Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VII
Module-V
Response time & Noise in Detectors

by
Prof. Pradeep Kumar K
Dept. of Electrical Engineering
IIT Kanpur

Hello and welcome to this module on optical communications. In the previous module we have talked about photo detectors in the last two modules. In this module we will talk about remaining aspect of a photo detector two are quite important the response time of a photo detector, because that determines what would be the maximum rate at which one can transmit signals, because if you overcome the transmitter rise time, if you minimize the fiber rise time by appropriately performing the dispersion management, then the last thing that is remaining which limits the bit rate of the communication system is the receiver rise time.

And we have talked about it in the last module saying that it is necessary to reduce this life, you know the response time of the APD which means that one has to try and make the bandwidth of the, not just the APD for both PIN detectors as well as the APD detectors. One has to make the bandwidth to be very large okay.

So bandwidth is inversely proportional to the response time of the photo diodes. So what exactly limits this photo diode response time, why we cannot have communication, I mean why we cannot have bandwidths which are set tera hertz or maybe even more than that, we will see the reason why it will be so, just a small point which I would like to make here, the primary response time limitation comes from the holes and it is kind of not possible for me to cover that one in this course at this point as to tell you why the holes are the ones which are moving at a slower velocity compared to the electrons okay.

So we will take this fact that holes move, you know even if both the electric fields applied to the electrons and holes are the same, the mobility of the holes is actually smaller and therefore holes move at a slower speed compared to that of the electrons. So electrons move fast, but for the complete current to flow through the circuit you have to also have weight until all the holes are collected in the region right.

So it is essentially this hole velocity that fact that hole mobility is smaller compared to the electron mobility in the photo diodes which essentially limits the response time of the detectors okay. In addition to response time which you would like to minimize it as much as possible, you also want to minimize the noise in the photo detectors. Now photo detectors are not nice ideal components which will just take optical energy and convert that into electrical energy.

They will also contribute a good amount of noise, some of the noise comes from the photo diodes structure itself, the way you have constructed a photo detector that structure itself will contribute to some noise okay, then thermal agitations inside the material which will cause a little bit of juggling up and down of the electrons and the holes, you know constituting a small amount of leakage current will also contribute to the noise process.

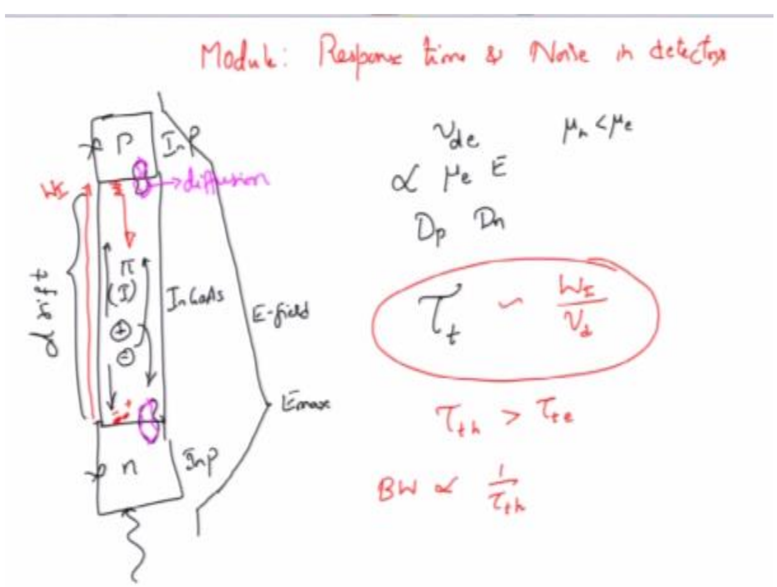
In addition to all this, the fundamental noise limitation comes from the fact that the conversion of photons into electrons right, is not a very deterministic parameter or deterministic process, there is actually a, it is actually a stochastic process in the sense that, you can imagine someone taking a bullet and then firing at you okay. So someone is firing at you and if you can kind of put up a metal box or something to collect you can hear this sound right.

So one bullet comes in there will be a sound of ting, one more bullet ting, one more bullet ting, sometimes you will have multiple bullets coming at a particular time, there will be ting, ting, ting. So this kind of a short, you know the phenomenon which kind of resembles this short of a bullet is called as short noise and this comes from the fact that electrons which are generated, electron hole pairs which are generated they are this discrete carriers and they do not constitute a continues current flow actually current flows in the form of this bullets you know elections go in the form a bullet sometimes you get one bullet sometimes you get two bullets sometimes you get three sometimes you get ten sometimes you hindered but regardless less whatever that one it is actually a statistical process so there is always a fluctuation about the photo current which will lead to certain amount noise.

Interestingly this short noise we will discuss it slightly later but here is a summary this what happens with a short noise, short noise unfortunately does not reduce with the increasing optical power you might think that well increasing the optical power should kind of reduce the short noise but unfortunately the opposite happens because increased optical power gives rise to a larger photon you know the photo carriers and these photo carriers will amplify the noise associated with them so this short noise limitation is not something that would decrease with increasing photo diode.

So you can see that this kind of counter intuitive right so we will talk about that noise as well let us first look at the response time.

(Refer Slide Time: 05:15)



Okay we have seen the structure of a PIN diode right so you can assume that this is the P region and then there is this large π are the intrinsic region and then you have the n region of course they dopant profiles have to be chosen appropriately such that much of the photons may be if the photons are incident from the N side then much of the photos will be observed only on the intrinsic region how can we ensure that we take the material band gabs materials of different band gabs for the P and N type regions and a different material for the π or the intrinsic region right this where this what we called as hetero structures right.

So if take this as the indium phosphate indium phosphate and then if you take this one as the in gas material then these N and P type regions in the foot pin photo detector will be transparent to the light at 15, 15 nana meter anything more or less around the conversional band of our optical communication these two regions will be transparent and it is the intrinsic region which observes the light, now look at what happens once you have an electron and hole pay realized as a result of absorption of a photon then there is also an inbuilt electric field correct so there is also an inbuilt electric field which if you remember when something like this right.

And they went back to 0 I am exaggerating the electric field out there but this is how more or less you saw the electric field across PIN junction current and we assume that the reverse π as with we have applied to this diode is sufficiently large so that the electric field here is sufficiently strong okay and because this electric field you know the strong's comes mainly because of this E max thing for the pin diode you simply have a maximum electric field and from there it will reach down to the minimum value right.

So this is how you would actually see the electric field which has gone to 0 up to these two points this field which I had just drawn if you remember it was for the APD diodes because there is a N + and P region that is the multiplication associated before the intrinsic absorption region correct so the point to note here is that you have a strong electric field which will then separate this positive and negative charges okay so this charges will travel in the opposite direction and they will be collected in the appropriate regions okay.

So may I think this should be the other way around because electric field is increasing this way so it is the hole which have to move this way and the electrons which have to move that other way around regardless of the fact that there will they will simply go in the opposite direction let us not bother about where they go what you have to absorb here is very interesting this region wherein the intrinsic region is there much off the current happens because of the phenomenon called as drift, okay. There is a drift velocity which is related to the mobility so if $V_{d\,e}$ stands for the drift velocity of the electrons and μ_e stands for the mobility of the electrons.

Then this V_{de} is directly proportional to this mobility times electric fields which is where the field experienced by the electrons similarly if you change this V_d into V_{dh} V_{de} x V_{dh} will get the whole thing and as I said whole mobility is less than the electron mobility therefore the speed at which these two photo carriers electrons and holes travel will also be different, now you might ask why there is a speed problem at all?

Well the current in the intrinsic region is mostly drift, right but once they come into this majority carrier regions okay what would be the main current component here, the main current component has to be diffusion, right they have come upto here but the concentration of electrons in this region is much larger, so if they have to contribute to current they have to diffuse into this other layer not the electrons the holes actually.

So the holes of the diffuse into the n region the electrons have to diffuse into P region so that you are going to get a current, okay. So this diffusion currents are the once which you will see at the material interfaces at the P and I interface and I and N interfaces you will see this diffusion current, okay. And diffusion is characterized by diffusion constants Dp and Dn, Dp stands for diffusion constant for a P type or a hole.

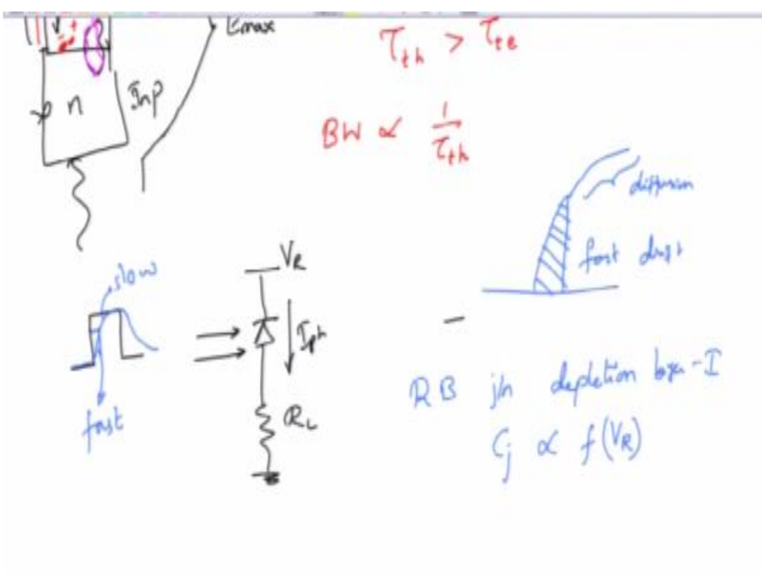
And Dn stands for diffusion constant for a electron, okay. So we are of course not going to look into the full details of this derivation but I will just briefly motivate you to what is happening, what would be the transit time taken by this electrons and holes, what would be the transit time, you look at what happens, suppose the generation of these electrons are happening at this edge right.

Electron hole pairs are getting generated here then one of this carrier has to go all the way through the intrinsic region of width WI, correct it has to go all the way to that one, what time would it take in order to reach to the end, it would be whatever the width divided by your velocity, right. So that would be the drift velocity, on the other hand if generations happens here I mean for some miracles region I mean reason.

The electron hole pairs are generated at this interface then again there is a travelling of WI length in order to obtain I mean in order for it to be corrected onto the other region, so it is this fact that transit time is inversely proportional to V_d which causes the transit time to be larger for the holes compared to the transit time for the electrons, okay. And bandwidth or the response time so this could be the response time.

Bandwidth being the ruffling the inverse of this transit time to see that this is almost limited mainly because of this whole percent right, so bandwidth gets reduced because of this reason okay, this can be observed in practice.

(Refer Slide Time: 11:24)

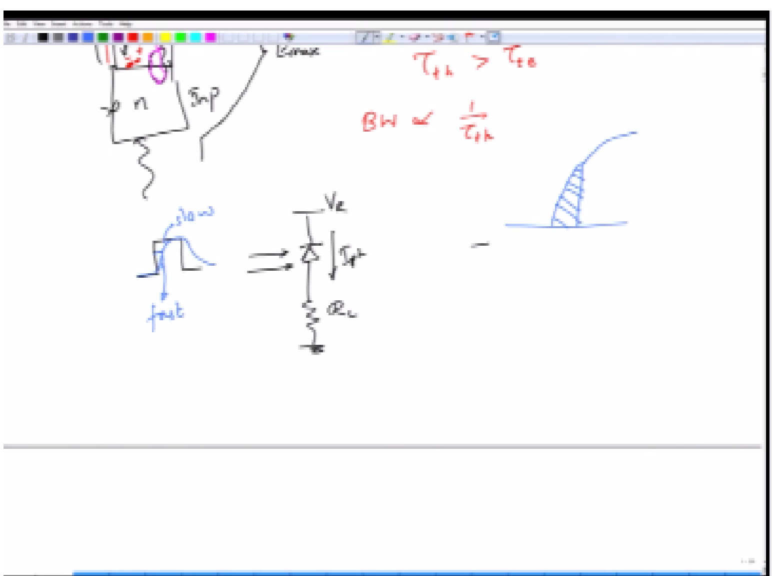


If you take P_{IN} photo diode okay so you take a photo diode you reverse bias this one appropriately and then send in an optical signal shine light on it, how do you shine light on it, so you can shine light on it by focusing light onto that but what I was interested is to see what kind of change that you have apply in the optical power, so if I somehow I am able to apply this step optical input.

Then what happens is that the output photo current right the photo current actually does not go like that but rather it takes a this kind of a response, okay. In fact you can see that initially there will be a fast response then there will be a slow response, okay I have might not have succeed in to write to the responses clearly to show you maybe you know the fast response is the one which takes you up to 50% of the final value and then there is a slow process which takes over, okay.

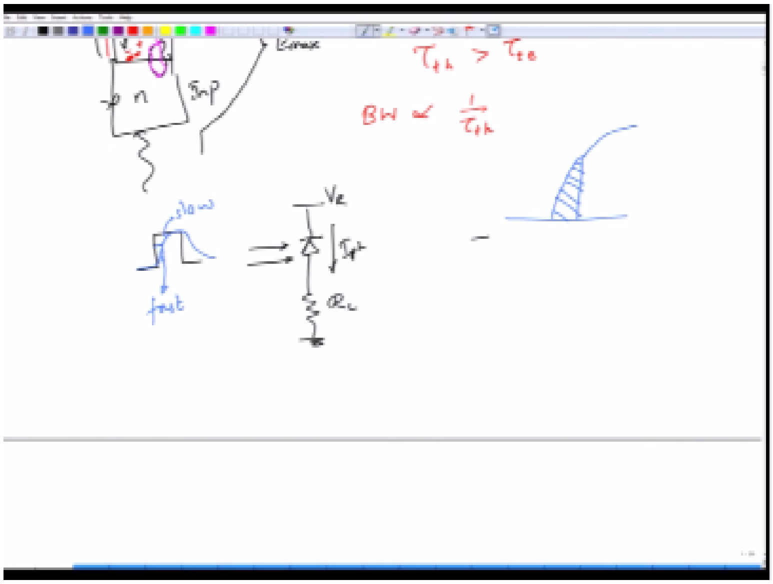
So this fast process is because of that drift components I have generated they have reached. But now the diffusion time becomes larger, okay depending on the doping concentration the diffusion time will become larger.

(Refer Slide Time: 12:39)



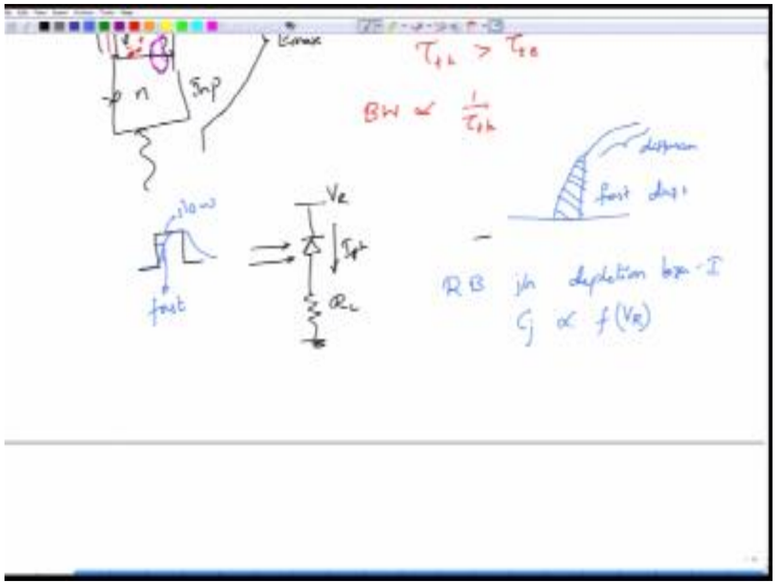
So it is effectively the diffusion which limits, okay the total rise time of your photo diode, again when I say this is fast I am only implying that this is fast with respect to the diffusion process, okay it is not the receives infinitely fast that the moment you are electron whole pairs are generated they would have reached the other end, okay.

(Refer Slide Time: 12:58)



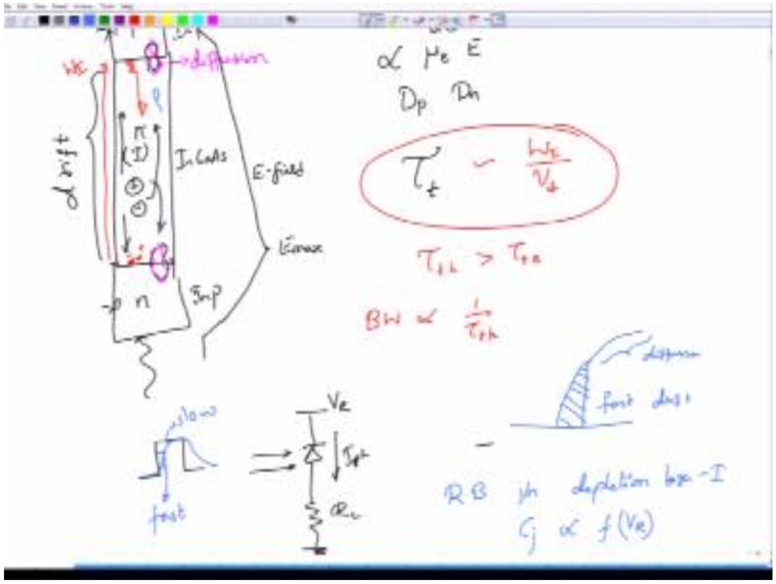
So this fast process is mainly due to the drift process and this slow response is mainly because of the diffusion, so you can see that even if you make WI smaller that is reduce the drift time, right you still would not succeed unless you bring down the diffusion time, right. So you have to bring down the diffusion time in order to make the overall response reach as fast as possible. The other way to understand this one is that a reverse biased junction, okay.

(Refer Slide Time: 13:27)



Which is essentially the depletion layer that we have here for the I type material this depletion layer actually is associated with a certain junction capacitance, right or it is associated with the certain capacitance, right. This capacitance of course is a function of the reverse bios voltage and in fact reduces when you increase the reverse bios voltage, this is one of the reasons why you want to include a ray in a very high reverse bios voltage. So biased at a very high reverse bios voltage your junction capacitance reduces, okay.

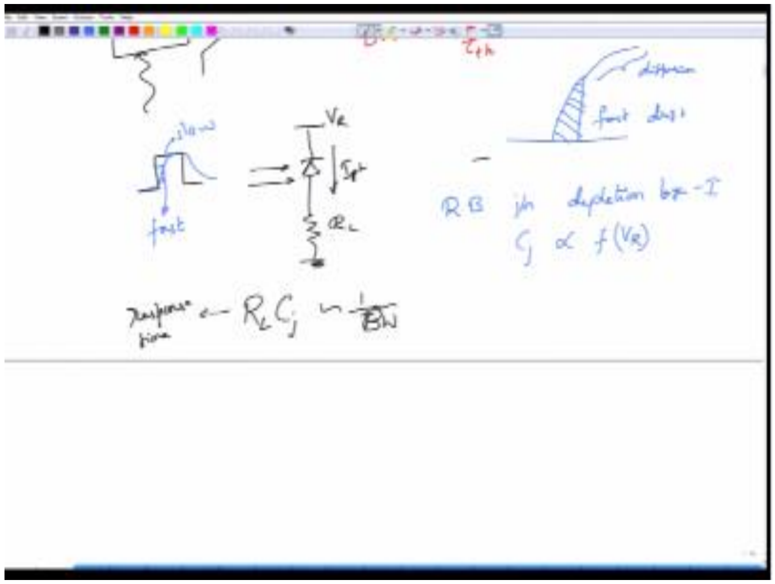
(Refer Slide Time: 13:58)



There will also be some amount of conductivity of the material in the I region I am talking only of the I region response here, so there will be some conductivity or equivalently some resistivity row, resistivity row depending on the semi conductor bar the width in the geometry of that one will give rise to some amount of resistance R, right. So even if you are external resistance RL where to be made infinite, right so that it is not loading the photo detector, not exactly in this configuration but in the op amp TAM configuration which we will discuss later.

Even if you make that part not depend on anything you are fundamental limit again comes from the transit time which is again basically because of the capacitance because the transit time is essentially how you are taking the semi conductor I region and then charging the I region, right. So you cannot just bypass that capacitance that is sitting there. So put all these things together the response time of a photo diode you know is determine by all these characteristic.

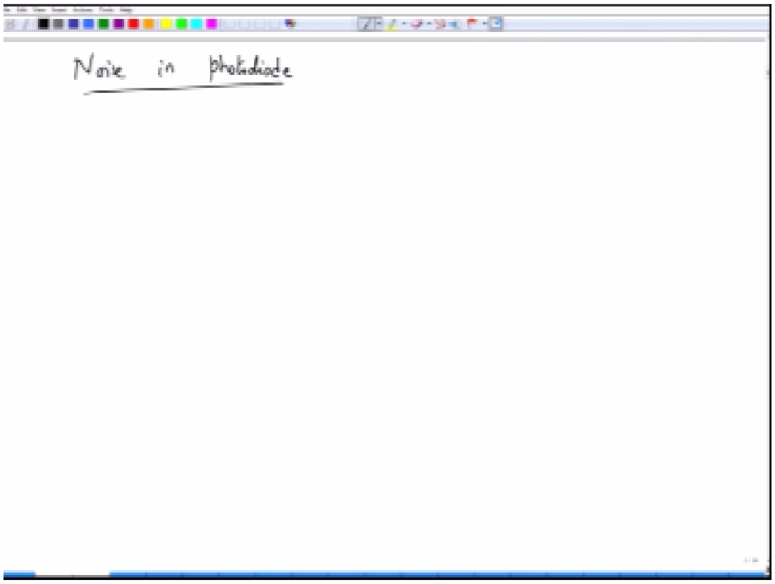
(Refer Slide Time: 15:00)



In most circuit applications it turns out that RL is sufficiently the one which determines the RL and the junction capacitance Cj is the one which determines the band width of the photo diode, okay so one can write this as 1/band width and clearly this RL into Cj is the response time of the photo diode, okay. Thorough analysis of all this requires has to write down the diffusion currents, requires has to write down the drift currents, solve the equations using certain boundary conditions which is all in my opinion little more complicated than there is sufficient for our course.

So we are not going to look at that one in this course, rather we will move on to considering an important aspect of the photo diode.

(Refer Slide Time: 15:46)



Namely the noise in the photo diode, okay. Now how do you define noise the most common answer that I get when I ask a question, how you define noise is that noise is an unwanted signal. It is not a very good definition of noise because nothing is unwanted the devise does not discriminate whether you are supplying with a signal or whether there is just noise as for as the devise is concerned noise photons or the noise electron whole pare are just as legitimate as your signal photons okay.

So there is no difference between a noise and a signal and this simplistic stateme3nt which mean is people answer when you ask for what is a noise is kind of misleading what you have to say instead is that noise is a stochastic process which you can characterize averages statistical averages and in a signal bandwidth of interest of course you have a signal which you have transmitted in that band width of interest it is the stochastic process which crapes your signal.

Because it is that noise I mean it is that part of the signal which is unpredictable only in the sense of statically averages and it is something that would writes it is it right in the band of your signal interest to see what I actually mean by this is this that to see that one you consider modulating your optical signal so you are sending out some information you modulated it you can take a look at the power spectral density of the modulated wave form.

Okay will talk about power spectral density lightly later in connection with photo endowed noise as well but you can also defines power spectral density for your input signal as well okay. so you define the power spectral density you see that it is a essentially the shape of the furrier transform or at least related to the shape of the furrier transform and then this power spectrum density passes through the channel at the receiver you are looking at what is the inn coming power spectral density.

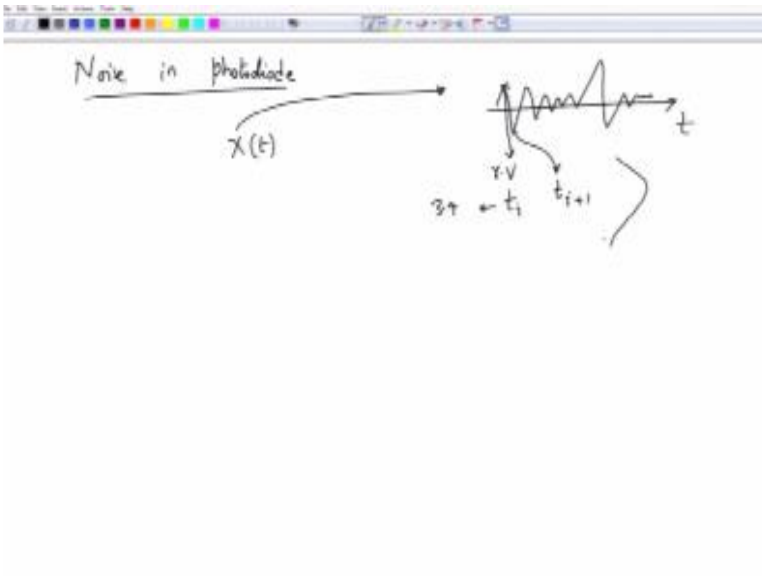
Correct so because this is optical power we are talking about there is an optical power density then there is a broad band this is one of the other characteristic of the noise okay most noise of course, is broad band much more broader in it is band width compare to the signal okay and signal band width. Now you can try and eliminate all those noise which is not in your receiver pan pass filter you know you put the receiver in a nice pan pass filter.

So that you let in only the decide signal that is what you would think right so it is only that particular signal component within this band width is coming in, of course in the band width you actually find to you know outputs or rather two components of the output one component will be the decide signal that you have transmitted right so it is a essentially the signal that writing which you expect to extract and you know read the message or you know extract the data out there.

But each of those values at every time within that you band width of that one that value will have a fluctuation about it is you know there will be a fluctuation about it is mean value so this fluctuation which is characterized only by the statistical averages is the one that constitutes noise. So the proper way or mostly the engineering way of characterizing noise is to actually talk about the noise spectral density okay.

We say noise spectral density and we connect that noise spectral density to other term called as correlation okay.

(Refer Slide Time: 19:17)



Suppose I considered stochastic process x (t) what a stochastic process means is that if you take a certain you know time and then measure a quantity so let us call this quantity as x okay then you will see a wave form that would look like this each of this sample values is a random variable you cannot specify once your sample this values say at some t = ti of sample date you cannot tell us what would be the value of this process x(t) a t I + 1 that at the next sampling instant.

Okay of course it can be continues I'm just showing you the idea in terms of the discrete once so I cannot tell you what exactly ti+ 1 is suppose this amplitude is 3.4 I cannot tell you what the amplitude here at ti+ 1 will be with 100% certainty rather I can tell you that there essentially a probability distribution of the values okay suppose the probability distribution is centered at 0, which means that most likely next time you are going to get a 0 volt, assuming that this is a noise voltage which we are measuring, you will going to get 0 volt, okay.

Of course someone else might say no you won't get 0 volt, but you might also get – ∞, or may be this side is a , – ∞, or someone will say no you will actually get + ∞, what differentiates between these 3 statements is what is the likelihood of each of those statements being true, right? And that likelihood is essentially determined by the probability distribution function.

So stochastic process is essentially a sequence of random variables, these random variables actually follow a certain probability distribution function, okay the characteristic of the stochastic process is that you can actually talk about what is the average value of x(t), okay there is a certain average value which you can talk about.

Then you can also introduce what is called as the autocorrelation, you can actually write down this autocorrelation in typically denoted as $R_{xx(T),}$ okay , or sometimes a shorter version called $R_x(\tau)$. If you talking about two different random process, or two different random variables you can talk about R_{XY} or R_{YX}, there are certain properties associated with that which makes that these two are essentially symmetric.

By the way these random process can be complex, it doesn't mean that there are complex random variables are occurring in nature, it simply means that you can think of this complex random process as something that has in phase and Quadrature component, okay just assume you would think of a signal modulated signal envelope has something that has a in phase and a Quadrature component.

Remember that analytical you know representation of the signal that we talked about, s+t the Hilbert transform the up converter the down converter this is exactly coming from that. Okay so noise also can be characterized as having in phase and Quadrature components, and it will separately add to the in phase component of the signal and to the other you know the Quadrature phase component of the signal, okay.

And the point is that these two which know together this random process is something that actually fall within the bandwidth of the signal there is no way you can eliminate them, there is no way you can eliminate it, you can just have to live with it, okay ,how do you live with it? You expect or you want the system designed to ensure that whatever you receive that is mostly signal with very little amount of noise.

Okay, so that ratio of mostly signal to less amount of noise is quantified by signal to noise ratio, you want the signal to noise ratio to be as high as possible, okay. So coming back to the auto correlation, auto correlation can be defined as you know you take the two sample values, $X(t)\ X\ (t+\tau)$,τ is called as the lack of the auto correlation ,and then find the average value of this ,ok so this is what is brackets which I am drawing is the average value or the statistical average value, and this will tell you the auto correlation.

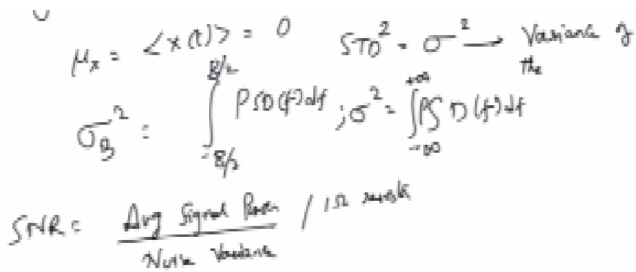
But this is something that is done in the time domain, right? This is done in the time domain but power spectral density as its name would suggest is the quantity that is defined in the frequency domain, so how can I define that one? Well power spectral density is basically the Fourier transform, of this $R_{XX}(\tau)$, okay so you compute the auto correlation of the process and then take the Fourier transform of that then you will get the power spectral density.

But in addition to this one there is also another quantity that we normally use, this σ^2 is called as the mean square value of the signal, okay. Mean square value for a process is basically given as the average of $\sigma 2^{=} < x^2(t) - < x\ (t)\ ^2$, actually this is coming from $< x\ (t) - < x\ (t)$, so it's like the deviations from the mean and then you taking the squarer of that deviation, okay.

So in case where the average of $< x(t) = 0$, that is the process has 0 mean as what we would call then standard deviation will be exactly equal to this quantity $\sigma\ ^2$ or $STD^2 = \sigma^2$, wand the $\sigma\ ^2$ is called as the variance of the process, okay. Variance is in some sense the power of the process variance will actually tell you the power, because it is actually from the Fourier transform relationship, you can show that σ^2 is actually given by the power spectral density integrated over the band width.

So if you looking at the low pass bandwidth then this would be the power spectral density of course if you're looking for the infinite case, then that would be the total power that is contained inside the σ^2. So it would actually be the power spectral density over the entire band, from minus infinity to plus infinity. Now why is this σ^2 important? Well we define the signal to noise ratio as the average signal power to noise variance, both measured with respect to say 1Ω resistor, that is to say you assume that the signal is actually dissipating some power in resistor.

(Refer Slide Time: 25:47)



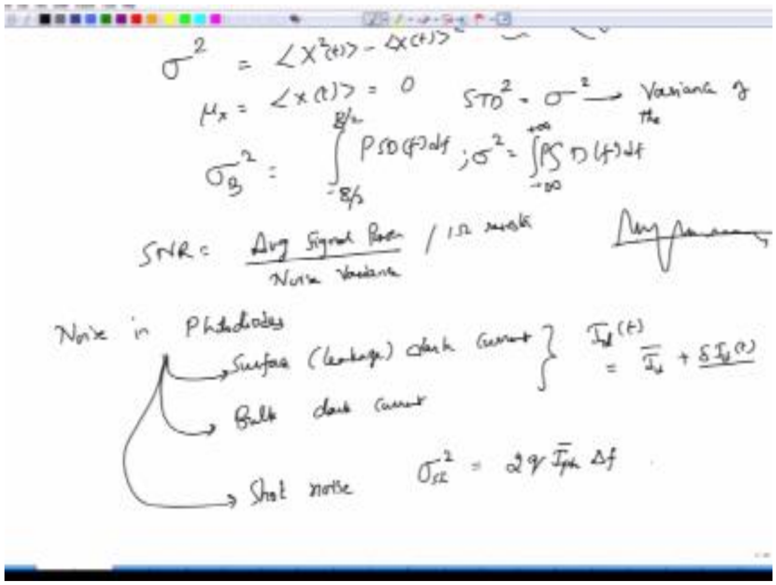
For simplicity we take this resistor to be 1 Ω and noise variance again is the power of the noise inside that Ω resistor, this would be the total noise variance inside the bandwidth that you're looking at, so you have to be very careful, if I change the bandwidth, the signal noise ratio will change. F I increase the one, the noise variance will increase, I have to little careful as to what I'm actually doing over here, this is for the same bandwidth. So that's essentially the signal noise ratio.

Now what kind of noise can you expect in photo diodes, you will see that there are two, again the photo diode noises are also expressed in terms of variance and everything, so you see that there are many noise processes, one is called as the surface or the leakage dark current, sometimes called as the bulk and addition to this there will also b a bulk dark current, together you cal this simply as I_d, I_d will be a dark current noise that is even when my photo diode is not illuminated, I still get some signal of photo current $I_d(t)$.

This I_d (t) will have a certain average value + a variation, it will be a average value on top of it, it would be like this Varian, this average value is I_d bar and this variation is Δ I_d (t), so if you look at this mean of this I_d (t) process, this is now a stochastic process, the mean of this process is I_d

itself. The mean of this $\Delta I_d(t)$ is 0, because you simply extracted the average quantity out, so this one noise component and as I said, important noise component is the so called short noise.

(Refer Slide Time: 27:50)



The short noise variance, let's call this as σ_{sl}^2, the short noise variance is actually very interesting, it is given by $2q\bar{I}_{ph}$ bar times Δf, where Δf is the bandwidth, over which you are integrating the whole thing. So this is the short noise variance, as for the variance of this $\Delta I_d(t)$ process, the dark current process is also given by 2q I_d bar into Δf, Δf being the bandwidth over which you're looking for, noise processes, so these are the two main processes that you get in the photo diodes.

Put a photo diode in the form of TIA or simple load resistor circuit, the load resistor R_L will also give raise to an additional noise called as thermal noise, many earlier generation photo diode circuits are limited mainly by the thermal noise of the circuit. Thermal noise current has a variance, the thermal noise current has a variance of $4KT/R_L\ \Delta f$, this variance actually reduces as the value of R_L increases, so these are the two noise processes that you will find in the optical receivers. WE will talk about how to optimize optical receiver in the next class. Thank you very much.

Acknowledgement

Ministry of Human Resource & Development

Prof. Satyaki Roy

Co-ordinator, NPTEL IIT Kanpur

NPTEL Team

Sanjay Pal

Ashish Singh

Badal Pradhan

Tapobrata Das

Ram Chandra

Dilip Tripathi

Manoj Shrivastava

Padam Shukla

Sanjay Mishra

Shubham Rawat

Shikha Gupta

K. K. Mishra

Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

an IIT Kanpur Production