FIBER OPTICS

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Lecture: 20

Photo-Detectors and Detector Noise
When the output light from an optical fiber is incident on the material of a photo-detector, a part of the incident photons get reflected from the material surface due to Fresnel reflection and the other part is absorbed, which, in turn, is used to generate electron-hole pairs in the material. These generated electron hole pairs generate an external circuit current whose magnitude is proportional to the amount of absorbed photons and is known as photo-current. The photo-current generated in a photo-detector circuit due to absorption of photons in the material of a photo-detector upto a depth ‘x’ is given by equation 20.1 below:

\[
\text{Photo – Current, } I_{ph} = \frac{q}{hv} (1 - R)(1 - e^{-\alpha x})P_0
\]  

(20.1)

All the terms in the above equation have the same meanings as they did in equation 19.4 from our earlier discussion. The responsivity of the photo-detector material to the incident light is defined to be the ratio of the photo-current to the total incident optical power onto the material. This quantity is denoted by ‘\( \rho \)’ and is measured in microampere per microwatt. Responsivity can be calculated from the equation 20.1 as:

\[
\text{Responsivity, } \rho = \frac{I_{ph}}{P_0} = \frac{q}{hv} (1 - R)(1 - e^{-\alpha x})
\]  

(20.2)

For a given device, the quantity on the R.H.S. of equation 20.2 is a constant. This fact suggests that the relationship between the total incident optical power and the photo-current is linear in nature. However, one should note that the above equation assumes a material that is 100% efficient, i.e. the number of electron-hole pairs generated is equal to the number of photons absorbed by the material. Yet in practice, such a material never exists. This ushers the need to define some kind of an efficiency factor for the material of the photo-diode which would help us in qualitative comparison of different available materials. Such efficiency is known as the quantum efficiency and is defined as the number of electron-hole pairs generated in a given amount of material to the total number of photons incident onto the material. That is,

\[
\text{Quantum efficiency, } \eta = \frac{\text{Number of electron–hole pairs generated}}{\text{Number of incident photons}}
\]

\[
\Rightarrow \eta = \frac{I_{ph}/q}{P_0/hv}
\]

\[
\Rightarrow \eta = (1 - R)(1 - e^{-\alpha x})
\]  

(20.3)

The quantities in the R.H.S. of equation 20.3 are constant for a given amount of material. The quantum efficiency indicates the portion of the incident photon that is actually responsible for generation of photo-current.
To collect the photo-generated electrons and holes in the material of the photo-detector, an appropriate electric field has to be applied to depletion region of the p-n junction formed in the material. These collected electrons and holes constitute the photo-induced current in the external circuitry of the photo-detector. Needless to say, more the number of generated electron-hole pairs, more the photo-current. However, one should note that the p-n junction in this case has to be reverse biased so that, the current flowing in the external circuit is only due to the photo-generated electrons and holes in the material and not due the forward biasing of the device. The situation discussed here is depicted in the figure 20.1 below:

![Figure 20.1: Reverse biased p-n junction of Photo-detector](image)

The above configuration would, hence, enable us to detect small amounts of photocurrents in the material because in reverse bias the current in the p-n junction is, ideally, zero. But in practice, due to thermal generation of electrons and holes, a very small amount of reverse saturation current flows in the external circuit under reverse bias condition of the p-n junction. So the total current in the external circuit would be the sum of the reverse saturation current and the photo-current generated by the incident photons onto the device.

Although the above configuration looks promising, figure 20.1 is just a schematic representation because, in practice, light cannot be made incident on the depletion region in a practical p-n junction diode. The reason for this assertion is the fabrication technology of the device which does not allow the light to be incident on the depletion region of the device. Figure 20.2 shows practically fabricated p-n junctions:

![Figure 20.2: Structural description of practical diodes](image)

Figure 20.2 shows the possible configurations of the practically manufactured p-n junction diode. From the figure, it is clear that light has to be incident either of the p-type material or on the n-type material. That is, light can, no longer, be considered
to be incident onto the depletion region but has to be considered to be incident onto the p-type or n-type regions. This situation is schematically shown in figure 20.3:

![Figure 20.3: Incident light on practical diodes.](image)

The process of generation of electron-hole pairs begins right from the point of incidence of the photons onto the material and this generation continues along the entire path of absorption of the photon flux till the absorbed energy is no more capable of generating more carriers. In a biased p-n junction, the depletion region is a region of high electric field and its magnitude remains almost constant throughout the region. So the electron-hole pairs that are generated outside the depletion region have to undergo a process of diffusion for a distance \( d \) to reach the depletion region before they can be collected as photo-current in the external circuit by virtue of drift current in the depletion region. The total current in the external circuit is, hence, composed of three currents- reverse saturation current, the drift current in the depletion region and the diffusion current outside the depletion region. Also, since the width of the depletion region is very small in comparison to the width of the non-depletion regions, the contribution of the diffusion current, to the total current, is more than the drift current. However, the process of diffusion is a slow process which causes the device response to be very slow. Thus in order to decrease the response time of the device to incident optical signal, the diffusion current has to be as low as possible i.e. the width \( d \) of the non-depletion region onto which light is incident, should be as narrow as possible so that most of the electron-hole pairs get generated in the depletion region ‘\( D_p \)’ and get directly drifted by the constant electric field present across the depletion region. Also, for generation of a satisfactory amount of drift current, a considerable amount of photons must get absorbed in the depletion region which necessitates the availability of considerable length of the depletion region (about 10-20µm) for the incident photons to get absorbed in the depletion region of the device. The electric field in this region must remain uniform too so that the generated carriers get drifted uniformly over the entire region. For a typical reverse biased p-n junction diode, the width of the depletion region is a function of the bias voltage. This is undesirable for a photo-diode because if the width of the depletion region decreases, the diffusion current would increase causing the device to be slow. Thus in a photo-diode, the depletion region must be a wide, uniform electric field region whose width does not vary as a function of bias voltage and the non-depletion regions (p-type and n-type regions) should be very narrow so that the diffusion current is as low as possible. One must note that the depletion region of a p-n junction is almost like an intrinsic semiconductor region because it is depleted (devoid) of free charge carriers but has a high, uniform electric field across
it. Keeping these facts and requirements in mind, researchers came up with an intuitive structure for the photo-diode which is shown in the circuit (figure 20.4) below:

![PIN photo-diode](image)

**Figure 20.4: PIN photo-diode**

In this new device, an artificial layer of intrinsic material is inserted between the p-type and n-type regions. Hence the name of the device is p-i-n photo-diode. The p-type and the n-type regions are much narrower in comparison to the width of the intrinsic region. This causes the diffusion current to remain low and, hence, enhance the speed of the device. The intrinsic region has a uniform electric field. The generated photo-current passes through the external circuit and the load resistor. The voltage generated across the load resistor is proportional to the current passing through it. This current is proportional to the photo-current. Hence, the output voltage is indirectly proportional to the amount of light incident on the p-i-n diode. The p-i-n diode is (as seen from the circuit above) is basically a photon to current converter which may be replaced by a constant current source in parallel to an ideal diode in its equivalent circuit and hence is a current controlled device. However, the electronic circuits that follow the photo-detector circuit are of the voltage-controlled type. Therefore a load resistor is used in the photo-detector circuit in order to convert the generated current into proportional voltage. In terms of circuit symbols, the above circuit may be represented as:

![Photo-Detector circuit schematic](image)

**Figure 20.5: Photo-Detector circuit schematic**

In order to have a substantial output voltage, the value of \( R_L \) has to be large. However, this increases the output impedance of the photo-detector circuit which
causes erroneous loading effects on the above circuit if it has to be connected to a subsequent circuitry such as an amplifier, etc. Therefore a buffer circuit with high input impedance but low output impedance is always coupled to the above circuit and this combination of the photo-detector and the buffer circuit is then used to connect to subsequent electronic circuitry at the receiver. The net circuit then can be represented as:

![Figure 20.6: Modified Photo-detector circuit](image)

The AC equivalent circuit of the above circuit may be drawn as:

![Figure 20.7: AC equivalent circuit of the photo-detector circuit](image)

'C_j' is the junction capacitance of the reverse biased diode in the circuit and 'R_a' and 'C_a' are the input resistance and capacitances of the subsequent circuitry connected to the photo-detector circuit. Due to the presence of capacitances, the above circuit has an equivalent time constant, which is equal to the product of the equivalent resistance and equivalent capacitance of the circuit. This value is given as:

\[
\text{Time constant, } \tau = (R_L|R_a) \cdot (C_j + C_a) \tag{20.4}
\]

The value of the above time constant for a practical circuit is quite large and this restricts the use of the above circuit only at low frequencies and the above circuit exhibits the frequency response that is identical to that of a low pass filter. To
overcome this hurdle, an ‘equalizer’ circuit is connected to the above circuit and it is the output of the equalizer that is used for further processing. The equalizer, in principle is a high-pass filter and it renders the above circuit useful for a wide range of frequencies.

When the optical output from an optical fiber is incident onto a pin-diode, a very small amount of photo current is generated because of the already small magnitude of photo flux from the optical fiber owing to the loses in it. This current is further reduced by the internal resistances of the photo-detector device itself and we have a very low amplitude electrical signal output as a result of the conversion from the optical to electrical signal. Therefore it is very desirable to have amplification in this output signal. This is done by introducing another heavily doped layer into the p-i-n structure to achieve avalanche break-down of charge carriers thereby giving a large current. The electric field in the heavily doped region far exceeds the break-down voltage and when the photo-generated charge carriers travel through this high-electric-field region, they initiate an avalanche break-down of charge carriers and this results in a high output photo-current from the device. This device is called the avalanche photo-diode. However, to get a high electric field, the applied bias voltages have to be large too so that the avalanche condition can be reached.

The process of generation of electron-hole pairs in a photo-diode is a rather statistical process which has certain amount of probability associated with it. In other words, every photo absorbed by the material giving an electron-hole pair is rather a probabilistic process. Therefore there are fluctuations in the rate of generation of charge carriers in the photo-detector material which lead to variations in the photo-current. Hence the variations in the electrical output signal may be either due to the actual fluctuations in the optical intensity (which is due to the data signal) or due to the probabilistic nature of generation of photo-current (which is undesired). This, in fact, leads to noise in the photo-detection process. To top this, the avalanche process is a statistical process too and due to this more noise is introduced into the photo-detection process. The noise that is introduced into the photo-detection process due to probabilistic nature of photo-current generation is called as quantum or shot noise.

Noise power in a signal is measured by its mean square value. Hence the mean square value of the variations in the photo-current is a measure of the amount of the noise in it. This value is given by the following relation:

\[
\langle i_q^2 \rangle = 2q \cdot I_p \cdot B \cdot M^2 \cdot F(M)
\]  

(20.5)

Where,

\(i_q\) = Mean value of photo-current variations; \(q\) = Charge of an electron; \(I_p\) = average value of photo-current; \(B\) = bandwidth of the device; \(M\) = avalanche gain factor; \(F(M)\) = noise figure of avalanche detector.
The above equation suggests that the quantum noise in the photo detector is proportional to the average photo-current in the photo-detector. This is due to the fact that the statistical processes of photon flux fluctuations, the electron-hole pair generation and the avalanche generation are indeed Poisson’s processes involving Poisson’s statistics. The noise is also proportional to the bandwidth of the device which means, more the bandwidth, more is the noise introduced. The presence of the noise figure, $F(M)$ of the avalanche photo-detector, in the above expression suggests that the avalanche process not only amplifies the photo-carrier magnitude but also introduces some amount of noise. The amount of noise introduced is determined by $F(M)$ which is a function of the avalanche amplification factor ‘M’ and if no noise is introduced by the avalanche detector then $F(M)=1$.

The second type of noise present in the photo-detector output signal is the dark current noise. The term ‘dark’, here, represents the absence of the actual (desired) optical signal from the output of the optical fiber. When a photo-detector is used in practice, even in the absence of optical signal, there is some amount of current flowing in the circuit due to the photo-excitation by ambient light and thermal excitation in the material. This current is called the dark current and the associated noise is known as the dark-current noise. Perfectly dark environment and absolute zero temperature is not possible under operating conditions and so the above noise, however small, is always persistent in the output signal of the photo-detector. There may be two different types of dark currents based on the nature in which they flow through the photo-detector material. If the charge carriers of the dark current flow through the bulk of the material then the current is referred to as bulk dark current. On the other hand, if the current flows along the surface of the material then it may be referred to as surface dark current. On account of the different nature of flow, the two currents respond differently when they travel through the avalanche breakdown region of the detector. The surface dark current cannot initiate an avalanche breakdown and so it is not multiplicative in nature, but bulk dark current can initiate avalanche process and so is multiplicative in nature. That is why, we obtain two different expressions for dark-current noise one of which signifies bulk current ($i_{DB}$) and the other signifies surface current ($i_{DS}$). The two expressions for the mean square values of the variations in the two currents are given below:

$$\langle i_{DB}^2 \rangle = 2q \cdot i_B \cdot B \cdot M^2 \cdot F(M)$$  \hspace{1cm} (20.6)

$$\langle i_{DS}^2 \rangle = 2q \cdot i_S \cdot B$$  \hspace{1cm} (20.7)

In the above equation, ‘$i_B$’ and ‘$i_S$’ are the average values of the bulk and the surface dark current variations respectively. The reader should note that the avalanche gain terms are absent in the expression for the surface dark-current noise because the surface dark-current does not stimulate an avalanche breakdown and hence is not multiplied by the avalanche gain factor and also there is no avalanche noise introduced by this current such that $F(M)=1$. One should also note the fact that
dark-current noises are present even when the material is illuminated by desired optical signal. So the total noise in the output signal from the photo-detector thus consists of noises due to two main types of currents- photo-current and dark-current.

The third type of noise exhibited in the photo-detector circuit is the thermal noise which is produced when the noisy output current from the photo-detector material passes through the external circuit and the load resistance and causes random motion of electrons in the resistances. The amount of thermal noise can be determined from the following expression:

\[ \langle i_T^2 \rangle = \frac{4KTB}{R_L} \] (20.8)

In the above expression \( K \) and \( T \) are the Boltzmann’s constant and the absolute temperature of the resistance respectively. From the above expression it is instantly clear that unlike the other two types of noises, this noise is does not vary with any quantity but bandwidth. Thus for a photo-detector with a constant bandwidth, thermal noise introduced into the output electrical signal from the photo-detector is almost constant. As such, thermal noise, unlike the other noises is not multiplicative in nature but is additive in nature.

All of the above mentioned types of noise are independent and the total noise may be expressed as a sum of all of the above noises. If we assume \( i_p \) to be optical signal current, then the expressions 20.5-20.8 can be used to obtain an expression for the signal-to-noise ratio (SNR) of the photo-detector which may be given as:

\[ SNR = \frac{(i_p^2)M^2}{i_q^2 + i_DB^2 + i_{DS}^2 + i_T^2} \] (20.9)

SNR of a communication system is a very important quantity which helps as an evaluating factor for different types of communication systems and also serves as a performance evaluation parameter for an existing communication system. A system with a higher value of SNR is always preferred.