Optical Sensors
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Lecture – 18
Interference, Diffraction and Optical Fiber Sensors
Fabry Perot Sensors, Diffraction Gratings, XRD, FBG, Multichannel & Distributed Sensing

Welcome to Lecture 18 of Optical Sensors course. In the last lecture, we studied Interference. In particular we studied what is Michelson interferometer and what is Mach-Zehnder interferometer, and we used it for sensing applications. There we also introduced one very interesting application of Michelson interferometer that was Fourier transform spectroscopy and from there we saw that how Fourier transform infrared spectroscopy works.

And, why we work in infrared because you have water absorption band there and then there are many beautiful optical properties. Today, we are going to study more on Interference. Today, we will see what Fabry-Pérot interferometer is and how we use it for sensing; then, we will briefly discuss what diffraction is and then there can be different kinds of diffraction and I will choose couple of them for sensing and then we will see various optical fiber sensors also.

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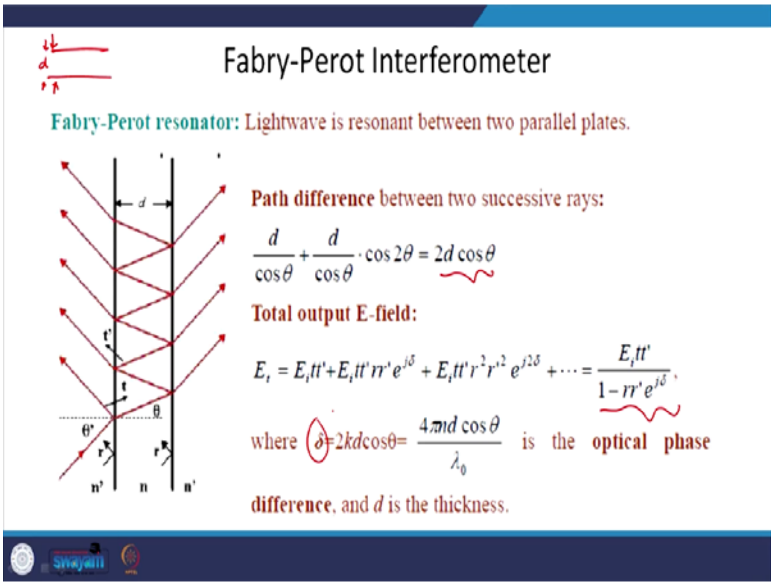

If you see a Fabry-Pérot interferometer, basically this is a thin film which has two mirrors facing each other and when a ray of light enters to it, it gets partially reflected from one boundary and then transmitted through the medium and then again back and forth reflections. We have solved these kinds of equations, if you remember, for one reflection, we solved it for the Fresnel equations.

Because of multiple reflections, you have an interference pattern which is - again it is if you remember for a Michelson we used to have this thickness between the mirrors was approximately d and then we used to have a fringe pattern. Here there are multiple reflections. So, we will have a similar kind of fringe pattern, but it will have more contrast and visibility because it has a greater number of reflections.

If you consider the path difference between two successive rays - say, this one and this one, then it is 2d cos theta. The output field - total output field at E can be given by this relation which is a function of this delta; delta is the phase difference. If you remember that if the delta is multiple of 2m pi that is it is in phase, then you will have constructive interference. If delta is an odd integral multiple like 2m plus 1 pi, then you will have destructive interference. That is how you how you work with it.

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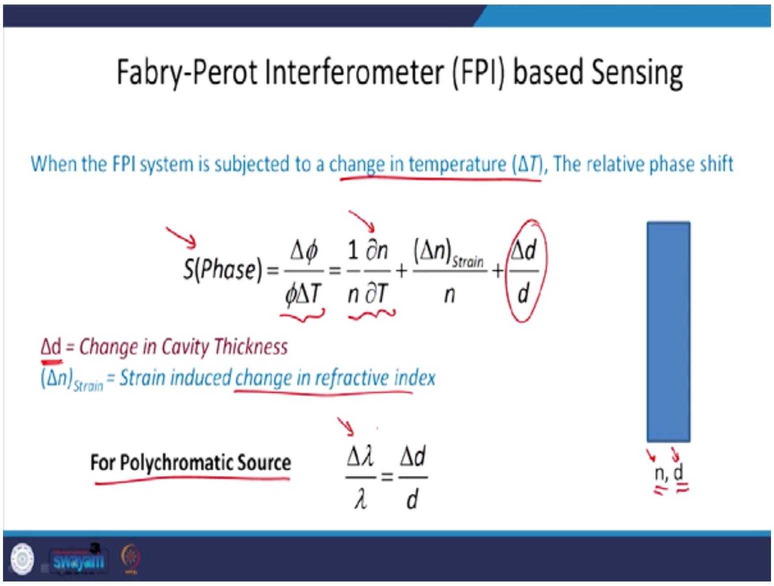

How we use it for sensing that is what we want to focus on. If we have, say a thin film which has refractive index n and thickness d, what can we do - what things can we do? Then here is - either you change the refractive index, or you change the thickness.

Anything which leads to change in n or anything which leads to change in d will basically get transformed into the output fringe pattern and then you can easily determine that what was the factor and how much was the factor which affected this parameter. Let us take an example of change in temperature and you see that the relative phase shift can be defined by this.

So, what it will do? It will lead to slight changes in reflective index with respect to temperature that is due to thermo-optic coefficient. If you remember - you can go and see the definition - this is called thermo-optic coefficient. What happens then? It will lead to change in the thickness of the film. So, if you have a small change into the film thickness and then you have a change in refractive index, there will be strain and that strain will induce refractive index change. So, these are the things you have to consider while you are considering the change in phase difference.

If you use if you want to simplify it and say that there is not much change in this and this parameter, all you know is that for a polychromatic source, the change in, say, delta d is proportional to change in delta lambda. We will come to that and I will show you how it works as a sensor.

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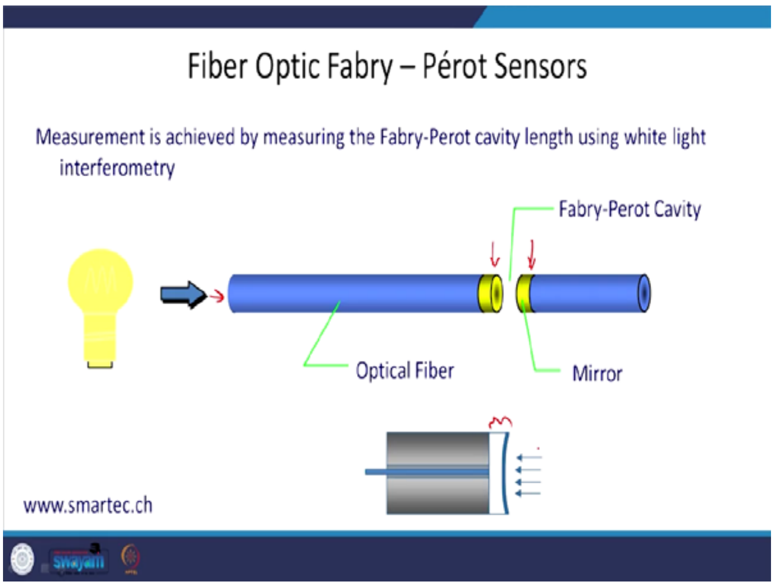

If you want to use fiber optics for Fabry-Pérot sensors, you can have a couple of configurations. One of the configurations is that you place two small pieces of this optical fiber where light can be incident through this end, and it is the polychromatic light. And, then you have these coatings of, you know, metals so that it becomes kind of mirror; you can also have something called fiber Bragg gratings, we will come to that. And, then this small space works as a Fabry-Pérot cavity.

Other way - what you can do is that you do a small coating of Fabry-Pérot cavity on the tip of optical fiber. For example, if you apply pressure on, say, - if it is a polymer then it will get, you know, pressed and then it will lead to change in the thickness of the cavity and then it can be transformed into sensing application with respect to pressure.

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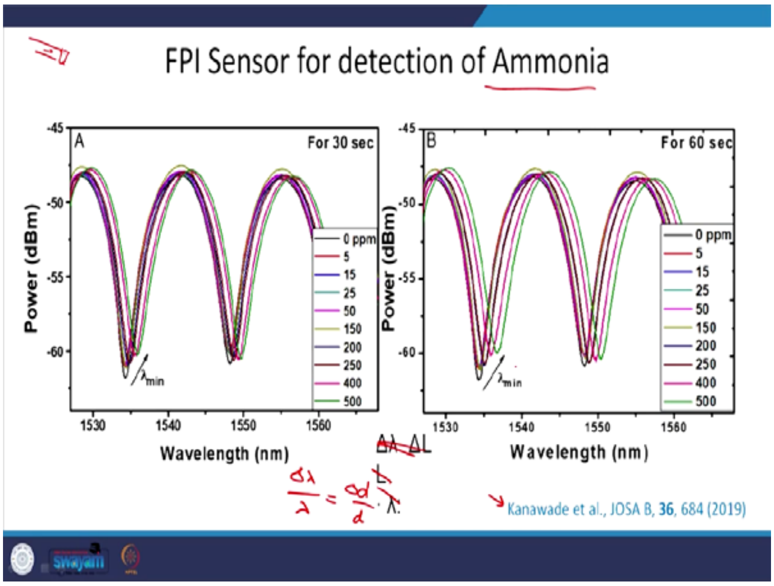

Let us take a one example here. We have from this work - we can show that this can be used for detection of ammonia. What they did is that on the tip of optical fiber which was sending collimated light they put a polymer layer of PDMS and they expose to various concentrations of ammonia, say from 0 to a 500 ppm and for 30 seconds, you can see that the interference fringe shows a shift in wavelength. And, this wavelength - actually it should not have been here - delta lambda by lambda is actually delta d by d, if you remember. So, from there you can always calculate what is d.

If they keep it for 60 seconds, you can see that the interaction is large amount - for larger time and then the shift is larger, but if you calculate the sensitivity it does not make much difference there, ok. The more amount of time you put it the better you see the change. So, if you do not have a much sensitive spectrometer what you do is that you increase the interaction time, so that you can see how much change in wavelength occurred with respect to change in the concentration of ammonia.

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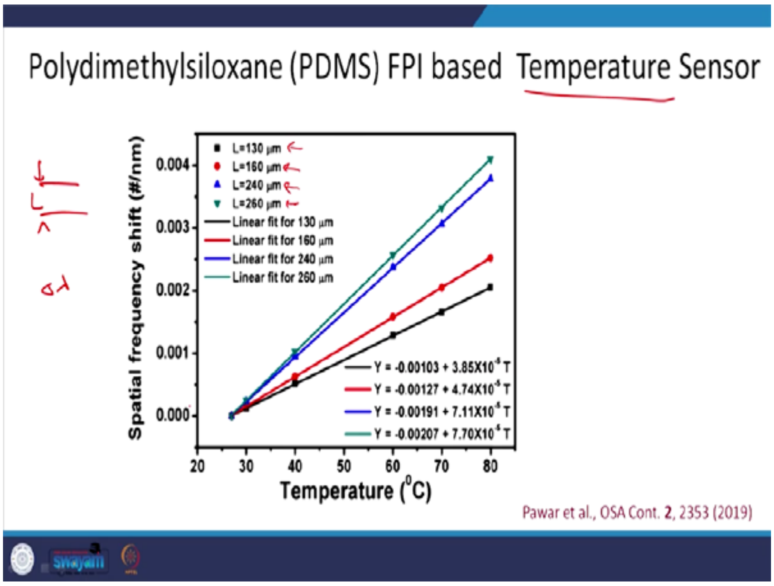

Here I will show you another sensor which is a temperature sensor on similar kind of structure. What you see is that for different thicknesses of this cavity - L is the thickness of the cavity. You can see that for different thicknesses, it shows shift in wavelength that is delta lambda basically and you can see that with an increase in temperature, there is a red shift. That is how you can use it for sensing applications.

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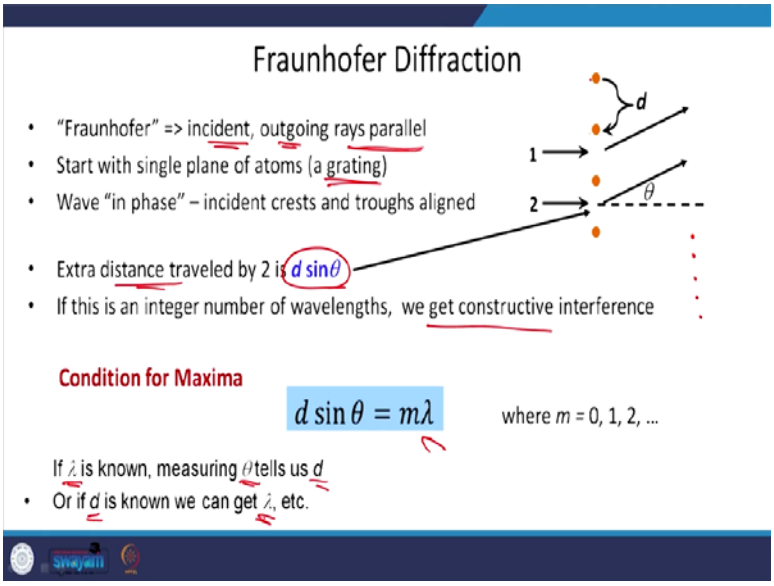

Let us come to diffraction. You know there are two kinds of diffraction. Diffraction is like encroachment of light within the boundaries of geometrical shadow region. It is an intrinsic property of a beam of light. Even if you do not have any medium, say, even if the light is traveling in vacuum, it has a tendency that it will diffract. It will either diverge or converge from the area of its geometrical region - that is the width of the beam. So, it will either increase or decrease. It is a natural tendency of light.

There are two ways to study this kind of phenomena: one is Fresnel diffraction, another one is Fraunhofer diffraction. We will consider here Fraunhofer, because mathematical treatment is quite easy. In Fraunhofer diffraction, you have incident and outgoing rays parallel; that means, they are coming from infinity. So, it is like that the source and the diffracting aperture they are kept at infinite distance and then same for the observer case.

We can consider it like a plane of atoms or maybe grating. Let us say grating first. And if the waves coming out of these apertures - diffracted from these - if they are in phase, then you have maximum. If they are out of phase, you have minimum. For example, here we are considering two rays, 1 and 2 getting diffracted by a series of atoms maybe and, they are displaced - they are put at a distance d.

What happens actually - that after the diffraction, suppose I am measuring at angle theta, then condition for maxima is d sin theta is equal to m lambda. What happens actually that the ray 2 has to travel some extra distance - that is d sin theta; and if it is an integral number of wavelength because we have to have waves in phase, you will have constructive interference. That is the condition for maxima. So, m are the orders of the diffraction. If lambda is known, measuring theta will tell us how much d is or if d is known, you can get lambda. So, both way - I mean, we will see how it can be used for sensing.

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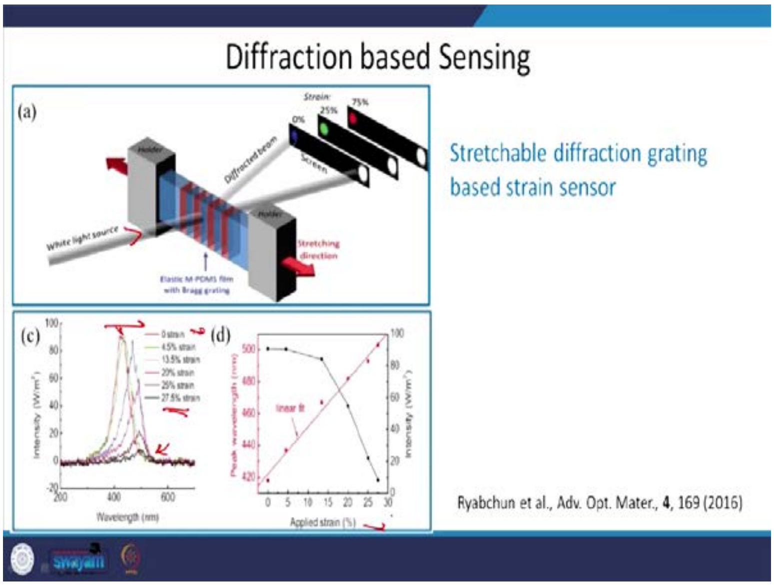

Let us take this example - where there is an elastic grating. It has a periodic variation of refractive indices which is shown here by different colors. So, red one and the green, blue one and then a white light beam is incident on this grating; what will happen? So, you will have diffracted beam on certain screen and then - it will be a function of stretching. So, what you can see here that with zero strain you see the red curve and then for 27.5 percent strain, it shows this curve - the black one.

It continuously shows a red shift and also decreases in power, but you can see here that as a function of applied strain, the peak wavelength - the red one, it shows an increase; while the black one - it shows the decrease in intensity. So, if you know lambda, you can have d. This particular thing - it is stretchable diffraction grating based strain sensor. Here you are applying a strain - basically you are changing d; you are controlling d and for different d you have different lambda maximum for the same order of diffraction and that is how you use it for sensing application.

Let us consider what is X-ray diffraction. You know X-rays have wavelength around 10 to power minus 10 meter and that is comparable to atomic sizes and spacings.

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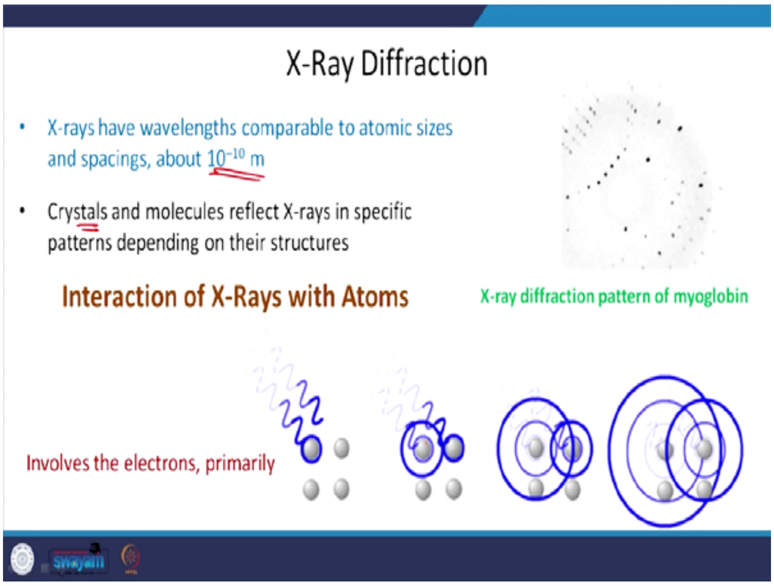

For example, I have shown here X-ray diffraction spectrum of myoglobin and what happens actually that these crystals and molecules reflect X-rays in a specific pattern depending on their structure. If you have an atom, there are basically electrons and it comes and interacts with these electrons. It can either expel it to the outer cells and then again it comes back and gives the radiation. So, it is basically involvement of electrons, when you consider the interaction of X-rays with atoms.

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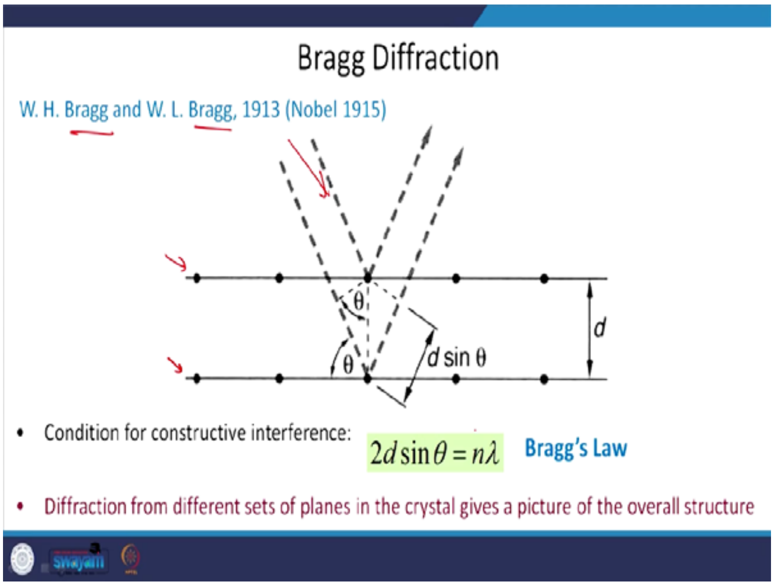

What happens is actually that - actually it is Bragg diffraction. It was first studied by W. H. Bragg and W. L. Bragg and they got a Nobel Prize in 1915. What happens actually that - if you have two atomic planes at a distance d, and the beam is incident at an angle theta, then you have 2d sin theta is equal to n lambda, where n is the order of, again, order of diffraction.

Diffraction from different sets of planes gives the picture of overall structure. For the same order of diffraction, you will have diffrent lambda values for different d - that is how it works.

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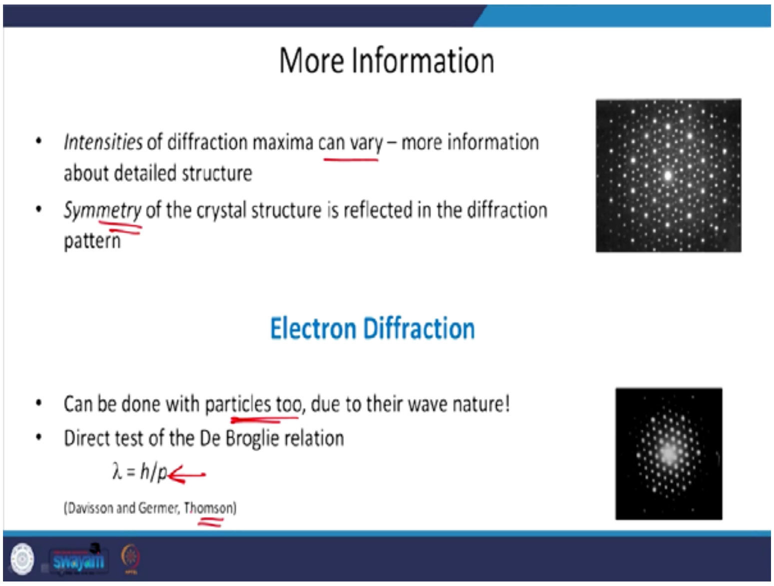

Intensities of diffraction maxima can also vary, and it gives more information about the detailed structure. Suppose sometimes the intensities will also vary and that will give you an exact information, we will come to that. And symmetry of the crystal is also reflected in the diffraction pattern.

Similarly, you can have electron diffraction. Diffraction can be done with particles too, due to their wave nature inherent - you know with the de Broglie waves. And this is given by direct test of the de Broglie relation. It was done by Davisson and Germer, and GP Thomson, who showed that electron is a wave.

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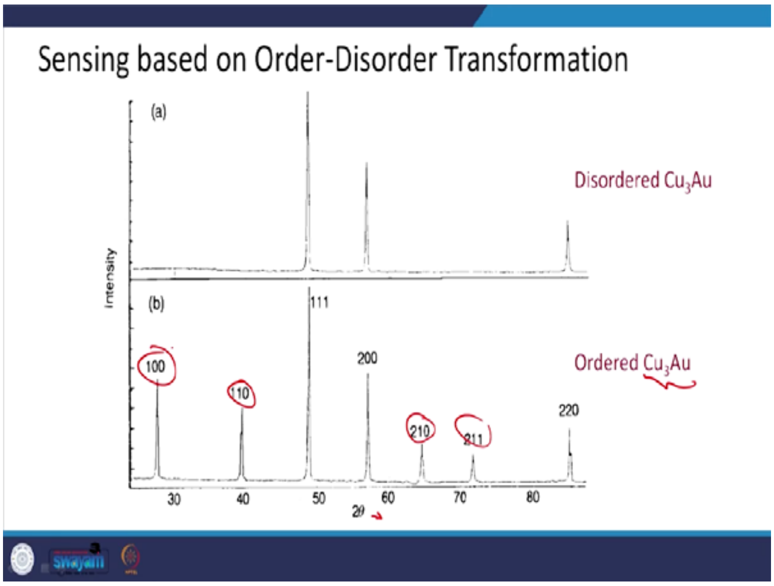

Let us see one case - sensing based on order-disorder transformation. I have this Cu 3 Au molecule, where you can see that for this compound these are the diffracted peak positions as a function of 2 theta. These are the XRD patterns. And when it becomes disordered, then these peaks disappear - you see. So, what it essentially means? It essentially means that you can use it for sensing application.

Suppose, there is a gas or say - let us say temperature. You can measure temperature by using this ON or OFF state - ordered or disordered state and also the degree of disorderedness will give you as a function of the measurand (Refer Time: 16:41) because the intensities - relative intensities will change. So, diffraction intensities will give you how much disorderedness is there; and if it is completely disordered system, then you will not have these peaks. If you have less disordered, then you will see these peaks in certain proportion. That is how you use it for sensing, ok.

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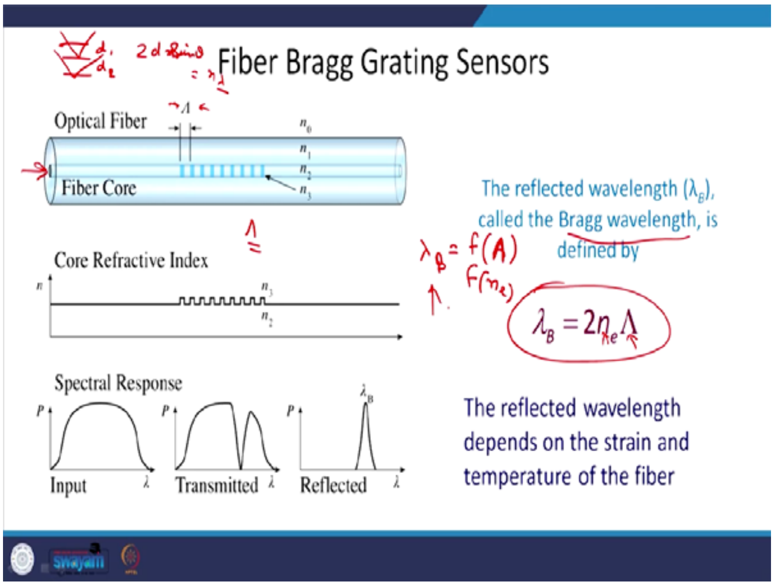

Fiber Bragg grating sensor: We saw Bragg diffraction and there we saw that if you had different layers placed at d 1, d 2, d 3 - something like this and then light comes and strikes like this, then we had this condition - 2d sin theta is equal to n lambda; or maybe you can say n lambda - something like this we saw. Here if you have refractive index, then there will be n term also.

This kind of this of structure with periodic variation in reflective index can be drawn in optical fiber also. You can see here a cartoon of an optical fiber Bragg grating and here what happens actually that the refractive index of core is modulated in such a way that it is shows a periodic variation. So, it goes high and low and high and low between one region that is called the pitch of this grating, given by capital lambda.

And, what happens actually when you shine light here? Then corresponding to this grating, if this condition is satisfied, where n e is the effective index of the medium around then you have - what happens that - if you shine with a polychromatic light, in the transmitted light you get a sharp dip or in the reflected one you get a sharp peak that is called Bragg wavelength and this is a characteristic of this grating period.

If, somehow, you change this capital lambda - lambda B is a function of capita lambda; also, it is a function of n e - refractive index here. So, if you vary this or this, - then you can have different lambda B, that is how it works for sensing.

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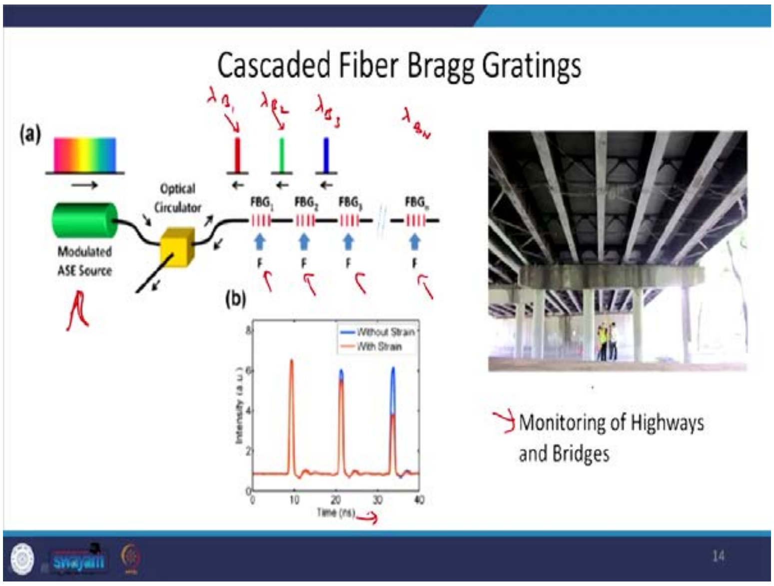

Suppose you apply pressure or temperature that leads to change in this grating parameter, then you will have different lambda that is lambda Bragg - Bragg wavelength and that will be for resonance. Now, suppose you cascade various fiber Bragg gratings, say 1, 2, 3 and n gratings like this, then what will happen if you send a pulse - polychromatic pulse and also we know that these have different spectral response. So, if lambda B 1, lambda B 2, lambda B 3 something like this; so, these are designed such in such a way that they will have different responses.

So, if you send a if you send a polychromatic light what will happen - that if there is a change at any of the gratings it can tell which of the gratings there was a change. You can also use a similar kind of fiber Bragg grating and then you send a pulse. So, depending on the time of flight in nanoseconds, you can say that where did the change occur. Suppose in this particular case, I have three peaks, and these correspond to different FBGs and now, I say that I applied more strain here, less strain here and no strain here. What will happen? You will see that changes with time.

These kinds of cascaded FBGs are generally employed in monitoring of highways and bridges. So, what you to do is that you put this FBGs sensor optical fiber and it keeps on online monitoring health of bridges and pressure on it, when lots of loaded trucks are moving through, then you can know what is the pressure and if it is good for these trucks to go at once or maybe you pause them accordingly. That is how you use it for cascaded Bragg grating sensors.

It means that you have multiple channels of sensing and you can also use it for multiple parameters, be it temperature or pressure.

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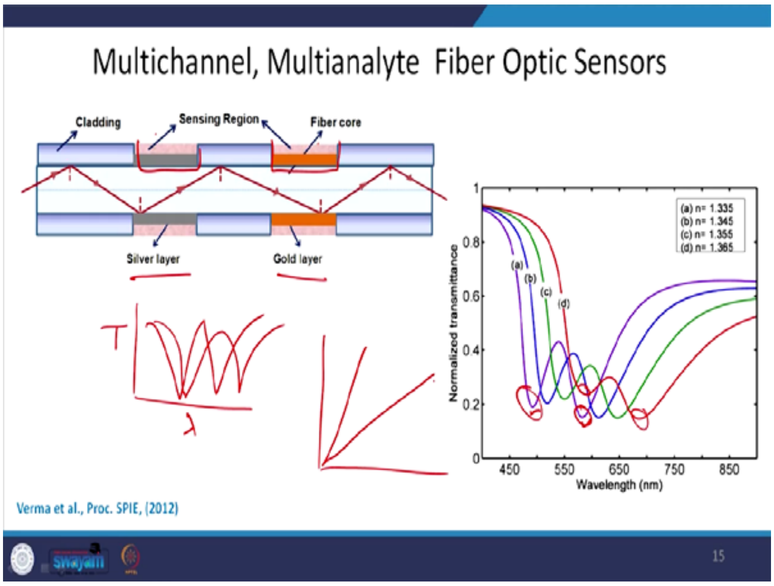

So, what you have to do is that at multiple segments of the optical fiber you make different sensors and then it works as a cascaded sensor or multichannel sensor or you can use it for multi-analyte sensing also. We are taking another example of an optical fiber SPR sensor. We already discussed what is SPR. We also discussed how to excite SPR in a fiber geometries.

In this particular case, what we are considering is that you take cladding out of two small regions from an optical fiber and then we do coating of different materials. So, for example, in this particular case we have done coating of silver and gold and these two works as sensing regions. We can put a sample here or here and it will show different response. So, in this particular case you can see that for putting the same solution in both the channels, it shows that this has two dips – one is here, one is here; for each refractive index value.

If I am considering (d), then you will have one here and one here, what does it mean? It means that this kind of multichannel sensor has two response curves - it is like this and if you change the refractive index, what happens is that both will show red shift differently. It has different curve, it has channel first maybe have this curve, channel 2 maybe have this curve. So, you can use this both for sensing applications in different regions.

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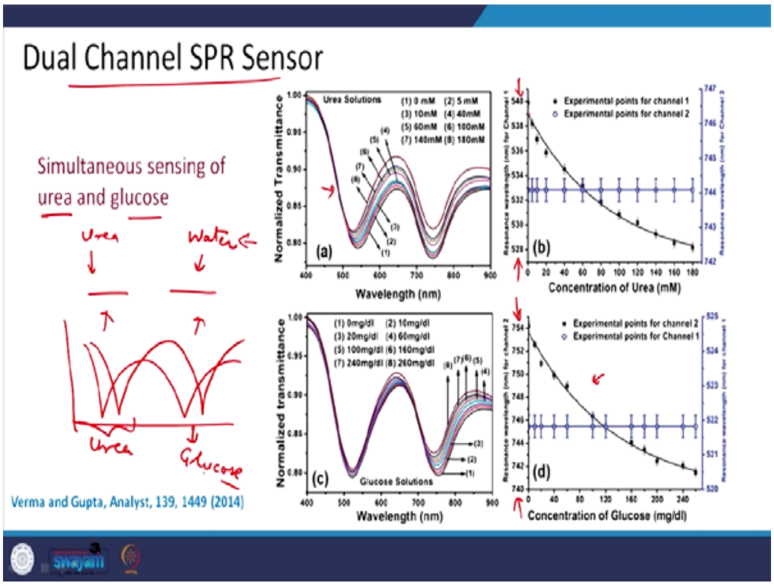

Let us take an example here. It is a dual channel SPR sensor and it does simultaneous sensing of urea and glucose. We have two channels as we discussed here. In one of the channels, let us say, that we put urea solution and in the other channel we do not put anything, what will happen? Let us say this is water only and urea here, what will happen?

You will get this kind of curve for different concentrations of urea and you can see that it shows a decrease or change, while in the second channel there is no shift with respect to change in concentration in the first one. If you do it other way, so, suppose you put glucose solution here and here you put water, same - this kind of curve.

So, these two channels are not talking to each other - one is responding to one kind of analyte, another one is responding to another kind of analyte. Now, suppose you use a mix solution, then they both will follow different characteristic curves. So, this characteristic curve - you can see that it varies from 540 to 528 nm, while this one is 744 to 740 nanometer. So, this means that you will have this one here and another one here. So, they do not talk to each other. So, this will show urea, here it with show glucose.

That is how you can have a cascaded - basically any two sensors together to form a multichannel or multianalyte sensor. Actually, when you make a sensor, this is something which is very important because if you make a real sensor no one wants to buy just one sensor. Say for example, if you want to have a water sensor, people are not just interested in detecting metal ions; they also want to detect if there are bacteria; they also want to detect if there are other compounds, which are not required.

So, all one has to do is that one has to integrate various sensors together to give you a complete analysis of a complex matrix of analytes. That is how you can achieve multichannel or sensing or multianalyte sensing.

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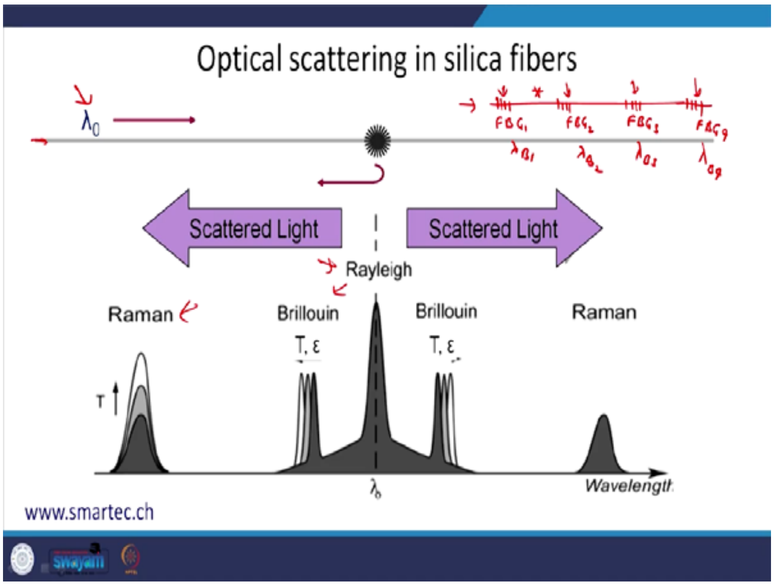

Optical scattering in optical silica fibers: we know that when light travels, say of wavelength a lambda 0, through an optical fiber what will happen that a small part of it will get scattered and back is scattered also. So, the scattered light will be everywhere, and we know that what kind of scattering can there occur. We already talked about Raman; it can also be Brillouin scattering, which is very close to - bands very close to - the incident wavelength.

And, we can use it for sensing application. We saw that when we had these cascaded gratings, say here and then here and then here and then here. Suppose, this is FBG 1, FBG 2 making this kind of structure is very complicated, it is not that easy. Why? Suppose, you are writing gratings and you want them to perform at desired wavelengths say lambda B 1, you want them to perform like this, and then fabrication tolerances do not allow you to make this kind of gratings all the time.

Also, suppose you sent a wavelength here and then something happened here, will it detect? No, it will detect any thing which is happening on these gratings, right! and Suppose, these gratings are 20 meters away, then between these 20 meters what happened can never be guessed. So, what is other way of doing it? Distributed sensing! What is that?

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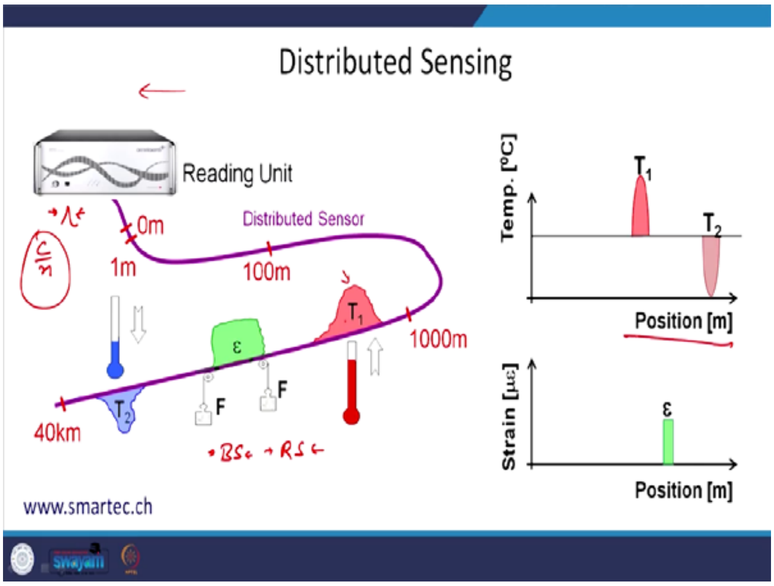

You have the reading unit and you have an optical fiber that is distributed sensor - at 0-meter, 1 meter, 100 meter, 1000 meters, 40 kilometers, you want to sense - say temperature and strain. Suppose, this temperature change occurred somewhere here, you do not know what the distance is. It is also possible then you send a pulse it shows that at this particular position, you have this much change in temperature.

Suppose, there is certain strain - a heavy person went there and stood on the optical fiber like that - what will happen? Certain weight - it will say at that particular position, there was a change in strain. Another change in temperature, at another place maybe it was cooled down; it was heated up - you will see like this. So, that is a distributed sensor. So, what it does actually is that you will study SBS - Brillouin scattering that called Brillouin scattering or Raman scattering, and you see these signals and analyze. What do you do is that you send a pulse of light and you know that a it is going with the speed of light that is c by n at that particular lambda. You can know when you send this pulse what will happen is that if there is a scattering from this point you will always get signals in the reflected one. Now, suppose you increase the temperature here what will happen? It will show a change in scattered light, right! And that you can measure that position of this change happening by measuring the time of flight. So, by time of flight you can say that what is the position; where this is occurring. That is how you work on distributed sensing.

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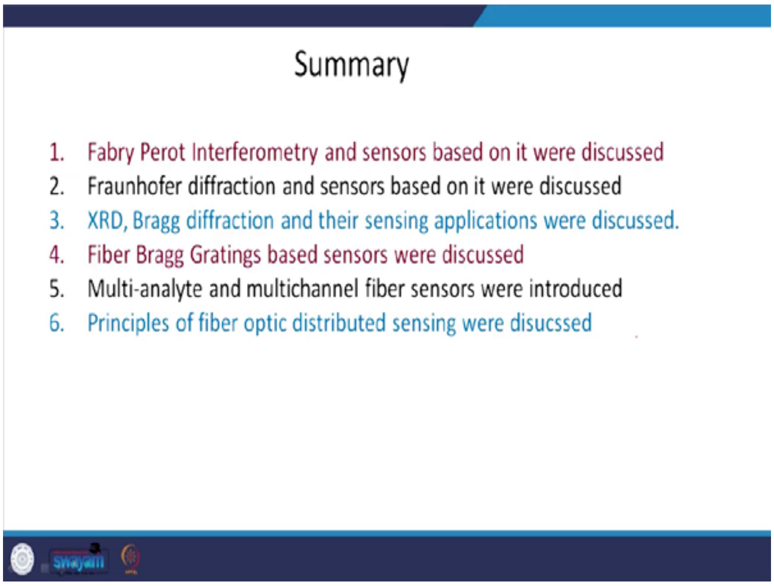

Let us summarize this talk. Today we studied what Fabry-Pérot interferometry is and how we use it for sensing applications. We also discussed briefly what Fraunhofer diffraction is and how we use it for sensing. Also, we saw XRD and Bragg diffraction and their sensing applications. We also discussed fiber Bragg gratings and how to cascade them to achieve a multi-sensor response and then we talked specifically about multi-analyte and multichannel fiber sensing using optical fiber configurations where we showed that two different spectral regions can be used for sensing different analytes on the same fiber - that is the beauty of fiber optic.

And, we discussed the principle of fiber optic distributed sensing and how it can be used for detection of pressure or temperature at various positions.

Thank you.