperature, let us say at T greater than 0 means now we have thermal energy.

Some of these electrons which are very on the top of this valence band they have high probability that they will receive this energy from thermal energy and this electron will jump from maxima of valence band to the minima of conduction band because this is the least amount of energy they need to jump and this electron will jump from here to here this electron can also jump. So some of these electrons which are already high in the energy they can jump from valence band to the conduction band. So this is EB and this is EC energy of conduction band some of these electrons will jump to conduction band at T greater than 0 kelvin when the thermal energy is available to all these electrons. Then we have these electrons in the conduction band now if we apply a external electric field these electrons. let us say this is the case when now we have these electrons available in conduction band these electrons are here and rest of the electrons are still in valence band.

Now if we apply a electric field this is with external bias at T greater than 0 kelvin. So when we apply the electric field these electrons will see a potential difference or electric field in let us say x direction and they will shift or they will move in a particular direction for example these electrons will see a drift because of this electric field. This shape is not symmetrical now some of the electrons will be towards the left because of the external bias what we apply. And based on the electrons are there in the conduction band based upon the curvature of these bands these conduction band the electron mass is different which is called the effective mass of electron and this effective mass of charged particle depends on the curvature of this conduction and valence band. So the relation between this the effective mass and the conduction and the curvature is one over m0 which is the mass of charged particle is equal to one over h square into d square e by dk square.

So this is the relation between the effective mass and the curvature. Curvature is d square e by dk square is the curvature of this conduction or valence band and m0 is the effective mass of electron. So we discussed today the Bragg grating based sensor and some of the device physics what we need to understand the optical sources and optical sensor. Next lecture we will continue from the device physics and We will see how the optical source actually works.

So this is all for today.

Thank you.