Advanced Optical Communications

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Lecture No. # 20

Photo Diodes and Detector Noise

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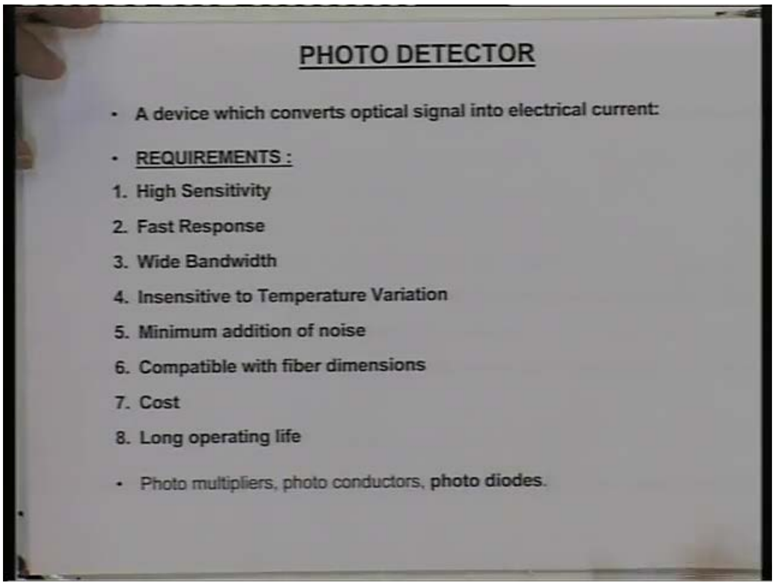

We are discussing photo detectors. In last lecture, we spelt out the general requirements of photo detector that means, it should have a very high sensitivity, fast response, wide bandwidth, insensitivity to temperature variation, minimum addition of noise, compatibility with optical fiber dimensions, cost and long operating life. And then you found that a photo detector, which can meet all these requirements is semiconductor based, which is nothing but a photo diode. And then we found that there are certain materials, which are more suited for realizing a photo detector.

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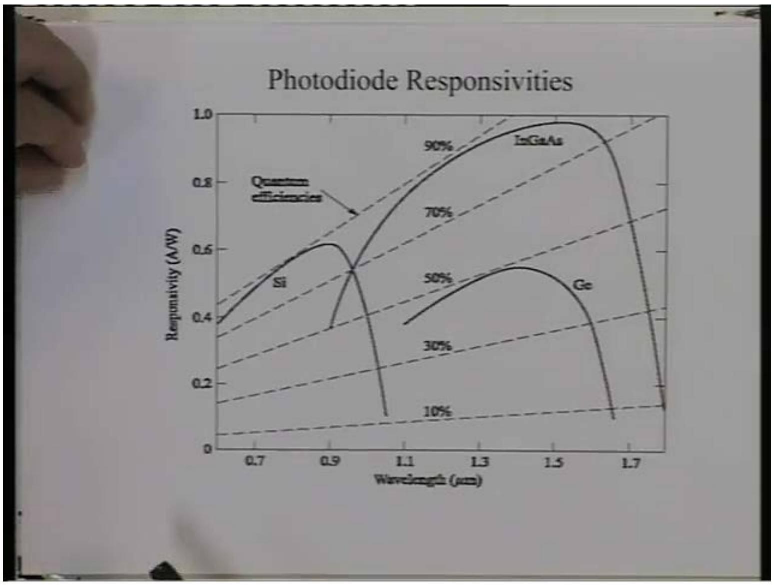

So, in the wave length range in which we are interested in that is arranging from about 1200 nanometer to 1700 nanometer. The indium, gallium, arsenide is a photo detector, which has the better response. Also germanium can be used in the same wave length range.

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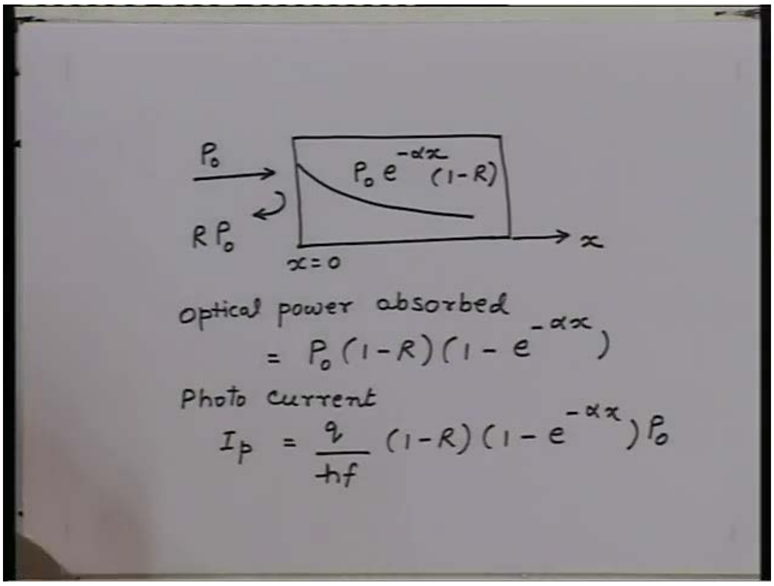

Then we took a very simple analysis that if a optical beam is incident on this semiconducting material which has a absorption coefficient alpha, then the light will get absorbed inside this material. So, the light intensity will exponentially decrease as the beam propagates inside this material. However at the beginning part of the optical energy will get reflected from this phase of the material and the parameter will be reflection coefficient, which is related to the change in refractive index between these two media. So, you found that the total power absorbed over a distance x inside this material is essentially given by this.

And if you could collect the carrier generated by this photo absorption, then we get what is called photo current. So, here we are saying that when the photon is absorbed inside a material, essentially a carrier is generated; electron hole pair is generated. And if you create a mechanism by which the electron hole pair can be collected, a current will flow in the external circuitry which we call as the photo current. So, we saw that the photo current is nothing but the charge of the carrier divided by the energy of a photon which is h into f, where f is the frequency of the optical radiation. So, for a given device that this quantity is constant that we have the size of the device; that means the x over with the absorption is taking place is fixed.

The reflection coefficient which depends upon the refractive index of the material that is fixed; for a given wave length, the frequency of light is fixed; say f is fixed. So, this h is Planck’s constant which is universal constant; q is the charge of the carrier which is constant. So, we essentially have this photo current which is proportional to the optical intensity. So, we have a linear relationship between the incident optical power, which is P naught and the photo current which will be induced because of the flow of the carriers generated because of photon absorption process.

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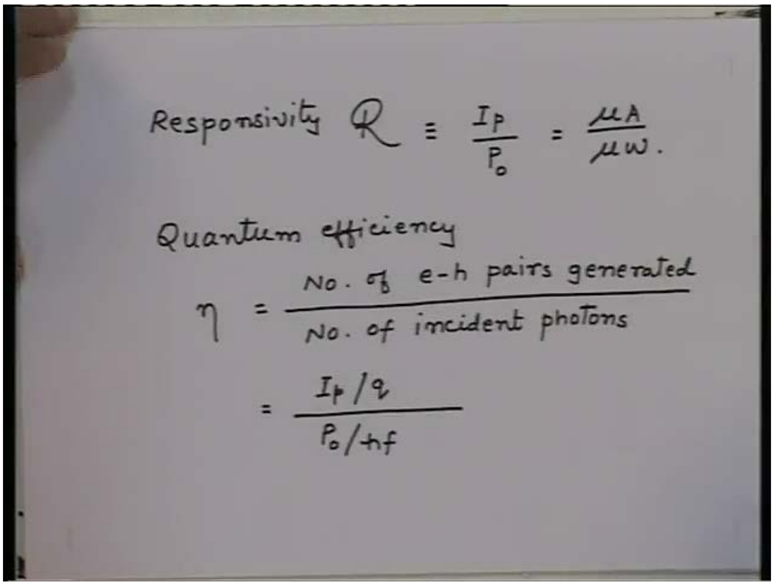

And then we define the parameter, which is the sort of a characteristic parameter of a photo detector what we call the responsivity, which is the ratio of the photo current divided by the optical power. So, it is measured as microamperes per microwatt. One can also define a parameter what is called the quantum efficiency for this device. So, recall when we talked about the quantum efficiency for light generation that time we had said the efficiency is equal to number of photon generated divided by the total number of electron hole pair recombination. Here in this case, since we are now generating electron hole pairs from their absorption of the photon, the quantum efficiency will be defined as the total electron hole pairs generated divided by the total number of photons incident.

So, in this case then we can say that you can have the quantum efficiency eta; that is equal to the number of electron hole pairs generated (No audio from 05:52 to 06:01) divided by the number of photons or number of incident photons. (No audio from 06:13 to 06:24) So, number of electron hole pairs generated is nothing but per second is nothing but the photo current divided by the charge of the carrier divided by the total number of photons incident, which is P naught divided by h into f. So, while look form this expression now here (Refer Slide Time: 01:45) I p divided by q divided by P naught divided by h of f h into f, which is the photon energy. This quantity essentially gives you what is called the quantum efficiency.

So, quantum efficiency in this case includes the energy, which is reflected from this material. And also since you may have a limited region for absorption of light, the entire light which is going inside the material may not be absorbed in this region. So, this factor essentially tells us that out of so many photons which are incident on this material, how many actually will contribute the generation of the electron hole pairs. So, like responsivity this parameter also is one of the useful parameters. But it tells you essentially efficiency of conversion of the photons to the electron hole pairs. Having said that, then now we are saying that electron hole pairs are let us say generated in a region.

And now, these electron hole pairs have to be collected efficiently to have the current flow in the external circuitry. So, firstly to collect these carriers, we require a potential. So that, these carriers will start moving in the presence of the potential difference in the presence an electric field. And therefore, there will be a current flow inside the external circuitry. And precisely that is what is done with the help of the p n junction that if you create p n junction and if you put a bias across the p n junction, then across the depletion layer we have the potential difference and then you have electric field in the depletion region. So, the electron hole pair which are generated in the depletion region will start moving in the influence of the electric field and therefore, we will have a current flow in the external circuitry.

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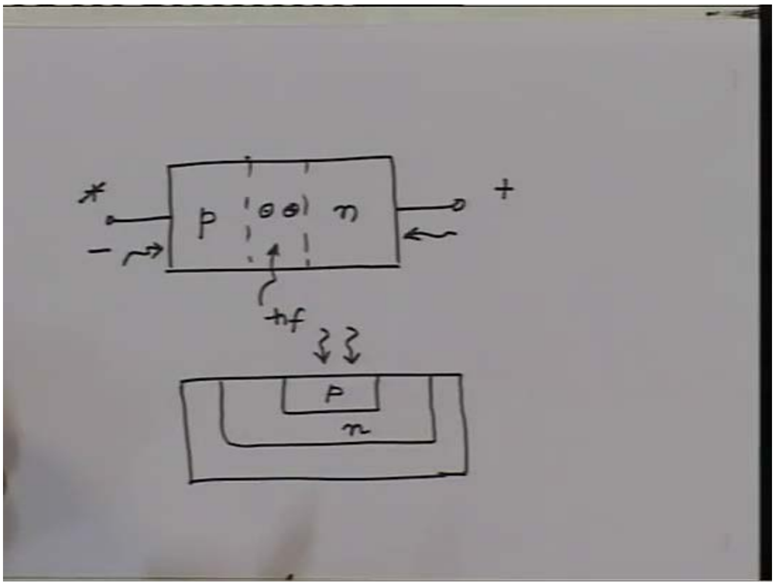

However what one should realize is that, schematically then one can say that I have a device which has a p n junction like this. This is the depletion region, where the photon is incident; energy h f; the electron hole pair is generated in this region; this is minus; this is plus. And if I apply the positive and negative voltage, this this is positive; this negative; the electrons and holes will start moving and we will have a current flow. So, first thing to note here now is that the current, which should flow in this external circuitry should be only due to this electron hole pair, which is generated because of the incident of the photon.

So, if there is no generation of this electron hole pair, then there should not be any current flow in the external circuitry. It is the immediately clear that we cannot have this p n junction in the forward bias condition. Because it forward bias, then you will have the current flow which will not depend on this photon incident. But the current will be flowing just because of the forward bias condition of the diode. So, essentially this p n junction has to be operated in the reverse bias condition, which in ideal situation in the absence of this electron hole pair generated due to this photon, the current flow will be 0.

Ofcourse, in practice because of the thermal excitation, we also have the electron hole pair generated because of thermal excitation and we get what is called the reverse saturation current inside the p n junction. So, now we want that essentially the reverse saturation current, which is flowing into the p n junction; that added with the photo excited carrier current what is called the photo current; that is what is the one, which is useful, because this photo current will be proportional to the photon flux, which is incident on this device. Now, schematically we have shown that you have a p n junction here; say this is p and this is n or you want to make a reverse bias, so if you make this p n, then it should be negative; this should be positive.

But in real fabrication of the device, the photon is not incident in the depletion (( )) the way we have shown here; because if we consider the fabrication of a device, it will look something like this. We have a p type material and we have n type material created this way and then the photon will be incident on like that. So, the photon when it goes inside the p n junction, it does not go side wise; this way. But actually it will be incident either from this side or from this side depending upon whether this material is t material or this material p material. So, if we take this is p and this is n, then the photon will be incident from the p side.

So, now the as soon as the photon beam enters inside the p n junction either from this side or this side, the absorption process starts. You essentially have the carrier generation right form this point, as the beam propagates inside this p n junction. Now, the carrier which are generated in this region does not have much electric field experience; because most of the electric field is present inside the depletion region. So, if these carriers have to be collected into the external circuitry. First, they should slowly move to a region, which is the diffusion region depletion region and then from depletion region, in the influence of the electric field you will have a current what is called the drift current.

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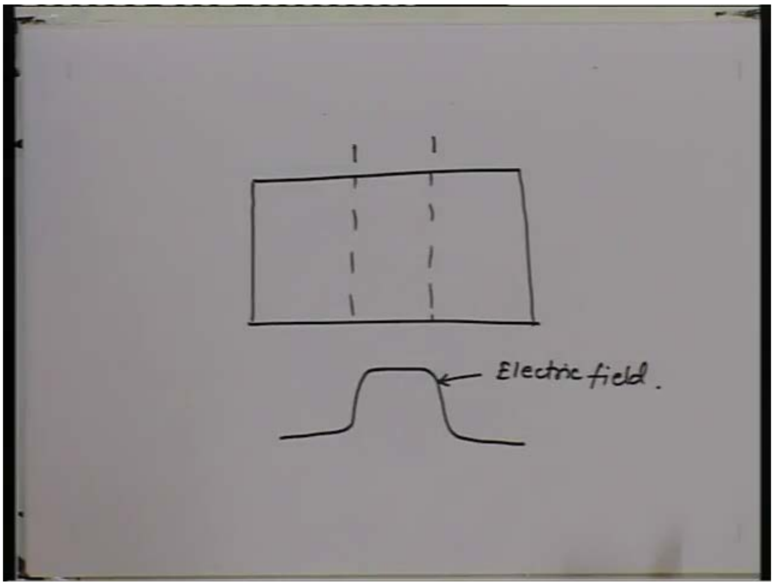

So, inside a p n junction what we are now looking for is a region, which is the depletion region and the electric field is more or less constant in this region something like this. This is the electric field. So, if the carrier is generated in this region, then it will be immediately swept away because of the drift in the presence of this electric field. However if the carrier is generated outside the depletion region, seen there is no electric field in that region. These carriers have to diffuse into this region first, then only they will come under the influence of the electric field and then will have a drift (( )).

So, essentially in the external circuitry, now we have two types of currents which will be flowing. One is due to the diffusion of these carriers in this region outside depletion region and then the drift current, which is because of the carrier moment in the depletion region in the influence of the electric field. (( )) in the diffusion process is the slow process; if you want that, the current should respond as quickly as possible to the photon flux. Essentially, this diffusion process would be minimized. What that means is that most of the photon now should get generated inside the depletion region. So, first thing that is should happen is that this region should be as smallest possible.

Second thing what happens is that if you take a typical p n junction, then the depletion width this is of the order of about one micron; whereas, if you take the typical absorption coefficient for the material, the effective length over which you will have a substantial absorption of light, which will be one over the absorption coefficient; that length will be typically of the order of about 10 to 20 micron. What that means is that if you make a p n junction, then this length over which the electric field is present is much much smaller compared to the length required for absorption of the photon or the characteristic absorption length of this material.

So, most of the photon absorption will take place outside the depletion region. So, what that means is that if you take a typical simple p n junction, then the diffusion current is the one which will be more dominant compared to the drift current and as a result, this device responsibly very very slow. So, now to make the absorption of the photon more efficient, first thing we have to do is we have to increase the length of this region the depletion region over which the electric field is practically constant. Also since this device is a reverse bias device, we know that the depletion width varies as a function of bias voltage.

So, we want that the region over which the absorption of the photon takes place; that should be practically independent of the bias voltage. So, now we have to modify our simple p n junction in such a fashion; that firstly we have the constant electric field region as wide as 10 to 20 microns and then only, you can have the contribution of the drift current increased and also this region this length should be reduced. So that, the photon when incident, practically it sort of gets absorbed into this region which is this depletion region; that is what essentially is realized by introducing an artificial layer of intrinsic material between the the p n junction.

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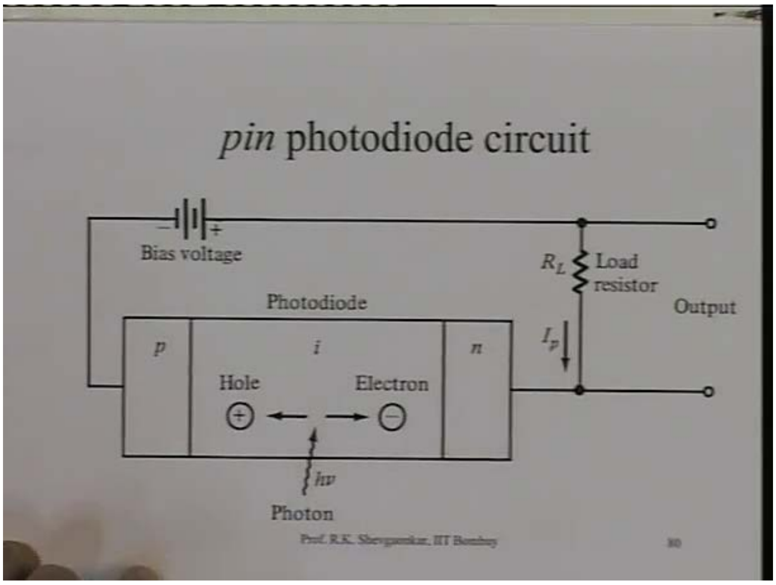

So, what do we have? We do not have a diode which is the simple p n diode. But we have a material which is p material; then we have a intrinsic layer in between and then you are having a n material. And now the photon is incident from this side; not the way it is shown here; it is essentially incident from this side. So, this thickness should be very, very small.

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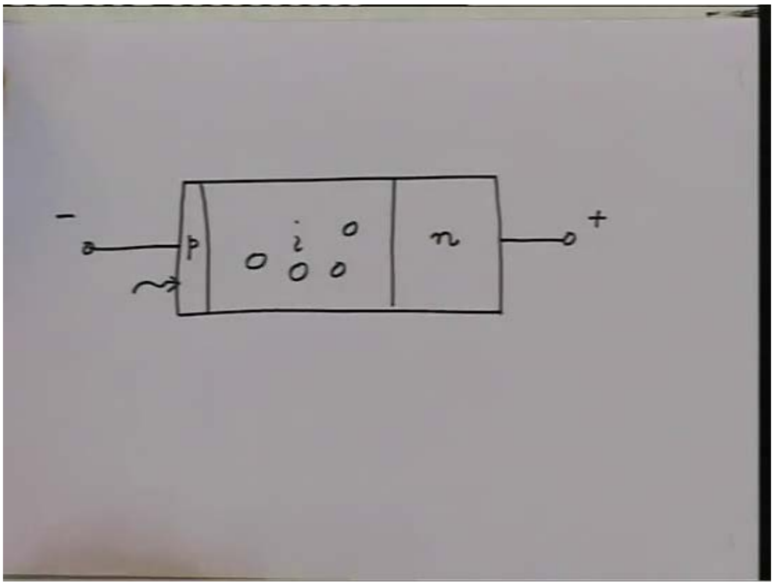

So, actual device should look something like this. This is the p material which is very small. Then you are having the intrinsic region i and then we have n and this device is reverse biased. So, you apply negative voltage here; apply positive voltage here and when the photon is incident on this, very quickly is process this layer and most of the electron hole pairs are going to get generated inside this region. So, the photo detector which is commonly used for detection of light is not the p n junction. (Refer Slide Time: 19:07) But we called the p i n junction and we call as the p i n photodiode or pin diode. So, once you generated pin diode, then now the photon is going to get a absorbed over this region which is 10 to 20 micron.

So, most of the photon flux is absorbed inside this region. So, the quantum efficiency is large and at the same time, we have a good response also. The speed of the switching of this device also is very good. Once we get that, then this reverse bias junction has a current in the external circuitry and the current flows through what is called a load resistance. So, you have a voltage developed across this resistance here. So, basically this conversion process of light to electrical signal is basically photon to current generation; that means this device essentially is a current operated device or for a given photon flux, essentially we have a constant current source here.

Incidentally, so happens that the following circuitry which you required after detector, they are invariably not current dependent, the current controlled; but they are voltage controlled. So, essentially you have to convert this photo current in the corresponding voltage and that is what we do essentially by passing this current through a resistance what is called road resistance. And this voltage now is proportional to the photon flux, which is incident on the device. So, we have got proportionality between this output voltage to the optical power incident on this photo detector.

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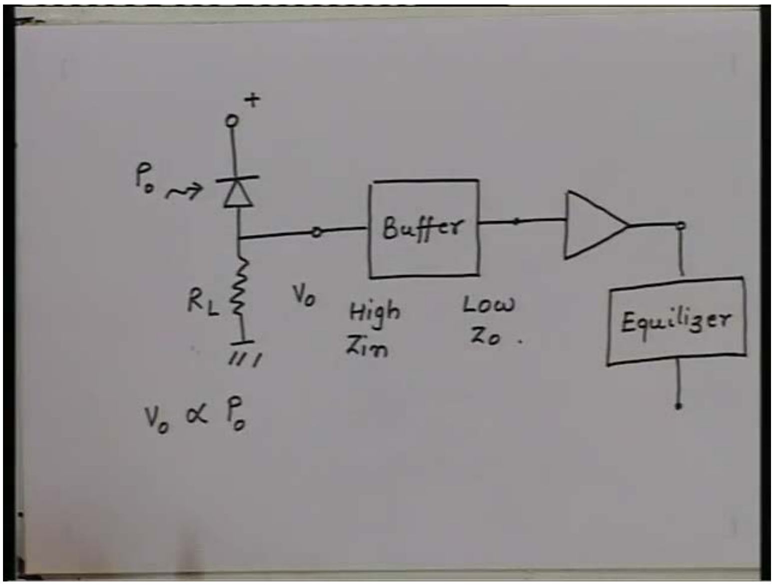

So, schematically than if you want to show, essentially we have a voltage source positive; you connect this to a photo detector is a photo diode connected through a load resistance R L. And the voltage which you get here will be proportional to the optical power, which is incident on the photo detector. So, you got here a voltage V o and we have got V o proportional to the incident optical power. So, if the optical power fluctuates, this voltage also will fluctuate. So, essentially we have information transfer from the optical signal to the corresponding electrical signal. Now, since this device is the constant current device; if you want to have a substantial voltage developed across this, then the value of R L should be large.

But if you make the value of R L very large, then it will be immediately clear that the output impedance of this circuit will be very large. Or in other words, we will not be able to connect any device in front of this without loading this circuit; because the output impedance of this is very very large. So, what that means is that if this circuit has to be connected to the following circuit like an amplifier or something, then the output impedance of this configuration should be reduced. And that is what essentially is done by putting what is called a buffer, which has the very high input impedance; but very low output impedance. So, what we will do is take this output and pass it through a buffer, which has high input impedance; it has high z in and low output impedance.

So, this configuration that a photo diode connected to a load resistance connected to a buffer, this can now is a more usable configuration. But at this point now the output impedance is very very small, which can be connected to the the following circuit. So, let us say the following circuit which you want to connect to is an amplifier, which has certain input impedance. Generally, we have combinations of capacitances and resistances and so on. So, that is the configuration which we will get. So, now if you right down the equivalent circuit of this full configuration, the equivalent circuit will typically look like this.

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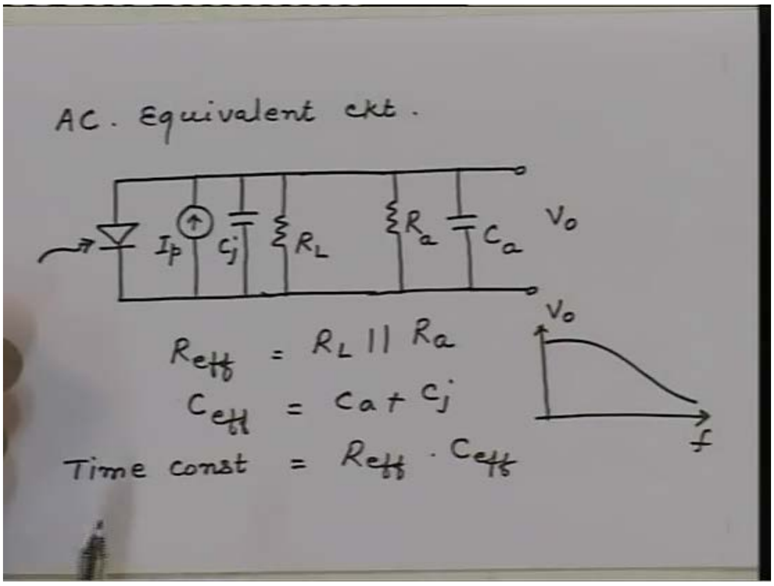

Here writing out the A C equivalent circuit. (No audio from 25:56 to 26:06) So, I have ideal diode which is equivalent to a current source; this is the photo current; this gives me I p. This is connected through a load resistance R L, which is now connected to this combination which has the high impedance and capacitances of the input impedances and so on. So, you may have a resistance here and some capacitance or let us say capacitance of an amplifier; this is the resistance of amplifier and seen this is the reverse bias junction. You also have a substantial capacitance for this junction of the photo diode. So, you also have a capacitance here, which is the junction capacitance.

So, now we have a combination of the resistances and capacitance. So, when the photon is incident on this junction, this circuit now has a finite time constant; because of this resistances and capacitances. So, you have the effective resistance with this circuit would C which would be R effective, which will be R L parallel with R a and the capacitance may be equal to C a plus C j. So, this circuit has the time constant, which is R effective C effective must since this R a and R L are reasonably large at the correspond to the input impedances either for the amplifier or the load resistance. The time constant for this circuit is reasonably large. As a result, essentially the response of this circuit is low frequencies response or in other words the high frequency response for this circuit is rather poor.

So, if we typically look at the response of this circuit, the response essentially would be low pass type should will have response which will go something like this. This is the function of frequency; this is the output V o; yet here. So, the bandwidth of this circuit would get other limited. So, one of the requirement then is that the loss of response which we have in the high frequency has to be restored. So, we have to essentially provide a equivalent high frequency circuit. So that, this frequency response becomes reasonably flat over a wide range of frequencies; that is a device which is what is called an equalizer, which has a frequency response which is more or less opposite of this frequency response.

So, you get an output, which is more or less flat over very wide band. (Refer Slide Time: 22:20) So, the configuration for a wide band response and would be that you have to take this and pass it through an equalizer, which essentially is the high pass filter; that is the output which will have a substantially large bandwidth. Or in other words, that is the one which can respond fast to the incoming photon flux. So, the typical configuration which you require for the operation of the photo detector is a photo detector connected to a load resistance forward by buffer forward by an equalizer. And ofcourse, an amplifier to increase the optical signal that is the configuration, which will be required minimum on the detector side in a optical communication system.

Now, since the photon flux which is incident on the optical detector is very very small and after the photo current is created, you already have some kind of a loss which is taken place inside this device. We want that before the signal is converted from the optical to electrical and comes out of the circuit. It would be desirable to have some kind of internal amplification with the photo current inside the device itself. Now, a simple p n junction or pin diode is amplification is not possible. So, essentially what we do is we modify this device to get what is called avalanche photo detector; in which, we essentially introduce one more layer in between the p n junction, where the electric filed now exceeds the break down field.

And therefore, the electron hole pair which are generated in the i region; when they try to cross this high electric field region, there is a break down; avalanche break down. So, there is the internal multiplication of the carriers. So, the photo current which flows into the external circuitry gets enhanced by the multiplication factor. So, if you want to have the internal multiplication of the signal can essentially should go to the device, which is the the avalanche photo detector device. So, in avalanche photo detector device essentially the configuration is as follows.

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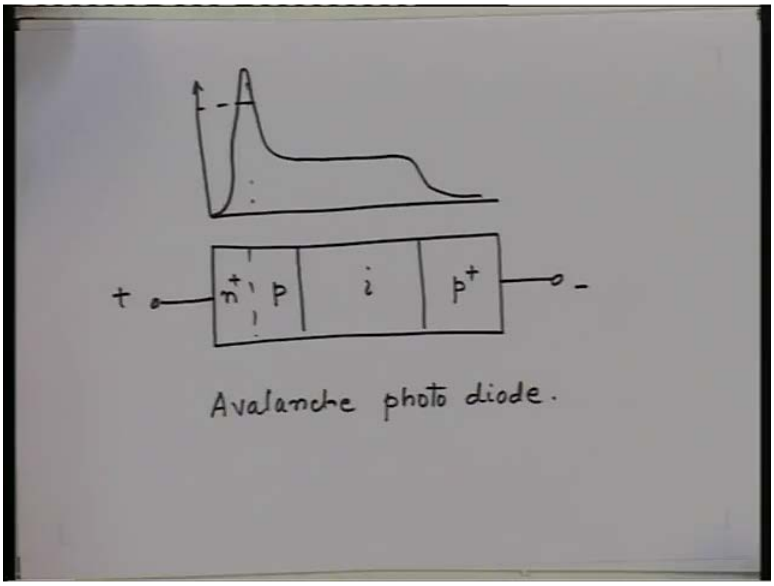

We have now a region; say this is the n plus; then you are having a region here which is p; then you have region i and this is p plus. And if you draw the electric field, variation inside this; the potential applied to this which is the reverse bias. So, this is positive; this is negative. The electric field variation inside this would be here you will get a large filed something like this. So, note here most of the carriers are going to get generated in this region, where the electric filed is practically constant. But the break down filed is something here. So, in this region we have the field intensity which is larger than the avalanche break down field. So, when the carriers try to cross this region here, there is a multiplication of the carrier because of the avalanche process.

So, the current which flows into the external circuitry is now amplified by that avalanche gain factor. So, this diode is what is called the avalanche photo diode. However to get this electric field large here, the voltages which has to be applied to the photo detector are now much larger compared to what we could get for the simple p n junction. So, when we use for the pin diodes, the voltages are small few volts; whereas, if you want to go to the avalanche photo detectors, then the voltage difference has to be typically of the order of about few tens of the voltages. So, depending upon application either the pin diodes can be used or the avalanche photo detectors can be used.

Now, when the photo generation is taking place, the electron hole pair generation is taking place from the interaction of the photon with the material. This process is not really a deterministic process. What that means is that when the photon is incident on the material, there is a certain probability that this photon will interact with the matter and will lead to the electron hole pair generation. So, the quantum efficiency factor now all that which we talked about; it essentially talks in some average sense. So, if you say that some n photons where incident on the material on an average; if the quantum efficiency is 1, on an average you will get the n electron hole pair generated.

However, no one can tell with certain t that every photon is going to create one electron hole pair. So, the whole process of photon to the electron hole pair are the current generation is essentially a statistical process. And as the result, you always have a fluctuation now in the electron hole pair generation, which essentially get reflected into fluctuation in the photo current. So, now if the photon or the current which is flowing to the external circuitry, which is due to this photon; the fluctuations are coming because of some fluctuation into the light and the fluctuation in to interaction of light with the mat. So, the fluctuations are now due to two things.

One is intrinsically when the photon flux is coming, the photons do not arrive in a constant flow; infact, the photons always arrived in a form of some bursts. It has a distribution and the when the photon interacts with the matter, again there is a probability that the photon will interact with the matter and would give electron hole pair. So, this process now essentially leads to what is called the the noise process in the detector. So, whenever we have a detection of the light by photo detector, there is always some noise introduced in to this conversion process. At the top of this when the device use is the avalanche photo diode. Then every electron hole pair when it tries to cross this region where the electric field is large, even that multiplication process is a statistical process.

So, over and above the statistical variation of the current which we have just the detection process of the photon; when the carriers get avalanche multiplied, you again get a noise introduced; because this avalanche process is again a statistical process. So, the noise fluctuation which you get into the external circuitry because of this intrinsic nature of the photon and the statistical interaction of the photon with the matter is what is called the shot noise. Now, the noise is measured in terms of its mean square power or means square value. So, if I have a certain current flowing into the external circuitry, then I can find out what is the mean square fluctuation in that current.

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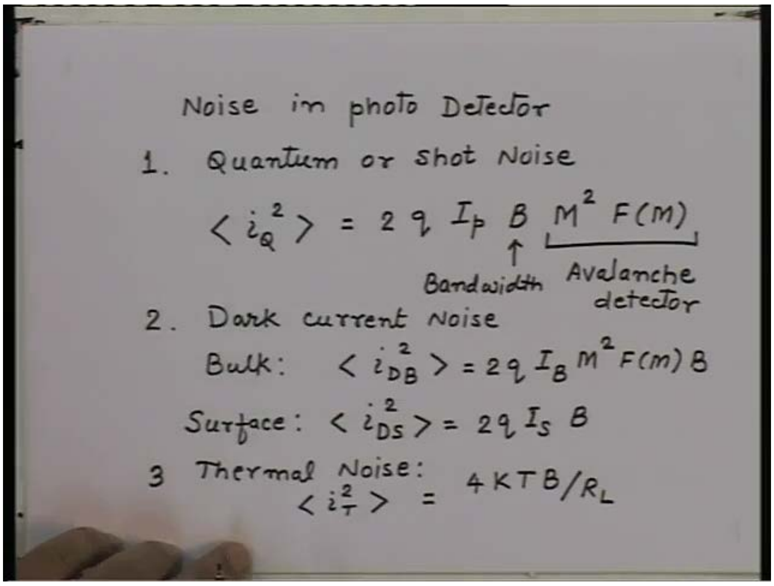

So, now we have the noise inside the detector (No audio from 39:49 to 40:02) and the first component of this is due to what is called the quantum noise or the short noise. So, we have here quantum or shot noise. So, if I say that the fluctuating component of the current is denoted by small i, then the means square value of the fluctuation current i q square is equal to two times the charge of the carrier multiplied by the average value of the photo current, which is I p multiplied by the bandwidth of the circuit multiplied by the avalanche amplification factor square and multiplied by the noise figure of the avalanche multiplier. Now, note here what we have got?

Firstly, what we are saying here is that the mean square value of this current fluctuating current is proportional to the average value of the current. This is the nature of this noise; because this noise which we are talking about now is because of the statistical fluctuation of the photon and the photon interaction process, which is essentially a poison process. So, if you look at the statistics of the photons and the electron hole pair generation, that is the poison statistics; so, the mean square value of this fluctuating current is proportional to the mean value of this current. Also this fluctuation is proportional to the bandwidth; that mean larger the bandwidth, more will be the noise collected and then M is the amplification factor for the avalanche detector.

So, these two quantities are for avalanche detector. (No audio from 42:38 to 42:48) For pin diode, these quantities are not there. So, for pin diode, you have simply the mean square value of the photo current; that will be two into q into mean value of the photo current multiplied by the bandwidth. The F M which is what is called the noise figure of the avalanche photo detector; that means, this process avalanche process is not only amplifying the photo current by factor M; but it also introduces additionally certain noise into the current and that essentially is captured by this factor what is called F of M. So, if no additional noise is added by the detector, then this quantity F M will be equal to 1.

The second noise which is generated is what is called the dark current noise. Now, note here when we are talking about a detector, the light which is falling on this is not only the one which is coming from the optical fiber; that will be ideal situation that only light which comes from the optical fiber, which is signal there should fall on the detector. However, in practice we always have some ambient light, which also falls on the detector. So, even if the signal light is not present, there is always some photo excitation or even thermal excitation and that essentially leaves to the current in the external circuitry; that current we call as the dark current; that means in the absence of the desired light, whatever current flows that is as if the device was kept in dark conditions and even then, some current flows in the external circuitry.

So, we have now the current which is in the absence of the photon, which is coming from fiber and even then certain current flows in the external circuitry. As seen this current again is because of the similar process, it has a noise component and that noise we call as the dark current noise. So, second component of the current or noise which we have is what is called the dark current noise. Again the dark current has two components. One is this current may get generated deep inside the p n junction or this can get generated only like a surface phenomena on the p n junction; but then the two current when they tried to go inside the region where the avalanche breakdown takes place, they will undergo different treatment.

The current, which is bulk deep inside the material that will undergo the multiplication process; so, it will have avalanche gain; whereas, the current which is showing on the surface that will not undergo the avalanche break down. So, it will not see the avalanche amplification. So, the dark current can be divided into two components. One we call as the bulk dark current. Then the mean square fluctuation of bulk dark current; dark current bulk square that will be equal to two times q I which is bulk dark current into M square into F of M into the bandwidth , which is B. So, this quantity as you mentioned this is bandwidth.

The other component which is the surface dark current; the mean square value of that would be dark current surface square that will be equal to two times q I surface current and there is no amplification for this current. So, there is no question of this factor here; multiplied by B. So, inside the photo detector, now I have the currents photo currents which could be due to two components. One is due to the signal, which is coming from the optical fiber as incident on the detector. And other one is even in the absence of this signal, there is some ambient light which might be falling on the detector or could be because of thermal excitation, could be certain current which will be flowing.

These two together essentially would contribute to the noise in the current. Now, when this current goes outside the external circuitry and passes through the resistance, we have the noise generated inside the resistance what is called the thermal noise. So, outside this photo detector, we have the noise generated which is because of the random motion of the electrons inside the resistance. So, we get the third type of noise, which we call as the thermal noise (No audio from 49:41 to 49:49) and the mean square value of this thermal noise that will be given as 4 K T B divided by the load resistance, where B is the bandwidth; T is the temperature of the resistance and K is the Boltzmann constant.

So, note here now that when we are talking about these noises the quantum noise and the bulk noise, they are related to the photo current or in some sense these noises are essentially multiplicative noises. Take example this one; since the mean square value of this fluctuation is related to the mean value of the photo current; if I increase the photo current, the noise also will increase in the same proportion. So, this noise is a multiplicative kind of noise; whereas, if I look at the thermal noise here, this is not related to the intensity of the optical signal or the value of the current or average value of the current. So, this noise is not multiplicative in nature. This noise is essentially additive in nature. Now, one can get these noises, then we can write down the signal to noise ratio.

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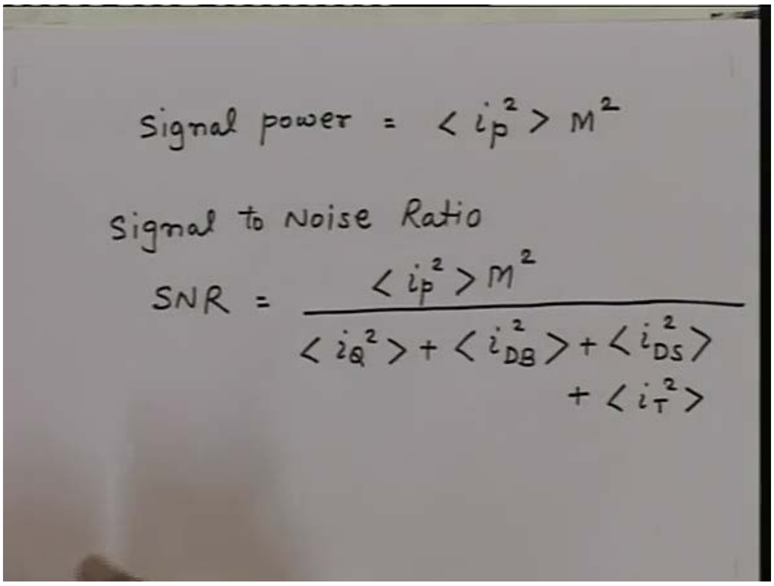

So, if I say that the signal has a current which is i p, I can get the signal power, which is i p square into M square, if you are using the avalanche photo detector. And once you know the signal power and the total noise, (Refer Slide Time: 39:55) again what we can say is that since the noises are independent, the mean square value of the total noise is sum of these mean square values. So, total noise will be this plus this plus this plus this, and this is the signal power. So, you can get a quantity, what is called the signal to noise ratio or SNR that is equal to the signal power divided by the total noise power, which is i q square plus i D B square plus i D S square plus i T square.

And we will see that for optical communication system, this is the quantity, which is the important quantity, but that will essentially decide the overall performance of the system. So, we will make use of this expression later on, when will try to estimate the performance parameter like bit error rate or something; that time we will come back to this expression, but at this point, what we see is that having identified the sources of noise, now we can get the characteristic parameter of a receiving system, what is called the signal to noise ratio, and that is what is essentially shown here. So, in the following lectures, essentially we will try to make use of this expression to find out the system performance in the presence of the noise in the photo detector.