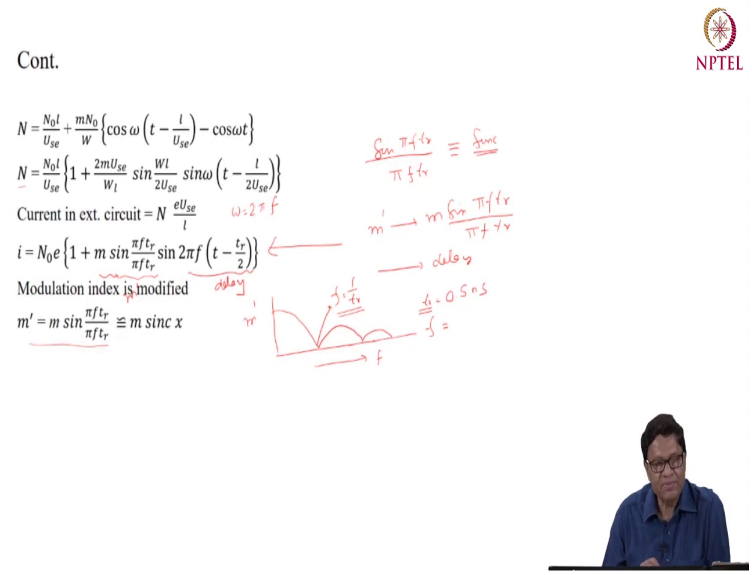
Optical Wireless Communications for Beyond 5G Networks and IoT
Prof. Anand Srivastava
Department of Electronics and Communications Engineering
Indraprastha Institute of Information Technology, Delhi

Lecture - 05
Part 2
Photodetectors (to be contd)

(Refer Slide Time: 00:22)



So, I can do the integration there. So, I will get 2 cos terms after putting the limit 0 to l. So, I will get 2 cos terms and these cos a minus cos b I can convert into you know product terms which is sin into sin. So, after doing some mathematical computation here N is actually N 0, N 0 is the initial carrier density into l divided by saturation velocity plus into 1 plus twice m saturation velocity of the electron into omega l omega here is the frequency l is the length of the device and sin omega l 2 vse sin omega t minus l by 2 se.

So, if I want to calculate the current in the external circuit the current in the external circuit will be number of electrons into e saturation velocity divided by l. So, this i value after putting and putting omega is equal to 2 pi f I get something like this. So, this is the current which is produced in the electric in the external circuit.

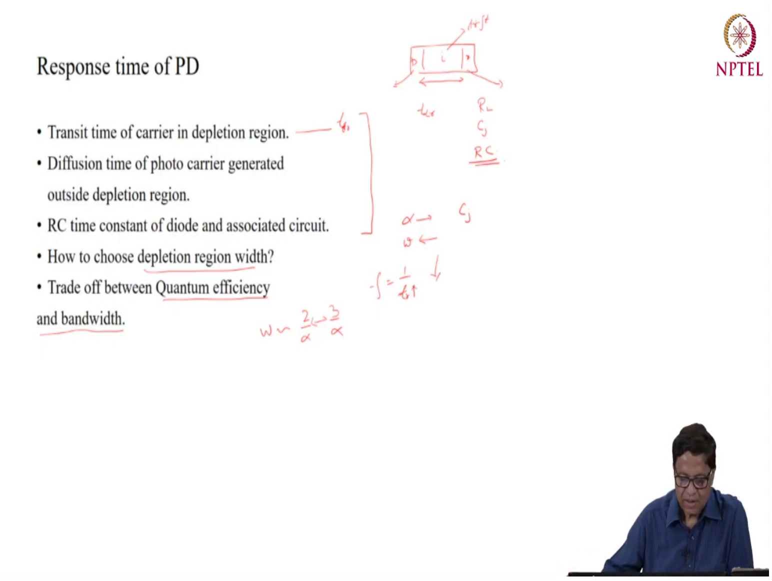
So, the current which is generated in the external circuit is N 0 into e 1 plus m sin pi f t r t as a transit time sin into 2 pi f into t minus t transit by 2. So, this is the current which is generated in the external circuit. Now you see there are two things here this modulation has got is modified earlier it was m sin omega t or m 2 pi f t. Now it has become m sin pi f t r f t r something like you know this sin f pi f t r over pi f t r is you know sinc function right.

And the other thing which you notice here is that there is a delay which is given by this term. So, the resultant current which is generated follows the modulation index is modified from say m to m dash and it has become m sin pi f t r divided by pi f t r and the second thing it has introduced some delay. Because, this term basically is the delay part and this is your modified modulation index.

And if I plot to this is the modulation index m dash rather it will be sinc function and basically this is say f and this f is equal to 1 by t r. So, you can take the value of t r as some 0.5 nanosecond and accordingly you can calculate the value of f. So, that actually becomes the response time of the device. So, it basically depends on the transit time and the contribution to this transit time is both coming from drift as well as diffusion.

So, you have to make your device in such a way that diffusion component is much less and the whole electron hole pairs are generated inside the i region. So, that your transit time is as low as possible and you get good response speed of the device. So, this is what I had explained that modulation index is modified m dash has become m sin f pi ft r or m sinc x of this form.

(Refer Slide Time: 04:59)



So, now just to put the things in perspective the total response time of the photo diode depends on the transit time of the carrier in the depletion region this we have seen this is a function of t r transit time. It also is function of diffusion time of photon carrier generated outside the depletion region. Remember our structure p n i. So, there is a diffusion component here, there is a diffusion component here, there is a drift component here.

So, this response time will depend on this diffusion time will be photo carrier generated which are generated outside the depletion region which is by i region here. The third component is you know you have when you use this device you have some you know external component R l right and then there will be some capacitance of the device some call it junction capacitance and if you have some equalizer then it will have some some R and C component.

So, basically it depends also depends on the because ultimately I have to see the response time of the whole device not just the photo diode it is a receiver part so, RC time constant of the diode and the associated circuit. So, these are the 3 things which will dictate your response time the transit time in the depletion region i region and the diffusion component which is there in the p and n region and the associated circuit and the RC time constant of the photo diode.

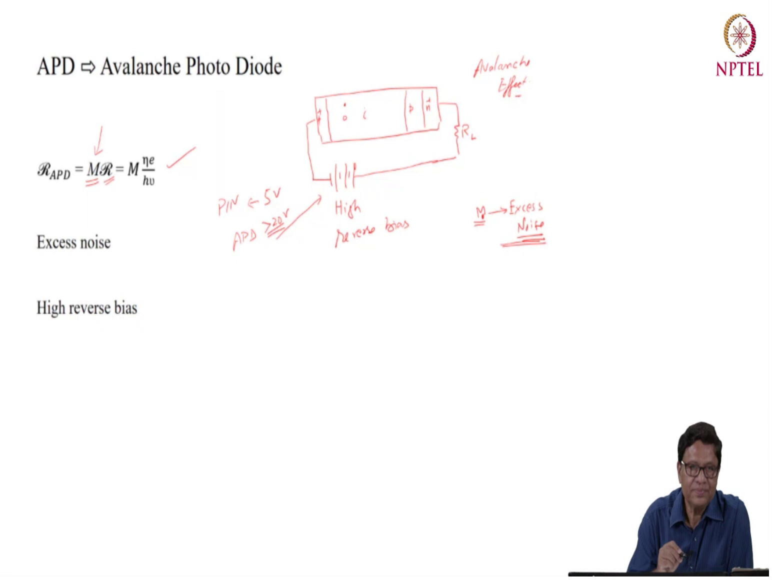
So, now the question is how to choose your depletion region width? Because no not everything is in your control. For example, alpha is not in your control, then there will be some components C j junction capacitance and associate circuitry will require some component. So, and then you have one component which is the length or the w width of the depletion region which is in your control which you can reduce or increase.

So, let us understand what happens if I increase w to a high value or decrease w to a very low value. So, so there will be a trade off let us try to understand see what I want that my when I am when my intrinsic region is wide. So, there is a greater chance that the photon will get absorbed and electron hole pairs will get will generate which means my efficiency will improve if I make it wide.

If I make it narrow the chances are that photon may not get absorbed because it is quite narrow the probability is low. So, it will may not result into electron hole pairs as that efficiency will go down. So, making it wide ensures that I have high quantum efficiency, but if I increase width the transit time increases because this distance is increased t tr increases and when t tr increases might that f will get reduced.

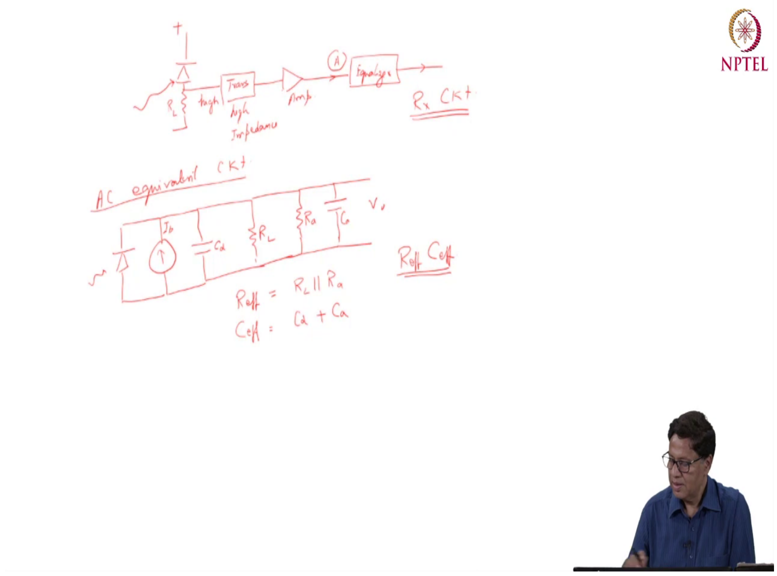
If this increases; that means, the bandwidth of the device gets reduced. So, there is a tradeoff between quantum efficiency and the bandwidth of the device. So, accordingly you have to you know select the value of junction width whether you want high quantum efficiency or you want high bandwidth. So, generally this is kept as this value is generally kept as let us see.

(Refer Slide Time: 09:20)



So, generally this is kept as w is you know 2 by alpha or 3 by alpha, alpha is your in between in this range that is ideal value to (Refer Time: 09:54) So, you get a good compromise between the quantum efficiency and bandwidth. So, before we start the discussion on the avalanche photo diode. So, let me just give you an idea about the circuitry which is generally used in the photodiode.

(Refer Slide Time: 10:26)



So, you have this is a photo diode light is falling onto it and this is the positive part this is the negative part and then you have the current flowing here. So, let me put a resistor here this is say R L and this R L is generally high. So, before you give it to the next circuitry you some sort of trans impedance amplifier which changes the high impedance input high impedance to low impedance.

So, this is trans high impedance circuit. So, what you get is sort of low impedance and then you give this to some sort of amplifier and you collect it here say let me write this as A. So, if I draw a equivalent circuit of this or AC equivalent circuit AC equivalent circuit it will be something like this. So, this is the photo diode and this is the current which got generated because of the power here.

So, let me call this current as I p photo current and this is C d junction of the diode C d capacitance of the diode C d capacitance of the diode this includes all the capacitance, and this is the amplifier part say this is amplifier, and this is the load part and this is the amplifier resistor, and this is the C a part and then this is the output here v 0. So, this is the equivalent circuit which includes is capacitance of the diode the load and the RC values of the amplifiers.

And if I see the R effective if I calculate then this will be R L parallel R a that is R effective and if I see C effective this is C d plus C a. And the total time constant will be R effective into C effective as a total time constant. So, so this will actually give distorted.

So, after this if you want to correct this which has the distortion has happened because of all these you know junction capacitances and the amplifier circuitry then you have to use some sort of equalizer here, which will equalizer that which will equalize the distortion which has occurred in the circuit.

So, at the output you get rather clean you know pulses on the replica of the input. So, this is how the whole receiver circuit will behave receiver circuit. Now, let us go to another type of device which is called as APD, Avalanche Photo Diode. So, avalanche photo diode let me first draw the structure of avalanche photo diode.

So, it is again a structure where p is heavily doped n is heavily doped and then you have the i region as well here. So, there is a i region here and this device is actually this is reverse biased, but heavily reversed biased reverse biased with a very very high value. So, I am making more cells here which in actually in indicates that it is high reverse bias.

So, when electron hole pairs are generated here then these electron hole pairs because of this high reverse bias they have extra energy and they enter into avalanche effect and generate additional electron pairs, which actually results into some multiplication gain and that happens because of this high reverse bias.

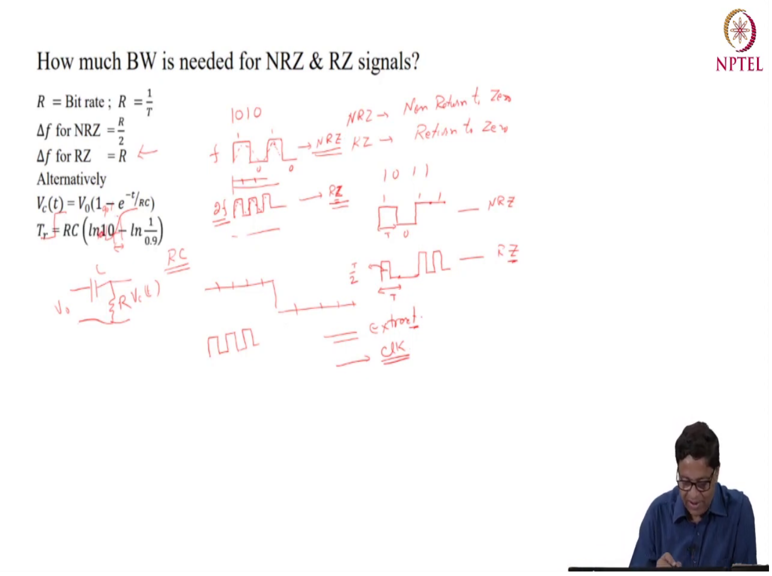
So, there is a avalanche effect happening here, which results into more number of electron hole pairs which are generated inside the i region and if you see the responsivity of such diode it gets actually multiplied by a factor M which is MR there is a responsivity if there was no avalanche effect. So, this M is the gain which you get and the putting the value of R and the responsivity which you had calculated as efficiency into e by h nu multiplied by n.

So, that becomes the responsivity of the APD there is a gain of M here. And this M is actually not constant. So, it is a very it is a fluctuating value right. So, this M because of this fluctuation this M will keep changing around some middle value. So, this because of this process random process random generation of like more in the electron hole pairs this will generate some sort of noise in the APD additional noise we have not discussed the noise of p ended that we will discuss once we have discussed the APD part.

So, this will generate an additional noise other than the noise generated in the flow diode which I discuss subsequently is called as excess noise. So, on one hand it gives you a gain, but at the same time this diode also generates an excess noise and it requires high reverse bias.

So, you require reverse bias earlier in p ended diode maybe the requirement is about 5 volts say for the PIN whereas, for APD it is greater than 20 volts if you want a good gain. So, the high reverse bias is required and it also generate some excess noise, but the flip side is that it gives you a gain of M.

(Refer Slide Time: 18:38)



So, now, we will try to see the another about the bandwidth let us try to understand how much bandwidth is needed for different signals. So, we have been discussing about the bandwidth of the source bandwidth of the photo diode. But let us understand suppose I am transmitting a NRZ signal or a RZ signal and RZ is non-return to 0 and RZ is return to 0. So, suppose you have 1 0 1 1 if I make a NRZ signal.

So, this is my 1 and then this is 0 and this is 1 and this is another 1 right. So, this is corresponding to 1, this is 0, this is 1 1. So, this is NRZ signal. The RZ signal will be in 1 it will for half of the time it is 1 and then it will come to 0. So, this 1 will behave like this. So, this is RZ signal and 0 will be; 0 will be like this and then again it for half of the time it is 1 and then 0 and then.

So, if this is T this is here T and this will be T by 2. So, this is RZ signaling the data which is coming can be in either NRZ form or RZ form. So, what is the bandwidth or device required if you are having NRZ data or RZ data? So, let us define R as the bit rate and so, R will be divided by R will be equal to 1 by T. So, if I see here in a for example, I plot 1 0 1 0 to make it a little simpler. So, this will be this is 1, this is 0, this is 1, this is 0.

So, if I see the principal component sinusoidal component here is this, I mean if you sort of Fourier analyze there will be different frequency component, but the principal component will be something like this is in case of NRZ. And in case of RZ if I see here the principal component first let us draw the RZ will be I mean if the frequency here is f and the principal component if I draw the RZ which it will have basically f by 2 right.

So, this is giving you say total f frequency the principal component in a NRZ signal whereas, if you make if you have RZ kind of signaling the principal component will be actually will be f by 2. So, for NRZ I require you know equivalent to this distance let me first explain you this. So, the delta f the bandwidth required for NRZ will be actually R by 2 half here if you I am sorry this is not f by 2 this is 2f sorry, this is let me redraw this.

So, if I draw this. So, this will becomes RZ let me see for example, suppose I have all 1s or you know that kind of thing all 1s for example, and if I draw the RZ return to 0 signal then this will be this is 1, this is 1. So, this will be so on and so forth and the principal component if you see of the sinusoidal in this is we will have a frequency 2f. So, if I am transmitting RZ signal I require high bandwidth and if I am transmitting through a transmitting NRZ signal I require smaller bandwidth as compared to RZ.

So, normally for RZ why do you need RZ I mean why you want to use high bandwidth because, when you have you know raw data and suppose it has a continuous run of continuous runs of 1s or continuous run of 0s because as the receiver you have to extract you know timing from the signal. So, extracting timing where you have very less number of transitions in extreme case of high you know long sequence of 1s or long sequence of 0s it will be very difficult to extract the timing.

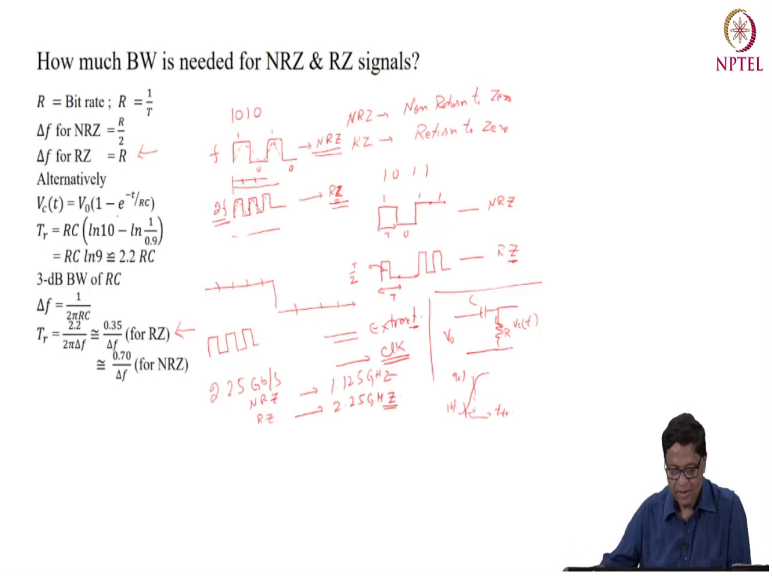
So, you convert this into a signal which is rich in timing. So, that is why you use you know the RZ kind of thing. So, that you introduce you know transitions and then when you extract you are able to extract the timing information or the clock from the signal. So, that is the advantage of using you know RZ over NRZ and NRZ also has a benefit, but timing recovery will be a little tough here, but it will require less bandwidth.

So, the delta f which is required for NRZ is R by 2 half and delta f for RZ is R alternatively we can also understand this using suppose I have a pulse like this it passes through a you know circuitry which is in my case receiver, which is equivalent to a RC circuit, it will degrade the rising time and the fault time of the pulse. So, you will get something like this.

So, this degradation is actually measured by finding of the 10 percent point and the 90 percent point and then between this whatever you get is the degradation. So, this is how you can find out the degradation and if I try to find out for a typical circuitry, this is the equivalent circuit for example, I want to find out the degradation.

So, the voltage V c t this is V 0 will be this is V c t and V 0 is internal voltage it will be V c t is equal to V 0 into 1 minus e raised to power minus t the RC time constant. And this if I find out this transit time let me remove this definition of transit time and let me draw here.

(Refer Slide Time: 27:53)

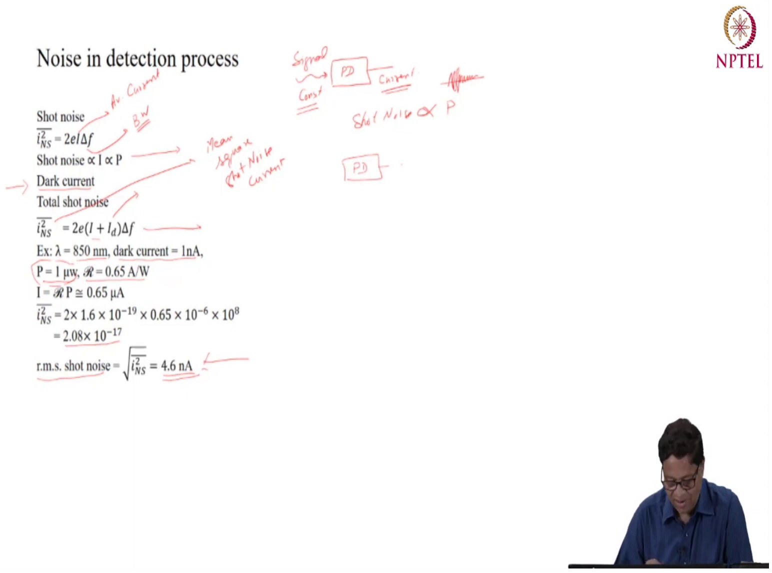


So, this is the equivalent circuit RC equivalent circuit of the say receiver and this is V 0 this is V c t this is C this is R and this is my t 10 percent point and this is my t 90 percent point. So, this is called as the transit time t tr will be given by just finding of the 10 percent the degradation in the rise time can be found out by RC ln 10 minus l 1 by 9 and then you do some simplification.

So, this is equivalent to 2.2 RC and the if you calculate the 3 dB bandwidth of this RC circuitry here this will be delta f divided by 1 by 2 pi RC and if you put these values of RC here then what you get is T r is equal to 0.35 divided by df this is for the RZ signal. And this is 0.7 this will become double because the bandwidth requirement for RZ is R and the bandwidth requirement for NRZ is half.

So, this will be 0.7 by delta f for NRZ signal. So, this is the transit time calculation for RZ and NRZ signal. So, the bandwidth requirement for example, if you are transmitting a 2.25 gigabits of signal. The bandwidth and this is NRZ signal the bandwidth of the receiver which I require is half of it say 1.125 gigahertz for example. And if this 2.25 gigabits is a RZ signal the bandwidth of the device which I require is 2.25 gigahertz right.

(Refer Slide Time: 30:08)



Now, we will try to understand the noise in the detection process. So, briefly we touched some noise in case of APD which is the excess noise. So, we will now try to understand the noise in the detection process. So, in a photodiode there are basically two types of noise; one is called as shot noise.

So, suppose this is your photo diode and there is a continuous light say constant light falling on to this photo diode it will generate some current. Now this conversion of photon to current or photon to electron hole pairs is a statistical process, it is not you know constant number of electron hole pairs will be generated and constant current will be generated.

So, what you get is actually this current keeps changing though it has a mean 0, but it is changing with time because this is a statistical process this conversion of photon to electron hole pairs. So, this is called as a shot noise, so, more is the power more is the shot noise. So, this is the source of shot noise and this is mathematically written as shot noise I square NS this is shot noise the average value is given by 2 e I delta f where, I is the average current.

And delta f is the bandwidth over which we are trying to measure this shot noise or the bandwidth of the device this is the depends on the bandwidth of device as well. So, the expression for shot noise is 2 e I delta f e is the electronic charge and as you see the shot noise is proportional to the current the shot noise which is generated is proportional to the current and this current is proportional to the power.

So, the shot noise which is generated this is very important is proportional to the power. So, the or optical power falling on to the device more the optical power falling onto the device there will be more amount of shot noise current. So, this is the shot noise current let us discuss what is the dark current. So, if there is no light this is a photo diode even then because of the thermal excitation some amount of current is generated in the circuitry.

So, that is called as the dark current. So, in the absence of any optical light falling onto the photo detector because of the thermal excitation some electron hole pairs are generated and then result into some sort of current and that current is called as a dark current the value may be small, but it has some finite value.

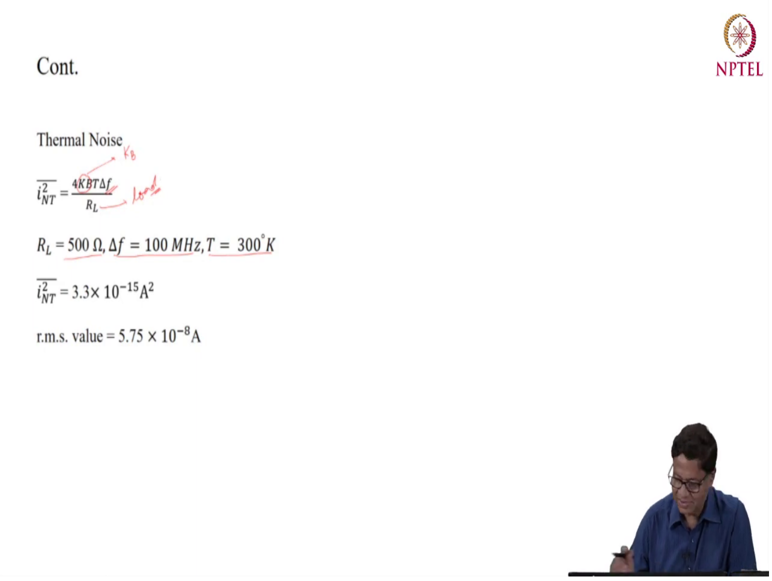
So, the total shot noise one is because of the signal because of the this is because of the signal and the other is because of the dark current. Those total shot noise will be combination of this is the current which is produced because of the thermal excitation in the absence of light I is in presence of light. So, the total average I square NS is 2e into I plus id.

So, these two currents are added into the bandwidth. So, that is the total shot noise current. Let us understand what typical values or try to calculate what typical values the shot current has. So, if I work at 850 nanometers and I assume there is a dark current of 1 nano ampere and my power is 1 micro watt and responsivity is 0.65 amperes per watt. and so, the I which is generated that is the photo current which generated is responsivity into power which is 0.65 micro amperes and if I plug these values into the shot noise expression here.

So, mean square value or shot noise current. So, this is let me write here this is mean square shot noise current you have to put all these values in place and what you get is 2.08 into 10 to the power minus 17 remember this is mean square shot noise. So, if I take the rms value of the shot noise that is the square root of this I get 4.6 nano amperes.

So, in this case it is quite low, but it can be high in some applications or in some devices depending upon the numbers or depending on the power level. The power level was very very low 1 micro watt that is why you could see you know shot noise quite low nano amperes. If you increase the power level to some milliwatt you know there will be a immediately there will be increase of shot noise.

(Refer Slide Time: 36:15)

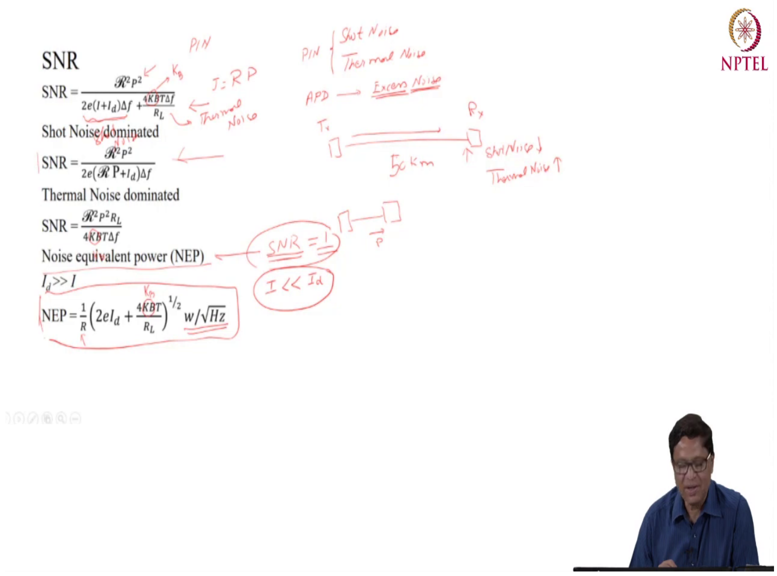


The other source of noise is thermal noise. Thermal noise that is in the resistor because electron hole pairs in the resistor is always there and they are always moving and because the moment there is some current happening there some current flowing there and that is called as the thermal noise.

This you must have also studied in some (Refer Time: 36:38) classes. So, the value of the thermal noise current average value is average square thermal noise current is 4 KB this is actually Boltzmann constant. So, this is actually this 4 KBT delta f into R L, R L is a load, KB is a Boltzmann constant, T is the temperature and delta f is the bandwidth.

So, let us now get some indicative value of thermal noise current R L suppose I keep 500 ohms the bandwidth of the device is 100 megahertz or I am trying to do measurements over 100 megahertz and T is a 300 degree kelvin. And if I plug in these values I get 3.3 into 10 to power minus 15 ampere square and if I take the rms value this is 5.75 into 10 to power minus 8 ampere and accordingly we can convert into micro amperes or amperes.

(Refer Slide Time: 37:45)



So, these are the noise which is there in the photo diode. So, in just to recap initially there was shot noise for the photo diode which depends on the input power and then thermal noise which is because the source is from the load resistor because the (Refer Time: 00:00) are load resistor. This was for the PI and PIN photodiode.

And similarly APD we studied one additional noise which was excess noise which came because of that multiplication factor which is not constant which is again a statistical quantity. So, that generates some noise. So, which is an additional noise which is there in the APD now let us try to calculate the total signal to noise ratio we know about the signal power which is coming and we have already studied now different noise which are generated in the photo diode.

Now, let us try to calculate signal to noise ratio. So, signal to noise ratio first we will do for the PIN diode. So, I am sorry about this mistake this is actually Boltzmann constant K B. So, signal to noise ratio this is the current part I is equal to RP responsivity into P and I square is R square P and this is the noise part. So, this was the shot noise component shot noise and this is the thermal noise component.

So, shot noise has both from the signal single contribution and the dark current contribution. So, if system is shot noise dominated it is possible that in some system there is more shot noise less thermal noise or more thermal noise less shot noise. So, accordingly you can classify the system either the system could be a shot noise limited or a thermal noise limited if the link is very long say 100 kilometer or say 50 kilometers the power which you get is here very low because it is attenuated here.

And the power here low is; that means, the shot noise component is low, but if you calculate thermal noise that may be high thermal noise may be high. So, such a system is generally referred as shot noise or sorry thermal noise limited system. On the contrary if you have a link very which are very close to each other the power, which is coming on to the receiver is high.

Because the length is very less the distance is very less there will be less attenuation there will be more power here. So, in this case the shot noise component will be higher and thermal noise component may be lower as compared to shot noise component. So, this system would be a shot noise limited.

So, you can have either a shot noise dominated system or a thermal noise dominated system if you have a shot noise dominated system then the first component the first this quantity will dominate as compared to the thermal noise component and SNR can be approximated as responsivity square into P square divided by the shot noise component.

If on the other hand you have thermal noise dominated then this expression will be this R L will come up and then this is also a KB Boltzmann constant. So, this will be responsivity square P square R L 4 Boltzmann constant into temperature into the noise. So, now, let us understand the noise equivalent power of the photo diode.

The noise equivalent power of the photo diode is actually when suppose you are calculating SNR it has you know some signal power and the noise power. If that is signal power and noise power are same I mean that is the quantum limit I mean if the noise power is more than signal power I cannot detect my signal I mean the best is my signal power and noise power they are same there may be a possibility of recovering the signal.

So, the power which is required or the power which is required where SNR is equal to 1 is referred as a Noise Equivalent Power or NEP. So, we will try to calculate this NEP what is that limit or what I mean 1 can call this as a quantum limit. So, what is that power which will define this SNR is equal to 1. So, in this case because the signal is very very low; that means, the current which is generated I is much less than the current which is their I d.

So, in the expression of SNR we will use this inequality that is I much is much much less than I d we approximate you know where wherever it is I plus I d we will assume that is I d only because I is much less than the I d because we are trying to calculate noise equivalent power and putting this SNR is equal to 1.

If you do these two things then you get an expression for noise equivalent power which is given by this NEP is given by this then the units here are watts per square hertz. So, NEP is 1 by R, here R is this responsivity it should be curly R 2 e I d this is again Boltzmann constant KB into temperature divided by R L square root. So, you get the units of NEP R watts per square hertz.