Optical Fiber Sensors
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Lecture No. 14
Amplitude modulated sensors – I

Hello. So, far we have been looking at different types of sensors. We started with just introducing different types of optical sensors and then we started looking at the essential components of an optical sensor that is the optical source and then the optical receiver, we looked at the typical characteristics of these sources and receivers and then went on to look into the design of a receiver in detail including some of the noise characteristics.

And recently we have been looking at mitigation of noise including lock-in detection is what we saw in the last lecture. So, with all these tools that we have procured the platform that we have set up now, we are ready to jump in and start designing sensors for various applications and various types of sensors like I said previously an optical sensor would consist of optical source.

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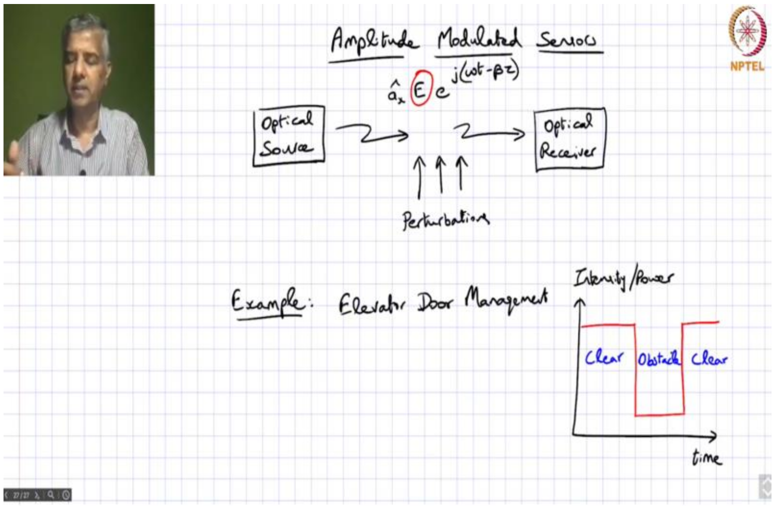

It is emits certain radiation which can be expressed in terms of an electromagnetic wave with certain polarization and then certain amplitude and then a certain phase with a certain frequency. This is what we looked at previously. Now this light could now undergo some or it could be subjected to some perturbations. And that introduces a certain modulation in in different properties of the light maybe in the polarization amplitude frequency and phase.

And then we said we will take this modulated light and use an optical receiver to convert this modulated light into some voltage signal. And based on the corresponding signal voltage signal we can actually learn something about the perturbations that were happening. So, the specific class of sensors that we will be looking at for the next few lectures are amplitude modulated sensor.

So, essentially we are saying we will look at only changes in the amplitude or more popularly you know you can look at it as the changes in intensity or intensity modulated sensors and essentially changes in the optical power. So, there are several examples of this and it is 1 of the relatively easier sensors to build because the optical receiver can clearly make out any changes in the intensity or the power that it is receiving.

So, if there are any changes in that it directly picks it up whereas, if you remember what we talked about previously if it is polarization or frequency or phase change then you need some demodulator before the optical receiver to pick it up. So, so that way you know it is straightforward case but then it does come with lot of associated baggage associated challenges. So, we will look at some of these challenges as we move on.

So, one example, one very simple example that you would have probably come across these days we have these elevators automatic elevators. So, you you get inside the elevator the door closes by itself and more importantly if you are in the way if you are between the doors it knows that you know some somebody something is obstructing and so it it does not try to close the door anymore, that is an essential component of this elevator. So, we are talking about elevator door management. So, what does it have to do in this case?

Well, it would have to measure at the receiver it would have to measure the intensity or power of the light that is that is coming through from the source as a function of time. And if it is you know normally there is no obstruction then you would have a high intensity. But if there is an obstacle between the path of the source and the receiver, then it goes to a minimum and then it stays low as long as that obstacle is in place. And then it goes back to a maximum once the obstacle is cleared. So, so we are talking about in this case there is a clear path in this case also there is a clear path but in this case there is an obstacle which essentially is cutting that light.

It is it is basically blocking that light and so you would see a corresponding change in the intensity. So, that is that is actually a very simple sensor to incorporate so you would see that in the door if you look closely on 1 side there will be some led which is illuminating the path across the door on the other side of the door you will see that there is actually a corresponding receiver, that is picking up this light. So, if you just get in between those two, then then the door should not close you know if it is programmed properly. So, that is actually a very simple example of a amplitude or intensity modulated sensor, so that is got some limited utility.

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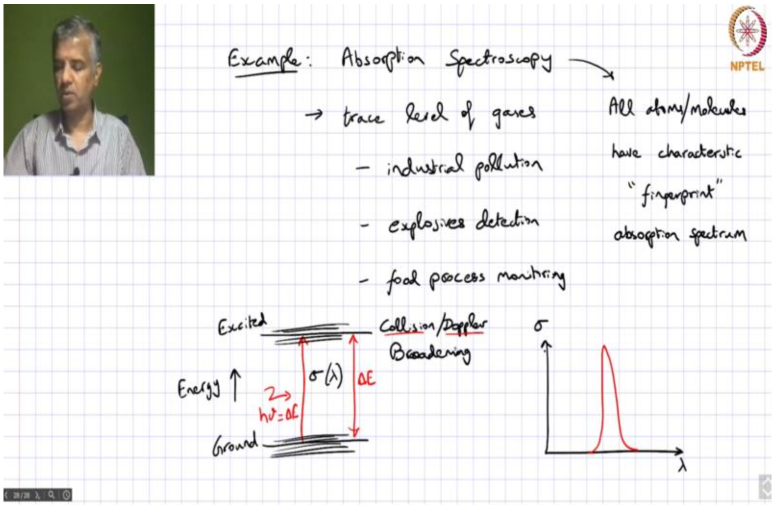

Example: Absorption Spectroscopy → All atoms/molecules have characteristic "fingerprint" absorption spectrum

→ trace level of gases
- industrial pollution
- explosives detection
- food process monitoring

But let us just look at a little more challenging example. So, a little more challenging example as in the case of, I will just use the other color. So, another example is absorption spectroscopy. So, why is absorption spectroscopy useful or where can it be used for? Well you can use it in a variety of manner. So, one possible thing is to use it to detect a trace level of gases ok, so trace level of gases. So, where is this useful?

Well, it could be useful in applications such as you know industrial pollution monitoring. So, you if you are setting up an industry and say the byproducts of whatever you are manufacturing are some toxic gases. So, there are some regulations which are saying that the whatever gas whatever output that you have from your chimney it should not be more than certain parts per million of a certain gas. So, there is some regulations also. So, you would have to put sensors there in the chimney which is also called as stack I think. So, you could you could actually pick up the gases you you are looking for very specific gases this pollutants and you are looking at the level of those pollutants. So, you that is that is 1 example.

And another example is in explosive detection. So, you might have say a bomb threat maybe at some place and then you want to look for you know trace levels of these constituents, let us say rdx or something like that you know. So, you want to pick up trace levels of that so that you can sense whether there is there is really a bomb in a particular place or not so some explosives detection is another common application of absorption spectroscopy.

And these days people use it for a lot of other cases also like in the food industry you want to actually monitor what are the kind of gases that are coming off while you process the food and that might actually decide whether the quality of the food that you are processing is good or not. So, there is a lot of applications I mean you can keep building on this but just gives you an exam some idea as to where these things would be useful for. Then the question is ok great it is it is useful for a lot of things and then how do you do that? And what is the basic principle behind absorption spectroscopy?

Well, the principle is this absorption spectroscopy relies on the fact that all atoms or molecules, all atoms or molecules have a specific or maybe I want to say have a characteristic which you may also want to call as a fingerprint. It is got a it is got a fingerprint in terms of this absorption spectrum. So, atoms or molecules have characteristic fingerprint absorption spectrum. So, just like we identify people by their fingerprints you could identify you know different atoms molecules in this case. We are looking at some trace level gases by fingerprint which is through their absorption spectrum. So, how does that how does that work?

Well when you consider an atom right it could it could have energy levels like this. Here we are plotting in terms of energy so this is like your ground level that could be like your valence orbital in your atom. And then at a certain higher energy you will have an excited level. So, this is actually typically like a metastable state. It goes to that other orbital it jumps from this orbital, an electron basically jumps from this orbital to this higher orbital and maybe it just holds there for a little while before it it gets processed into some other form of energy or maybe it will even re-emit at some point.

But the point is that this transition where it so this this transition is is happening whenever you have an incoming let us say photon for example with energy H new, such that H new is equal to delta e you say that this energy difference corresponds to delta e. Then it basically absorbs that photon energy and then it basically takes this electron from one of the valence orbital to a higher orbital.

So, that process is what we are calling as absorption and what we are saying is that different atoms molecules will have different locations of this excited energy level. And so it is it is almost like you cannot absolutely say no to atoms will have the same location of energy levels but it is almost like that. So, you have some unique structure of these energy levels that correspond to a particular atom or a molecule. And so if you can probe it with the wavelength of light or energy of light then you can actually have this absorption taking place. If it is not absorbed the light would have just gone straight through. So, it should not be absorbed it gets transmitted but because it is absorbed you lose light.

So, essentially if you had to make a sensor based on that you look at the output of this and you flood it flood this gas cell with so much so many photons or say so much intensity of light and then you look at what is the transmitted intensity and based on the level of the transmitted intensity you can possibly tell how much how many number of these atoms are present within that gas cell. So, that is what absorption spectroscopy is all about.

But before we go into such details which is also important to note that whenever we talk about a gas cell whenever we talk about a collection of atoms or molecules you never have a single level like this. You have these what are called this collision broadening and you have doppler broadening. So, you have collision or doppler broadening which actually makes this not a single transition.

But the transition could happen across a range of wavelengths. So, what we are talking about is if I am looking at let us say by the way so how do you characterize this probability of absorption that is characterized through what is called the transition cross section which is now a function of wavelength. So, if I were to plot the transition cross section as a function of wavelength it will look something like this.

Because of the fact that there is there is broadening of these energy levels like I said it is due to collision or doppler broadening. So, that sigma as a function of lambda we are saying is different for different atoms and molecules and that is what we are going to be using for absorption spectroscopy.

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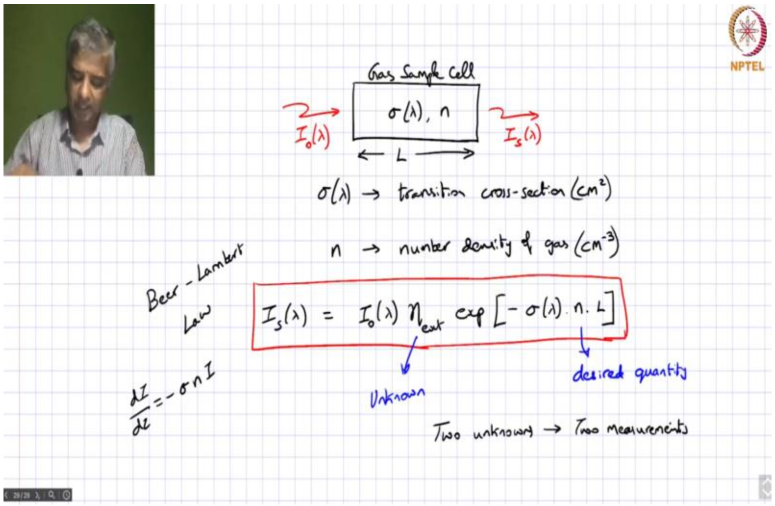

Gas Sample Cell

$I_0(\lambda)$ → $\sigma(\lambda)$, n → $I_s(\lambda)$

← L →

$\sigma(\lambda)$ → transition cross-section (cm^2)

n → number density of gas (cm^{-3})

Beer - Lambert Law

$$\boxed{I_s(\lambda) = I_0(\lambda)\, \eta_{ext} \exp\left[-\sigma(\lambda) . n . L\right]}$$

Unknown

desired quantity

$\frac{dI}{dz} = -\sigma n I$

Two unknowns → Two Measurements

So, let us look at one practical realization of a sensor based on absorption spectroscopy. So, what do you need as part of that? Well what you are looking at is basically a sample cell basically a gas sample cell which actually consists of some species some gas species let us say which has a transition cross section of sigma of lambda. And it also has certain number density so sigma of lambda corresponds to the transition cross section which is measured in terms of area.

It is like a area of cross section and n is the number density of the of the species that you are trying to of the gas species that you are trying to pick up and that is per unit volume. So, it is inverse centimeter cube that is that is the number density. And of course it could be of a certain length. So, now you say I am coming in with some intensity of light let them let me call this I naught of lambda.

And then I go out with a certain other intensity let us say IS of lambda. So, I know what is going in I can you know put a power meter for example to measure the power that is going in and then I can put the take the power meter and put it here and I can measure the power that is coming out and then of course I can relate write a relationship between the two. So, I would say that IS of lambda is given by I not of lambda. But that intensity that is going in not all of that is getting absorbed maybe some of the light is also getting scattered.

For example at the interface of the gas cell or because of some other impurities that are present within the gas cell there is a certain loss of photons so light is getting scattered and so on. So, you can represent that say as eta external that is basically the external that is the fraction of photons that are lost due to some external processes that has nothing to do with the absorption itself. And then of course you account for the absorption itself which is given as exponential of minus of sigma of lambda multiplied by for each one it is going through this transition cross section sigma multiplied by n where n is the number density multiplied by l so, this is happening across the entire length.

And why is it an exponential because this is what we call as Beer Lambert law which says that di over dz, let us say this is along the z direction di over dz, the rate at which the intensity is dropping across this thing so di over dz is minus of it is according to this sigma multiplied by n multiplied by the I the the intensity at any particular point. So, it drops as a rate of that so the solution for that would be an exponential. So, that is why we denote this entire thing as an exponential.

So, this is quite useful now to pick up so what exactly are we trying to find out we are trying to say this is my desired quantity that I want to measure. And so do I have enough measurements or enough do I know enough about all these quantities that I can pick up again. Let us look at each 1 of this in detail l, yes I do know what l is so I gone through the cell, I know what is the length of the cell, what is the interaction length essentially. So, I know l do I know sigma? If I am looking for a particular gas species I would have you know picked up a wavelength that is resonant for that particular gas species and not to any other gas species because cross sensitivity is very important. So, you do not want to have cross sensitivity.

So, you would pick a wavelength where only that particular gas is absorbing. So, if you have picked up the wavelength then what is sigma for that that particular gas species it is all sort of tabulated it is all well characterized and we can pick it off that. You know of course IS of lambda because that is what you are measuring at the output I naught of lambda that is the measurement you have done at the input.

So, you know all that but the problem for us is that this is actually an unknown quantity. So, you do not know how many of how many photons you are losing because of some external processes it has nothing to do with absorption because once again you are making a measurement at the output. You know that so many photons have been lost but you do not know what caused that loss. Because it could be because of absorption which comes in this exponential or it could be some other factor that is not related to the absorption.

So, that is typically the challenge as far as absorption spectroscopy is concerned. You have 2 unknowns and you are making only one measurement. So, how do you fix it? Well you just have to make 2 measurements. So, what we are saying is you have 2 unknowns here so you need to make 2 measurements. So, one measurement is this what about the other measurement?

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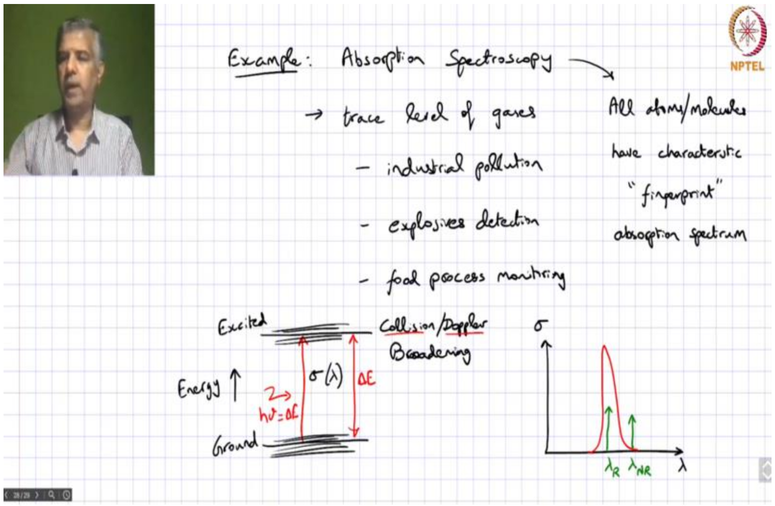

Example: Absorption Spectroscopy →

→ trace level of gases

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All atoms/molecules have characteristic "fingerprint" absorption spectrum

Well the other measurement could be something like this. So, 1 measurement you clearly want to do over here which is at a wavelength you can call that as lambda r that is the resonant wavelength. So, the that that is hitting this transitions in a resonant manner. So, that is lambda r but you could also make another measurement somewhere out here where it is non-resonant. Meaning this you do not expect any absorption happening or you expect only negligible absorption happening at that other wavelength. So, let us let us look at that. So, you are making 2 measurements and hopefully that should fix our problem.

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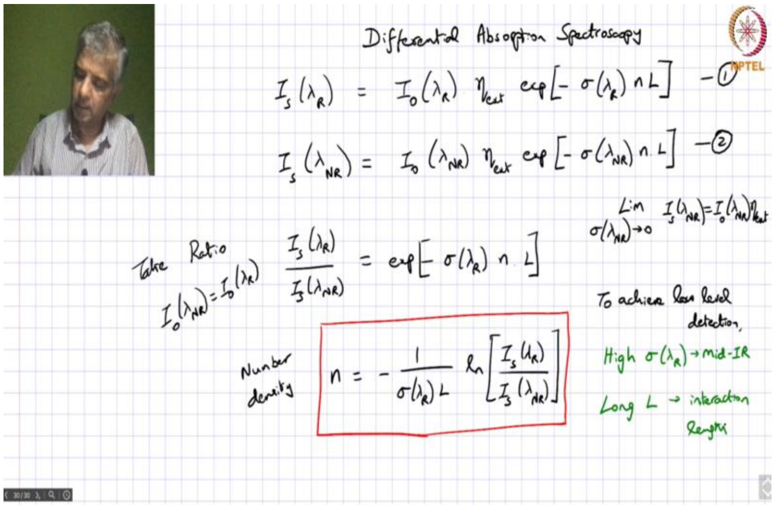

Differential Absorption Spectroscopy

$$I_s(\lambda_R) = I_0(\lambda_R)\,\eta_{ext}\exp[-\sigma(\lambda_R)\,n\,L] \quad -①$$

$$I_s(\lambda_{NR}) = I_0(\lambda_{NR})\,\eta_{ext}\exp[-\sigma(\lambda_{NR})\,n.L] \quad -②$$

$$\lim_{\sigma(\lambda_{NR})\to 0} I_s(\lambda_{NR}) = I_0(\lambda_{NR})\eta_{ext}$$

Take Ratio

$I_0(\lambda_{NR}) = I_0(\lambda_R)$

$$\frac{I_s(\lambda_R)}{I_s(\lambda_{NR})} = \exp[-\sigma(\lambda_R)\,n.L]$$

To achieve low level detection,

Number density

$$\boxed{n = -\frac{1}{\sigma(\lambda_R)L}\ln\left[\frac{I_s(\lambda_R)}{I_s(\lambda_{NR})}\right]}$$

High $\sigma(\lambda_R) \rightarrow$ mid-IR

Long L → interaction lengths

So, let us see if it does ok so let us first write out the expression for the resonant wavelength. So, that is going to be given by sorry that is happening at lambda r. So, I would say this is the output intensity that I am measuring at the resonant wavelength. And that is going to be given by whatever I had incident I naught or at lambda r multiplied by you have some losses which we are calling as eta external and multiplied by exponential of minus sigma.

But sigma you are measuring at lambda r right that corresponds to a peak of the resonance that you are trying to pick up. So, that that peak transition cross section is what you are having and then multiplied by whatever the gas species is the concentration of the gas species and multiplied by l. So, you make 1 measurement like this and then you go on you do not touch anything. All you do is let us say your source is tunable. So, what do I mean by that now we typically said we are using a semiconductor laser? Semiconductor lasers you are injecting some current and based on that you have a certain wavelength that it is oscillating at.

Now if you change the level of current the carrier density inside the semiconductor is changing and because of the change in carrier density the refractive index of the medium is changing. So, whenever the refractive index of the medium is changing there will be a corresponding change in the wavelength of light that is emitted. So, that is what we call as current tuning we did not talk much about it before but I am just giving you the that information so you could do something like that to tune to a non-resident wavelength.

So, what is the non-resonant wavelength coming back to this picture that is the wavelength at which there is negligible absorption that is happening. So, at that you have once again you need to make a measurement at the input. The external losses you expect them to be the same especially I mean this is important that the non-resonant wavelength is not something that is like you know 30 40 100 nanometers away. The non-resonant wavelength is like a very close wavelength so close that none of the other loss mechanisms are affected by that. So, that is the assumption here.

But the big change is that sigma of lambda nr is not as high because you are you are going off the resonance but other than that everything else remains the same. Now you can call this 1 and you can call this two. You basically take the ratio of 1 and two. So, you say IS of lambda r divided by IS of lambda nr that is going to be given by just the ratio of this. And let us just assume that for simplicity or I mean in practical application also is not too difficult that between the resonant wavelength and the non-resonant wavelength there is not much of a difference in terms of the intensity.

So, you take the ratio and have such that I not of lambda nr equal to I naught of lambda r. So, those 2 when you take the ratio those 2 cancel. And like we talked about this eta external if it is such a small difference in the wavelength that should not change so that should also cancel of this and then you look at this exponential this non resonant wavelength you can actually pick it such that in in in 1 limit that sigma goes to 0.

So, you pick it that the limit sigma of lambda nr goes to 0. It is it is almost at the end of the tail of the absorption peak in in in that limit what you get is IS of lambda nr. So, this goes to 0 it is just I naught of lambda nr multiplied by eta external. So, in in that limit you can make basically make that assumption and if that is the case then you have basically this ratio being equal to exponential of minus sigma of lambda r multiplied by n multiplied by l. And of course you can rearrange terms because what you are interested in the other day is the number density.

So, this is actually the number density of the gas species that you are interested in. So, that number density is now given by minus 1 over sigma of lambda r multiplied by l and then this would be lon of IS of lambda r divided by IS of lambda nr which of course corresponds to the output intensity that you are measuring for the 2 cases when lambda equal to lambda r and lambda equal to lambda nr.

So, you make those 2 measurements and based on those 2 measurements you can actually you know take out the uncertainty related to external losses and you can actually precisely pick up the number density of the the gas species that you are interested in. So, one thing to note here so that is that is actually so this this sort of a thing where we are actually doing 2 different measurements and we are relying on the differential absorption between these 2 measurements, so this technique is called differential absorption spectroscopy.

So, differential absorption spectroscopy is actually a fairly powerful method to achieve very high level of precision a very low level of this concentration you can pick up using this differential absorption spectroscopy. So, essentially to achieve low level detection low level basically trace level detection, we are talking about parts per million or in some cases even parts per billion. If you want to achieve that low level direction, what are the keys? We need clearly high value of because this is at the denominator high value of sigma of lambda r.

So, you want to pick up you want to use a wavelength where the absorption is very high for a given gas pieces. And it so happens that if you go towards the mid infrared and the far infrared those type of wavelengths there the absorption cross section for these gas pieces is much higher than what you see in near infrared or even visible radiation. So, it is actually a it would be a good idea to go to mid-air region because sources are becoming more and more available in the mid-air region.

So, you can go to mid-air region and thereby you can achieve high cross-sections and that enables you to do extremely low level detection like I said you can you truly achieve parts per billion type of sensitivity. And the other important aspect is you need to have long length so you need to have a long interaction length. So, it is basically saying the interaction length is is large. And that could possibly be enabled by going to a gas cell where it is not a single pass but even within a compact gas cell you have say a set of mirrors where the light could bounce maybe even

100 times before it goes out. So, if it if it goes through that goes across that sample cell 100 times it is it is actually the effective interaction length is 100 times more.

And that also helps in achieving 100 times more you know precision in in terms of your ability to pick up these gas species with very low level concentrations. So, so that is actually absorption spectroscopy and this is actually an excellent way of actually realizing an intensity modulated sensor and then picking up you know this this gas concentration. And this is actually the way I described it is like a free space technique where you send light out in a free space and then go through a gas cell and you can pick it up the same you could possibly realize in an optical fiber sensor as well.

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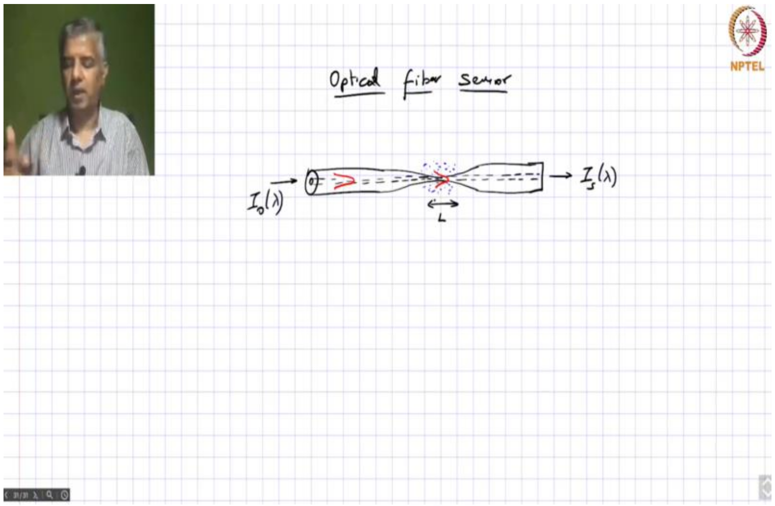

The way you can do that is in an optical fiber sensor so you could you could have a configuration like this. So, let us say this is your core and your cladding and you you go out like this and then maybe you could have the the fiber taper down. So, we will see what is the effect of tapering down but if you can get the fiber to taper down like this, so you are essentially going through the core region like this and that is also getting tapered down and then you are expanding out like this.

So, if you are looking at your optical mode the that that mode is mode profile is going to be something like this it is going to be primarily focused and confined in the core of the fiber but there is going to be this evidence and field. And when it comes to this region actually the evanescent field spills over spills out of the fiber. And in that region if you have these gas species then if your wavelength is correct if it is a the wavelength then it undergoes absorption and then whatever light that you get out the other end it is you once again you send I naught of lambda and you get out IS of lambda. And you do the same trick like this differential absorption spectroscopy you can do.

And you can actually try to you know measure that absorption you can I can try to do this differential absorption spectroscopy. But of course that is limited by your interaction length. So, that the interaction length may not be as large as the kind of lens that we are talking about with the gas cell. So, that might be a limitation of this technique but people are coming up with newer and newer ideas.

So, for example one of the ideas that we are presently exploring is the use of what are called whispering gallery modes. So, this whispering gallery modes are essentially modes that are propagating close to the periphery of this fiber and they can propagate just like what we said in a gas cell it is reflected multiple round trips sort of thing and then thing enhances the interaction length because of the fact that it actually propagates in sort of a helical faction and the period of the helix could be very short submicron period or close to micron period.

In those sort of cases even within a centimeter long interaction length you could actually improve the effective length of interaction by a factor of 1000 or even 10000 people have looked at. So, that actually gives us exciting pathways to realize an optical fiber sensor using based on differential absorption spectroscopy for trace gas level sensing. So, let us stop there.