Biophotonics
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Lecture 32
Optical Fiber Sensors

Welcome back, we were discussing optical biosensors and today we are going to go on to a specific type of optical biosensor and that is the Optical Fiber Sensor. Fiber optic sensors are also common name and this is one of the oldest and one of the most versatile and very, very ubiquitous sensor that that we can see all around us. In order to understand optical fiber sensors obviously, we need to understand what optical fibers are.

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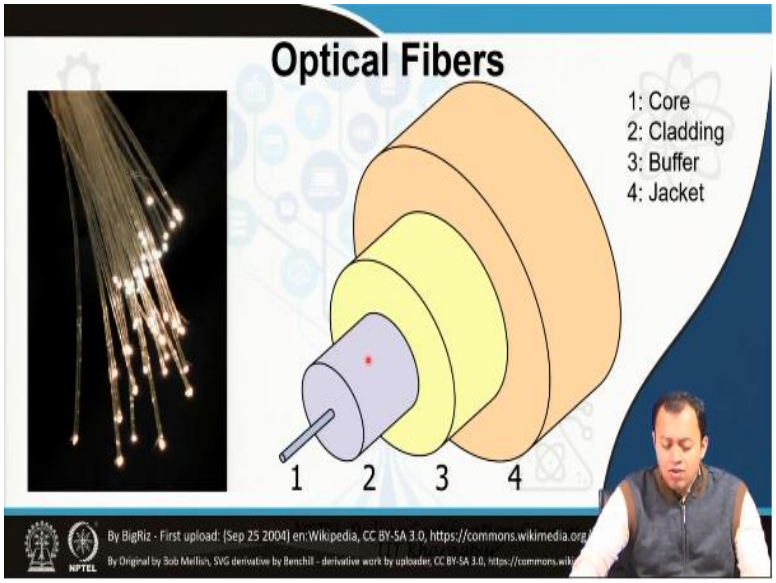

I think all of you have a rudimentary idea what optical fibers are, you have seen it in at least in festivals, all our data communication is taken through, most of our data communication through not all are through optical fibers. Optical fibers contain high refractive index area and optically dense material which is called the core, that is surrounded by a cladding part, this is the low refractive index material which is then covered by this buffer, the buffer is some kind of a chemical element that prevents this cladding from moisture or any other kind of wear and tear.

And finally, the entire thing, entire thing is covered by the jacket which is a resin, some kind of a hard plastic which prevents against mechanical wear and tear, this does not contribute anything

to the optical part. So, the mostly the electromagnetically active element or the optically active element are the core and the cladding overall, there are other parts buffer and jacket they are mostly to give it robustness, give it strength, protect it from the elements etcetera. So, overall an optically dense material surrounded by an optically rarer material.

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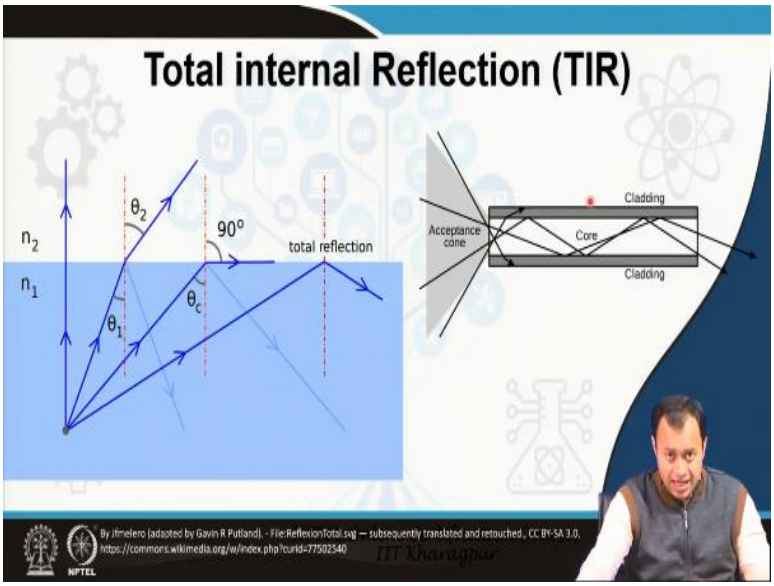

And how do they work? Well they work by this concept the light is guided through the core, that is the optically dense material, do not fall for the color, this is denser, this is rarer, this has a higher refractive index, this has a lower refractive index, the light is guided, I think I discussed it a little bit before by the process of total internal reflection, what does total internal reflection means, all of you know it from your high school but I will just revise you once again.

So, Snell's law states that whenever light enters from a rarer medium to a denser medium it moves away from the normal. The opposite is also true whenever light moves from a rarer medium to a denser medium it moves towards the normal. Normal is this imaginary perpendicular line between two lights, if it is just the same angle then it goes through but otherwise if this is a light source and if n1 is optically denser material, a thicker material, a refractive index high material compared to n2 which say air or vacuum, a rare optically rare medium which is much rare much thinner.

Then there will be a change in the path, there will be a change in the path of the light wave which is travelling and there is a difference of this angle, angular movement theta 1 versus theta 2, this is Snell's law you know sin theta 1 by sin theta 2 is at the end of the day refractive index n1 versus n2 or n2 versus n1 however you want to put it. But it was since there is an angular dependence theta 1 versus theta 2 and theta 1 and theta 2 are never same unless it is you know perpendicularly shine, forget about this particular case, most of the light are shown at a specific angle.

If you keep on increasing the theta 1, if you keep on increasing this particular angle, so instead of going like this, instead of going like this it goes in this direction. There comes a point when this theta 2 becomes more and more so, previously it was like this, then it bends, then it will further bend, then it will further bend, then it will further bend, then finally it will graze the surface, it will finally graze the surface because the theta 1 have been made such a large we call it theta c or a critical angle.

The critical angle is that part where the output light is no longer in the other medium but at the surface. What happens when we further increase the angle after critical angle theta c? If the angle is, if the launch angle, this is the source, this is the source light if it is more than theta c, then because of Snell's law because this output angle is so high that the entire light is completely reflected and nothing is getting refracted.

So, total internal refraction, total internal reflection is the one where because of your critical angle, because of the way you have launched the light the entire light falls back on to the same medium there is no refraction. Refraction is where light moves from one medium to another medium and there is an angle dependency whatsoever.

If you modify the angle there comes a particular case that the entire output light falls completely inside the same medium that it has started its journey with, i.e., there is no more any refraction, the entire light is reflected, entire light is reflected so we call it total internal reflection, i.e., the entire light is reflected internally, the entire light is reflected internally there are beautiful videos of this happening in real life just go to YouTube and put total internal reflection and you will see how beautifully, the entire light is confined within the medium you are not because of the angle in which it has been launched you are disallowing the light to go out.

We do the same thing in an optical fiber, this has a higher refractive index like this, this has a lower refractive index and we launch a specific light at specific angle. So, that it keeps on bouncing, it keeps on bouncing from the top surface to the bottom surface zigzag, zigzag, zigzag, yes, there was a question that what happens if it goes straight away, then straight away is like this there it can go straight away but usually the source of light is much bigger than this core diameter. So, if it is a light bulb or a laser source like this it will be this big.

So, it is very difficult to send a small light like this and that does not matter, the this was a question that was asked to me hence, I am saying. The idea here is if you launch a light like this by total internal reflection, the entire light will simply bounce from the top surface to the bottom surface and will carry itself forward without going into the cladding, without going into the outer surface, without going into the other media.

Some of the light obviously goes because of the difference in angle and that is lost, that is lost, that is the loss that you suffer. Now, optical fiber technologies have become this fine and this specific and this precise that the losses are very, very minimum, less than few dbs less, than 10 or 20 dbs per kilometer.

So, think about it, these are the cores, these are the materials that carry transatlantic, these are the transatlantic cable, these are the optical fiber cable that are at the bottom of the sea connecting continents and you are getting your internet through that, yes, you are getting your internet through optical fiber cable and these optical fiber cable are coming through the sea beds and how much of a loss of data you see, because entire light which contains the signal is enforced, is entrapped in the core part by total internal reflection.

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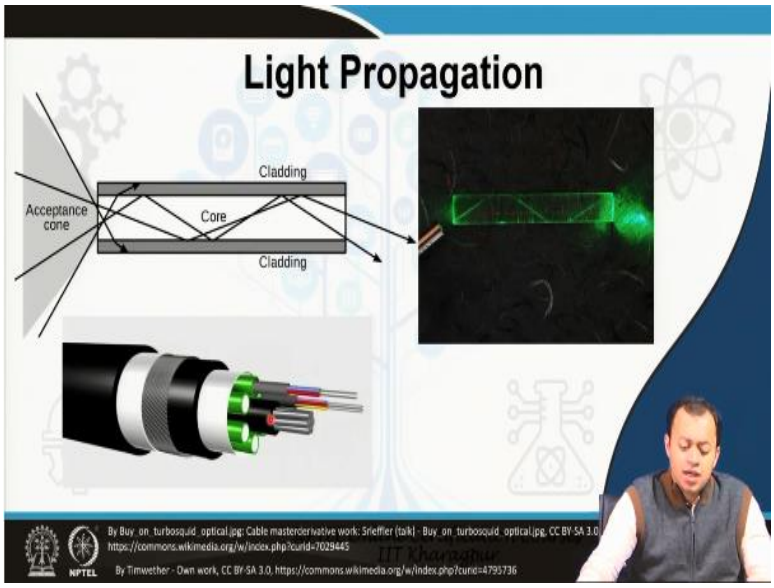

So, this is how, this is a depiction like that, this is an acrylic fiber and you have sent a laser light and you see it simply bounces of its surface and go through without any of the light going to the surface or very minimum amount of light going to the surface, this is a typical real-life example. So, if this laser light contains some sort of an information at the input that information could be decoded or received at the output.

So, this is how light propagates and obviously we have now made it much more complicated there are several jackets several buffers and there are more than one attached together and these are multimode fiber meaning, multiple amount of light, multiple modes of light, multiple type of signals can either be carried in the same core or multiple cores or separate cores, one could be used for transmission, one could be asked for reception. So, this humble thing has become much, much more complicated and very common, very easy.

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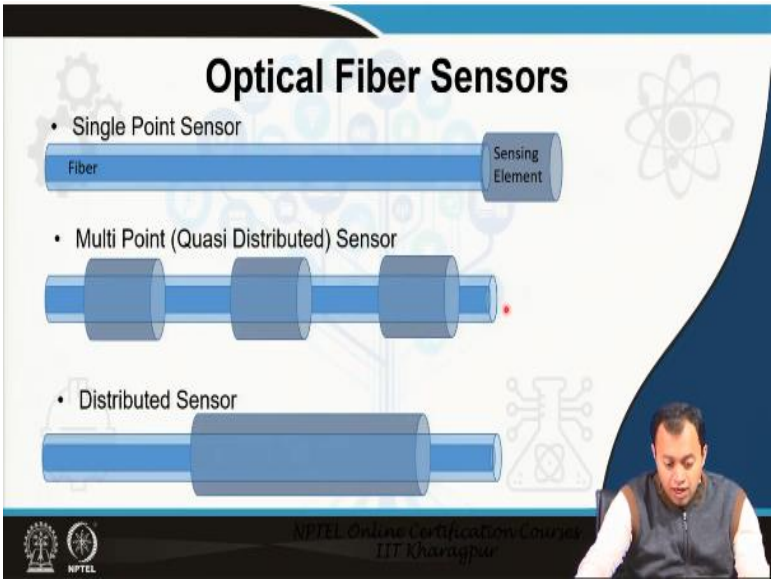

So, how does that have to do anything with sensing, biosensor? Now, believe you me, optical fibers were first used as sensors before they were used to transmit data. I am not joking, this is what it is in 1950s I think Narinder Kapany was the first person along with his colleagues in Imperial College London who use these optical fibers to send some kind of images at a distance of 75 centimeters, how big is 75 centimeters think about it, to send images from that. Now, we have transatlantic cable connecting Europe to America to Asia to Japan and Australia and what not.

In the 1950s they sent the signal, they sent images by 75 centimeters, then it was immediately used is endoscopy, endoscopy we consider it as imaging or sensing. Only during the late 60s, 65 onwards German researchers started utilizing it for sending data, sending data and now as I said transatlantic cable you are getting your internet, you are able to see this lecture all through this optical fiber. So, how do we use this as a sensor?

Well basically either single point or multi point or distributed sensor, where one end or multiple ends or the entire area of the optical fiber is coated or covered with a sensing element. Remember, sensing element from last class, if this is the transducer, this could be the biorecognition unit and the biorecognition unit can be attached either at the end, so that input versus output has a change or simultaneously at different points they all attaches different structures, they are all specific for specific analytes and then you have the output coming up.

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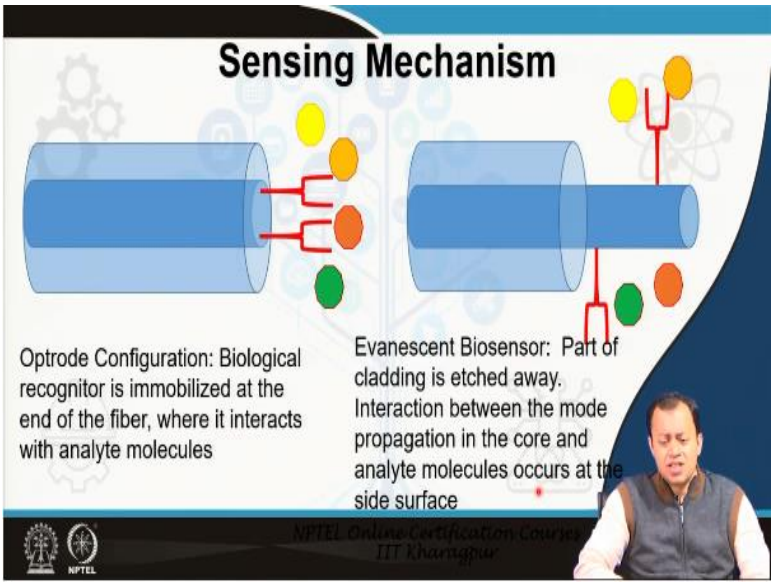

I will give you a bit more detail on the sensing mechanism part, what is the sensing mechanism, you have first the Optrode Configuration. The one which I showed single point, where the output you have put these kinds of antibodies, these kinds of immobilizer, these kinds of biorecognition units which are specific to a specific pathogen or an analyte only and when these gets attached there is a change in the overall refractive index.

Previously it was just air or previously it was just air plus this, now it was air plus this plus this and there will be a change in your light, change in your output data from before and after. Biological recognitor say an antibody is immobilized at the end of the fiber where it interacts with analyte molecules and these are very specific, they will only attach to a specific molecule and thereby change rest of them might sit some amount of agitation will throw them away, this will be attached and rest will go away.

Or you have evanescence biosensor where instead of the end you have put it at the side, you have stripped a part of the core, the light is moving some amount of light there will be an evanescence field, this is the near field that I discussed. Remember, evanescence field or near field, this near field will be interacting with this particular immobilizer, these particular antibodies which have attached or not attached and thereby you see a difference in the light propagation, difference in input light versus output light in normal circumstances, in normal circumstances.

As I said there is no difference between input light and output light, input frequency and output frequency. There is the delta lambda, lambda 1 minus lambda 2 is very, very little. Now, there is a change in refractive index because of the presence of analyte, because of the presence of the molecule, because of the presence of the virus, because of presence of the pathogen, antigen and thereby there is a change in refractive index, that refractive index results in change in frequency, that frequency is monitored, input versus output and you are seeing what exactly is going on, as simple as that.

They are very, very common, very, very ubiquitous, most optical biosensors these days are making optical fiber-based sensing sensors. So, they are pretty common, most sensor you find optical sensors are optical fiber based but we are trying to modify, we are trying to go for further more selectivity, further more sensitivity etcetera.

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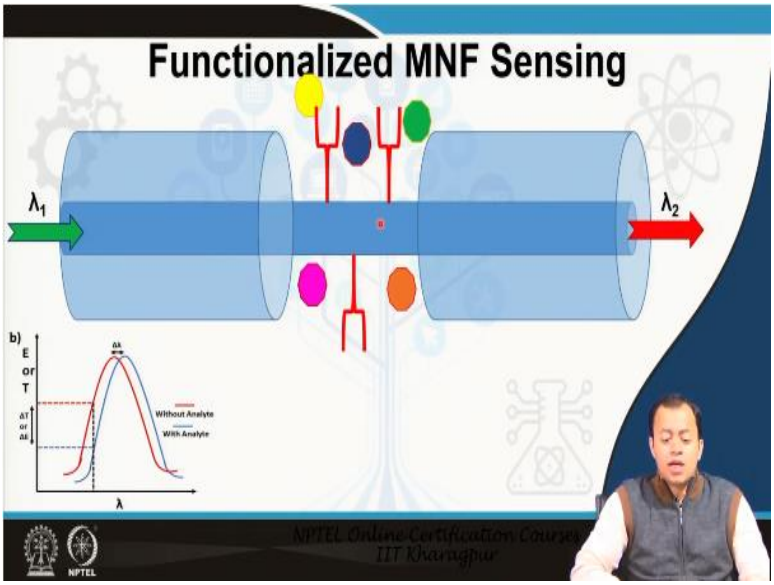

Easy example is that MNF sensing, its micro nano fibers so do not worry too much about that. Micro nano means the diameter is smaller than the, diameter of the core is much smaller than your regular fiber. So, you strip a part of the cladding, it obviously will induce noise, there is a reason why the cladding is put but bear with me.

You put antibodies here, these antibodies will upon attachment with a particular antigen, the light previously traveling through this will undergo a difference light travelling through this because

there is a refractive index change from this to this and lambda 2 will come up, lambda 2 minus lambda 1 is delta lambda and this delta lambda is what it is you are measuring.

Remember, this graph from your previous lecture, this is very, very common, this is how it is, there is no such complication as such. You put your immobilizer either here or at the side and there is a shift in the frequency lambda 1 versus lambda 2 and that difference lambda 1 minus lambda 2, delta lambda is what it is measured and directed and analyzed and thereby you are detecting a particular set of analytes, particular set of molecules.

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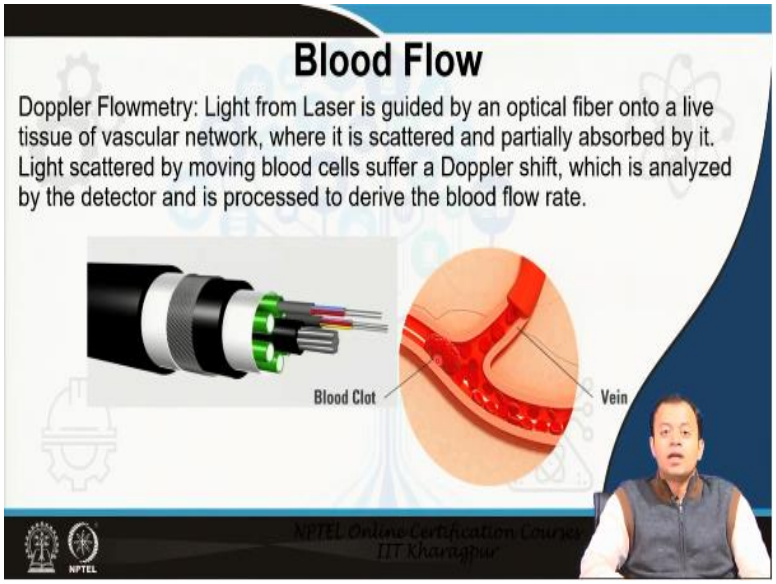

A very common example is where we utilize optical fibers for detection of blood flow. Now, this is not as common as pulse oximeter where we use those devices to detect the oxygen saturation of your blood. This is there using Doppler Flowmetry to detect blood clot or I think medical students call it thrombus. So, sometimes your blood clot if it is a wound and your blood is coagulating, the fibrous protein, fibrin proteins are coagulating its fine, your cut has been sealed and thereby the internal mechanism keeps on happening.

But the same clot, same combination of clot happens inside your artery or in your vein, you have a chance of a heart attack, that is why they ask you not to eat highly fatty foods or cholesterol is increasing because that causes clogging of your arteries and they are a different thing lipids and

fats but similarly, your blood can also clot internally in your veins, in your artery and thereby restrict the overall flow of blood.

We detect it using an optical fiber biosensor, how we utilize Doppler Flowmetry, we utilize Doppler effect. What is Doppler effect? All of you know high school physics again, if this is a source of frequency and this is the observer, this is a source of frequency this sends a signal of a particular frequency, particular energy, particular wavelength a signal, what is the difference between signal and wave again? Wave contains signal plus noise, may contain, signal is pure signal, we are ignoring the part of the noise here.

So, this is a source which gives signal and this is your observer, the observer is getting the signal and deriving its frequency, energy etcetera, but if the source is not constant but moving, then there is a shift in the frequency, there is a shift in the pitch that the observer gets depending on the relative distance of the source vis-a-vis the observer. It further gets complicated when the observer is also moving, this is sending signal with a particular constant frequency, no problem, but this is not static, the source is moving and the observe is also moving.

The shift in the overall original frequency we call it Doppler shift and this is very common in astronomy where we try to measure the signal coming from distance stars, distance galaxies, quasars, pulsars etcetera. Why? Because the star, the galaxy is also moving and you, the observer on planet earth is also moving.

We see this normally here say you are standing at a particular place in the road and a car is honking its horn and monotonously driving, you hear the pitch of the horn differently if the car is away from you, different pitch you observe or you hear when the car is close to you. Why? Because the horns frequencies remain same, the horns frequency remains same it has not changed, but when it was previously, when it was far away from you, the wave front that is creating takes more time to reach you, more time less frequency, less energy, energy is lost.

When it is closer to you, when it is equally close to you the wave front takes less time to reach you. So, thereby frequency is high, thereby we talk about this Doppler shift or we talk about red shift or blue shift, when something moves away from there is a red shift, meaning there is a loss of energy, red shift means it goes into the red part of the visible spectrum, red color you know

larger wavelength lower frequency or when something comes closer to me it is a blue shift, blue as in smaller wavelength high frequency.

So, by that Doppler effect, radar and everything all of that uses this Doppler effect, you must have known or must have heard what Doppler shift is, Doppler effect the change in the pitch of the frequency depending on the relative position of the source of the signal, of the frequency vis-a-vis the observer. I think Christian Doppler, Austrian physicist first proved this and he did a very nice experiment.

He put an orchestra, a group of people who plays band on a train and the train was supposed to go from station a to station b, he put observer onto the platform, onto the station and the person and the orchestra needs to make that music of a specific, they will, they were asked not to change but as the train was moving, coming towards them people who were standing in the platform were going away from the platform they could hear a change in the pitch of the frequency though the people the orchestra the musicians on the train were not changing their note.

And thereby this particular phenomenon, this is a fascinating story, I will not go too much into it because I read complaints that I am discussing too much about the lives of scientists, so some people like it some people do not like it. So, it is fine but how do we utilize it in medical field? We utilize it for detection of blood clots, thrombus.

So, you have a vein which has these red blood cells, they are constantly moving and you have a blood clot, this is a clot and hence it is not moving and you subject it to some kind of an optical fiber-based laser light. The laser light is guided onto the area of your tissue or the vascular network or basically an artery. The laser light, partially it gets absorbed, fine, you check for the oxygen saturation and what not and some of it will be scattered, some of it will be scattered.

So, the light scattered by the moving blood cell will suffer a Doppler shift, so the blood cells are continuously moving, consider this as a car, this is an observer. So, they are constantly moving, so thereby they will have a Doppler shift, if they are moving away there will be a red shift, if they are coming towards the source there will be a blue shift, but there will be no shift if it is constant, there will be no shift if there is a blood clot.

So, imagine this thing as an endoscopy, imagine this thing is an endoscopy you know from endoscopy that optical fibers are used for imaging and what not because they are very small and they could be put, keyhole surgery you make a hole and then insert it or if it is already an orifice inside our human mouth you can simply put it and you are, you want to see some kind of a blood clot somewhere, somewhere an internal bleeding has happened, somewhere something has happened and you want to see it with this, you do not need to open it up, you do not need to open it up you are simply inserting a very, very thin fiber.

The fibers can be very thin I told you 5 micrometer, 2 micrometer like the capillaries of your blood and then you monitor the Doppler shift encountered or the Doppler shift provided by the moving blood cells, this moving part is important, the blood this part is constant this is somewhere here, the blood cells are moving either towards it or away from it and thereby it shows some kind of a Doppler shift, either red shift or blue shift coming towards you or coming away from you.

As long as they are moving it is fine, but if you see there is a no shift in the frequency, there is no shift in the scattering of light which will be then, so if this is the input light this could be used as an output light, these are the output signal, these are the input signals so the light that gets scattered can be returned back here. So, this is the input light that gets scattered by this and returned back.

The scattering part is then analyzed and if there is no change in the frequency you think something is wrong, this is a fascinating way, a real life, real practical example of where you are able to detect blood clot, where you are possibly suspecting. And obviously since, there are so many of these, so many of these fibers you can do so many different things, not only just detect the blood clot but from the scattering you can see some amount of absorption.

So, how much amount of oxygen has been absorbed, pulse oximetry you can see, you can see if this blood clot is because of a foreign body, because they have a specific vibration, they have specific absorption they are made up of blood and fibrous protein, fibrin protein but if you see something else have come up is this thrombosis caused by an external source.

All of this can now be detected, this is a real-life practical example of your optical fiber acting as a blood clot sensor. My question, what is the immobilizer here, what is the biorecognition unit here, what is the transducer, what is the display and what is the analyte, can you tell me, if you know it please answer in the forum, the forum has become very popular, if you are not using it you are missing something utilize the forum, if you do not have any questions to ask still go to the forum and see the questions being asked by students and I am every day learning more from the questions that you are asking.

So, I would ask you to go into the forum and answer me in this particular example. See this has to be active this cannot be passive, I am not a news network or a channel which is entertaining you, which is a one-way traffic giving you information and you are passively listening. You have to give me some amount of input, the forum is a very good such mechanism in which I can have a two-way traffic. In this particular case, let me repeat my question, what is the analyte, what is the biorecognition unit and what is the display.

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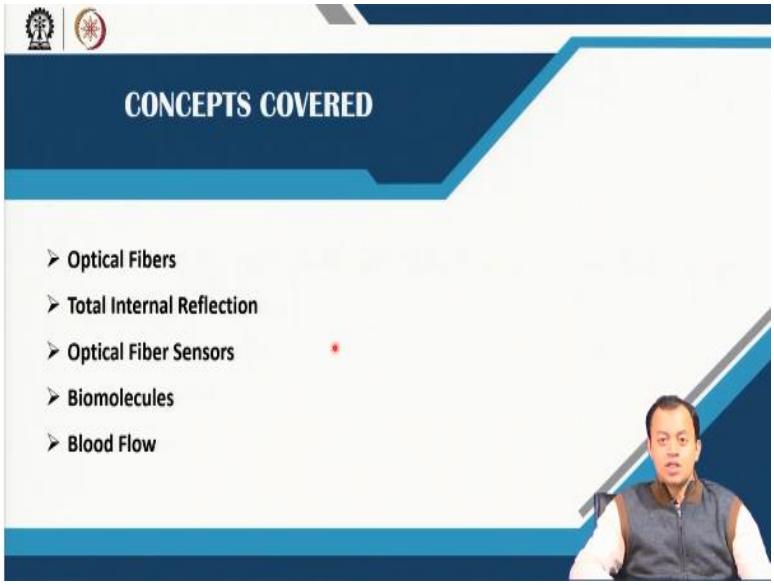

So, these are the concepts that I covered for today.

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And this is my reference. I am extremely grateful and I am biased obviously towards this gentleman Richard Michael De La Rue, he happens to be my PhD supervisor and I am obviously using his book and I am so very grateful to be his student and to learn from him and this is a fascinating book I am not saying that because it is written by my supervisor but because it is a fascinating book and obviously professor Prasad's book is constant companion of mine as well. So, thank you, thank you very much we will continue our studies in the next class. Thank you.