Transducers For Instrumentation
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Lecture - 14
Optical Sensors: Signal Propagation

Hello, welcome to the course Transducers for Instrumentation. Last lecture we were discussing about the optical sensors, we saw the basic building blocks of a optical sensor which are three mainly. One is the optical source where we generate these optical waves or the light. The second element is the optical fiber which carries this light from the source to the destination and in between we have the sensing done in the measurement zone. This is the second element, and the third element is the optical detector where we receive this optical wave and compare it with the generated wave and we compare how the property of this wave is changed. Based on this change in the property we detect what is the measurement in between.

So these are the three elements what we discussed and then we discussed about the classification of optical sensors. So today we will discuss a little bit more about all these basic building blocks and some basic understanding about the optical waves. So we have the first object which is the optical source. So optical source is the element where we generate these optical waves or the light.

So mainly we have heard about the LEDs or the light emitting diodes and the second one is the laser. So these are the few devices by which we generate these optical waves, these elements, these LEDs they receive the electrical signal from external in the electrical circuits and generates a corresponding light wave or optical wave which is then coupled to the optical fiber. So these devices or LEDs they work on a principle that the optical wave it propagates in form of some quantas, quantas of energy. So these optical waves are nothing but that quanta of energy which transmits at the velocity of light and these quantas are called photons. So these photons are generated by these LEDs or lasers and they are coupled to optical fiber where they propagate.

So we have a certain structure of these LEDs. So for example, the first point is these optical sources operate on the quantas, these optical sources operate on the idea that electromagnetic energy can appear in discrete amounts which is known as quanta. These quantas are called photons. So when this energy is radiated in terms of optical light in fact this consists of the quantas which is finite amount of energy and they are discrete in nature. It is not a continuous band of frequency, the quanta or this energy is fixed with this photon.

It is not a continuous band, it is discrete in nature. So the amount of energy one photon is carrying that is discrete in nature. These energies depend on the frequency of the photon. So the energy of these photons varies directly with the frequency. And some typical optical sources are. For example, LEDs or the light emitting diodes. We call them LEDs and the second one is the lasers. So these are two types of optical sources which are used in semiconductor industry to generate these optical waves. The first one is light emitting diodes where this emits the light and the second one is the lasers which also emits light which is slightly different. The mode of operation of laser is slightly different than LEDs.

We will discuss that in detail. So these are the two types of optical sources we use and typical construction of LED is something like that. We have a anode contact. On top of this we have a insulating layer. This is anode. On top of this we have gallium arsenide layer which is doped p-type. So we can say this is a p-type gallium arsenide layer. On top of this layer we have let us say n-type L-Gan layer, L-gas layer. This layer is n-type aluminum gallium arsenide. This is the n-type layer and on top of this we have cathode contact. This is the cathode contact. So this is a typical structure of a LED or light emitting diode. And in this structure we have an anode and cathode and in between we have layers of aluminum gallium arsenide and gallium arsenide. These layers actually generate these optical photons when we excite this layer with electrical signal when we bias a voltage between this cathode and anode. And when these photons are made by this layer they are actually coupled directly to the optical fiber. For example this is the optical fiber. These photons will be generated at this layer between L-gas and gas layer and these photons will be traveling this way and then they will travel within this optical fiber. Let us say this photon this generates here and that travels this way. So all these photons are generated between this p-type gallium arsenide layer and n-type aluminum gallium arsenide layer. Here we have used this special material which is gallium arsenide and aluminum gallium arsenide. We have not used silicon here because silicon is not suitable for optical devices. We typically use gallium arsenide devices because the gallium arsenide device or the gallium arsenide material is a direct band gap semiconductor. For optical device to generate these photons we need a material which has direct band gap semiconductor which is a direct band gap semiconductor that only can generate these photons efficiently. However, silicon is a indirect band gap semiconductor. If we plot briefly about the band gap of silicon so the maxima of valence band and the minima of conduction band is not exactly for the at the same K point which is the momentum axis. So this and this, this is the band gap for silicon. This is a indirect band gap material so when a electron jumps from this minima to the maxima this has to take two path one is from here to somewhere in between here and then it has to jump from here which is a inefficient process. However, for the gallium arsenide this is a direct band gap semiconductor and these both maxima and minima both are at the same K axis for the same K value. So electron can directly jump from maxima to minima and can generate photons in this process. However, in silicon we generate here from here to here this energy is lost in terms of phonons which is not a optical particle it is actually dissipated in terms of heat in the crystal.

So silicon if we use silicon to make a optical devices and we bias the silicon with electrical signal instead of generating the optical photons actually silicon start heating up because of the generation of these phonons. So silicon is not very much suitable for optoelectronic applications we use something called gallium arsenide material which is a direct band gap semiconductor. So these are the some optical sources where we have LED's the light emitting diodes and the lasers we will discuss in detail later on in other lecture but this is typical structure of a LED. Next is the optical detectors. So optical detector is the element which receives this light these photons these are captured within this device and corresponding to these photons this optical detector generates a electrical signal according to how many electron how many photons are actually received at the interface and these optical detectors mainly we use P-I-N diodes which is called P type intrinsic and N type.

So it is a short form of P-I-N positive intrinsic and negative diodes P-I-N diodes. So the most common optical detectors used in fiber optic systems is P-I-N diodes. These diodes operate in reverse bias mode. Next is the P-I-N diodes which is positive intrinsic and negative this is the structure of these P-I-N diodes we always apply a reverse bias voltage across these devices so that we have a very high electric field built up inside this device. So when a photon comes this has a particular energy when this photon hits this area of very high electric field it generates this electron hole pair corresponding to its energy how much energy it is carrying and these electron hole pairs are generated which is a electrical signal these are the charged particles they generate this electrical signal across the load which is connected outside to this P-I-N diode.

So in this way we generate a electron hole pair which is electrical signal from this optical signal which is the photon. So this is how we generate these electrical signal and these devices they operate in the avalanche mode. Avalanche is something when a single photon comes in that hits the interface and generate a electron hole pair. This electron hole pair again gains some energy from the external applied electric field which is very high. When they start receiving this energy and they become energetic enough to knock one more electron hole pair and in this way because of this chain reaction one electron hole pair again generates two more electron hole pair, two electron hole pair make one three like four electron hole pair.

So in this way there is a chain reaction and suddenly we have we see so many electron hole pairs generated in the device. So a single photon knocks one electron hole pair but eventually generates so many electron hole pair this is called the avalanche effect. So these all these pin diodes or P-I-N diodes they work on the avalanche effect to generate electrical charges. As a photo detector P-I-N diodes takes advantage of its wide depletion region. In which electrons can create electron hole pair.

And for these devices the junction capacitances should be low to allow for fast switching. So these devices these photo detectors they generate electrical signal from the photons and the junction capacitances which is the parasitic capacitance of any of the electrical device. This junction capacitance or parasitic capacitance should be low enough so that these devices can operate at very high speed. We want higher and higher speed from these devices. So we intelligently design these devices so that the junction capacitances or the stray capacitances between two different materials these capacitance should be as low as possible.

And the cross section structure of these LED's are like this these P-I-N junctions are like this. We have first a cathode. This is cathode. On top of this we have n type layer. On top of this we have intrinsic region which is little wider than these doped layers. This is intrinsic region. And on top of this intrinsic region we have p type layer. And on top of this we have second contact. These are our anodes. Now we apply a very high electric field in the reverse bias condition across this device between the anode and cathode. So when we apply a very high voltage across these two terminals a very high electric field is developed in the device and that electric field will be confined more into the intrinsic region which is already having no charged particles within inside.

So all this high electric field appears across the intrinsic region which is shown here. Now if the photon comes in that strikes this intrinsic region where we do not have any charged particle and because of the energy of photon it generates electrical charged particle electron hole pair which then again start receiving energy from this high electric field and knock down one more electron hole pair. And this process continues and within a fraction of time this single photon leads to thousands of electron hole pair and that electron hole pair gives us the electrical signal which we can take across anode and cathode. So these photons or this light they come here and strike this intrinsic region and generate electron hole pair and these electron hole pair further creates two more and then they again create few more.

So this is avalanche effect. So this is how these optical detectors work based on the avalanche effect. The third element of optical sensors are the optical fiber. So optical fiber is nothing but a kind of wave guide for optical signals for these lights. So this light when we couple this light to the optical fiber this light always stays within this optical fiber it does not come out because of the total internal reflection. This light propagates within this optical fiber from one distance to another and this distance is very long.

This light can travel even thousands of kilometers without even degradation in its parameters. So the structure of a optical fiber is something like this. So first we have optical fiber which is nothing but a wave guide for light. An optical fiber is essentially a wave guide for light. The optical fiber consists of two main components one is the core and second one is the cladding. This is the second component that surrounds the core. And the index of refraction of the cladding less than that of the core which causes these rays of light. Leaving the core to be refracted back into the core. So we have for example if we see the cross section of a optical fiber it looks something like we have a core. This is the core of this optical fiber and around this we have a cladding which is let us say this. This is cladding and above this we have the jacket. This is for the protection of these optical fiber. So this is the cross section cut of this optical fiber and we have the cross section. This is how this optical fiber looks like. And this we have this cladding and then we have this jacket for protection. So, this on the left side this is a cross section of fiber. And when we send these optical photons into this optical fiber they all travel along the length of this optical fiber through total internal reflection. These photons they never goes out from this core to the cladding and they always remain within itself and they can travel in this way to a very long distances. So this is how a optical fiber look like. These optical fibers are made up of either some glass or plastic and they can be made in a very long distances.

Their dimension is very thin but the length of these optical fiber is very long. So, these optical fibers are made from thin strand of either glass or plastic. We can use any one of it. So, they must be enclosed in some protective jackets. These strands these are very thin and they run for kilometers and they have very mechanical strength. So, what we do on top of core and cladding there is one more layer which is the jacket or the protective jacket which keeps these optical fiber from breaking because of the mechanical shocks. So, we have this protective jacket. Often these fibers we do not rely actually on the single fiber because of some unexpected damage happen in between. So generally we use 2, 3 or more optical fibers in the same protective jacket or even with other protective jacket but we use 3, 4 or 5 optical fibers or more than 5 just to increase on the redundancy if there is a breakage of optical fiber some of the fiber at least one of the optical fiber will be running fine. So often we use more than one optical fiber just in case one or more optical fiber breaks.

So, this is due to mechanical shock or some other factors. Another important property about using optical devices is we can make a full duplex system using these optical fibers. What full duplex system is in the same fiber we can send one signal from one direction and the another signal from the reverse direction. This is not possible in electrical wire transfer because the voltage from one signal if we send one signal from the left the voltage is there along this electrical wire. If we send another signal from the right side this voltage is going to interference with the first signal and we these signals actually corrupt each other. However in case of optical fibers we can send one optical wave from left to right and another optical wave from right to left. So we can use the same hardware to communicate both the sides. This is called full duplex system and it is easy to make in optical devices. So we can make it is easier to make full duplex system. So, using optical fibers or using these optical fibers.

So, these are some properties about the optical fiber system which we are going to use for optical sensors. Now let us discuss more about how a optical wave actually transmits or it propagates through the optical fiber. So these optical fibers work on the principle of total internal reflection. So, let us see. So, all these transmission of these optical waves in the optical fiber that works on the principle of total internal reflection. It means when this optical wave hits the interface between core and the cladding this does not propagate to the cladding and it remains in the core itself if the angle of incidence is greater than the critical angle. So when this wave is traveling in the core it does not refract to the cladding and it keep on bouncing back in the fiber itself and it can travel a long distance without even getting out to the cladding. So this is called total internal reflection and the angle of refraction is governed by the Snell's law. So, this angle of interface between these two medias is governed by the Snell's law. And this law says N1 into sin theta 1 is equal to N2 sin theta 2 where this Snell's law says N1 sin theta 1 equal to N2 sin theta 2 this N1 and N2 are the refractive indices of both the medias N1 is the refractive indices of media 1 N2 is the refractive indices of media 2 sin theta 1 the theta is the angle between the perpendicular to the interface and the angle of incidence at what angle the wave is actually coming and theta 2 is the angle in media 2. So we can plot this for example, if we have two medias let us say this is media 1 the with refractive index media N1 and this is media 2 where refractive indices is media N2 and this is the interface between these two media this is the perpendicular axis to this and a wave is actually coming from media 1 to media 2. So this is the angle which is theta 1 and this is the angle which is called theta 2 and the relation in between these theta 1 theta 2 N1 N2 is governed by this Snell's law. This is the case when we have eta 1 or N1 is greater than N2 or N2. So where here we have this wave which is coming from media 1 with the angle theta 1 and goes into media 2 where the angle is theta 2. We can see here the theta 2 is greater than theta 1 because we have N1 greater than N2. So this is a typical case when wave is incident at a particular angle theta 1. Now if we keep on increasing the theta 1 at some point this theta 2 angle will becomes 90 degree. It means when the wave is incident on this interface this wave does not go into N2 or the another media or we can call this is cladding and this is core. Let us say N1 is our core of optical fiber and N2 is the cladding. So now a wave is coming from the core at angle theta 1 and theta 1 is such that theta 2 becomes 90 degree.

In that case the wave does not go into the cladding, but it remains at the interface. So we can draw that particular case. This is theta 1, this is theta 2, this is the interface and the wave comes from media 1 and it remains this theta 2 becomes 90 degree. This is 90 degree. So this is a particular case when the theta 1 is such that the theta 2 becomes 90 degree and in this case we call it the critical angle. Theta 1 is called the critical angle. So if the incident wave from material 1 has an angle which is greater than critical angle this wave does not go into the cladding, but remains itself in the core only the core of optical fiber and if we further increase this theta 1 this incident wave angle then instead of having on the surface itself this wave actually bounce back into the core itself. So we can plot that third case where this angle this is N 1, this is N 2 and now the incident angle is more than theta 1. In this case this wave actually comes back into the cladding into the core itself. Let us say this is the angle theta where theta is greater than theta 1. Let us say we call it theta critical. This is our theta critical angle and now our theta 1 is greater than theta critical. So this wave actually does not go into the cladding it comes back into the core itself. So this is called the total internal reflection. In this case where the incident angle is more than the critical angle it is called total internal reflection. By this phenomena this wave can travel a long distance whenever it is hitting the core and the cladding interface it is bouncing back into the core itself. So the whole of this optical wave remains within the core itself it does not go into the cladding or does not lose out the photons outside into the cladding. In this by this phenomena this wave can travel even very long distances even kilometers as well. So this is the phenomena which is used in the optical fiber transmission. The next important thing is the numerical aperture. When we couple these optical devices for example the optical source when we couple this optical source into optical fiber these waves need to be incident on the optical fiber at a particular angle not greater than a certain angle which is governed by numerical aperture.

When we couple these optical source with optical fiber there is a cone shape of structure where this angle actually is very critical so that all the optical wave is coupled into the optical fiber and it does not bounce back or get outside. So we have something called numerical aperture. This is closely related to the critical angle. For example, we have a optical fiber here which has core and cladding in itself. So now let us extend this axis and we see there is this cone sort of area.

If the light is incident within this angle then only this light will be coupled to the fiber. If the light comes away from this or the angle of incidence is more than this then this light is not coupled to the optical fiber. So this critical angle is governed by numerical aperture and this is given by angle of acceptance. This angle let us say theta this is the angle of acceptance. This is twice the angle of given by the numerical aperture. This theta is 2 times sin inverse numerical aperture. So this angle of acceptance is double of this angle what this cone actually is making at this horizontal axis. This N1 and N2 are the refractive indices of both the media N1 and first and second. In these optical we can also make switches in optical devices and these switches are unlike the electrical switches in electrical switches we have relays and transistors. Here we can use make use of prism which is optical device and we can make switches using these prisms.

So we can make optical switches. So one way to make switches for example we have 3 fibers coming in and we want to switch the input from one of this to the other one at the output we have this one fiber. We can physically move this fiber up and down. We can align first we align with this so the signal goes here then we can move this whole fiber up. We make into this position then the signal is coupled from this let us say we number it this is 1, this is 2, this is 3. So we can couple the input from either from fiber 1 or fiber 2 by moving this fiber up and down. This is one way of doing it however we can use the prism which is like this we have let us say these 3 fibers let us say this is input fiber and this is output fiber 1 and this is output fiber 2. Now in this assembly input fiber is carrying this optical wave which need to be switched between output 1 or output 2. So we can make use of prism a prism something like this. So in first case we have prism placed like this so now our optical wave goes here this bounce back here and then goes to output 1. So this is first case when the output is switched to When the input is coupled to output 1. In another case we can move this prism to the down physically move it in the downward direction and let us say this is the second case where we move this prism something like this and now the wave is coupled to this prism goes down and coupled to output 2. So this is case 1 and this is case 2. So in case 1 we see if we keep the prism on the upward direction then input is coupled to output 1 if we move the prism down the input is coupled to the output 2. So, in this way we can make these optical switches though there is a physical motion involved moving of the prism is not very much accurate way of steering the signal from one fiber to other fiber. Electrical ways of switching the signal from one to other is easy and more reliable compared to physical movement of prism.

The problem with physical movement is the wear and tear along with the time and the reliability of how accurately you can place or you can place this prism so that the input is coupled reliably to the output. So, this is the problem with using these optical switches, but these are available to use. Another point we need to notice we need to use lenses. These are necessary with these approach to avoid excessive heat excessive loss of light. So, we can use this prism as optical switch, but the problem is the reliable connection so for that to keep the loss of light under control we need to further use the lenses so that we can direct this incoming light at a very particular point and reflect it back and couple it to the output. So today we see the optical sources optical detectors and the basic working principle of how the light propagates into the optical fiber.

So, this is all for today.

Thank you.