Advanced Optical Communications

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Lecture No. # 21

Photo Detector

We have been discussing the photo detectors; we saw that if we identify a proper material, then the photon can be absorbed inside this material. And if the material is the semiconducting material, we have electron hole pair generation. And if we create a mechanism by which this electron hole pair is collected, we will have a current flowing in the external circuitry, which we call as the photo current. And then we will have proportionality between the photo current and the photon flux. So, for efficient absorption of a photon inside this photo detector, we found that a modified version of the p n junction, what is called p i n junction or p i n diode is more suited.

So, if the light is incident on a p i n detector, then most of the photon absorption takes place inside this artificially wine depletion region. And then we have a efficient photo absorption device, for which the current is proportional to the photon flux. Then we investigated the characteristics of the noise of this detecting device. We saw that the interaction of the photon with the matter is the statistical process. And therefore, whenever we have a detection of the photon and electron hole pair generation, you have some kind of fluctuation in the external current. So, in last lecture, we saw the noise characteristics of the photo detector.

And we saw there is a noise what is called the shot noise, which has a mean square variation proportional to the mean current; that means higher the value of the average photocurrent, more will be fluctuation in the current. This noise is called the shot noise or the quantum noise. Then we saw in the absence of the signal, which is coming from the optical fiber, there is always some ambient light falling on the detector or even because of thermal excitation, there is always a current, which is flowing in the detector and that has fluctuations, that gives rise to what is called the dark current noise.

And then origin of essentially is the average current, which flows in so called dark condition that be the signal is not incident on the detector. Then we saw when the detector is connected to the electronic circuitry like the amplifier, then we have thermal noise, because of the resistances which has present; and then this noise is independent of the average value of the current. So, this noise is a additive noise; whereas, the shot noise and the dark current noise are essentially multiplicative noise and then we found the expression for the signal to noise ratio. We will make use of that expression, when we talk about the system performance, the calculations of the beta error ratios and so on.

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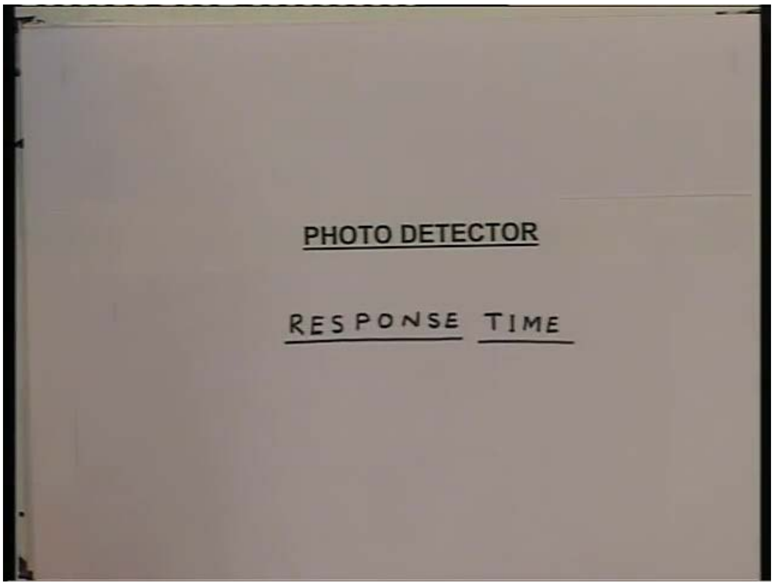

PHOTO DETECTOR

RESPONSE TIME

Today, we will discuss another aspect of the photo detector and that is what is called the response time of the photo detector. We have seen to detect the signal, which is fluctuating at a high rate; that means if the bits are coming at high speed, then your photo detector must respond properly to the fluctuating optical intensity. So, today essentially we investigate the response time of the photo detector or in other words, the frequency response of the photo detector. So, first let us take a very simple model and ask questions why there is a finite response time associated with a photo detector.

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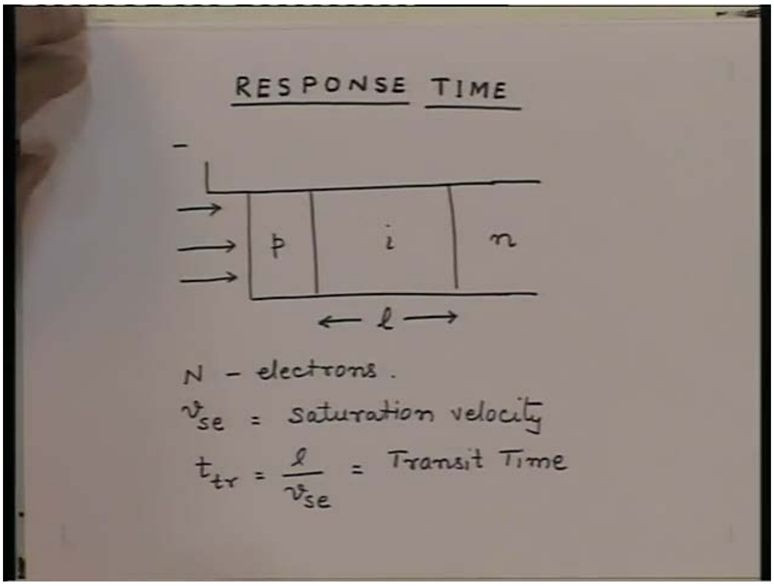
RESPONSE TIME

N - electrons.

v_{se} = saturation velocity

$t_{tr} = \frac{l}{v_{se}}$ = Transit Time

So, as we have seen that for a photo detector, let us say the light is incident from the p type material. So, we have this material which is p; then we are having the intrinsic layer which is i and then we have the n material here and this device is reverse biased; that means negative voltage is applied here and now the photon is incident from the p side. Now, as we discussed earlier, the photon might get absorbed in this region here. But in this region, there is no electric field. Most of the electric field is present in this intrinsic layer or there is most of the potential drop is across this layer. So, the carriers which are generated in this region outside the depletion region, they have to diffuse first inside the depletion region.

And then in the presence of the electric field, these carriers will drift and we will have the current which will be drift current. So, essentially as we saw last time that the current in the external circuitry has two components. One is because of the diffusion of the carriers and other one is because of the drift of the carriers. So, if the photon flux is incident on this device from the p side and since this thing is connected to negative polarity is negative here. The holes which are generated in this region are immediately swept away and the electrons are the one, which are essentially are going to cross the the intrinsic layer.

So, these electrons when they cross this, they require a finite time to cross this and as long they as these carriers are in transit, there will be a current flow in the external circuitry. So, let us say we have the length of this intrinsic layer is l. Now, one can show that for the typical biasing voltages which we have across this junction, the carriers acquire what is called the saturation velocity very quickly. That means, most of the passage these carriers travels through; they travels with almost a constant velocity what is called the saturation velocity. So, initially when the carriers are injected across the junction, the velocity will very quickly increase in a very short distance.

And most of the time, the electron or hole depending upon on which side the generation is taking place will travel with the constant velocity inside this region. So, let us say suppose most of the photon absorption has taken place right at this edge of the intrinsic layer. And as we said, electrons are the one which are going to cross this intrinsic layer. So, they will acquire a velocity what is called the saturation velocity for electrons. So, let us say the n electrons are generated inside this and they reached to the saturation velocity, which is given as let us say v s e that is saturation velocity.

So, the quantity which we call as the transit time for the electron to cross this intrinsic layer is nothing but this distance l divided by the saturation velocity. So, we have t transit that is equal to l divided by v s e is called the transit time. So, now we can consider a simple case that the light is absorbed very close to this region here on this edge. So, all the electrons are n electrons are generated right on this edge and then for a time which is t transit, this electron keeps moving over a distance l. So, we have a current flowing in the external circuitry for this transit time t t r.

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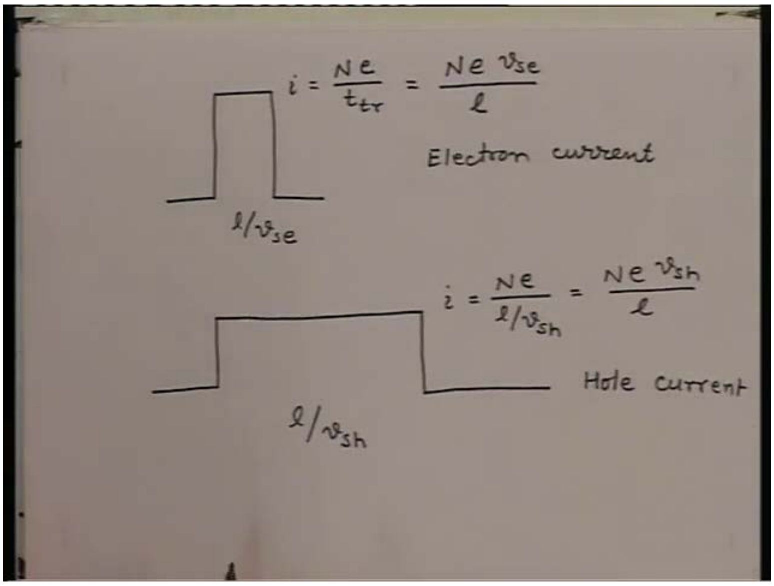

So, there one can say that for an absorption near the p edge of the intrinsic material, we will get a current pulse which will be like this and this will be flowing for a time, which is t transit which is l divided by v s e. And the current amplitude for this i that will be number of electrons the charge of the electron e divided by t transit. So, that is equal to N e v saturation velocity of the electron divided by the length of the depletion. (Refer Slide Time: 04:56) Similarly, if the light was incident from the n side and if most of the carriers were generated very close to this end, then the electrons will be the one which will be collected very quickly and the holes will pass through the intrinsic layer.

But then the holes have different mobility. So, the saturation velocity for the hole will be different than the saturation velocity of electrons. Typically, there is a factor of four differences between the saturation velocity for the electrons and holes. So, the holes will take a longer time to cross this. So, if you are having a N holes crossing this intrinsic layer, then the transit time will be l divided by the v saturation for the holes. And the current pulse will flow in the external circuitry for a period, which will be for l divided by v saturation for the hole and the current amplitude because of the holes now will be N e divided by t transit which will be l divided by v saturation of the hole that is equal to N e v saturation of holes divided by l.

So, in simple case as we see if the carriers were generated near this edge, we will get a current pulse for this duration; whereas, if the carriers were generated very close to this edge, then the current pulse will be this one. So, this one is the electron current and this one is the hole current. Suppose the carriers were generated in the middle of the intrinsic layer, let us say exactly half way (Refer Slide Time: 04:56) most of the carriers were generated here. Then the holes will move this distance, where the electrons will move this distance. So, both of them are going to travel a distance which is l by 2. So, you will have now the combination of the hole current and the electron current and both will be travelling essentially for a distance which is equal to l by 2.

These are the simple cases just to understand how the current is going to flow inside this intrinsic layer of the p i n diode. Most of the time (Refer Slide Time: 04:56) we will see that the electron hole pair generation takes place almost over the entire region. So, let us say that when the light propagates inside this material, the time over which the electron hole pairs are generated is very very short. So, entire region essentially gets filled almost instantaneously with the electron hole pairs. And then electron will start moving in this direction; holes will start moving in this direction. So, we will have a combination of the currents flowing in the external circuitry because of electrons and holes.

Now, one can see that as soon as the electron hole pairs are generated inside this region and they start moving. You have a very large value of current, which will be flowing in the external circuitry. And then as the electrons starts drifting the number of electron, which will remain in transit that number will go on reducing till all electrons have cross this edge of the intrinsic layer and same is true for the hole. So, we expect now that if we have a uniform generation on the electron hole pairs in this region, then the current which will flow in the external circuitry will be triangular in shape; because as soon as the electron hole pairs are generated, you will have large current. And as the electrons and holes are getting collected, as the time progresses the current will decrease.

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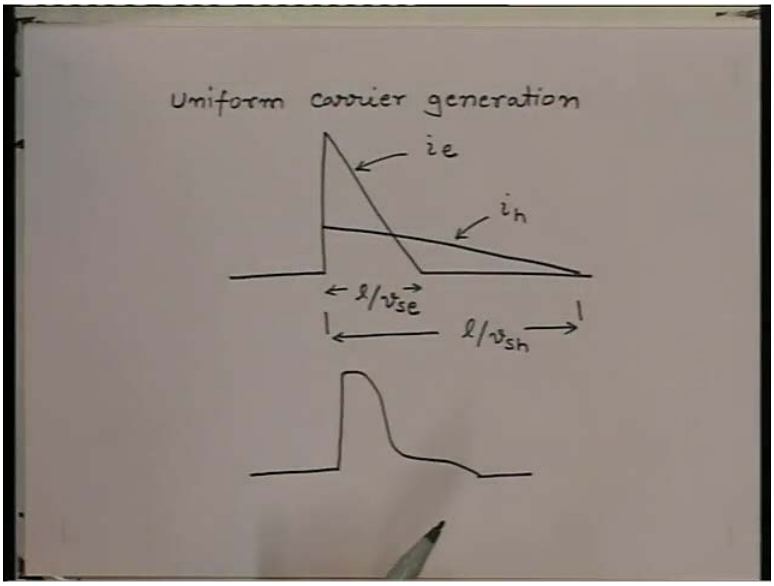

So, for a uniform carrier generation, we expect a current to flow which will look something like this. So, suddenly a current will increase and that die like this in a triangular fashion; again this time is the l divided by v s e. So, this is the electron current i e and then the hole current again will be which has same behavior like a triangular one. But its amplitude will be less and it will flow for longer time; say it will go like this. So, this current is i of h and this time from here to here will be l divided by v s of h. So, in the external circuitry, we will have a current which is sum of these two. So, we will get a current shape which will look something like this.

Again this is a simpler model; whereas, we know (Refer Slide Time: 04:56) that the electrons and holes are not going to be generated uniformly in this region. There is a exponential decay which is going to be inside this. So, we have a current pulse which will be close to this. But the actual pulse shape might look something like this. So, the important thing to note here is when a light pulse is incident on the photo detector, depending upon from this sight the light was incident on the detector and how quickly the light was absorbed inside the intrinsic layer of the photo detector, we will have a different shape of the pulse for the external current.

But one thing is clear that the shape of the pulse in the external circuitry is not identical to what shape of the pulse is incident in the form of light on the photo detector. So, we have some kind of a pulse distortion, which is going to take place during the detection process. So, this is one of the important aspects of the photo detection that when the light pulse is incident on the photo detector, the current pulse will have different shape depending upon the absorption process and so on. Also in addition to this, we will have the diffusion current and since the diffusion process is a slow process, the diffusion current will keep flowing for much longer time.

Now, it becomes clear that (Refer Slide Time: 04:56) in practical situation if you want to have this response time shorter, then this duration should be as short as possible for a impulse light. Or in other words, we want the electrons to cross this thing to give you the current in the external circuitry and the contribution due to hole should be minimized; because that is the one which is going to flow for much longer times is response time is much longer. Then it makes sense to have the photons incident on the photo detector from the p side. In this situation only, all the holes will be collected immediately and the electrons are the one which are going to remain in transit for much longer time.

That is the reason in a p i n detector the light is made to fall from the p side of the p i n junction rather than from the n side; where if the light was incident on the n side, then holes are the one which will remain in transit. And because of their saturation velocity smaller compared to electrons, we will have a much longer delay or the propagation time for the hole currents. Having understood this, then now I can one can do simple analysis to find out what would be the frequency response or the time response for the photo detector. So, let us do a simple analysis. Let us say we have a sinusoidally modulating signal, which is incident on the photo detector. So, we are having a photon flux, which is amplitude modulated with a modulation index some m and some frequency omega.

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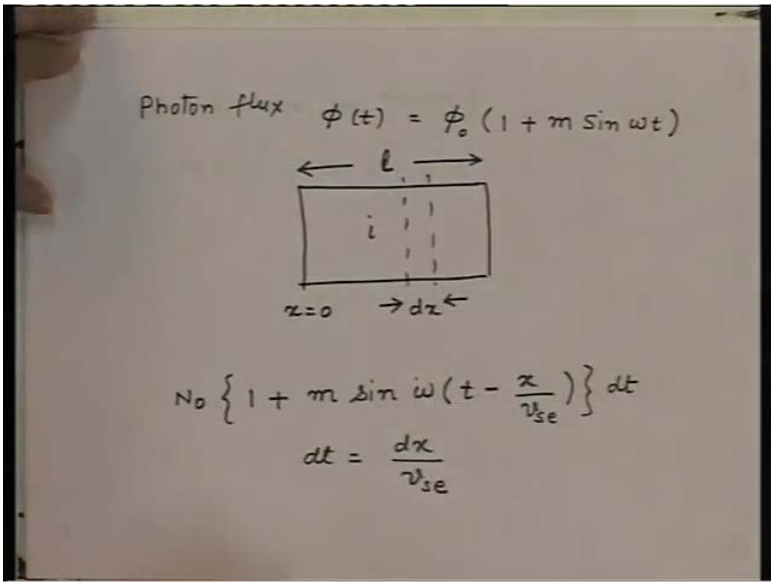

Photon flux $\phi(t) = \phi_0 (1 + m \sin \omega t)$

$$N_0 \left\{ 1 + m \sin \omega \left(t - \frac{x}{v_{se}} \right) \right\} dt$$

$$dt = \frac{dx}{v_{se}}$$

So, let us say we are having a photon flux, which is given as some phi of t which is equal to some amplitude phi 0 into 1 plus the modulation index m into sine of omega t. Assuming there is no delay in conversion of the photon flux into the corresponding carrier, let us say we have now the carrier generated which are also having exactly the identical form. So, let us see now that (Refer Slide Time: 04:56) when this signal now is incident on this and let us assume that the carriers are generated uniformly in this region for simplicity. If we consider any small section in this region, we will see the carrier passing through that; which will be the carrier generated at that instant of time in that region plus all the carriers which were generated some earlier time in these layers and now have travelled to cross through this particular layer.

So, what we are saying is if we consider now region, let us say this is x equal to 0 and I consider some small time here; some delta t corresponding to some distance delta x. The carrier which will be passing through this layer d x, they will be the carrier generated at that instant of time in this layer plus all those carriers which were generated in these layers, if the carriers are moving this way left to right with appropriate time delay. So, now if you are saying that the carrier generated in this region is nothing but have the same form, then in this region the carrier which will be present at some time will be given as N 0, which is proportional to this quantity phi 0 into 1 plus the modulation index m sine of omega t minus x divided by v saturation into d t.

So, what are these carriers? These are the carriers which were generated at time this much before and now I crossing through the junction or this layer of length d x. So, during this time d t in this layer, these are the carriers essentially which are passing through this. Now, since the carriers are moving with the saturation velocity which is v s e, we have here d t is equal to d x upon v saturation. So, now we can ask what are the total carriers, which are in transit? That means, at any instant of time how many carriers are in transit; because they are the one which are going to tell me the total current flowing in to the external circuitry.

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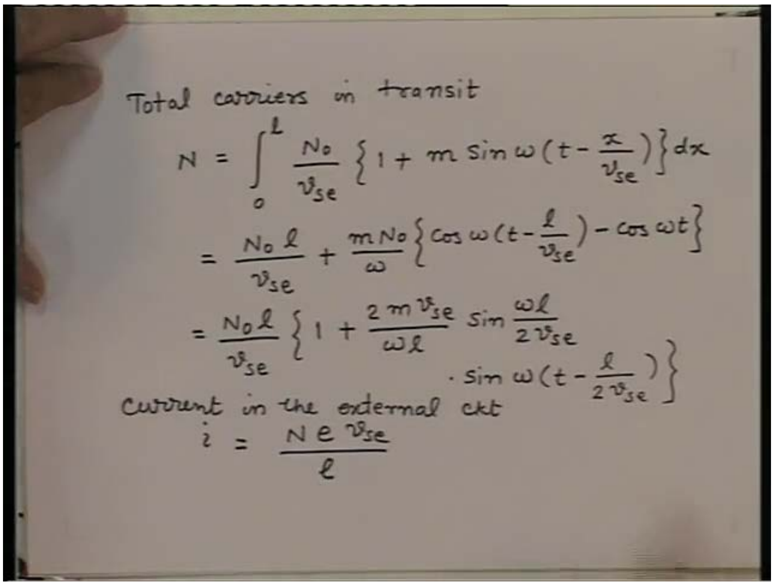

Total carriers in transit

$$N = \int_0^l \frac{N_0}{v_{se}} \left\{ 1 + m \sin\omega\left(t - \frac{x}{v_{se}}\right) \right\} dx$$

$$= \frac{N_0 l}{v_{se}} + \frac{m N_0}{\omega} \left\{ \cos\omega\left(t - \frac{l}{v_{se}}\right) - \cos\omega t \right\}$$

$$= \frac{N_0 l}{v_{se}} \left\{ 1 + \frac{2 m v_{se}}{\omega l} \sin\frac{\omega l}{2 v_{se}} \cdot \sin\omega\left(t - \frac{l}{2 v_{se}}\right) \right\}$$

Current in the external ckt

$$i = \frac{N e v_{se}}{l}$$

So, the total carriers which are in transit (No audio from 25:24 to 25:35) are nothing but this N integrated over the total length of this this layer. (Refer Slide Time: 21:12) See if I say this i layer intrinsic layer here is having length l, this is i layer; then if we integrate all these carriers over this length x equal to 0 to x equal to l that gives us the total carriers in transit at a given instant of time. So, we find the total carriers in transit which will be integral 0 to l N 0 upon v s e 1 plus m sine omega t minus x upon v s e d x. So, note here we have substituted for d t say d x upon v s e; say we have got a quantity N 0 upon v s e; that is what is come here. So, from here essentially we have now the term which is N 0 upon v s e and this term remains same.

So, now we are integrating over distance which is from 0 to l. By solving the integral, we get essentially N 0 l upon v s e plus integral corresponding to the second term which will be m N 0 upon omega cosine of omega t minus l upon v s e minus cos of omega t. Here two limits which you have substituted. Combining these two terms, appropriately we get N 0 l upon v s e 1 plus 2 m v s e upon omega l sine omega l upon 2 v s e multiplied by sine omega t minus l upon 2 v s e. So, if these are the carrier which are in transit at a given instant of time, the current which will flow in the external circuitry; that will be equal to N in to e into v saturation divided by l. Now, this quantity as we already know l divided by v s e is nothing but what is called the transit time of the carriers.

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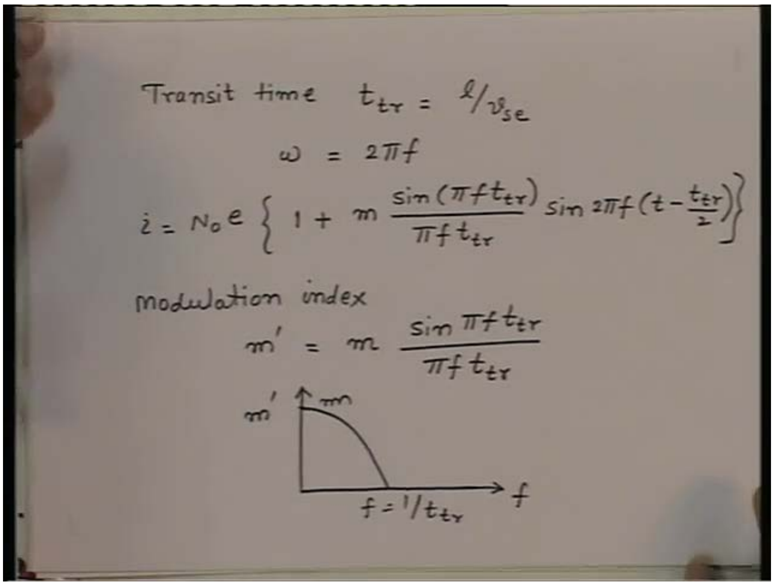

Transit time $t_{tr} = l/v_{se}$

$$\omega = 2\pi f$$

$$i = N_0 e \left\{ 1 + m \frac{\sin(\pi f t_{tr})}{\pi f t_{tr}} \sin 2\pi f \left(t - \frac{t_{tr}}{2}\right) \right\}$$

modulation index

$$m' = m \frac{\sin \pi f t_{tr}}{\pi f t_{tr}}$$

So, let us write that transit time t t r is equal to l divided by v s e and let us say we write the frequency explicitly. So, omega can be written as 2 pi f; omega is equal to 2 pi into frequency. So, this expression (Refer Slide Time: 25:23) which we have got for now the current. So, you have multiplied this quantity by e v s e upon l, we get this current. So, current expression can be written now i is equal to N 0 e into 1 plus m sine pi f t transit divided by pi f t transit into sine of 2 pi f into t minus t transit by 2. So, two things can be one noted here; firstly if I compare this expression with the original photon flux which is here.

(Refer Slide Time: 21:12) There is a delay now which is introduced in the signal, where this quantity is having now t minus t t r by 2. So, on average the signal is delayed by half of the transit time in this intrinsic layer. But more important that then that is that this quantity here which is the modulation index; that effective modulation index now is different than what we had for the original signal. So, original signal have the modulation index, which is m. But now we are having a modulation index, which is m into this quantity. So, we have got now the modulation index.

Let us call that some m prime; that is equal to the original modulation index m multiplied by this quantity. Now, this is the sin function. So, as we go to the higher frequencies, then the modulation index m prime is smaller than the original modulation index. So, if I plot now, this modulation index m prime as a function of frequency. Originally, we have modulation index which is equal to m and then the modulation index would reduce. So, when this quantity f is 1 upon transit time, that time the modulation index will go to 0. So, this time is this frequency is 1 upon t transit. So, what one finds is that because of the finite transit time of the carriers inside this, the device will not respond to the alternating signals beyond certain frequencies.

And physically, one can see this as follows that suppose we had given an impulse to this device, the current actually is going to flow for a duration which is equal to the transit time. That means every impulse is broaden by function, which is rectangular shape function of width equal to transit time. So, the impulse response for this device is nothing but a rectangular pulse, which you have seen for the current shape which you have shown earlier. So, we have got the impulse response for this device essentially (Refer Slide Time: 10:07) which is this. And therefore, the frequency response of this which will be Fourier transform of this function and that is the quantity essentially we have got from this analysis.

So, what we find here is that as the frequency increases now, the modulation index reduces. Or even if the light is fluctuating as a function of time, the current which flows in the external circuitry has lesser fluctuations in amplitude and where by the time the frequency reaches to 1 over transit time; practically the fluctuation stop. So, the external circuit has only the current which is almost a D C current, though the light is having the fluctuating component. So, essentially this gives me the uppermost frequency to which the device will essentially respond.

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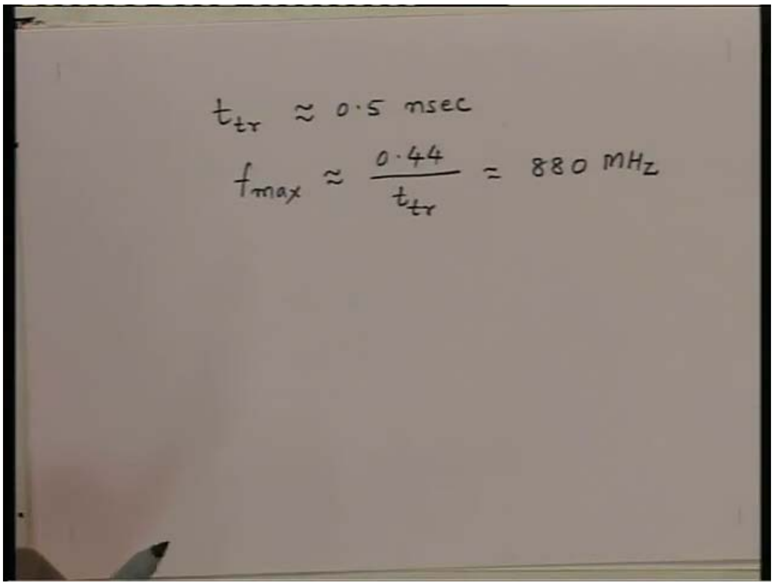

$t_{tr} \approx 0.5$ nsec

$$f_{max} \approx \frac{0.44}{t_{tr}} = 880 \text{ MHz}$$

So, taking typical numbers that a transit time t t r could be of the order of about 0.5 nanoseconds, we get the maximum frequency f max that is approximately divided by t transit; so approximately about 880 megahertz. So, the frequency response of the photo detector is one of the important components; because that is one which is going to decide now what kind of data can be received by this junction. Later on, we will see infact that this is the response which restricts the high data transmission on the optical communication link. We will see that now there will be fibers which have very low dispersion. We have lasers which can be switched at a very high rate. So, finally the limitation will come from the photo detector for realizing the high data rates on the optical communication link. So, now what are the factors which are contributing to the response time of the detector?

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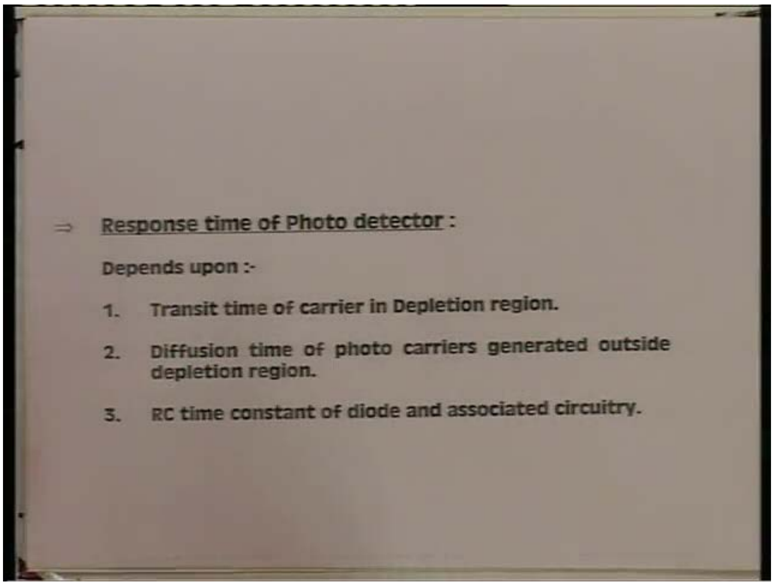

⇒ **Response time of Photo detector :**

Depends upon :-

1. Transit time of carrier in Depletion region.
2. Diffusion time of photo carriers generated outside depletion region.
3. RC time constant of diode and associated circuitry.

So, there are three factors now, which are controlling the response time or the frequency response of the detector; one is the transit time of the carrier in the depletion region; that is the analysis we have seen. We also seen that we cannot make the depletion layer region thinner, because if we do that, then there will be less absorption of the photon in that region. The diffusion current will increase. So, if we reduce the thickness of the depletion layer to reduce the transit time, then that diffusion layer component will increase and again a device will not be able to respond with proper speed. So, this is one of the prime parameters, the transit time of the carrier in the depletion region primarily decides the frequency response or the response time of the photo detector.

Other things as you have seen there are always certain carriers, which are generated outside the depletion region and then they have diffusion current. And then diffusion current keeps flowing for much longer time compared to the drift current. So, the response time will be decided by that, and we have also seen again that the efforts are made to reduce the component of the diffusion current as small as possible. So, most of the light absorption essentially should take place inside the depletion region, where there is electric field present. So, the diffusion current component is reduced. And thirdly, we have seen that for a reverse bias junction, there are junction capacitances.

When this capacitance is combined with the load resistance of the photo detector, have seen the load resistance the distance has to be very large; because the p i n diode basically is a current controlled device. So, to get a voltage, you require high resistance. So, that the constant current which is coming from the photo detector. When it flows through this, we get a substantial voltage development. So, since we are having a R value which is large, the R c time constant of the photo diode is rather large. So, these are the three prime factors which restrict the response of the photo detector or in other words make the device more and more low frequency a kind of device.

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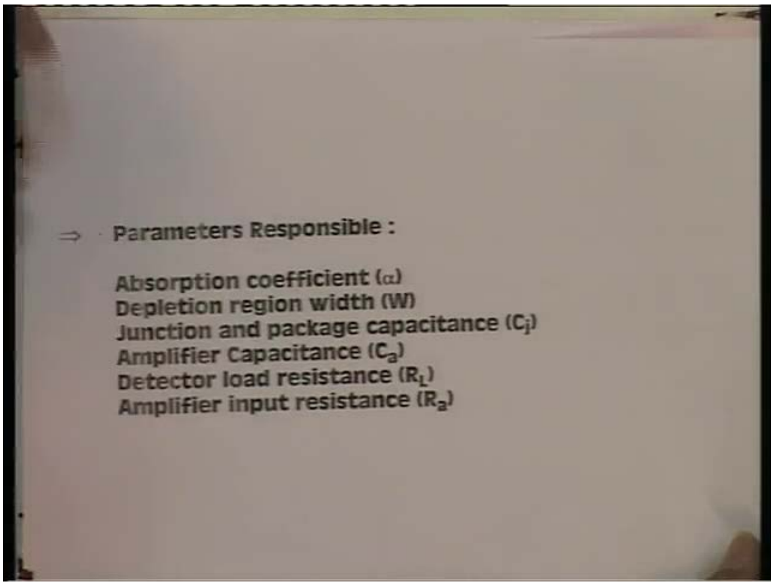

⇒ **Parameters Responsible :**

Absorption coefficient (α)
Depletion region width (W)
Junction and package capacitance (C_j)
Amplifier Capacitance (C_a)
Detector load resistance (R_L)
Amplifier input resistance (R_a)

So, from the junction point of view what are the parameters which are responsible for this low response time. Ofcourse, the absorption coefficient which is decided by the material properties; then the depletion region width, the junction and package capacitances, the amplifier capacitance, the detector load resistance and the amplifier input resistance. Now, absorption coefficient is purely decided by the material, which is used for making the detector though practically this thing is not much in control.

Depletion region width, however one can manipulate and as we have seen by increasing the length of the intrinsic layer, essentially the depletion region width is increased. So, you have a better absorption of the photons. So, this quantity can be controlled; can be modified. One can reduce the junction capacitances and amplifier capacitances. So, one can design the circuits appropriately; so that, the capacitances are minimized. And ofcourse, again one can choose proper value of resistances; so that, the R c time constant e can be made as small as possible.

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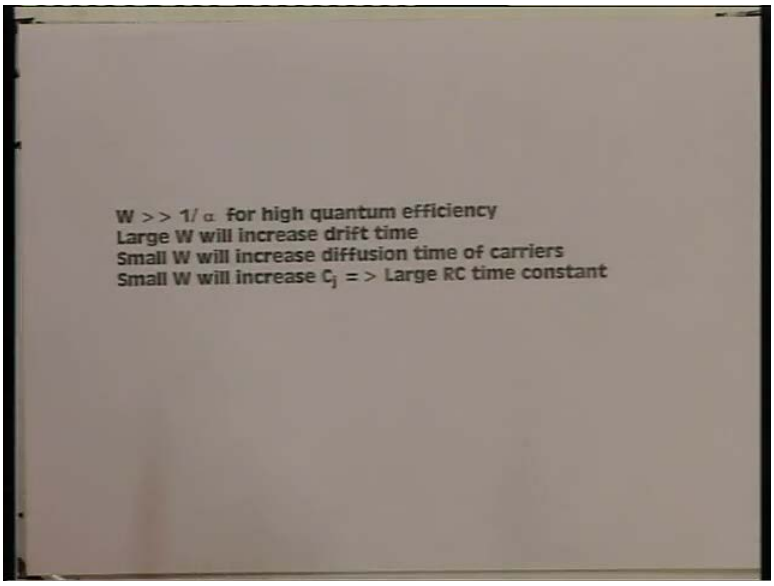

$W >> 1/\alpha$ for high quantum efficiency

Large W will increase drift time

Small W will increase diffusion time of carriers

Small W will increase C_j => Large RC time constant

However from these two point of view, absorption coefficient and the depletion region width, what we want from efficiency point of view that this width should be much much larger compared to 1 over alpha, where 1 over alpha is the effective distance over which the photon flux gets absorbed. So, if the depletion width is much larger compared to this distance, then we will have a better efficiency; because the most of the photons will get absorbed inside the depletion rate. So, for high quantum efficiency, we want that the depletion layer width should be much larger compared to 1 over alpha. However, as you have seen larger the value of this width w will increase the drift time.

And as you have seen the frequency is inversely proportional to the transit time, larger the value of w more will be transit time and lower will be the cut off frequency of your device. Small w however will increase the diffusion time of the carrier. Say you have seen if you reduce the value of w, that there is a substantial number of photons will get absorbed outside the depletion region. And then they have to diffuse to the depletion region first, then they will drift in the presence of the electric field. So, infact choice of w we have contradictory requirements. Larger the value of w will increase the absorption of the photons. So, the efficiency will increase.

But it will also increase the transit time; whereas, smaller value of w will reduce the efficiency at the same time will also increase the diffusion current which we again reduce the cutoff frequency. Also the small value of w will increase the junction capacitance, which will make the large time constant. So, infact these are some contradictory requirement which we have; with which one has to choose the proper value of w or the thickness of the intrinsic layer. So that, we get some optimum cutoff frequency for this device and a width of typically about 2 to 3 times the 1 over alpha, there seems to be some kind of a optimum situation. So, typical intrinsic layer width is about 2 to 3 times 1 over the absorption coefficient inside the material.

So, these are some of the aspects which we have for the photo detectors. That the photo detector essentially converts the light in the photocurrent; but this conversion process is a statistical process and the statistical process gives you the noise. Also when this conversion is taking place, there is a finite delay and also there is a distortion of the signal. So, this conversion of light to the photocurrent essentially introduces some distortion in the in the signals and which affect this performance of the system. So, essentially in the next lecture when we meet, we essentially try to get the expression which you have got for the signal to noise ratio for the photo detector.

And then during the signal to noise ratio expression and assuming that the noise is of additive nature, we try to calculate a parameter what is called the bit error probability. Now, note here that when we talked about this noise, the shot noise is the multiplicative noise. However the analysis for multiplicative noise is rather tedious, also we have seen that a statistics for the shot noise is poisson. So, in the calculation of the bit error ratio what we do? We calculate the contribution of noise with the poisson statistics. We calculate the mean square value of the noise and after that we treat this noise like a additive noise.

We assume that all the noises are independents, we find out what is the total mean square value of the noise. And then under the assumption, that now you have different noises for the 0 level of the data and the 1 level of the data; essentially we derive the expression for the bit error ratio. So, in this detection process now we see the noises which of different types. We see the noise which is poisson and multiplicative. This is when the signal level is 1, that mean last signal is present. When the signal level is 0; that means when the bit is 0 that time, there is no light coming from the optical fiber. But there is ambient light. So, this is again a shot noise; but now this is not depending upon the signal amplitude.

So, you may say this is something like additive phenomena; but the nature is the poisson noise nature. And thirdly, then we consider the noise which is the thermal noise, which is generated outside the device in amplifiers and resistances which has a Gaussian nature. So, we calculate the variance of the thermal noise. We calculate the mean square value of the shot noise and the dark current noise and then you find out what is the total noise present inside the system. We find out what is the power, which is present in the signal and as we have got last time, we will get the signal to noise ratio for the signal and from there, then we try to calculate the bit error ratio.

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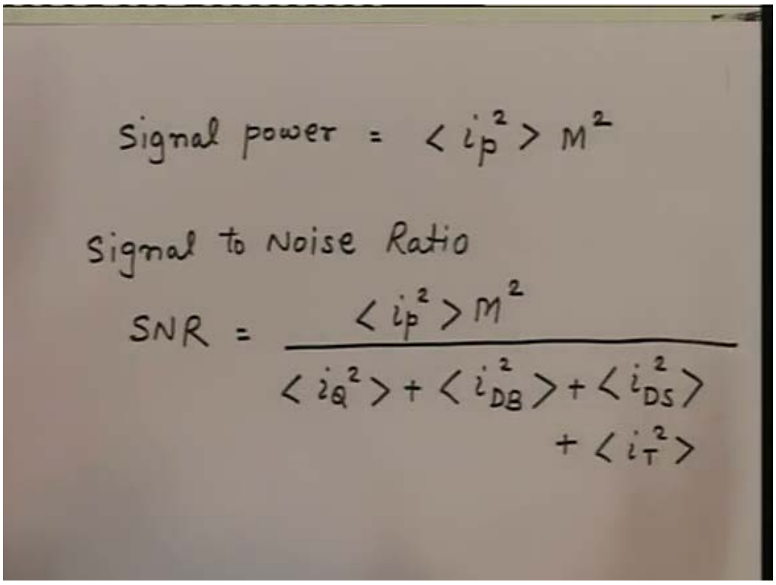

Signal power $= \langle i_p^2 \rangle M^2$

Signal to Noise Ratio

$$SNR = \frac{\langle i_p^2 \rangle M^2}{\langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle + \langle i_T^2 \rangle}$$

So, as we saw last time that the signal to noise ratio will depend upon the power in the signal divided by the mean square value of the quantum noise plus the dark current noise bulk dark current noise plus the surface dark current noise plus the thermal noise, which is in the resistances. Once you get the SNR value, then we can calculate, what are the corresponding bit error ratios? So, in the next lecture essentially, starting from the signal to noise ratio which you have derived here, we will try to get a parameter, what is called the bit error ratio. Also note here the SNR or signal to noise ratio is the parameter, which can be used for both kind of modulations. This parameter can be used for analog modulation. This parameter can be used equivalently for the digital modulation.

However when we talk about digital modulation, the more meaningful parameter is what is called the bit error ratio, which is related to signal to noise ratio. But normally for digital modulation, we do not talk about signal to noise ratio. We have a equivalent parameter which is VER; whereas, for the analog modulation, this parameter signal to noise ratio is the more useful and meaningful quantity. So, we will continue our discussion on this from the detection of light and the receiver performance point of view, and we will derive like then the expression for the bit error ratio for a digital modulation system.