Optical Fiber Sensors
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Lecture No. 15
Amplitude modulated sensors – 2

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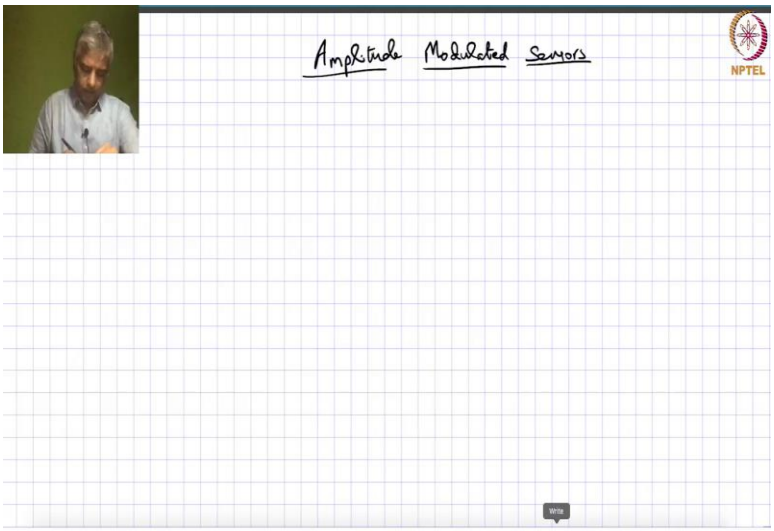

Hello, we have been lately talking about amplitude modulated sensors. And in the last lecture, we were talking about one example of an amplitude modulated sensor, we went into example a little more detail, which is based on absorption spectroscopy.

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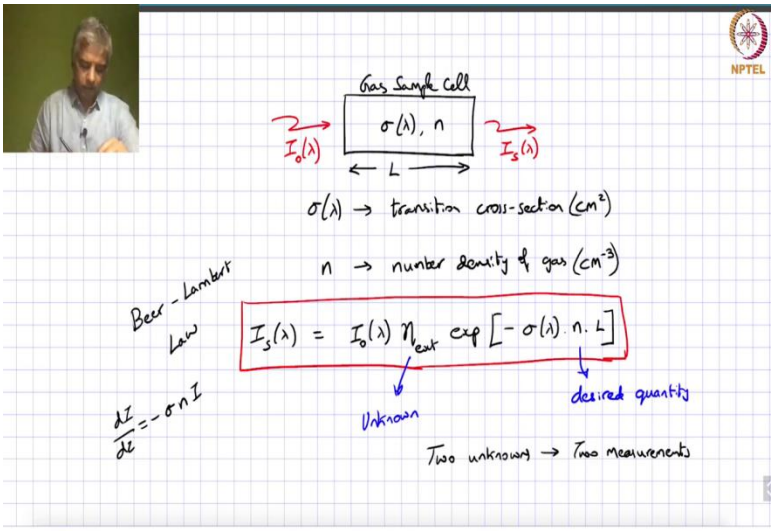

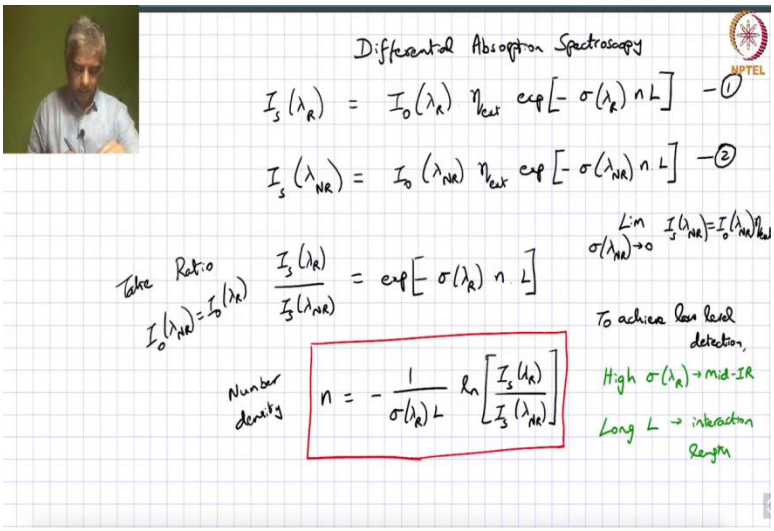

And we saw as part of absorption spectroscopy that we could you know, one of the applications of absorption spectroscopy is for picking up absorption lines of gases trace level of gases. And so, we looked at an example of how we can send light in through gas cells, which has got a particular concentration of a particular gas species and the idea is, how do you, determine that concentration. So, when we looked at how we can do these measurements especially with differential absorption spectroscopy, how we can get an accurate measurement of the gas concentration.

So, so, that part is great, but if you observe closely you know this gas concentration is not going to change over a period of time. So, you can actually make this relatively static, you can call this a relatively static measurement. So, you can certainly employ different techniques to improve the signal to noise ratio of the measurement. And, of course, you can do averaging as well. But we thought what we discussed previously was, you could if you could do locking detection, we could possibly get to very, very low level of detection.

So, we can really bring down the detection limit as far as our measurement is concerned. And while I was talking about locking detection, I casually mentioned that, we may want to do this at kilo hertz frequencies, like 10 kilo hertz frequencies and so on.

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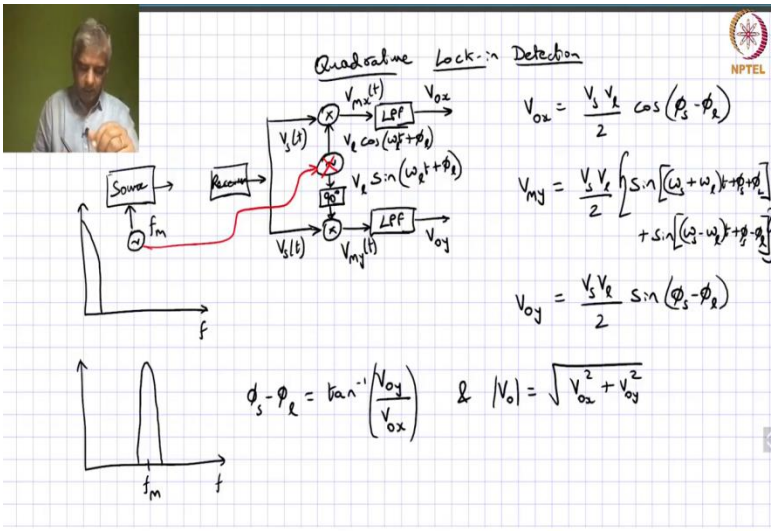

So, I am referring to the discussion that we were having here, where I was saying that, we may want to modulate the source at a particular frequency and that could be in the order of 10 kilo hertz. But I did not tell you why we are actually doing this?

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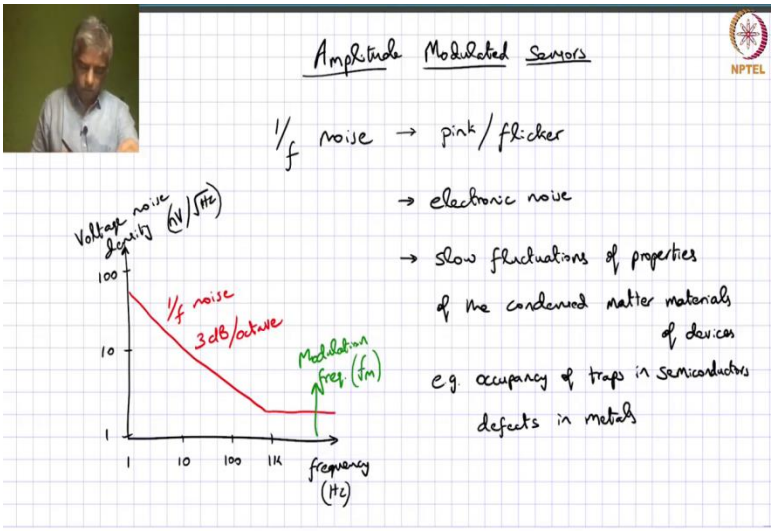

Why we want to do at such a high frequency. So, of course, we do need a frequency carrier so that we can lock into that frequency carrier, and then we can lock into the phase and achieve, fairly good signal to noise or improve your signal to noise ratio. But one of the reasons why we want to go to higher frequencies is because of the fact that there exists type of noise at lower frequencies, which is called the 1 over F noise.

As the term itself implies, the noise, amplitude or the noise power actually goes down as a function of frequency. So, it is predominantly available only at the lower frequency. And this 1 over F noise is also called the pink noise. Or, it is also sometimes called the flicker noise. It is something that I think we will familiar with the Johnson noise. The Johnson noise is something is another name for a thermal noise. But that is named after this person Johnson.

And when Johnson was actually making these measurements, he noticed that there is this 1 over F type noise at low frequencies that he was not able to actually comprehend what it was, but he was the first one to report such noise and that was subsequently you know termed as flicker noise. The origin of this noise is still being debated. So, there are different sort of explanations for this noise.

But what we are actually considering it as, it is electronic noise because it is actually showing up in our receiver electronics, and what it may be due to as far as receiver electronics are concerned, it is it could be because of slow fluctuations. It is slow fluctuations of properties of the

condensed matter materials, and I will explain this in a minute. That is in the condensed matter materials of devices that we use the electronic devices that we use.

So, for example, it could correspond to fluctuations in the occupancy of traps in semiconductors. Or it could be fluctuations in the location of defects. Fluctuations in the location of defects in metals, and so on. I of course, this has been observed in the chemical processes in the biological processes, and so on. So, the list is endless, but this is probably something that is relevant to us. So, there is there is this 1 over F noise.

So, to get an idea of this, if you are looking at, let us say, an op amp, you are looking at the voltage noise density of an op amp, it is typically as we saw before, it is expressed in nano volts per root hertz as a function of frequency in hertz. So, you say 1, 10, 100, 1k and so on. So, this can actually be significant value. So, it goes like it goes down like this and then it sort of attains a constant value.

So, so, this is what it is typically like, in the order of so this is the 1 over F noise that we are talking about, and typically in the order of it goes down by 3 dB per octave. The energy is fairly constant across these different octaves. So, that is actually a significant factor in determining where you want to do your detection, if you are doing your detection outside of this, let us say, at a frequency of, say, 10 kilo hertz or some, something greater than that. If you are moving your direction to these type of frequencies, then you can possibly avoid this 1 over F noise.

And, of course, you know, finally you will beat it down through the lock in detection back to the baseband to do your final, to extract your final signal, but you are essentially avoiding a lot of other components through which you can accumulate this 1 over F noise. So you essentially have this 1 over F noise contribution only from, from things beyond that mixer, as far as your lock in detection is concerned.

So, that is actually one of the main reasons why we may want to do lock in detection so that you can push your, instead of making a static measurement where you send some uniform intensity into your gas cell and make a static measurement. You could actually send modulated light, and then then you could actually do this detection, and then of course, you can demodulate that light, and move our, whatever measurement back to the DC and, and extract our signals that is in this

case, is the gas concentration, or the intensity that is representative of the gas concentration as what we are picking up. So actually, let me give you an example of this.

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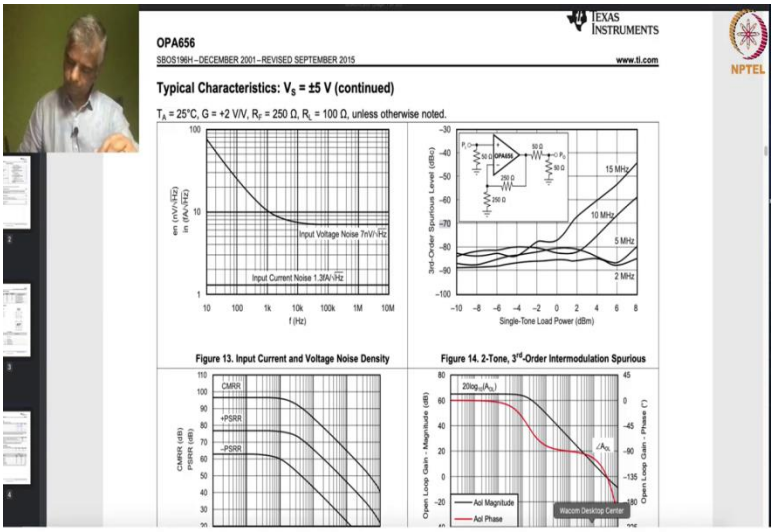

So, lets us take in one of the examples that we are considered, typically, is this OPA656. So, OPA656. So, this is actually the string to get to the, that particular opening page, but doesn't matter. But this is actually corresponding to OBA656. And this is actually the voltage noise density for OPA656, which basically says, ok, the noise density is very high at low frequencies. And then it comes down, as you go to higher frequencies. And beyond certain frequencies, in this case, it is 10 kilohertz, beyond certain frequencies is just white noise.

So, so that is what we are talking about, we are looking at, it is called pink noise, because it is happening at lower frequencies, in the wide spectrum, which color consists of blue, all the way to red, pink, and all that. This is actually, it is happening at lower frequency, which corresponds to longer wavelength. And so pink is one of the longer wavelengths so that is why it is called pink noise. Anyway, so you get the idea. So, it is to avoid the accumulation of noise at this level that we want to go and do this detection at slightly higher frequencies.

So, let me just go back here. And let us actually so, this is where this is the modulation frequency FM that we want to use. So, let us actually move on and say, that is the kind of one example of an amplitude modulated sensor.

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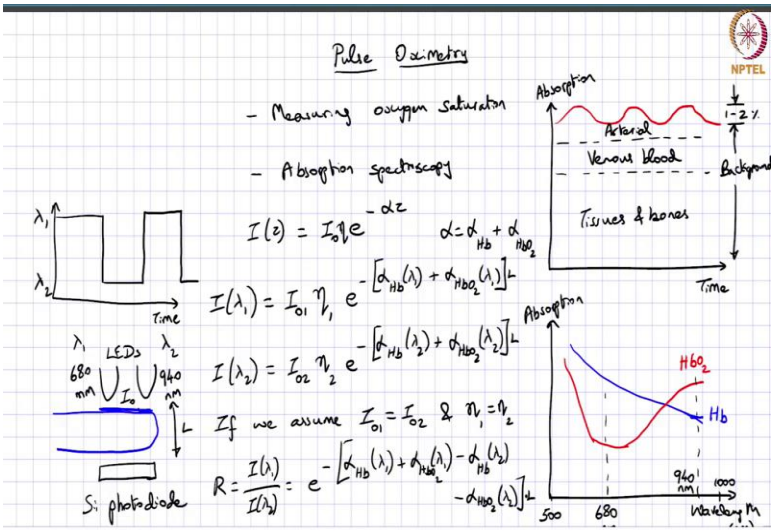

And so, let us actually move on to look at another example of an amplitude modulator sensor. And this example is what is popularly known as pulse oximetry. And this is actually quite popular these days, because of the situation that we have with COVID. And one of the things that it shows up as is breathlessness and, and that is actually a condition that is also associated with low levels of oxygen.

So, there is something called oxygen saturation, which is actually typically the value is between anywhere between 0 to 100, but we typically maintain a level of 95 and if it goes down below 90 percent saturation, then you have a problem. You essentially you know, you have some, some issue with with your breathing and then that that will help that will, you know, impact your health as well.

So, we want to be able to measure the, the level of oxygen in your blood. And we know that oxygen is primarily carried by hemoglobin. So, you have what is called oxygenated hemoglobin, which is actually carried, oxygen carried by the hemoglobin, and you also have non oxygenated hemoglobin, which means that the oxygen has already been, deposited somewhere it is been already extracted.

So, whatever is returning is non oxygenated hemoglobin. So, if you want to look at what is happening in our body the arteries are the suppliers of oxygenated hemoglobin. So, they oxygenated blood in general. And so they carry the oxygenated blood and then they carry to a

particular point and, and if they have actually been depleted of that oxygen, it comes back through the veins and goes back to our heart and then interacts with the pulmonary system and then gets oxygenated again, and then it is pumped out again, through the arteries. So, that is the kind of system that we have.

So, the blood actually has certain absorption characteristics, which you could possibly exploit to understand the level of oxygen that is present in our blood. So, to explain that, let us actually look at the oxygen saturation, what we mean by oxygen saturation in the blood? So, if you look at the absorption, of course, the blood vessels are within it is within our body within our within this tissue and bone, and, and so on.

So, it is all in here. So, suppose if you are trying to do a measurement of the blood absorption through your finger, then you see that a fairly high level of that absorption or the loss of light could come from just tissues and bones, the bones obstruct the light, and so, do not let it pass. So, you get a fairly high level of absorption or losses, because of that, and then you have certain absorption due to the venous blood, the blood that flows through the veins.

The veins are essentially not having or not likely to have oxygenated hemoglobin because oxygen has already been consumed, wherever the blood goes to, the arteries go to and then on top of this is what you have absorption of your arterial blood. And that arterial blood again, has some constant value, but more importantly, it is it is having certain structure. Do not worry about this exact structure of the waveform. But essentially, there is something that is changing with respect to time.

So, most of this is uniform with respect to time. But this arterial blood essentially has a component that changes with respect to time. And how does it change? Well, that corresponds to our pulse rate. So, whenever our heart is pumping, it is actually pushing blood through the arteries and that is actually oxygenated blood. So, this frequency will actually give you the pulse rate.

But what we are interested in is this component here which is a very small component, it is typically when only in the order of 1 to 2 percent of this entire thing. So, there is a much larger component, which is background for our measurement and we are actually trying to pick up this

1 to 2 percent modulation and based on that modulation, we can actually tell what is the oxygen saturation.

So, coming back we are essentially measuring oxygen saturation in blood and that measurement is through absorptions spectroscopy. So, it is through absorption spectroscopy, but if you try to do absorption spectroscopy this is what we see, this is a challenge that we have a very small varying component which we need to pick up and that is actually a quite a bit of challenge.

Well, what can we do to make this measurement as precise as possible? You can actually rely on the fact that your absorption as a function of wavelength is actually changing for the blood with oxygen or the hemoglobin oxygenated hemoglobin with this non oxygenated hemoglobin. So, we can draw this other plot where we are looking at wavelength in nanometers, let us say and, and and we are looking at absorption, but we are looking at absorption of the oxygenated and the non oxygenated hemoglobin.

So, if you look at the non oxygenated hemoglobin that would look something like this. Across this wavelength, which could be from 500 nanometers to about say 1000 nanometers that it might look like this. Whereas, if you consider oxygenated hemoglobin which is typically red in color, that would be something like this flat note and it will go up and then it will it will be something like this.

So, where this happens around a wavelength of 680 nanometers. And the other wavelength of interest is somewhere around here it is actually, this blue is actually a little flat over here. So, this is this is concerning a wavelength of about 940 nanometers. So, if you do sort of measurement at 2 different wavelengths, where one wavelength where the, the non oxygenated hemoglobin absorbs more so, that is the red color. And another wavelength where the oxygenated hemoglobin absorbs more. So, this is actually the hemoglobin with the oxygen, Hbo2 let me call that and this is actually Hb by itself without oxygen.

So, you are looking at the relative absorption for these 2 wavelengths, and based on that you are trying to make an estimate of the oxygen saturation. So, how is it typically done? Well, like we like I talked about, this is one of the most accessible regions, some people do it on the ear also. But, this is more common, just your finger you might have seen that as something like a clip that

goes over the finger and through that they do the measurement. So, what they are actually doing is, so you have your finger like this, let us say this is your nail across your finger.

So, you shine because the nail is sort of a transparent region compared to the skin which is highly absorbing. So, you could have these 2 different diodes. So, one is actually, so you have 1 diode at 680 nanometers and another diode at 940 nanometers. And so it is sending out some intensity and then you need to capture that intensity, which you can do with the photodiode over here. So, what type of photodiode would you use to pick up these wavelengths?

Well, if we consider 940, 940, you can actually pick it up using indium gallium arsenide or silicon. But if you consider 680 you can you cannot pick it up with indium gallium arsenide. Typically, it is got very low responsibility at 680. So, you typically use a silicon photodiode. So, now we will essentially go ahead and design a pulse oximeter. So, how do you go about designing a pulse oximeter.

So, so you would basically have 2 LEDs. So, these are the LEDs, which are driven by a certain current, so why why LED, why not a laser? Well, these features here are relatively broad, that in the things do not change very much over over this region. So, a LED is something that is more than for these wavelengths. So, you can basically use LEDs. And so, they are emitting this light and the light is actually going through this through the finger, and then you are able to pick up the intensity that is coming through.

So, if you talk about the intensity that is coming through you can just say I of z is going to be equal to I naught e power minus alpha times z, where alpha corresponds to the the absorption, but here we understand that absorption is actually a function of wavelength. Not only that, but absorption also consists of multiple components. So, so alpha is has got one component which is corresponding to non hydrogen non oxygenated hemoglobin and another component which corresponds to oxygenated hemoglobin.

So, we need to consider both of those and of course, there could be an external loss eta. You can essentially take all these losses due to tissues and bones, and you can put that in eta as well as any other scattering losses from the surface of your nail and so on. So, that that is an interesting thing. So, they suggest that you do not put nail polish because if you put nail polish there, then that can actually mess up this, that the nail polish has its own absorption characteristics and

different colors of nail polish has different absorption characteristics that will mess up all these readings. So, they typically ask you to remove your nail polish before they make the measurement.

Anyway, so, if we were to now look at the actual measurements that we are doing, so, let us just call 1 wavelength this lambda 1 another wavelength this lambda 2. So, you can write an expression for the intensity at lambda 1. So, that will correspond to I naught 1 which corresponds to is once again the I naught will be the source intensity. So, I naught 1 corresponds to lambda 1, I naught 2 corresponds to lambda 2 and then you have that external loss factor which can be which can be a function of wavelength.

So, we will come back and look at that, and then you have the exponential term. So, you have e power minus alpha Hb at lambda 1 plus alpha Hb o2 at lambda 1 multiplied by L, where L is the region over which the absorption is happening, that is, that is the corresponding to the thickness of your finger. So, similarly, you can write another expression for lambda 2. So, I naught 2 eta 2 e power minus alpha Hb or lambda 2 plus alpha HbO2 lambda 2 multiplied by whole multiplied by L.

So, you are essentially making this measurement. Now, of course, you would say that, why do not we use one photodiode for each one of these what are called light sources corresponding to each one of these light sources and make these measurements simultaneously. If you notice, I have actually shown that there is actually a common photodiode. So, why do I need a common photodiode?

It is because of the fact that when you eliminate, so, you can maybe focus your illumination in a particular direction also. But once it goes into the finger, the tissue, it will tend to diffuse that light in multiple directions. So, if you have 2 different detectors, it will essentially have a crosstalk with the other detector, not just the detector that it is supposed to go to, but the other detector will also start picking up.

So, one way of removing this crosstalk issue is to turn on only 1 led at a time. So, you basically you go like with respect to your drive it such that for certain time 1 LED is on for certain other time another LED on and then you repeat it. So, this is basically lambda 1 is turned on during

this time lambda 2 is turned on during this time, and you can essentially repeat it, as fast as you can make your measurement.

So, you can switch back and forth, you can switch the can turn on or off one of the LEDs at a time. So, and of course, during that time, you can make this measurement with lambda 1, which is what this measurement is. And then the next time slot you are making, you are turning on this LED, and you are making a measurement corresponding to this. So, once we have this, we can say if we assume I naught 1 equal to I naught 2. Then we are and also if we make this assumption that eta 1 equals to eta 2, you have to be very careful in making that assumption. But, but the wavelengths that we have picked, typically justify this assumption, or it could be sort of calibrated out.

So, if we assume that is the case, then when we take the ratio R, which is I of lambda 1 divided by I of lambda 2. So, what you have is just the exponential. So, you have basically e power, minus alpha Hb of lambda 1 plus alpha HbO2 at lambda 1 minus alpha Hb at lambda 2 minus alpha HbO2 at lambda 2 whole multiplied by L. So, you just get that factor. And then you can rearrange those terms.

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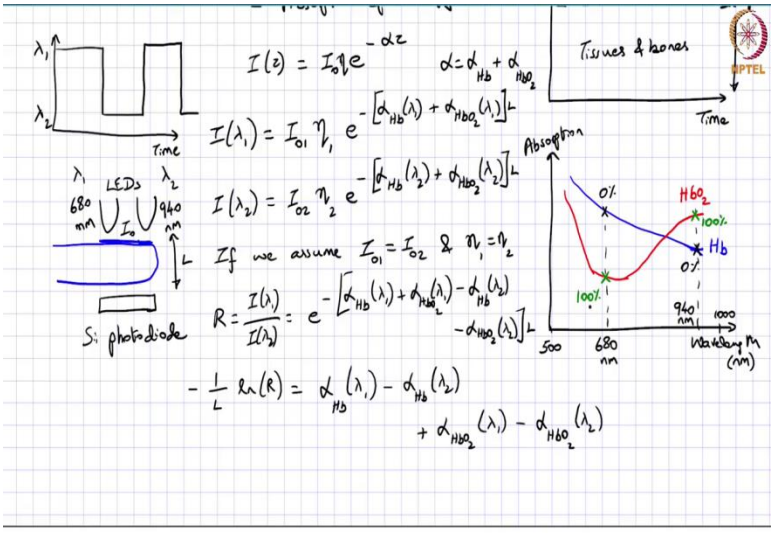

Let me see if we can go down a little bit, you can rearrange those terms and then you can basically get an expression in terms of the measured quantity. So, what is measured, is actually the ratio. So, from the measurement you need to infer the oxygen saturation. So, you can

rearrange it as so, this will become minus 1 over L log of R is is going to be given by just alpha Hb of lambda 1 minus alpha Hb at lambda 2 plus alpha HbO2 at lambda 1 minus alpha HbO2 at lambda 2.

So, you once you want to make this measurement and if you know you know what is the level what are these values of alpha Hb at lambda 1 alpha Hb at lambda 2 and similarly for the other oxygenated hemoglobin then from this you can actually figure out what is the level of oxygen saturation.

So, so, if it is 0 percent oxygen saturation what would these values look like? Well, that would correspond to this case, if it is 0 percent oxygen saturation, then that would mean of course, if we talk about realistic numbers 0 percent, you are not alive anymore. But anyway you will see basically these values so, at 680 you will see a value of alpha like this and at 940 you will see a value like this.

So, if you see these values and you will have a corresponding ratio based on that so, you can calibrate with respect to that ratio and you can say that this would correspond to 0 percent oxygen saturation. So, this is 0 percent oxygen saturation and on the other hand, if you have 100 percent oxygen saturation, then you will measure this value, at 680 and you will measure this value at 940. So, this will correspond to 100 percent.

And anything in between you will essentially have some other value over here and some other value over here. So, based on that the ratio is going to change. So, you can calibrate all of this, you can calibrate all of this and then you can say that this is actually the level of oxygen saturation that you have. And you can clearly see that, if you are talking about something like this, you are prone to noise.

So, if you are prone to noise, then this this value might fluctuate around some something the intensity will fluctuate around here. So, this intensity will also fluctuate, and then correspondingly, the ratio will fluctuate and because of that it will be certain uncertainty in there is a certain level of uncertainty in your measurement. And so that uncertainty in a practical device should not be more than, you know, say, 1 or 2 percent depends on the quality of the device that you have. So, you try to keep that as low as possible. So, that is actually pulse

oximetry. And that is actually another example of how we can use intensity modulated sensors optical sensors.