Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VIII
Module-I
Noise in photodiodes-I

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Hello and welcome to the moke on optical communications. In this module we discuss response time of a photodiode first, a very brief idea of what limits the bandwidth of the photodiodes which is the response time, which is determined by the response time.

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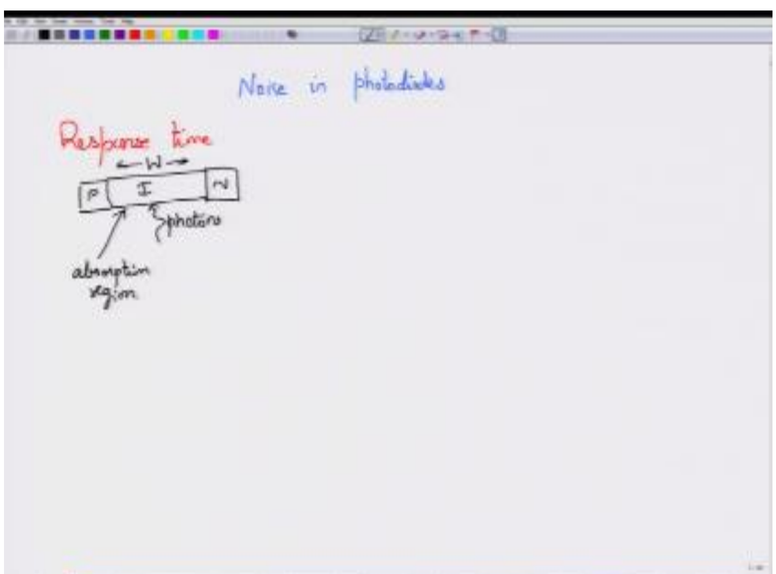

And then we will discuss couple of noise processes in photodiodes both PIN as well as APD structures. And then see what would be the signal to noise ratio if you use this photodiodes into making into a photo detector circuits or an optical receiver circuit. Now if you recall the structure of a Pin photodiode you have a P region, you have an N region and then there is in between an intrinsic region which is usually quite wide, because the objective of the intrinsic region is to absorb as many photons as possible.

So you have a wide intrinsic region to which the photons are supplied and the photons are absorbed by the material and the photo carriers are generated that is electron hole pairs are generated, there is a strong electric field in the region, both this is true for both PIN as well as for the APD structures. And what happens when you have a strong electric field is that holes and electrons will move in the opposite directions.

Of course, each electron hole pair moving in the opposite direction would constitute one electron pulse if, I mean one current pulse if you would think of right. So as this charge carriers move what is the distance over which they have to move. The worst case scenario is when the electron hole pairs are generated at one of the edges between IN or PI regions. Why is that so, because if you imagine that this is the PIN region at this edge if you have an electron hole pair generated, hole for example, if it is onto this side if it gets attracted to this side has very little distance to propagate so it quickly propagates out.

However, for the complete current component to occur we have to wait until the electron moves all the way from the intrinsic region and then gets recombined over here. So you will see that worst case scenario one of the electron hole pair carrier, it could be the electron or a hole, but it has to travel the entire length of the intrinsic width which is usually almost close to the width of the intrinsic region that we take, the actual width will be slightly smaller because of the biasing but that is for a good approximation one can think of the length over which they have to propagate as the entire intrinsic region.

Now, when and how do these electrons or holes actually propagate? They actually propagate under the influence of the applied electric field.

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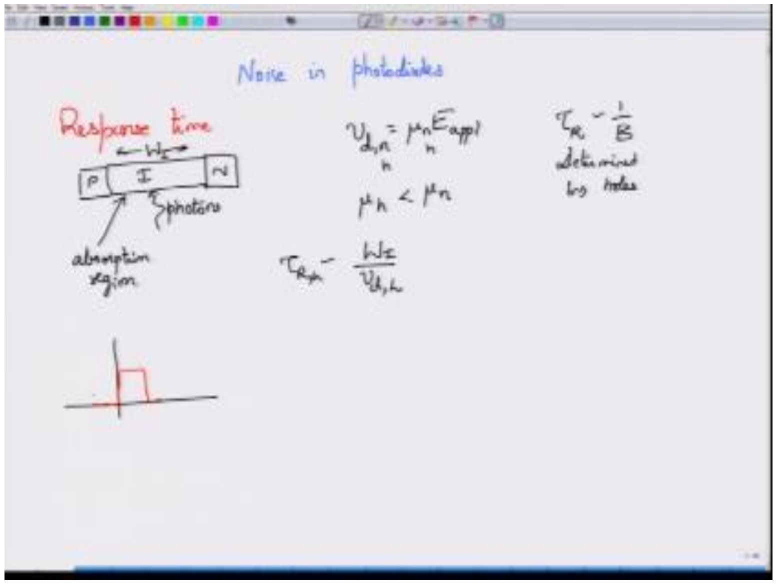

So when the electric field is applied, the charge carriers actually drift it is just a way in which connects are generated, this drift is acquired by the electrons or the holes which is proportional to the applied electric field, so this is the applied electric field which is the result of the reverse biasing of the photodiode okay.

And then whether you are dealing with the electron or the hole, the corresponding drift velocities will depend on the mobility of the electron or the hole. And it is, you can look at the semi-conductor literature and find that the mobility of the holes is slightly smaller than the mobility of the electron. What this simply means is that, electrons are faster, holes are slower and which of those two will give rise to a larger response time obviously the holes.

The holes have to take a longer time in traversing and therefore, they form the fundamental limitation and if you think that the response time tow r is in some sense inversely proportional to bandwidth of the operation, you know the speed at which one can generate repeatedly these electrons and constitute of current. Then this response time is more or less determined by the hole velocities or determined by the holes itself.

So you can have a very good idea or a very nice approximate value for the response time and write this as the width of the intrinsic region, so maybe we will write down W_I just to denote the width of the intrinsic region divided by the drift velocity of the hole. So the hole response time is $V_{d,h}$ and this kind of puts out the ultimately met in terms of the bandwidth of the photo detector okay.

If you look at the optical input, so for example if you supply an optical input that looks like a nice pulse here with very small rise time, you can generate this optical pulses by various processes, you can actually modulate a continuous web laser to generate the optical pulses are you can use mode lock lasers to generate this optical pulses these pulse have a very small rise time okay and if you give.

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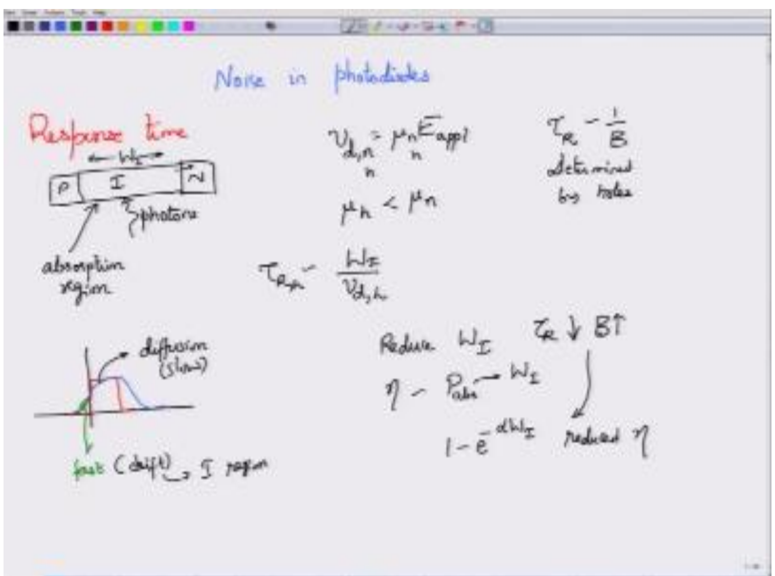

This optical pulse as input to the photo detector okay or the photo detector circuit and absorb the current wave from that is generated as the result of this optical input you will see that the current is not exactly following the optical input okay the shape of the optical input initially the current raise very quickly okay and then there is a very slow process and then it drops of later on okay so this initial fast process okay.

So this region is the fast process that we have okay followed by a slow process is because the fast process actually happens due to the drift where as the slow process is because of the diffusion and so diffusion this is slow fast is because of the drift is for both electrons as well as holes and this occurs in the I region or the intrinsic region however diffusion is the one that occurs in the P and N regions that are associated with that because these form the minority carriers and this minority carriers have to defuse into the next junction.

You know to the adjust region and this process which is happening at the junctions is slower compared to the drift because drift is because of the applied electric field and therefore it is considerably fast compare to diffusion is because of the concentration gradient okay so in that way you have a fast process and then you have a slow process which eventually you know contributes to the limitation of the speed at which you can operate this photo diode okay now what can you do in order to reduce the response time and increases the band width well one can element one type of the carriers.

So one can work only with the electrons or the holes but then you are not really utilizing a semi conductor material there so it is kind of out of scope solution for us the other solution that you can try is to reduce the intrinsic region width W_I but remember W_I makes a major appearance in defining the quantum efficiency the external quantum efficiency which is defined as the rate at which photo carriers are generated to the rate at which photons are incident depends on how much optical power is absorbed.

But this optical power is that is I absorbed depends on what is the width of the intrinsic region because the absorbed power is proportional to $e^{-\alpha}$ where α is the absorption coefficient of the material times W_I so if you reduce W_I you do not have good thinness or length of the intrinsic regions so has to absorb the photons so some photons might simply be not absorbed pass on and on to the other region and they just go way so your basically reducing the quantum efficiency we will later see that quantum efficiency is directly proportional to the sensitivity of the photo diodes okay so how low optical powers can be detected depends on the quantum efficiency.

So if you reduce the intrinsic width then response time decreases band width increases response time decrease but the band width increases but this comes at a price of reduced quantum efficiency something that you would not want to have when your are detecting low optical powers optical light at very low optical powers so there is actually a trade of between the two and there is essentially optimum that one normally says okay.

So you have photo detectors with larger bandwidth but reduced quantum efficiency or photo diodes with very small band width and increased quantum efficiency this later case you know where you have a reduced band width\ typically in tense of mega hertz but very high quantum efficiency are actually used for deducting very low optical power signals such as a photon counting circuit utilizes this fact so you have a smaller band width but a larger quantum efficiency okay that brings us to an end on response time of the photo diode we will now quickly jump over to noise process in the photo diode okay you might think.

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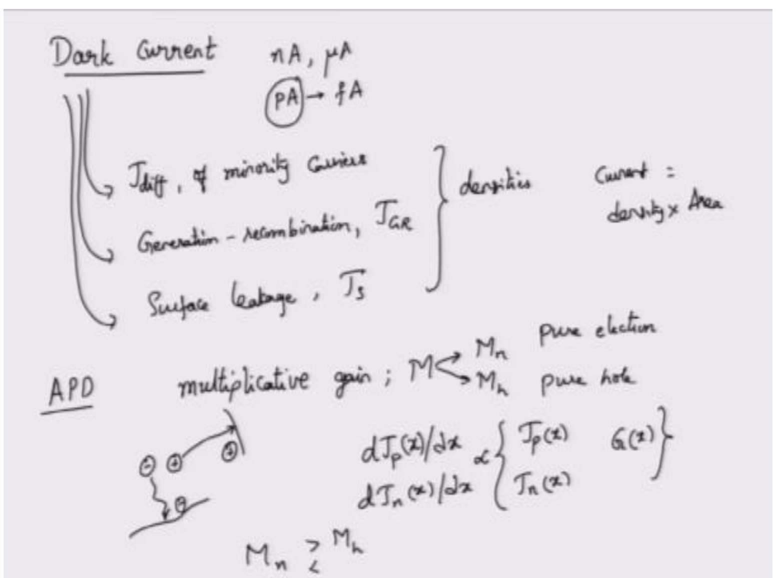

That there might not be any noise when the photo diode is not eliminated if you do not shine on a photo diode you think that there won’t be any noise but sadly that is not really the case because photo detectors kept on room temperature as a significant thermal energy the materials have significant thermal energy the atoms have significant thermal energy and occasionally one of these electron hole pairs might be generated.

And if you have reversed bias the photo diode which you are going to do for the photo diode operation these generated electron hole pairs will them accelerate and constitute a current, no photon but current. This is called as the dark current.

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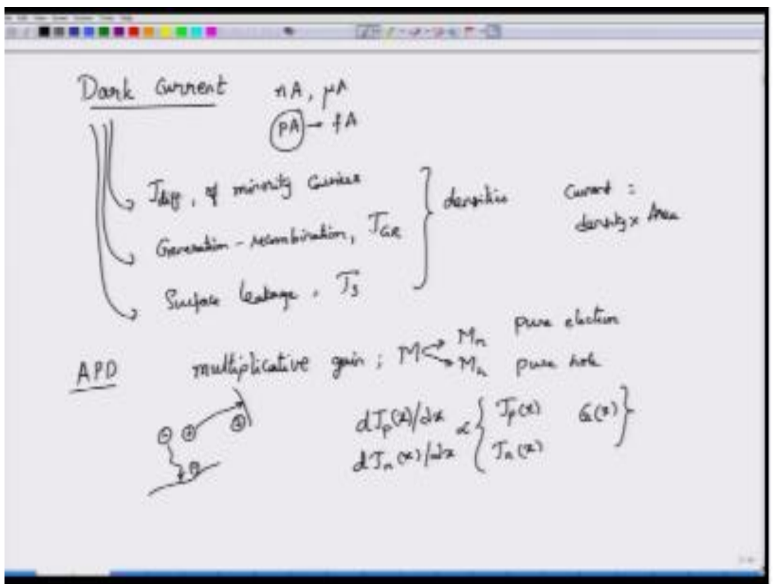

And dark current is a very difficult quantity to pin down because it depends on the device structure depends on the room temperature and hence what would be the temperature cooling facilities that you can the general rule is that the lower the temperature or a cooled photo diode will have lesser dark current, okay. But it also depends on the casing depends on all kind of other you know factors.

So it is usually something very difficult to theoretically explain but you can find photo diodes with dark currents typically in the range of Nano ampere worst photo diodes are in the range of micro amperes these days you get very good photo detectors with dark currents as low as Pico ampere to Femto Amperes, okay. So its component is kind of quite negligible when you are working with very good photo diodes especially at telecom applications you will now are able to obtain Pico ampere dark current photo diodes, okay.

So this is for the dark current there are three reasons why you get dark current, although evaluating them will be kind of very difficult, one is that diffusion of the minority carriers which is generated because of the thermal agitation, okay. As I said thermally agitated electron hole thermally generated electron hole pairs will drift under the application of the reverse bias voltage causing a minority carrier diffusion current.

Which causes dark current, okay, there are also other processes such as generation recombination happening okay and this generation recombination in turn gives rise to a certain current density or the dark current component, finally the surface is not very nice because it is kind of creates avenues for which electrons can be generated resulting in the form of a surface leakage current, okay. So this would be the surface current of a surface current component of the dark current, please note that these are all densities okay which means that if you want to find out what is the current.

Current is given by density times theory of the photo diode so one way in which you can reduce the dark current is to reduce the area of the photo diode but go back to our earlier problem reducing the area especially reducing WI would again cause problems, right because you are absorbed photon power would be reduced and hence you would not be able to get very good quantum efficiencies, okay.

So that is typically the dark current, now if you go to APD's which is the avalanche photo diode you see that we have already discussed avalanche photo diodes and they differ from regular PIN photo diodes in the sense that you actually have what is called as a multiplicative gain this simply means that in an APD once you generate an electron hole pair these electron hole pairs will impact ionize the material, right.

So they will go and hit the material creating ionization resulting in generation of extra electron hole pairs right, so quickly a pair of electron hole pairs can generate a million number of electron hole pairs leading to an internal gain of the device so there is no amplifier connected but there is an internal gain of the device, right. So this multiplicative gain is denoted by the parameter M.

And this M in turn consists of the multiplicative gain because of the electrons alone and multiplicative gain because of the holes alone, okay. These factors M_N and M_H can be obtained from some theoretical analysis which is kind of very difficult to do in this course so we are not going to look at that one but briefly the idea is that if you evaluate M_N by assuming pure electron injection and you determine M_H by pure hole injection.

And then look at the concentration gradient of the holes or the electrons okay, so concentration gradient is dJ/dx so if you look at the concentration gradients and calculate this you know relate these two the density J_p and J_n of the hole as well as the electron currents plus whatever the generation recombination I mean generation rate that is happening inside the photo detector these two are essentially functions of all these parameters, okay. And it is kind of little difficult to do the exact analysis.

Because this analysis has to be different for different kind of structures of the APD, so normally what we are assume is that there is essentially a homo- junction kind of a device, so that the multiplicative gain is assume to be you know for simple analysis it is assume to be not statistical it is assume to be kind of a deterministic process and you assume that all the optical power that is incident on the APDs completely absorbed, okay. So you do all that to evaluate M_n and M_h what is interesting in this M_n and M_h is that.

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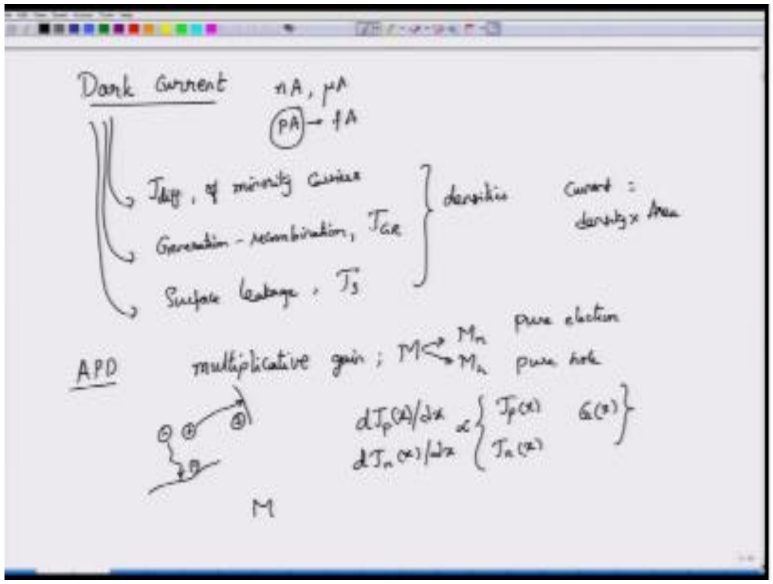

Depending on the ionization parameter, if electrons have a process band city ionize more compared to the electrons then M_n will be larger than M_h, okay.

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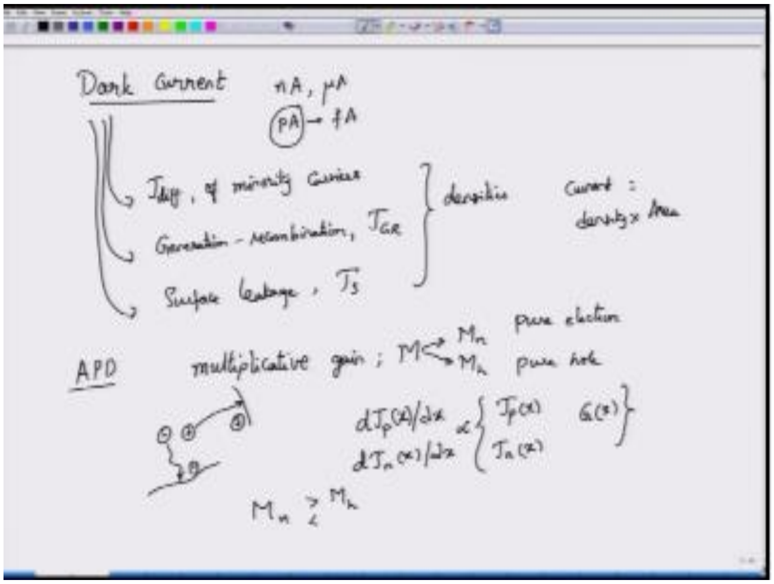

So depending on the parameters you can either have Mn larger then Mh, or you can have Mn smaller than Mh, okay and for a good APD we normally try to maximize one of those with respect to the others which means that the injection or the impact ionization happens mostly because the one type of the carrier, whose impact ionization is larger. So if you have electron impact ionization is larger you try to make APD in multiplication region mainly consisting of the electron impact ionization, okay.

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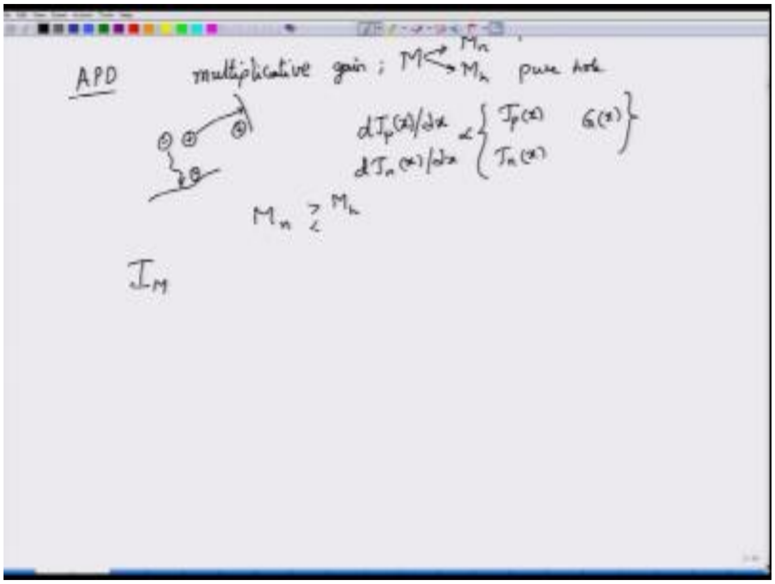

So these are something that are little advanced for the course to discuss so we are not going to look at that one. But associated with this M_n and M_h there is a photo current. If you look at the photo current, you will see that the photo current itself is not really a constant photo current for a constant optical input, but there is actually a fluctuation of that, and this fluctuation is because of the multiplication process that is fluctuating, okay.

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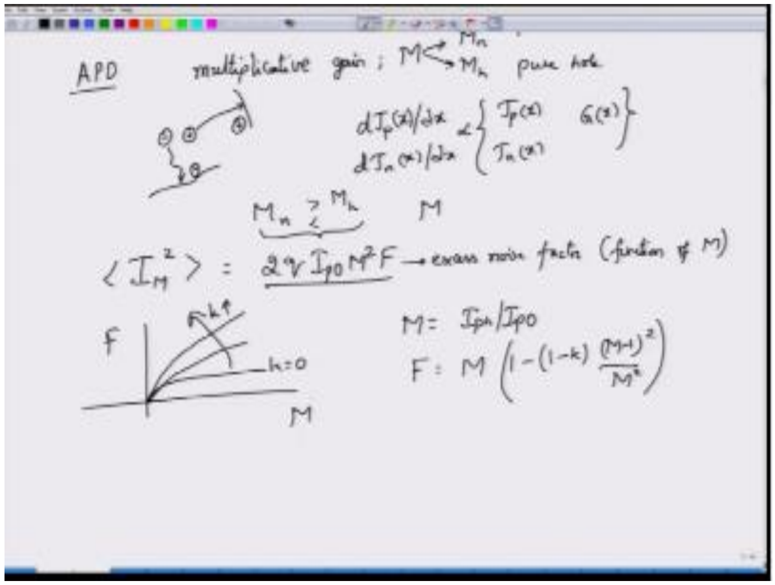

The variance of this fluctuation process is given by so there is a effective M that goes along with this one, okay so there is an effective M that goes along with this M_n and M_h and then you have the fluctuation of the current itself given by 2qIp0, Ip0 is the primary photo current that is generated times M^2 and F M^2 is the multiplication square, multiplicative gain parameter square and F is what is called as the excess noise factor, okay so this excess noise factor is actually a function of M itself, so making our APDs little more complicated you know they are excess noise factor itself depends on M if you look at the excess noise factor as a function of the multiplicative gain you will see something like this, so this would be the way in which this goes for there is a another parameter called k which I will just define in a minute.

But if you change this k you will see that there is actually a linear increase so as k parameter increases k is a constant which increases which depends on the ionization parameters of the electrons and the wholes and as k increases the excess noise increases for the increasing in, increased in a multiplication factor, okay. So they are actually related like this multiplication factor is basically how much photo current you are able to generate given what is the primary photo current Ip0 whereas the excess noise factor is given by M time 1-1-k as I said k is a constant which depends on the ionization parameters and $(M-1)^2/M^2$.

So you can see that this excess noise factor is actually is a function of M, okay. Now this is all about the APD we will come back to this equation slightly later, okay for now we will look at other noise processes that are there in the photo diodes, okay other noise process that is there in photodiodes.

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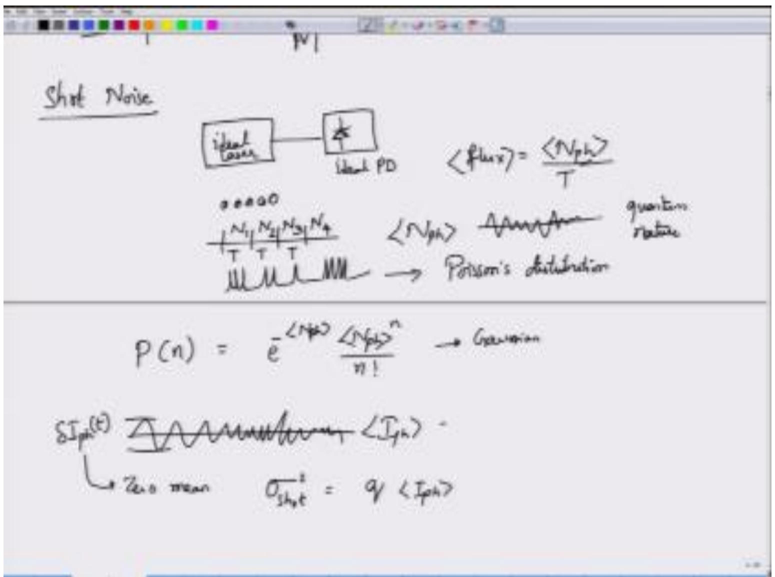

And that noise which is very important which is called as the short noise okay suppose you take an ideal light source an ideal laser and then you give it to an ideal photodiodes detector. Okay so this is an ideal photo detector right and this photo detector simply response by generating one electronic hole pare whenever it absorbs one photon. Now you expect if you keep the photon numbers constant that is it say the photons flex to be a constant value right.

It is like a continues wave power that you are giving you expect the current also to be just a continues line you know it is like a DC input and a DC output is what you expect right but unfortunately that does not happen because even in ideal laser when it is operating above the threshold does not send photons in a regular manner. So this is what you expect you know each photon coming in and therefore if you actually look at time access and then divide time access in to intervals of you know t duration.

Then see the number of photons here you expect the number of photons to be the same here right so expect at each interval t you expect the number of photons to be the same but unfortunately that is not what happens what happens is that the photon plugs which is basically define as a number of photons divide by the time interval time t or per time t there is actually a distribution of the plug itself.

It is not constant but here is a mean photon number which means in some times lot you get n1 sometimes lot you get n2 in sometimes lot you get n3 you get n4 and if you do an average of this one there will be an average photon number NPH around which photon numbers are fluctuating. Okay there is no this one for this is actually a quantum mechanics in origin this is the nature of light okay.

The nature of the light which does not allow photons to be a very regular manner is built in to light itself so you cannot do anything about that, however what is the effect of this statistical distribution on our photo detector well in some time units you are getting n1 photons therefore n1 electron hole pare generated or proportional to n1 so n2 photons are incident proportional to n2 number of electron hole pare generated and so on.

Right however there is one more story in to this the electron hole pare generation that itself is statistical it with the efficiency of η or with the probability of η if you normalize it appropriately electron hole pares are generated the probability that photons are incident but electron bole pare is not generated is $1-\eta$ so there is a statistical distribution in the way electron hole pares are generated in the photo detector.

There is a statistical distribution in the way photons are coming in to the photo detector itself from the laser so there are the effect of these two is that the current distribution becomes essentially statistical okay so if you look at the current pulses in some duration you might generate 3 current pulses next time maybe generate only 2, next time we have generate only one then there are 3 or 4 like this.

So there is essentially the satirical distribution in the way current pulses are generated and this statistical distribution follows what is called as poisons distribution are very closely follows what is called as poisons distribution. What is poisons distribution suppose you are looking at the number of photons that are generated in one rime unit okay you call that has probability of n photons being generated this is given by e^{-Nps} which is the mean photon number.

And the mean photon number to the power n /n! okay for large value of n this essentially approaches Gaussian distribution but for small values of n, which happens when the optical input power is low that is statistic is actually poison ion I mean it's actually poison ion everywhere but for large n you can approximated to be Gaussian, okay.

As we said this process also the same as the electron hole pair generation, okay so the combination of these two statistical nature is that, your current is not really a constant but there is actually a distribution around this current, okay, with a mean photo current given by the mean value of the photo current, and there is actually a time varying component which we can write this as Δiph (t), which has 0 mean but a variance which we call it as short noise variance.

Given by surprisingly it is also given by q(iph), so it is actually directly proportional to the mean photo current, so you might actually think that oh! Increasing the photo current value mean photo current value will increase the short noise variance, and you are right, short noise variance does increase, and increases linearly with the increasing photo current, okay.

However what you're interested not just this one, you're interested in what is the total noise power contributed in to the photo detector circuit having a bandwidth BE.

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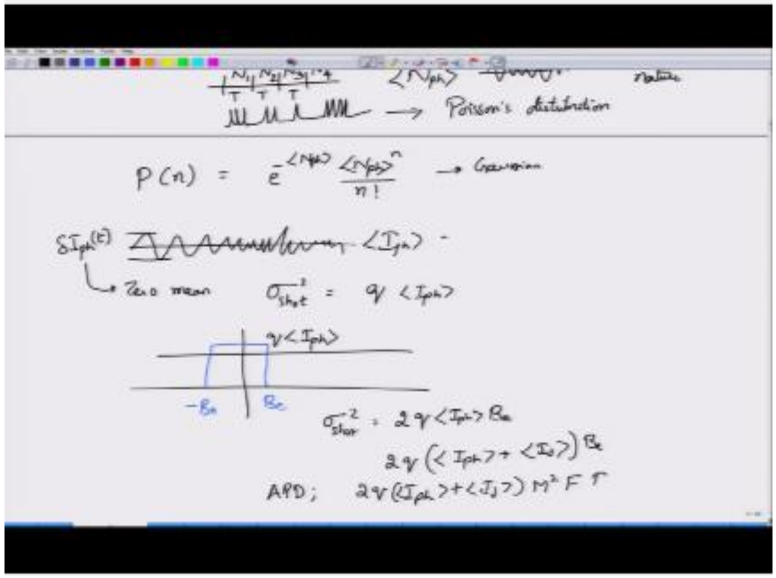

So let say this is the pars spectral density, pars spectral density is essentially constant, and therefore this is a white noise process, the value of the parse spectral density is q(iph), however now if you put in a band pass filter, okay whose bandwidth is BE, the low pass bandwidth is BE, right.

The total power contained within this bandwidth will be given by 2q(iph) which is the mean photo current, times BE, okay so this is your short noise variance okay, this is the variance because the variance actually power that is dissipated across average power that is dissipated across a 1 ohm resistor.

In case there is short noise then you replace this photo current wit the mean dark current, okay so the short noise variance simply becomes 2q ($<iph>+<I_0>$), because of this times BE, FOR APD'S the short noise variance is slightly complicated is actually given by, 2q($<Iph>+<I_0>$)m^2 F Be, which is the multiplicative gain , time is F, so this excess factor right? so this excess factor of m^2(f) is because of the APD structure, okay.
So we will stop at this point we have looked at the noise process in the photo diodes, in the next module we will give a small introduction on the other noise process which is thermal noise, and

then we put all these things together to discuss the signal noise ratio aspects of a simple photo detector circuit, thank you very much.

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