Photonic Integrated Circuit
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Lecture 45
Semiconductor Photodetector Noise

Hello everyone, let us look at more in detail about the photodetectors. So, we looked at how we are going to construct it and also how one can characterize the different performance metrics. So, one of the important metrics that we should be very careful about is the noise in the photodetectors, because you are converting optical signal to electrical signal. So, when you are doing this, we should make sure that whatever signal that you put in is reproduced at the electrical end. There could be lot of noise that could happen in this particular conversion.

So, we need to understand what all the different sources of this noise? Nature of this noise? And how one can control the noise in the system? So, it becomes very important when you are operating this at very high speeds and at the same time when you are having very low swings. So, when you have ones and zeros that are not very well defined in that, so when the signal to noise ratio is rather small in those instances you, your noise take over. So, you need to understand how to get rid of this noise from the system. So, let us look at how we can understand this noise system.

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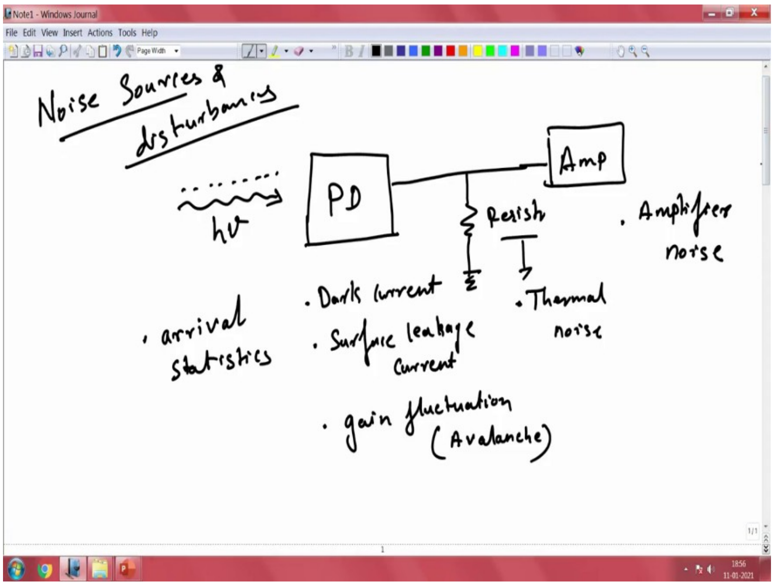

Noise sources and disturbances in the system. So let us look at a simple photo photodetector. So, you have a photodetector and then you have photons coming in, so it has a certain energy here and this is a stream of photons. So, they are continuously coming through. So, what are all the possible noises that you could have? Starts from the source side, on the, the detector side, on the output side it is connected to a load resistor, and it goes through an amplifier.

So let us start from the source side itself, so the source detection itself is, you could have a quantum noise because of the fluctuations in the incoming photons. So, you could, the noise could be from the source itself. So, you could have arrival statistics are going to be very different. And the next thing could be from the detector itself. So, the arrival statistics we know, we will discuss it shortly we will just list it out to start with, then you could have dark current, dark current of the photo detector, you could have surface leakage, surface leakage current, and you have a detector.

And then you could have when you when you look at avalanche type diodes you could have gain fluctuations particularly in avalanche type device. And then on the resistor side we could have thermal noise and then finally on the amplifier we will have amplifier noise. So, these are all the different noise sources that you could get when you are having a detector system. So, let us start with a photon noise, so or the arrival statistics.

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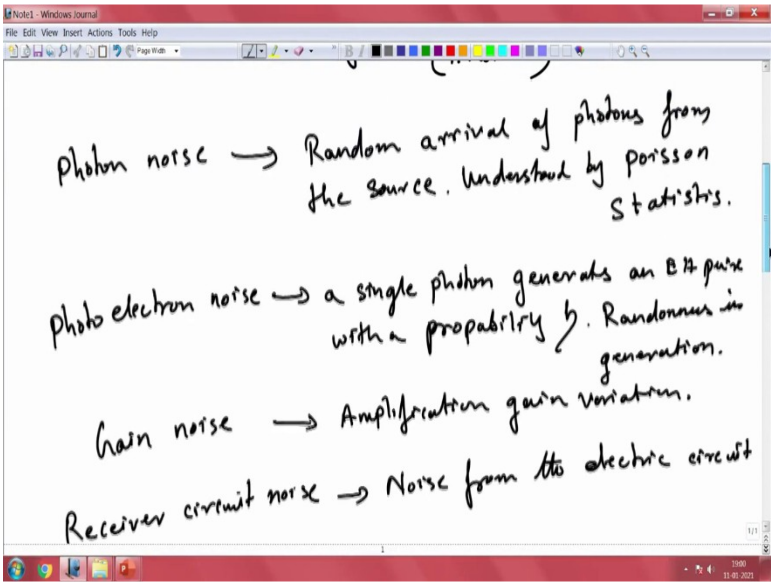

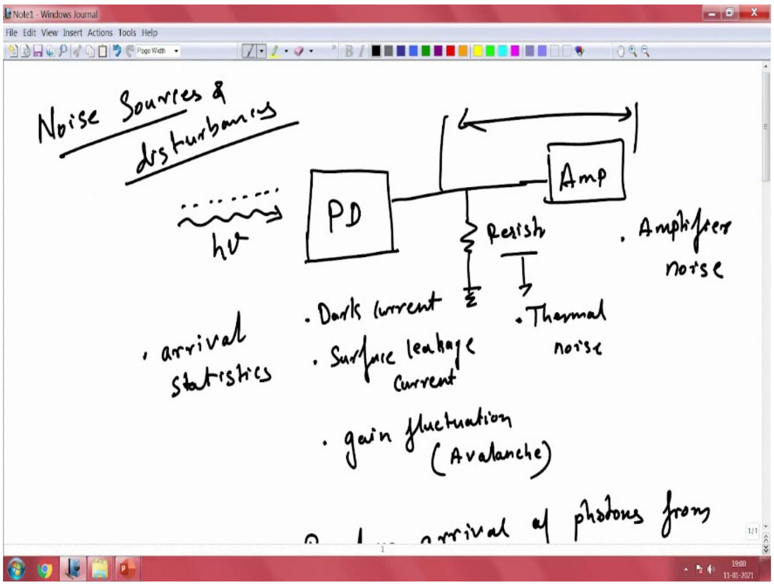

So, photon noise is primarily, it is fundamental, it is the most fundamental noise that you have. This is coming from the detector itself, so you will have a random arrival of photons from the source. And this is primarily described, could be understood by, by Poisson statistics. So, the emission is on Poissonian in nature, so you can use Poissonian statistics to understand this photon noise. We will look at this as we go along but this is one of the fundamental noise that we have.

The next thing is the photon electron. This is the current noise that we have. So, this is photo electron noise or photoelectric noise whichever way you want to call it. So, this is primarily dictated by the probability of creating an electron hole pair. So, a single photon generates an electron hole pair. So, this pair has a probability, with a probability of some η, and this generation could be random. So, there is a randomness in generation and that is characterized by this particular photo electron noise.

And the next noise is from the receiver itself. So, you can also add the gain noise. So, gain noise is primarily the amplification that you have in the photodetector, this is for the avalanche photodetectors. So, amplifier, amplification gain we can call it, amplification gain variation. And then finally receiver circuit noise. And here you have various components that could add to your noise.

So, you have noise from the electric circuit, so you have resistors that you have, and you have amplifiers that you have. So, all these things that are outside where you work with the electrons, so you are going to take the electron and then do some processing on those electrons and that would result in some noise from this electrical processes. So, these are all the fundamental noises that you could have from a, a simple photo detector detection.

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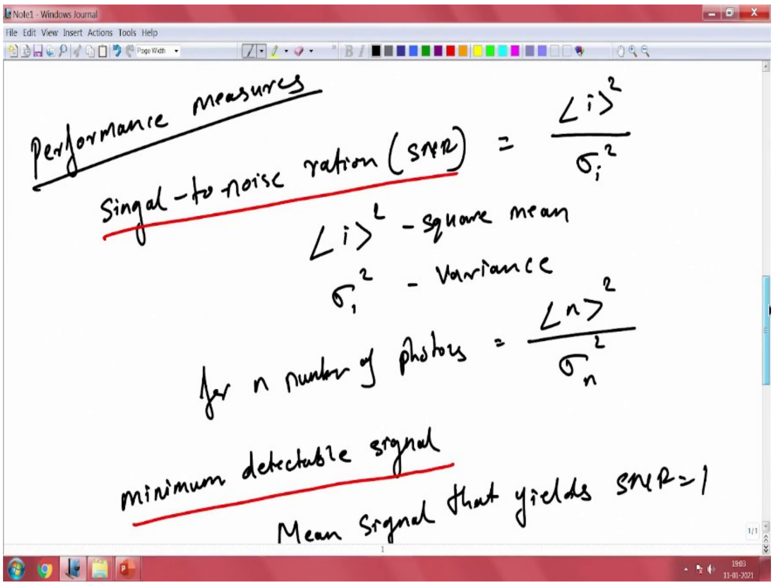

So let us look at what are all the performance measures of this photo detectors. We need to, we know the noise but what are, how do we measure the performance of a photodetector? So, there are few performance measures of a simple photodetector. So, the first one is fairly fundamental, that is signal to noise, signal to noise ratio, simply called SNR. So, this is nothing but the ratio of the square mean to its variant. So, this is simply that.

So, your SNR is nothing but the current mean squared to variance square. So, this is basically your signal to noise ratio. So, there will be a fluctuation in the current that you create and that average current fluctuation, it is a square mean to its variant. This is the square mean and then this is your variance that you have. So, this is very simple way of measuring your signal to noise ratio. So, for n number of photons this will be, for let us say for n number of photons it will be some σ, σ_n^2. So, this is basically your signal to noise ratio.

And what is the minimum detectable signal? So, you have signal to noise but what is the minimum detectable signal? So that is again an important performance metric, that is minimum detectable signal, and this minimum detectable signal is nothing but the mean signal that yields SNR of 1. That is basically your minimum detectable signal, that means you need to get more photons or more current than the, the variance that you have. So, then you your (sig) that is the minimum detectable signal. So that means you are more than the noise that you have in the system. Next is bit error rate.

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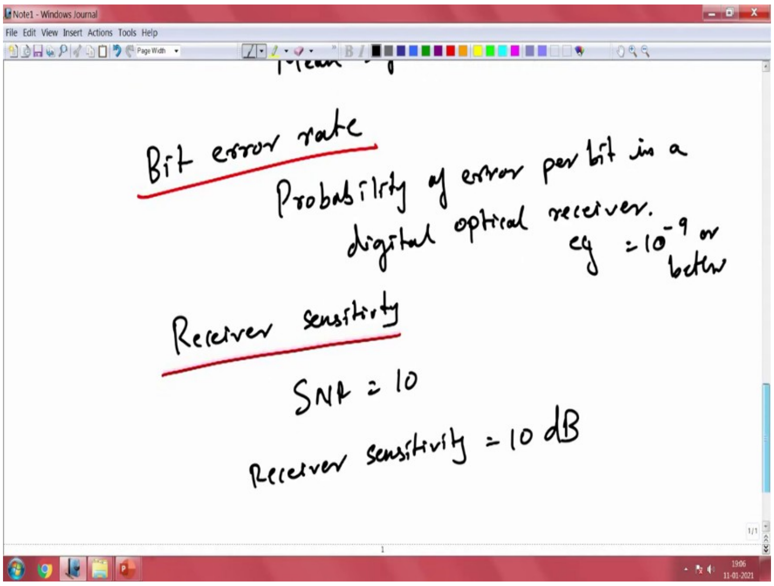

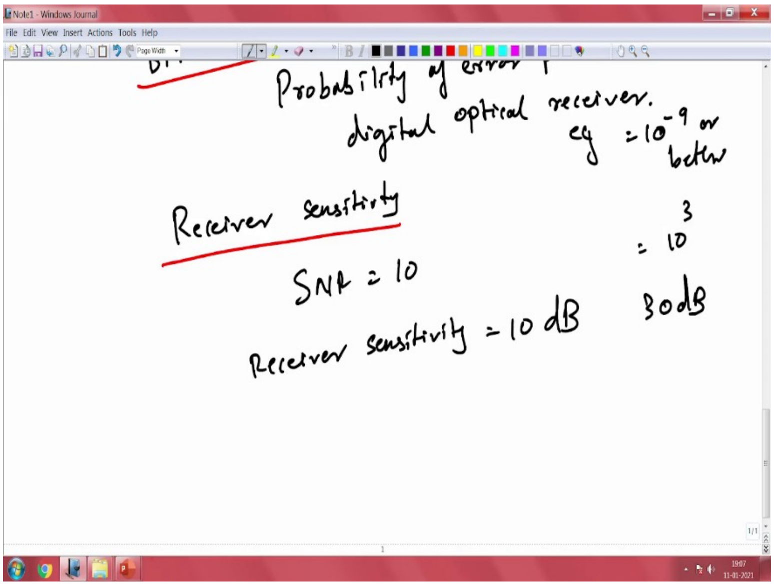

This primarily applies for communication applications, so this is nothing but probability of error per bit in a receiver particularly a digital receiver. So here, so probability of error per bit in a digital optical receiver. So, this is again another performance metric that we use and finally receiver sensitivity. So, receiver sensitivity corresponds to your SNR here. So, what is the minimum detectable signal? It is going to be 1, the SNR is going to be 1. So, the higher value of SNR gives you the more, the accurate value of your signal detection.

For example, if you have higher signal to SNR, so that means your receiver is much better sensitive. For example, if your SNR is 10, so if your SNR is 10 then what is the receiver sensitivity? Receiver sensitivity will be 10 dB. So, the receiver sensitivity is nothing but how much power is, minimum power is required or the detector is sensitive in order to achieve a given signal to noise ratio or you have better signal for that particular input.

This is also coupled with your bit error rate in any digital receiver, so you need a minimum energy that is required to, to get a certain bit error rate. So, the bit error rates for example, we give something like 10^{-9}, or better let us say so that means you, you need one, only one error in 10^9 bits. So, this is what you want for a as a bit error rate, so the error per stream of bits that you get.

So, this is also related to our receiver sensitivity, so we give a certain amount of power whether this power is good enough to get the right amount of sensitivity. For example, if your SNR is 30 sorry, your SNR is 10^3 or thousand then it is 30 dB sensitive. So, this is how we measure your receiver sensitivity or minus 30 dB. So, you want to have a really very high signal to noise ratio in order to make sure that you have better sensitivity. So, let us go one by one understanding this noise that we have, so starting with the photon noise.

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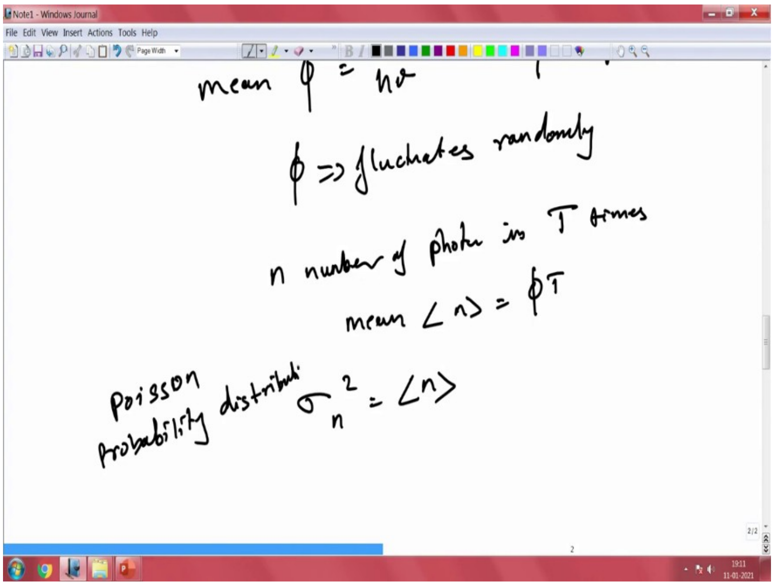

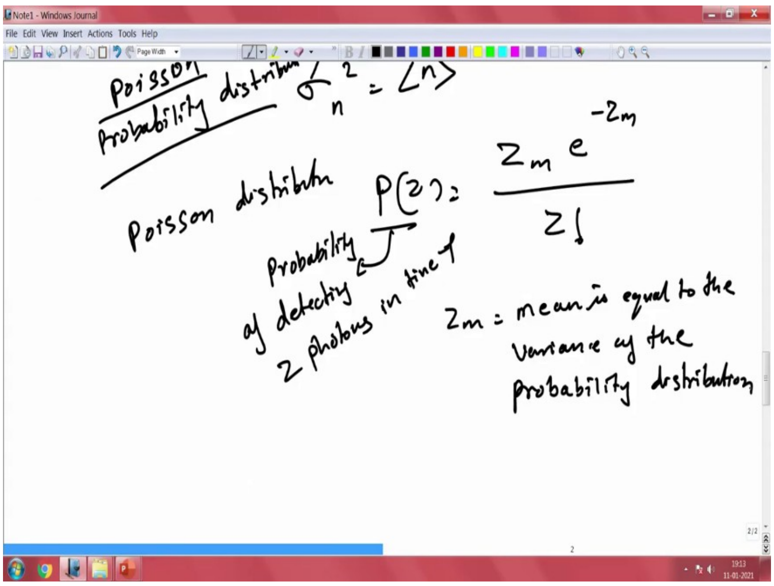

The photon noise is a source noise because the photon flux is associated with a fixed power. So, you have a certain power, and this is proportional to some n number of your photons here. So, your n number of photons are going to give you a certain power. But the flux, the flux that you have, the photon flux you have, this has no relevance in terms of the flux density. So how, how many photons are going to arrive at a given point of time, you could have bunching of photons here or less number of photons in this case.

So, this is for a very short amount of time, so how the photons are going to flow through this, this flux is not, the flux is here, so this flux of photon is uncertain. So, this this driven by the emission statistics, whether you are going to emit 5 photons, 10 photons, 20 photons, there is always going to be a difference in the photon flux. And what we need to understand is the mean photon flux, so the mean photon flux is related to your power to hν.

So, but this quantity will fluctuate, so this φ, the photon flux actually fluctuates randomly based on the emission statistics, and it strongly depends on the light source whether you have proper injection, whether your material is energized properly and how you are transferring the energy into the active layer and so on. So, this is something that we should keep in mind because we have given a certain power it does not really mean that you will get the required number of photons all the time.

And this shows up in your specification of optical source because random intensity noise, it is called RIN, is a RIN. So, this intensity noise is primarily coming from the fluctuations that you have in the photon flux. So, the number of photons that you get, let us say n number of photons is counted in a time interval of time. So, n number of photons in in T time means, is random, but then the mean number of photons is given by photon flux by T.

So, we need to look at what is the statistics that we can apply here, as I mentioned you can clearly apply the Poisson probability distribution here and that is your variance n^2 nothing but this. So, this is our Poisson probability distribution, we can apply this. So let us say the fluctuation could be say an average of 100 photons, would result in an actual number of photons that lights approximately between 100, 90 to 110 let us say, so there could be some fluctuation of 100, 10 photons in this case, let us say if it is 10% variation, this could be higher based on what kind of light source we have.

So, the arrival statistics could be given as this distribution, that Poisson distribution is given by $\frac{Z_m e^{-Z_m}}{Z!}$. So, what is is Z and what is Z_m? So, P(z) is our probability, so this is our probability of detecting Z photons in time T let us say, in time τ. So, then the average to detect is at m photons is given by these particular statistics. So that is what we are giving here, so Z_m here is mean, Z_m, mean is equal to, to the variance of the probability distribution.

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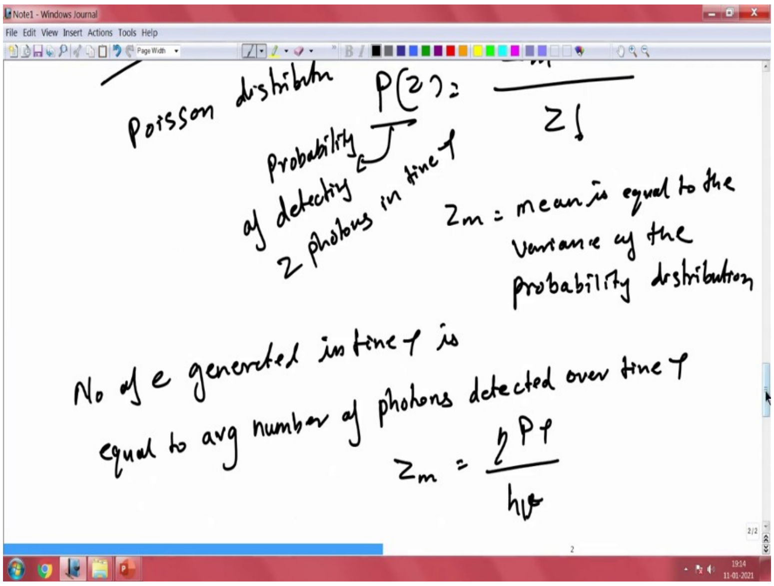

So now the number of photons generated in time tau is equal to the average number of photon detected over this time period tau. So, the number of photons detected, number of, sorry the number of electrons generated, number of electrons generated in time τ is equal to average number of photons detected over time τ and that is given by this one, $\frac{\eta P_\tau}{hv}$. So now we can look at the distribution from here.

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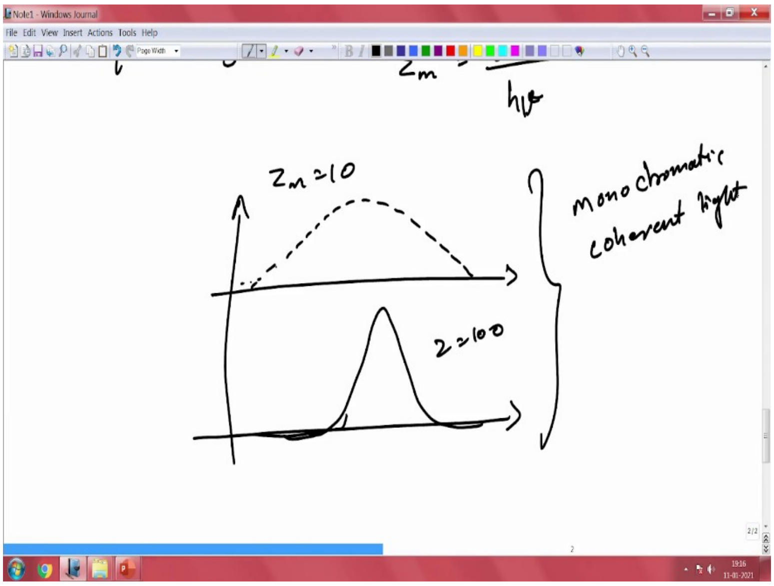

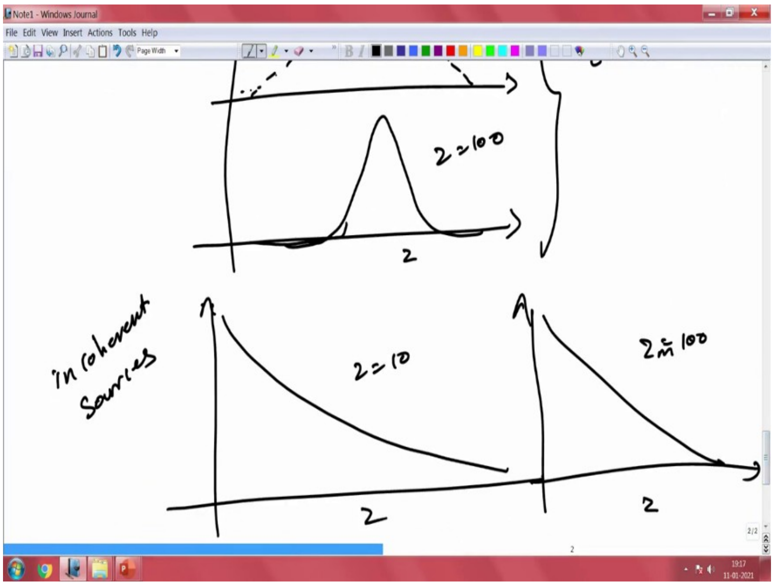

So, let us look at two different distributions when Z_m equals to 10 and is Z_m equals to 100. So, you have 10 photons, and you have 100 photons let us say, so your distribution here would look really sparse for Z is equal to 10 and then it is much finer when Z equal to 100. So, this is our simple Poisson distribution for very low number of photons and very high large number of photons. So, this varies for coherent and incoherent sources.

In a incoherent light, emitted by independent atoms and there would not be any phase correlation or phase relation between this and then this particular property is going to dictate how this distribution is going to be and, and, in that case, you are, your distribution will be similar to Bose-Einstein distribution of blackbody radiation than what we see here as a coherent distribution. So, this is for a monochromatic [source] that is something that should be mentioned, this is mono chromatic coherent source.

If you have a incoherent source, so this will follow similar to Bose-Einstein distribution and that will be just a decay like this. So, this is what you will see for Z equals to 10 and then for Z equal to 100 you will again see a similar kind of plot but only thing is the numbers are going to be different. So that is not really relevant, the absolute numbers are not relevant here. So, this is nothing but Z. So, this is for incoherent sources. So those are all the two difference that you, you would like to know from this. And the next thing is looking at the, the effect of this photon numbers that are coming a different rate on the signal to noise ratio.

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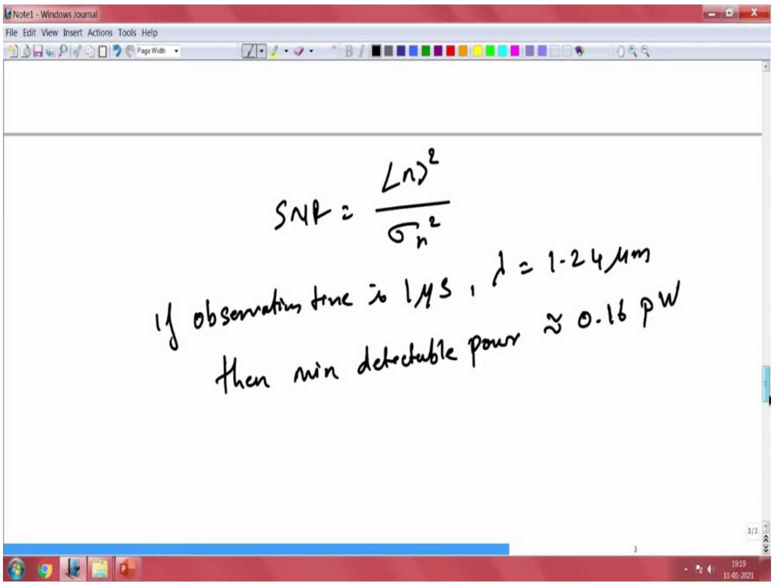

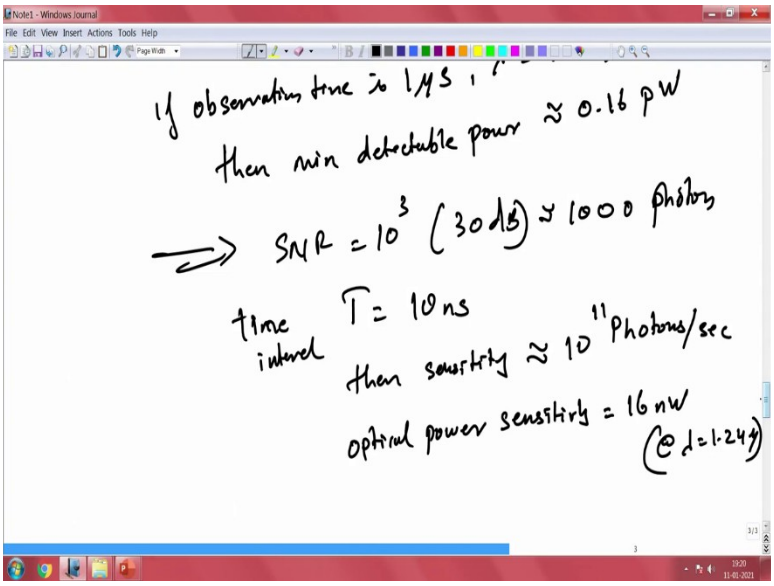

So how this signal to noise ratio is going to be affected because of this photon number? So, the signal to noise ratio here is the number squared, this is something we have seen. And you need to have a minimum detectable number, so that means the n should be at least 1 here. So, if you observe for a time a certain amount of time then we can say what is the minimum detectable photon within that time frame.

So based on this relation, we should be able to see if there is only one photon. So, what, what will be the detectable minimum power that you want? So just as an example, if observation time let us say is 1 microsecond and your wavelength is 1.24 micrometer. So, then the minimum detectable power, minimum power will be approximately 0.16 pico Watts. So, based on just the observation time or the time interval that you have can measure what should be the minimum, what, could be the minimum power that one could measure.

So, for example if you have sensitivity information that is given here for example if you have SNR is given as 10^3, in other words this 30 dB is nothing but 1000 photons. This is 1000 photons, is what we are looking at, so in this case let us say your time interval, time interval is about 10 nanoseconds let us say. So, then the sensitivity, then the sensitivity is about 10^{11} photon per second.

Or you have sensitivity or power sensitivity of 16 nano Watts, so of course this is at based on earlier wavelength at lambda equals 1.24 micrometer. So, you can calculate how much power you could get out of this system just based on the number density that you are going to get [at] the detector and also the observation time, how long are you going to wait to get at, get at the output.

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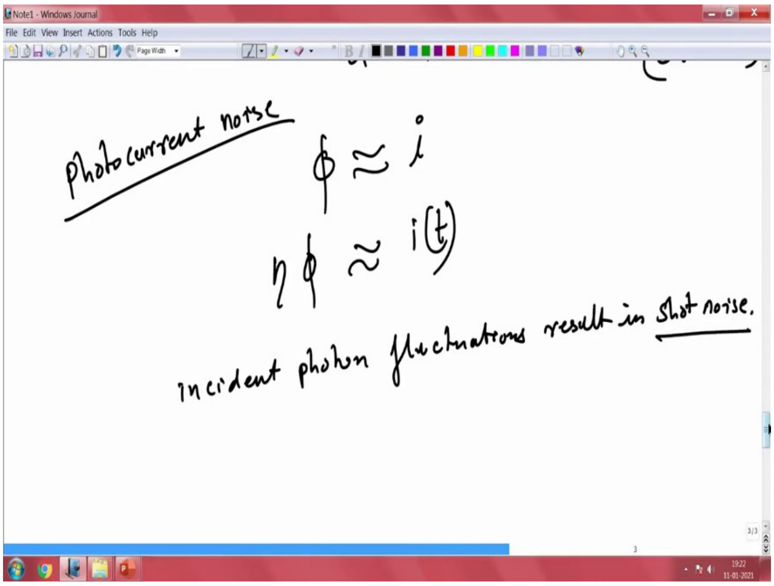

The next loss or noise here is the photo current noise. So, let us look at this photocurrent noise. So basically what you are looking at is, you should get a for a steady flow of, of photon flux, let us say I have a steady photo flow of photon flux, so this should result in a certain current ‘i', but now the flux is, is random, it is fluctuating that means you have a certain fluctuation of current and this would induce a time dependent current now so this is the fluctuation that we see it is supposed to be flat but it would not be flat you will have the current noise here because of the incoming photons.

So, this, this time response of this detector that you have, this could be filtered to a large extent. So, when these time constants are known then you can put a filter to take it out but then the fluctuations in the incoming photon that you have, that would result in what is called the shot noise. So, the, the incident photon fluctuations would result in shot noise. This is something you might have heard in the basic courses. So shot noise is a real problem. So let us look at how you can understand this shot noise from a very microscopic view.

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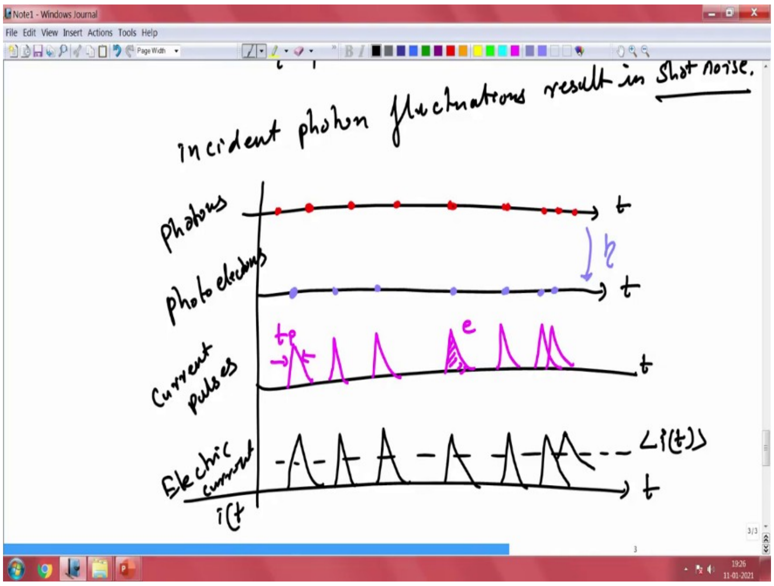

So let us look at various time events. So, I am going to put this as time. Let us start from the photon arrival, so we have photons that are arriving at random time events here, some very closely spaced, one sparsely spaced. And now once you have the photons come in, the next thing that is going to happen is the photo electrons, the charges, you are going to create these charges and you are not going to generate these charges for all the photons that you get. So, there is a statistics associated with this and that is your efficiency.

So, this conversion depends on efficiency, the conversion efficiency of your photodetectors that we already saw. So, you are going to generate photons maybe correspondingly sometimes there is no generation and here you have two for example like this, and once you have this electrons generated or charges generated, they are going to reach the electrodes now. So, this will result in current pulses. So, we are going to have current pulses because of these charges.

So, we are going to have current pulses generated by each of this, by this, so they are going to create this current pulse. And it will have a certain time associated with this, so let us say there is a time associated with this and this whole region that you have, this is nothing but 'e', this is the charge area that you have, this is area that you have. Let us define it as 'e'.

And now how is the current going to look like, this is electric current, and this is actually what you measure and that is going to have similar kind of profile here and you should look at here very importantly you have this but then when you have the next current it is going to be higher, and this is the average current that you have over time.

So, when you have two consecutive photons they are going to super position and then they will create an added current. So, the individual pulses here are nothing but exponentially decaying step functions but they could also have arbitrary shape. So here for convenience we have taken this a very nice decaying but the lifetimes could change.

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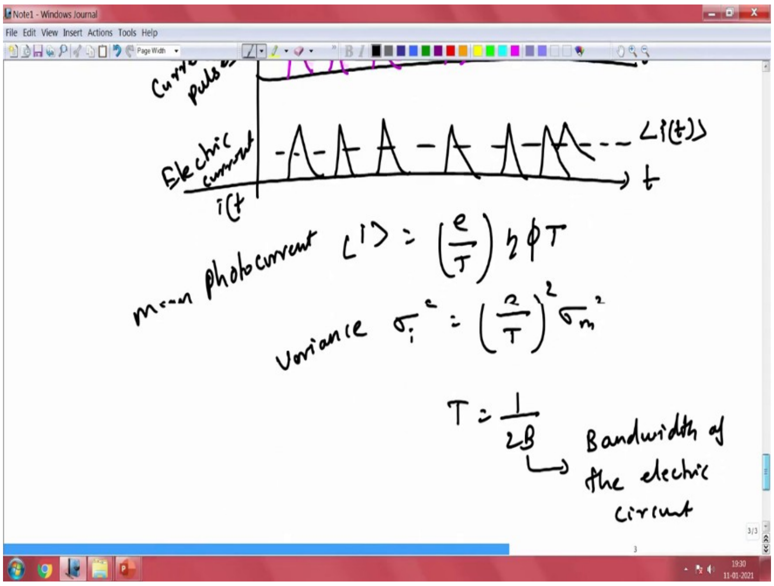

So now the photocurrent that we have, this written is given by $\frac{e}{T}\eta\phi T$. So that is for your photo current, this is your photo current or will say mean photo current and then the variance of current, the variance that you have is $\left(\frac{e}{T}\right)^2\sigma_m^2$.

So, this is how one could characterize your mean photocurrent coming from varying photon flux and also your variance from the system. So, a random number of photo electrons could be generated. So, this m is nothing but the random number of charges that are generated, with the time interval T within a certain characteristic time, time interval T, you could generate this, and this would result in the photo current that we saw as a result.

So, this is rather straight forward for you to calculate or understand what is the implication of having this stream of photons coming in and how you generate carriers out of this system and that would result in photo current at the end. The, what is the time interval is something that we should also understand. So, this time interval that you have, so because there are various time constant associated with this.

So, when you generate a certain photon, sorry, certain current pulse it needs a time interval to create that charge and create that current associated with this and that depends on two things, one is the generated pulse here and also it has to go through the circuit. We have to collect this one so that is given by this T here and for all practical purpose you could have you can call this T as the, the (trans) transient time given by the bandwidth of operation in this case.

So, we could call this as the bandwidth of the collection circuit, so based on the bandwidth of this circuit you, you can say that this is the time interval that I am collecting so many number of photons from the system. And also, you can, once you have so many number of photons that means you know your flux that you are collecting and from there you can calculate your total power and sensitivity and so on.

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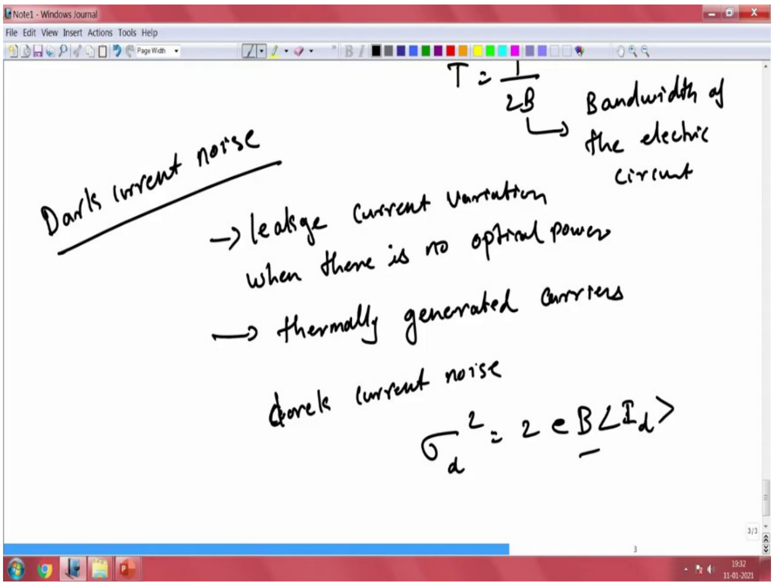

The next thing is about dark current, again the dark current depends on the, the variation that we have here, that is the variance that we just saw and the bandwidth here as well. So, when there is no optical power, you will generate some photo current that is called the dark current. So, the dark current noise is nothing but there is a leakage current variation, when there is no optical power. And this is primarily due to thermal, thermally generated carriers.

So, this random fluctuation, say about the average photo current that you, you create is, is basically your dark current. And this will look similar to the dark current or similar to the short noise that we have. So, the dark current here or dark noise, dark, dark current noise the variance is given by average current and what is the bandwidth of your, your circuit that we have and e which is your charge that you have. So, this is, this is how you can calculate your dark current from the detector here.

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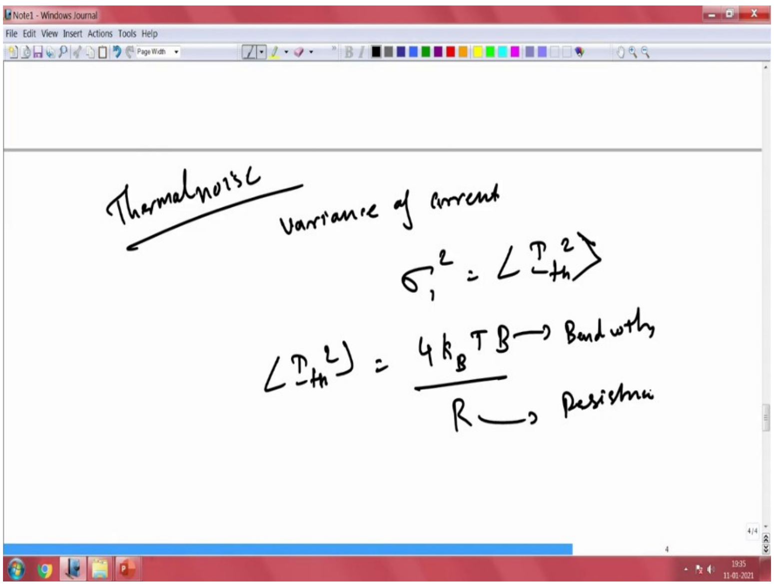

And the next type of noise is the thermal noise from the resistor itself. So, and this thermal noise is (prime) it is nothing but your, your Johnson noise or Nyquist noise, in whichever way you want to call it, it is a random fluctuation in the in the electrons. So random fluctuation in the electrons that you have in the conduction band or in the conduction in your resistor that you have, and that variance of current is given by, due to this is, is given by the, this threshold, average threshold current.

So, this is rather (you) let us say common for any resistive elements to have thermal noise and this strongly depends on the frequency of operation as well. The thermal noise power for a detector system depends on the bandwidth of operation as well. So, for a normal operation for any photodetector your frequency is, is much much lower, talking about room temperature operation the frequencies are going to be much much lower of these particular fluctuations that you have but then when you go to high higher frequencies and this thermal noise becomes a a serious issue.

So, it can be a few nano amps to few tens of nano amps depends on the bandwidth the circuit bandwidth and the temperature of, of operation. So, this is rather simply written like this but the way to write this is your thermal noise current is based on your k_BT thermally generated your bandwidth, so this is your bandwidth and your resistance that you have.

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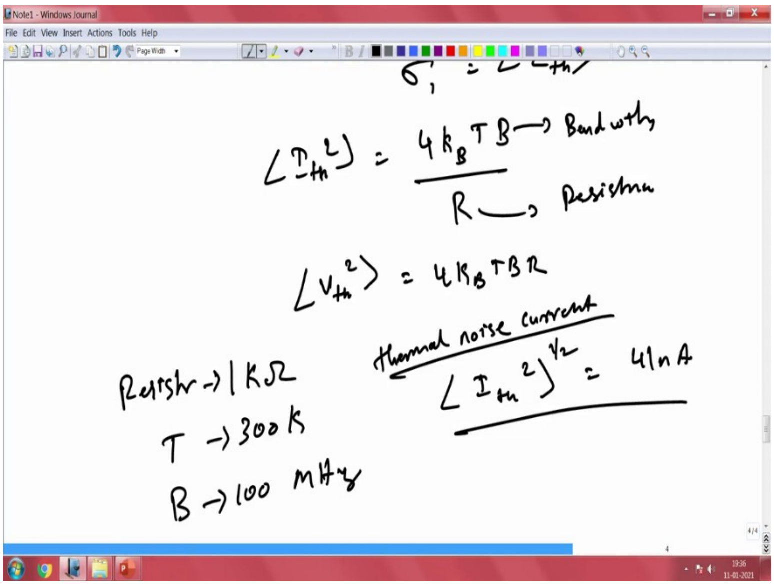

And similarly, your voltage the thermal voltage, average voltage fluctuation is given by the resistance and your current there. So, for example, if you take a very simple example where you have 1 kΩ of resistor that you use as a load resistor here at temperature, room temperature of 300 Kelvin and the bandwidth of about 100 megahertz, your thermal noise will be, your thermal noise will be about 41 nano amps.

So that just gives you an example of how one could calculate your or what is the relation between various circuit parameters and your absolute device parameter on the noise performance. I missed this, and this should be a half here. And finally let us look at something very interesting, this is similar to signal to noise ratio. So, we have a signal to noise ratio defined earlier here, so which is again a metric of, of input power or the measurable power with respect to the noise power that we have.

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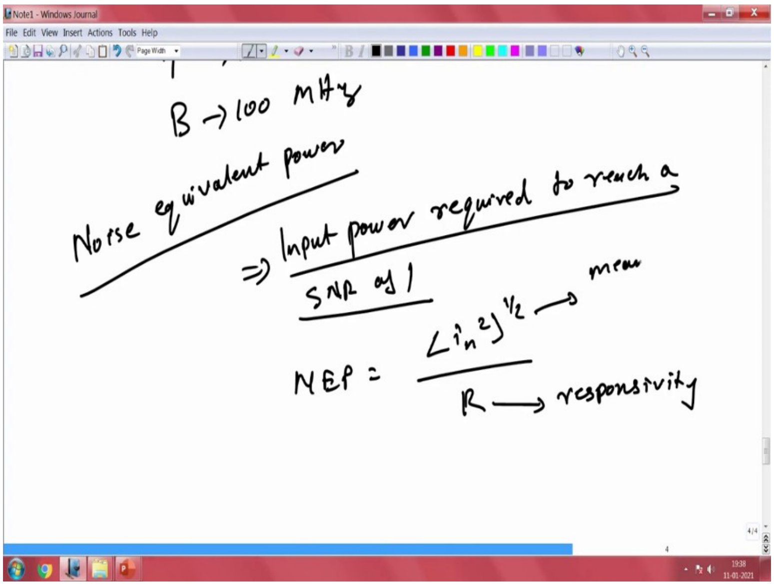

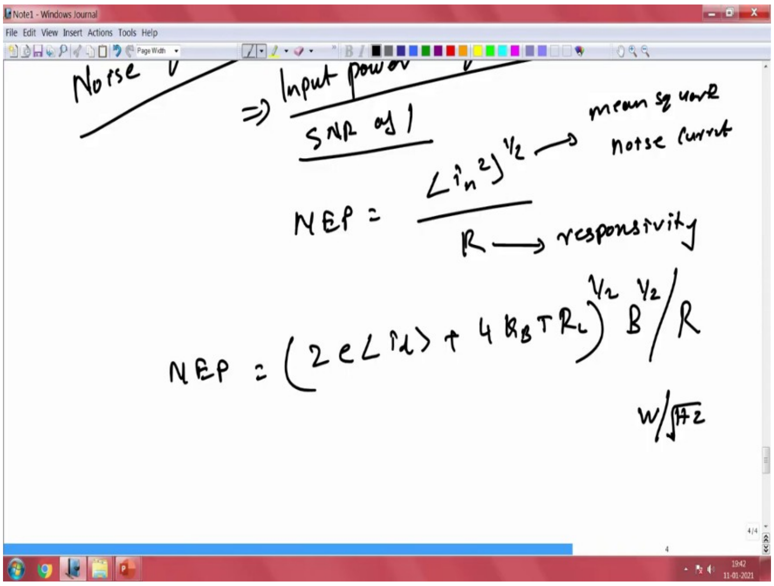

There is another quantity which is called noise equivalent power which we use to also characterize a photo detector, it is called noise equivalent power. So, this is defined as input power required, input power required, input power required to reach SNR of 1. So, this is what noise equivalent power is. So, your noise equivalent power can be achieved by looking at this particular configuration where R here is not resistance here this is the responsivity. So, this is your mean square noise current.

So, by looking at the, the responsivity and what is the base noise current that we have, one should be able to tell something about the minimum power requirement. What is the minimum power required in order to get the, the signal to noise ratio to be 1? So, signal to noise ratio one is the basic requirement to detect any signal, so you need to have that.

Since we, we know this mean square noise current, we can, there is a combination of dark current and our thermal noise current that we have. So, your noise equivalent power can be written as $\frac{\left(2e<i_d>+4k_BT\,R_L\right)^{1/2}B^{1/2}}{R}$. So, this is normally measured in terms of bandwidth as you can see there is a bandwidth under root is there. So, in terms of bandwidth is how we define with respect to the, the circuit that you have external because you cannot neglect that, when you talk about the thermal noise it is strongly a frequency dependent factor.

So, the unit for this will be Watt per Hertz, Watt per root Hertz sorry. So, this is given through this, so how do we control this by looking at the detector configuration. So, if you want to have a high-speed detector then you want to have a small area, so when you have a small device area then you can have high speed because your it depends on RC time constant. So, you can reduce this, and this will reduce your dark current but because of, of reducing your area, it requires also a small load resistor and because of this reason when your bandwidth is larger this will result in larger thermal noise.

So, there is a, a give and take here, so you when you have high speed detector you need to make sure your thermal noises are kept small because your load resistor will be also small. So, when you have a large load resistor, then your thermal noise will go down because it you, you do not want any current to flow through you will have very less fluctuation in your current.

However, when you reduce your load, when you reduce your size of your detector you will eventually need a higher load resistor or a smaller load resistor resulting in higher noise equivalent power. So, with this performance metric we, we have a complete understanding of photodetectors now, starting from the configuration, to how they detect and how you can control it till the loss effects in this detector. So, I hope this will be useful in understanding and also designing your photodetectors that you would like to do. Thank you very much for listening.