Optical Fiber Sensors
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Lecture No. 13
Lock in detection

So, we have been talking about noise in optical receivers corresponding to an optical sensor. And in the previous lecture we were talking about noise mitigation and we figured that maybe averaging or filtering could be effective techniques to mitigate the noise and hence improve the signal to noise ratio of whatever we are trying to sense.

Now there are conditions under which these techniques that we have considered are not good enough. And we need to look for even better technique in terms of mitigating noise and one of those techniques is a lock-in detection technique or in other words it is also called face sensitive detection technique. So, that is what we are going to look at today.

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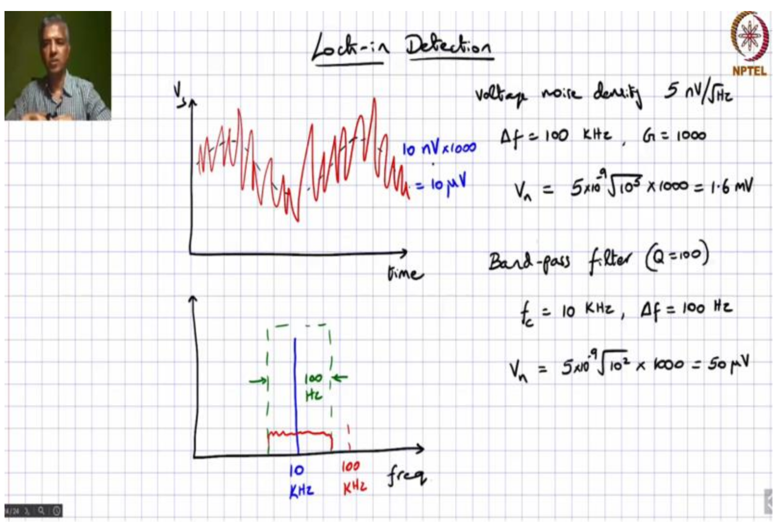

So, let us actually consider a signal. Let us say this is Vs as a function of time and let us say Vs is actually corresponding to RMS voltage of say 10 nano volts. So, you have a sine wave at 10 kilohertz corresponding to, you know with an amplitude of RMS of 10 nano volts. So, we are looking at something like this but of course we know that with the presence of noise you know it is it is going to get corrupted.

If you look at the corresponding say the frequency domain of the signal, what do you expect for a sine wave? Well for a sine wave what we expect is something a delta function right, if it is exactly at 10 kilohertz you expect a delta function at 10 kilohertz. But problem with this is this signal RMS is only corresponding to 10 nano volts and that is not filling your ADC, so you need to boost up the signal.

So, if you try to boost up the signal and you want to use a voltage amplifier, typically a op-amp based amplifier and we looked at the noise characteristics of different op-amps let us say you pick the best op-amp available out there like opa-657 or something like that a fit based amplifier. You have what is called the voltage noise density for the amplifier.

So, let us say we have the voltage noise density of this amplifier which is one of the best amplifiers that you can find op-amps that you can find in the market, you know it is in the order of 5 nano volt per root hertz so we have a signal of 10 kilohertz. So, maybe you need to have a bandwidth in the order of let us say 100 kilohertz. And let us say we are trying to boost up the signal by a factor of 1000. So, the gain that we want to achieve is as a factor of thousands so your signal actually you know gets multiplied by 1000 and becomes 10 microvolt which is a reasonable value. But the question is what happens to the noise?

Well if you make this calculation so you substitute I mean you, you multiply to get the voltage noise, the input referred voltage noise you have to multiply 5 nano volt per root hertz multiplied by root of this bandwidth of the amplifier which is a 100 kilohertz and if you multiply that and then then that is the input referred noise. So, you know if you want to look at what is the output of that amplifier you have to multiply that by 1000 as well. So, your noise voltage is basically 5 multiplied by root of 100 kilohertz is 10 power 5 multiplied by 1000. If you do this multiplication you get to say about 1.6 millivolt RMS of of your noise voltage.

Now your signal voltage is 10 micro volts and your noise voltage is 1.6 millivolts. So, that is much much larger than the signal. But of course you realize that your noise is actually something like this. It is it is basically it is it is broadband noise and you do not necessarily need to integrate of course we are talking about integrating up to 100 kilohertz here, that is the bandwidth that we are considering. So, we are integrating only up to 100 kilohertz but nevertheless, you do not necessarily have to I mean for a for a case like this where you are you are trying to pick up a particular tone at 10 kilohertz you do not necessarily need all that bandwidth from your amplifier.

So, you might argue that hey, why cannot I you know throw in a band pass amplifier right and and limit my noise. So, I would say, I use a band pass, so I use a band pass filter right I use a band pass filter with say a queue of 100. So, that is the q factor for the filter. Well which actually says ok the ratio of the center frequency over the the bandwidth of the filter that is a factor of 100. So, in our case our center frequency is 10 kilohertz. So, you would say that in if you use something like this your delta f, the filter bandwidth is going to be still you know 10 10000 divided by 100 so that is going to be 100 hertz.

So, effectively what we are saying is I am going to now filter my I am going to apply a filter whose width is 100 hertz and try to pick up the signal. And that way what I am doing is I am actually erasing all of this and instead I have only you know noise within that filter bandwidth. So, I am improving my signal to noise ratio. Now let us go back and compute what is the signal to noise ratio expected here. So, in this case if you do vn, vn is 5 multiplied by root of 10 power 2 multiplied by 1000 by the way so this is actually 5 nano volts.

So, this is there is actually 5 into 10 power minus 9 coming to the picture that is that is why you get this value here. So, this is 5 into 10 power minus 9 multiplied by this and if you do this you get something like 50 microvolts. So, better than before but you still have a signal to noise ratio that is much less than 1. So, we are not really doing the job we are not we are not actually able to pick up the signal very well from from the noise. So, so we are essentially still considering a case where this is looking like this. So, we are not we are not able to pick up the signal properly from this.

So, what do we do in in this case? Well 1 thing that you want to realize here is when we are doing this detection we are actually integrating over this noise and the noise essentially has a random face, the signal has got a very well defined face because it is got a nice sinusoid it has got a very well defined face. But the noise is is all over the place the the face of the noise is all over the place. So, if you are able to limit your detection to a face corresponding to only the signal phase and you are eliminating all other phase components of the noise. If you are able to do that, that will constitute a method where you can get the highest signal to noise ratio. So, what do I mean by that?

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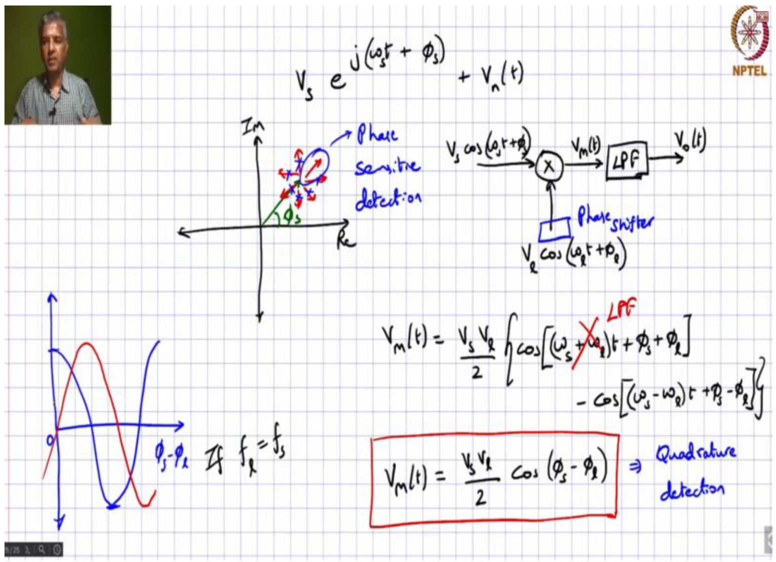

Well let me try to explain. So, let us actually represent our signal as Vs. You can just say it is it is it corresponds to a particular frequency we picked up 10 kilohertz as a frequency and some arbitrary phase is caught. So, you can represent it in terms of a phasor e power j omega t omega s is the, is the signal frequency multiplied by time plus some arbitrary phase phi s. This is a signal that we are trying to pick up but of course it is you know it is corrupted by some noise.

Now if I want to represent this signal you understand this is actually a complex signal. It is got a particular face associated with it. So, if you want to represent the signal you go for representation in the complex plane, you actually try to represent it as a phasor. So, you go for this complex plane representation where this is the real axis this is the imaginary axis. And the signal that we are trying to get is basically let us say a particular phasor here in this which has a particular phase we are calling it phi s. And of course this is a periodic signal.

So, it just means that as a function of time this phasor is actually you know just rotating around this plane 360 degrees for every 1 cycle of the frequency you basically complete 1 rotation that is what happens in a phasor. So, phasor does not really represent the frequency. So, it just it just represents the face because that is what we are interested in as far as what we want to discuss is concern.

Now that is actually the signal but what about the noise? Even if you consider noise at that particular frequency you will find that the noise has got arbitrary phase. Of course it can have 1 component along this signal, but it also has other components,. So, effectively it either adds to the signal or it acts against the signal or just add in some arbitrary manner and that is what we see as variations in your signal. So, that is that is what we get to see as these variations around the signal because that is because of this noise phasor is actually uniformly distributed over 2 pi phase.

Now is there a way we can actually pick up one particular phase vector of the phasor of the of the noise from all of this and reject all other phasors. Is there is there a way we can do that that is the key question we are asking. So, essentially what we are talking about is if we can do a phase sensitive detection, we can do a phase sensitive detection then you can eliminate all these other noise components.

And then of course, you still have to deal with this particular noise component which may not only be even though it is of the same phase it might still have some fluctuation in terms of the actual amplitude but that is the that is the limit whatever fluctuations is there you have got to take that and and move on. But you are still able to eliminate all the other phasors. So, that is the key part. So, how do you do that? Well we can do that provided you take this signal here this is basically let us just consider instantaneous representation of the signal. So, this is Vs cos omega s t plus phi s that is the incoming signal.

Now I beat it or mix it with another signal ok where we say this is Vl cos omega lt plus phi l. So, what is the resultant of that mixing? Let just call that say Vm of p. So, vm of t if you write it out that is going to correspond to Vs multiplied by Vl plus, multiplied by cos omega st plus phi s and cos omega lt plus phi l. So, let us say this is cos a cos b. So, you have a cos a multiplied by cos b. So, if you are taking if you are taking if you are looking at cos a cos be, then you say this is corresponding to cos a plus b minus cos a minus b divided by 2.

So, I would say this is divided by 2 and then you have a cos of a plus b which is corresponding to omega s plus omega l multiplied by t plus phi s plus phi 1. That is a clock cos a a plus b term minus cos of omega s minus omega l multiplied by t plus phi s minus phi l, the whole thing in this bracket. So, you that is actually the mixing term that we have at the end of this at the output of this mixer. Now you can easily eliminate this part. So, you say this is actually omega s plus omega l. So, that is actually fairly high frequency.

Let us consider a case where omega l is almost you know equal to omega s. So, you are talking about 2 times omega s type of frequency. So, you can you know deploy a low pass filter here and you get V naught of t. And on top of that let us say we have a way of tuning. So, so essentially we are we are getting this term. So, we so we get rid of this term because of this LPF and we are left with just this term.

Now what we can do is if we have a way of matching omega s and omega l, fs and fl let us say. If rather fl is made equal to fs then this component goes away then you have Vm of t corresponding to Vs, Vl divided by 2 cos of phi s minus phi l. Of course there is a minus sign I would not bother about that because that is just a pi phase shift and that is not really matter I mean we can we are just looking at the magnitude of this.

Now if we look at this, what does that tell you? It says that I am able to pick up the signal and I can I can basically my signal can be maximized by tuning this phi l and making it equal to phi s. Then this becomes 0 then cos becomes 1 so that is when you get the maximum signal. So, all we are talking about here is if I incorporate a phase shifter, a tunable phase shifter, I can tweak that phase until I see maximum voltage there. And at that point now you have maximized your signal and effectively what you have done in this case is you are picking up only this component only a very particular phase of your incoming signal. So, how does this differ from a filtering?

Well in filtering we are of course reducing the frequencies and we are limiting the frequencies to a to a very small part around the frequency of interest. But you do accumulate noise and the noise has some random phase. But in this case what we are doing is by actually doing lock-in detection you are doing phase sensitive detection. So, you are limiting the noise to essentially this this phase only. So, that is essentially the concept of lock-in detection. So, that seems fairly powerful but is that good enough?

Well the answer is it is probably not the best because when phi s minus so this is a cosine function so if you are plotting this phi s minus phi l so it is it is it is a maximum and a minimum and so on. But over here it is actually not very sensitive. It flattens out over here at a phase of 0. And similarly, you can say at this point it once again flattens out and at those places it is very hard to get your signal maximize the signal because the phase resolution that you get is is very small.

So, if you want to get around that what you need to do is not just this but you need to do quadrature detection. What is quadrature detection? What if along with your cos you are able to get a sine signal of the same phase difference as well. What if you are able to simultaneously get cosine as well as the sine. So, whenever the cosine it is relatively insensitive. If you are picking up the sign you can say that the if you if you have another channel which provides you this with this sort of a function, then wherever the sensitivity is very low. Here the sensitivity is very high. And just by looking at both of these components you can actually pick up the phase accurately. So, that is the advantage of doing quadrature detection. But I I do want to mention that a lot of these examples are being considered.

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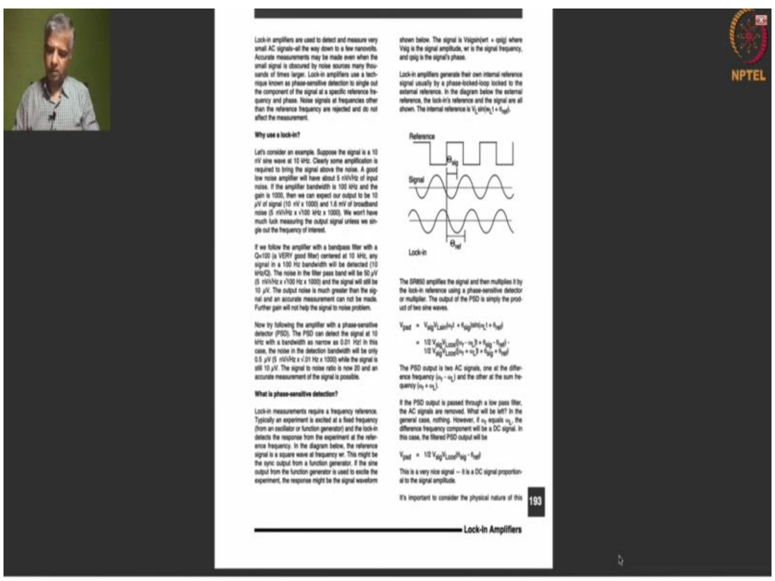

This is actually a very good reference Stanford research systems is a pioneer as far as lock-in amplifiers goes. And they have a very nice application note where they consider some of these examples which I have used here.

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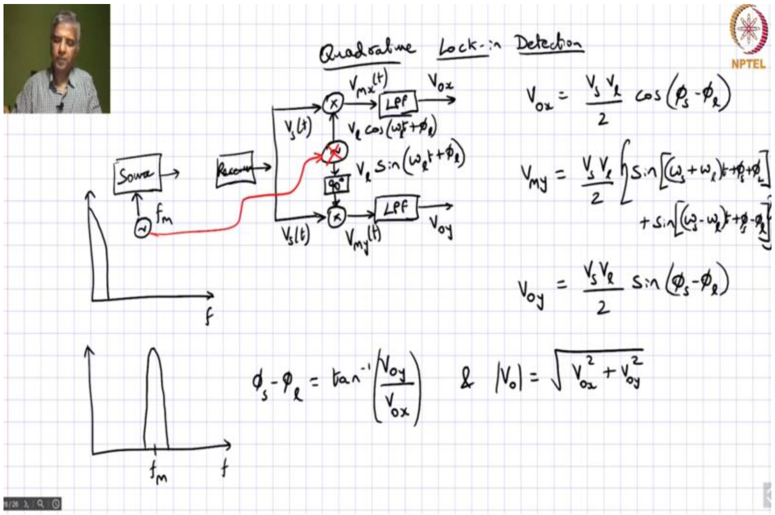

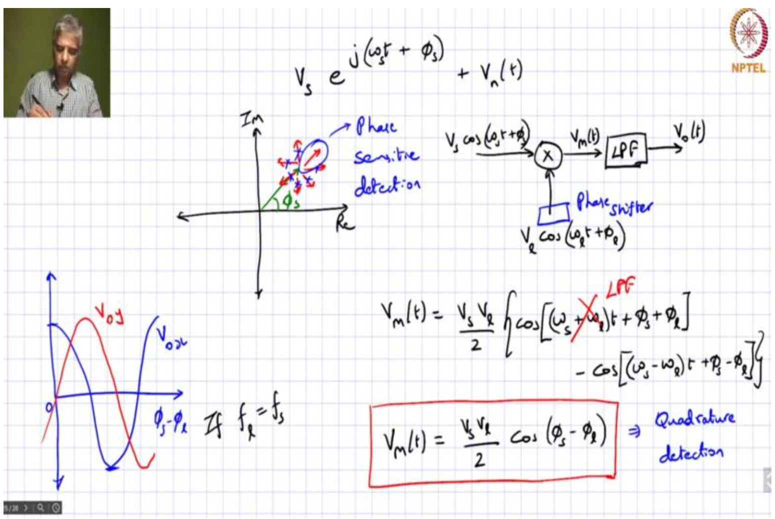

So, let me just get back here and let us actually explain what is quadrature lock-in detection. So, what if we are able to take this incoming signal and split it into 2 parts. So, let us say they are both equal parts Vs of t and Vs of t here and they go through their respective mixers. And the signal that you get from what that Vl of t that is actually called the local oscillator. So, the local oscillator let us say is this source which is providing Vl of t. In this case this will be like a cos of omega lt plus phi l.

But in the other side you actually have 90 degree phase shifter and then you do the mixing and then of course just like previously you take the mix output. Let us start let us say this channel is called Vmx of t and this channel is called Vmy of t and both are actually going through the respective low pass filter. And the output we call this Vox and this is Voy. So, in this case what happens?

Now of course Vox we can directly write right. So, Vox is gonna correspond to Vs multiplied by Vl divided by 2 cos of phi s minus phi l. So, that part we already know from our previous discussion but what about Voy? Here in this case this Vl of t for for this mixer corresponds to Vl multiplied by sine of omega lt plus phi l. In this case it is it is basically what is what is going in is Vl cos of omega lt plus phi l. That is what is going in here but what is what is actually going into this mixer is Vl sine because we have incorporated a 90 degree phase shift. So, then when you mix this so Vs of t is Vs cos of omega s t plus phi s.

So, when you mix with this you have a sine and cos multiplication. So, that you know it corresponds to sine of a plus b plus sine of a minus b. So, in in in that case and then of course you do your low pass filtering. So, what you get out of that is maybe l, I will just write it out. So, you have sine of omega s plus omega lt plus phi s plus phi t plus sine of omega s minus omega l t plus phi s minus phi l. So, this is actually what you have for Vmy of t.

So, if you send it through the low pass filter and also make sure that I mean as we did before we are already making sure that the frequency of the local oscillator corresponds to the frequency of the incoming signal. Then what you get is Voy corresponds to Vs multiplied by Vl divided by 2 sine of phi s minus phi l.

So, you can see that Vox and Voy are are in quadrature with respect to each other and that actually describes this situation that we have here where you know where you can say that this corresponds to Vox and this corresponds to Voy. So, so you you that is that is how we are able to implement this quadrature detection technique. And of course once you have this then you can you can say based on this you can say phi s minus phi l is going to be given by tan inverse of Voy divided by Vox.

So, you can get the phase of the incoming signal if phi l you you you are able to get the phase of the incoming signal and and if you want to get the magnitude of this so the magnitude is going to be root of Vox square plus Voy square. So, you can you can get both the magnitude and the phase of the you can retrieve the magnitude in the phase. And of course we are multiplying with

Vl here. So, effectively you know if you if you write it out that corresponds to Vs Vl Vs multiplied by Vl. So, that is essentially telling you that you can also boost up your signal by boosting up Vl to some extent you can you can you can do that as well. So, you get an amplification of your signal as well.

So, but the but the key point is this is actually phase sensitive detection. So, you are able to keep the noise level to a very low value. Now what is the downside of this? Well we are characterizing Vs as as a single frequency signal. So, if you have a single frequency signal then this this works out very well. In so how do you ensure that and also we are saying fs has got to be equal to fl. So, how do we how do we ensure that? What you can possibly do is and we will see examples of this.

We can modulate our light source we are talking about implementing this in a optical sensor. So, we have a light source and a light detector. This is actually you know what what we are seeing here is the input to this. This is beyond that initial photodiode and and tia you have a certain voltage and that is after that is where you are actually implementing this lock-in detection. So, what if you can actually modulate I mean let us say in a sensing application you are picking up strain or temperature which is varying very slow with respect to time. So, the most of my information is actually in in dc around dc right, it is it is it is quasi-static type of information.

So, let me just explain this. So, what what I am considering is if I am looking at the spectrum of my information my information may be the information that I am sensing may be only around this. But if I use a modulated light if I am if I am actually modulating at say a frequency of Vm, Fm, then I am looking at in a perturbations to that particular carrier the carrier frequency is Fm and I am looking at perturbations to that carrier.

So I have basically something like this. That is my information ok and since you know since you are the one that is providing this modulation frequency. So, you you say basically take the same so this is my let us say my, I should not draw there. So, this is my source I am modulating with this Fm. And that is actually going through perturbation and then it is going coming to the receiver. And within this receiver you basically need this reference.

So, this reference essentially could be the same reference as as this. So, that actually you do not need an independent source you basically use that same reference and think so that way you make sure that Fs and Fl are the same. And then you can do your entire detection to to get these signals. So, that is how you would implement in in a in a real sense as far as the optical sensor is concerned.