LASER Noise &
Introduction to Photo-Detectors
One of the main characteristics that enable us to ensure the quality of a communication system is its noise performance and one such related quantity is the signal-to-noise ratio (SNR) of the system. There are various sources of noise in a communication system. One such source of noise may be the modulator circuit itself. The noise generated by a system circuitry known as internal noise. Noise affects higher frequencies more than the lower frequencies. That is why it very important to study the noise performance of the LASER diode since it operates at comparatively high frequencies.

The optical output from a LASER diode is not constant at a particular level but has fluctuations in the light intensity levels. These fluctuations manifest themselves as noise in the transmission and are carried to the receiver end too. There are various sources of generation of noise in a LASER diode. These are discussed below.

Reflection Noise: This type of noise introduced into the LASER diode output due to the Fresnel reflections of the output light of the LASER diode at the tip of the optical fiber. Fresnel reflection is the phenomenon of reflection of a portion of light incident on a planar interface between two homogeneous media having different refractive indices. It is independent of the angle of incidence of light. When the output of the LASER diode is perfectly aligned to the perfectly flat tip of the optical fiber, part of the light energy is reflected back into the LASER diode and the phase of this reflected light depends on the relative separation between the LASER diode output and the tip of the optical fiber. Due to variation in mechanical vibrations or environmental factors the relative distance between the LASER diode output end and the optical fiber may vary and so does the phase of the reflected signal from the fiber tip. These variations in the phase of the reflected signal produce vibrations in the output of the LASER diode causing noise in the transmitted signal. This type of noise is, hence, the reflection noise.

Mode Partition Noise: In principle, although the output photonic flux emitted from the LASER has a precise wavelength that satisfies both the gain and the phase condition to get amplified between the two reflecting regions of the LASER, yet in practice, the output of a LASER has a finite spectral width. The spectral distribution of the LASER (as already shown) is given by the following figure 19.1.

![Figure 19.1: Spectral Distribution of Fabry-Perot cavity](image-url)
However, one should note that the above spectral characteristic is actually an average power representation with respect to time. In other words, although the total power in the output may be constant with time, yet the power level of the different wavelength components in the output of the LASER does not remain the same all the time. The power level of the different wavelength components in the LASER output vary as a function of time (the total power remaining the same) and only when they are averaged over a time interval, the spectral distribution of the LASER output looks like figure 19.1. These variations in the power levels of the different wavelength components of the output spectrum, cause different wavelengths to have the maximum power level at different instants of time. This leads to generation of noise in the transmission and is known as the mode partition noise.

**Speckle Noise:** The different frequency components in the optical output of the LASER diode move with different velocities inside the optical fiber due to dispersion phenomenon. This causes the output of the optical fiber at the receiving end to contain several small bright and dark regions called speckles of light. These speckles are shown in the figure 19.2 below which shows the optical fiber output at the receiving end of the optical fiber.

These speckles are produced by the constructive and destructive interferences of the fields of different frequency components in the optical signal as they travel along the optical fiber. The pattern of the bright and dark regions produced at the output side of the optical fiber is called the speckle pattern. Speckle patterns are characteristic to any coherent light. Since the total power in the cross-section of the fiber core is constant, the speckle pattern is rather a redistribution of power over the cross-section of the optical fiber core. However, due to temperature variations, the different wavelength components in the optical signal undergo different phase changes with respect to time and so; the speckle pattern slowly varies with respect to time. This effect coupled with the non-uniform power detection capability of the photo-detector over its entire cross-section creates fluctuations in
the output signal produced at the receiver. This is because, due to variation in the speckle pattern with respect to time, the once dark region now gets converted into a bright region and vice versa. So, the detector output varies accordingly since it has non-uniform power acceptance over the cross-section of the detector and thus noise creeps in. This noise is called the speckle noise.

Along with the above three practical sources of noise, the relaxation oscillations produced at the receiver output also contributes to introducing some noise into the optical transmission.

If we now make a comparative study between the two main available optical sources viz. LED and LASER, we may consider the following important aspects as given in the following table:

<table>
<thead>
<tr>
<th>LED</th>
<th>LASER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>Very expensive</td>
</tr>
<tr>
<td>Low output optical power</td>
<td>High output optical power</td>
</tr>
<tr>
<td>Poor power launching efficiency</td>
<td>Very efficient in power launching</td>
</tr>
<tr>
<td>Large spectral widths (70-100 nm)</td>
<td>Low spectral widths (2-3 nm)</td>
</tr>
<tr>
<td>Useful for short distance communication</td>
<td>Useful for long distance high speed</td>
</tr>
<tr>
<td>Due to incoherent output light, it is useful for intensity modulation only</td>
<td>Due to coherent and switching nature of optical output, it can be subjected to ASK, FSK, PSK. Also useful in non-linear optics.</td>
</tr>
</tbody>
</table>

Table 19.1: Comparative study between LED and LASER

Although the advancements in the optical source manufacturing technology has led to the development of very narrow spectral width sources having spectral widths of about 2-3 nm, yet these spectral widths are still large in view of the lengths of the optical communication links that have to be established. These distances may be of the order of few thousands of kilometres. So an optical source with even narrower spectral width is highly desirable. This can be done by filtering out the multiple frequencies that get amplified in the feed-back mechanism of the LASER and allowing only very few selected frequencies to get amplified. Such a mechanism can be developed by utilizing the mode-coupling phenomenon in an optical fiber. In this phenomenon, if the beat-length (already discussed earlier during birefringence) of the optical fiber matches with the distance between two successive perturbations, only then the two oppositely flowing degenerate modes couple strongly with each other. In order to achieve such a coupling inside a LASER diode, we need to redesign the mirror type feed-back, which in fact is a lumped-type feed-back, into a distributed type feedback which lies all along the length of the Fabry-Perot cavity. This means that the feedback takes place at every point along the cavity and are so adjusted that the modes of only particular wavelengths get coupled and are amplified.
and the other wavelengths are not. These types of LASERs are called as Distributed Feed-Back (DFB) LASERs. This is a very newly developed type of LASER which has a very narrow spectral width in comparison to its older counterpart.

A DFB LASER has a structure which perturbations created into it at intervals that match with the beat length corresponding only to that particular frequency which needs to be amplified. If the distance between two successive perturbations in the DFB LASER be ‘d’ and the phase constant of the oppositely moving modes between these two perturbations be ‘β’, then the following condition needs to satisfied by the modes in order to get coupled and amplified:

\[ 2\beta = \frac{2\pi}{d} \]  

(19.1)

So only those particular wavelengths that satisfy the above condition get strongly coupled to each other and are amplified inside the Fabry-Perot cavity and the spectral distribution of the LASER as shown in figure 19.1 now consists of very few wavelength components as shown in the figure 19.2 below:

![Figure 19.2: Spectrum of DFB LASER output](image)

Thus the DFB spectrum looks much more clean and precise with very narrow spectral width output as compared to the normal LASER diode output spectrum. Such a precise optical output wavelength source makes the amplitude modulation possible too, which was not possible earlier due to the wide spectral width of the source which would have made the side-bands indistinct. The side-bands of the modulated signal with the above output as a carrier signal would be clearly visible. With such a precise and narrow optical carrier signal, every sophisticated modulation and demodulation scheme is, hence applicable for data transmission because the spectrum of the carrier signal and as a result the spectrum of the modulated signal would be clearly visible, thereby enabling us to have information in both time and wavelength domains. So, the DFB LASER has brought about a revolution in the existing optical communication technologies.
OPTICAL DETECTORS (PHOTO-DETECTORS)

Optical detectors or photo-detectors are devices that perform the exact opposite function to that of an optical source i.e. they receive the optical signal available to them from the output end of the optical fiber and convert it to electrical signal. An optical detector may be hence termed as an optical transducer. In similarity with our discussion on optical sources, we shall first see the necessary characteristics that need to be possessed in order to qualify as a good optical detector.

1) Like any other transducer, photo-detectors must possess high sensitivity. Optical power output from an optical fiber usually ranges in the order of microwatts. Hence, the detector must be able to detect even such tiny amounts of power.

2) The photo-detector should have a fast response in order to have a faithful reproduction of the transmitted signal on the received side. In other words, the response time of the detector even to the slightest variation in the output optical signal characteristic must be very low.

3) In contrast to optical sources, optical detectors must have wide response bandwidth. This is because, unlike the transmitter there are no such stringent requirements of narrow spectral width to be met optical detectors and also, a wideband detector enables the same detector to be used from different transmission wavelengths.

4) The optical detector must be immune to different environmental factors such as temperature, pressure etc.

5) The internal noise generated by the detector should be as low as possible.

6) Needless to say, the detector must be compatible with the fiber dimensions.

7) The device should be cost effective.

8) The optical detector should be durable i.e. it should have long operating life.

Similar to the availability of various types of optical sources, there are many photo-sensitive devices that satisfy one or the other requirements mentioned above such as photo-multiplier, photo-conductors, LDRs etc. However, semiconductor based photo-detectors known as photo-diodes serve as more effectively than any other type of detector.

As the name suggests, the photo-diode is in fact a p-n junction put to the exact opposite use as the LED. In this device light is made incident onto the device and used for generation of electron-hole pairs at the junction thereby varying the current. The variation in current is a function of the incident light. It is, however, interesting to note that the same p-n junction used for photo-generation, can also be used for photo-detection. Different materials have different photo-responsive properties both- quantitatively and qualitatively. The photo-responsivities of different materials that can be used as material for photo-diodes are given in figure 19.3 below.
Figure 19.3: Photo-diode responsivities

In the photo-diode we make use of the stimulated absorption of light by the semiconductor material for the generation of electron-hole pairs. The energy of the absorbed photons is used to transfer the electrons from the ground to the excited state where they contribute to the variation in circuit current. The energy of the absorbed photon must at least be equal to the band-gap of the material for the material to respond to the incoming photons. That is why, in the above figure we see that, Silicon cannot be used as a material beyond wavelengths of about 1µm because those wavelengths correspond to energies less than the forbidden band. But the modern day optical communications (as already discussed) occur between wavelengths of 1.3 to 1.55µm. The semiconductor materials responsive at these wavelengths are germanium (Ge), Indium Gallium Arsenide (InGaAs), etc. as shown in the above figure. However, one should also note the fact that for the purpose of detection the direct band-gap nature of the material is not necessary. From the above figure, it can be easily seen that InGaAs is more preferable to Ge, not only because of its high responsivity but also due to the wideband nature of the material near the desired region of operation so that the same detector can be used for multiple wavelengths of operations in the future.

Having chosen a suitable material for designing the optical detector, let us now see into the absorption process of the incident photon in a detailed manner. For doing so, let us assume an output photon flux of power \( P_0 \) be incident onto the material of the detector. The situation is depicted in the following figure 19.4.

Figure 19.4: Light incident on the photo-detector material
As the incident light enters the material, the optical power decreases exponentially due to absorption. In the above figure, ‘R’ is the reflection coefficient of the material boundary against Fresnel reflection and ‘α’ is the attenuation constant of the material to the photonic flux. The total optical power absorbed up to any point is given by the difference between the initial incident optical power ‘P_0’ and the existing optical power at that point. That is,

\[ \text{Optical Power absorbed} = (1 - R)(1 - e^{-\alpha x})P_0 \]  \hspace{1cm} (19.2)

If the above expression is divided by the energy of a single photon, the resultant expression would give the total number of photons absorbed per second by the material. That is,

\[ \text{Number of absorbed photons per second} = \frac{(1 - R)(1 - e^{-\alpha x})P_0}{E_{\text{ph}}} \]  \hspace{1cm} (19.3)

If we assume the material to be 100% efficient (just for investigation sake) i.e. if each absorbed photon produces an electron, equation 19.3 would give the number of electrons produced in 1 second. So, if we multiply equation 19.3 by the charge of one electron ‘q’, we would get an equivalent current which is the current generated by the incident photons known as the photo-current ‘I_{\text{ph}}’. That is,

\[ \text{Photo - Current} I_{\text{ph}} = \frac{q}{h \nu} (1 - R)(1 - e^{-\alpha x})P_0 \]  \hspace{1cm} (19.4)

In the above expression ‘hν’ is the energy of an incident photon and ‘h’ is the Planck’s constant. The ratio of the photo-current (I_{ph}) to the power of the incident photons (P_0) is defined as the responsivity of the material of the detector. Responsivity is denoted by ‘ρ’ and is measured in microampere per microwatt (µA/µW). Although the unit effectively seems to be Ampere/watt, yet we do express it as µA/µW, because the photo-currents and the optical power levels that we deal with in practice are very small and are expressed in the micro-scale. If the material is not 100% efficient (as assumed above), the responsivity of the material is given by ‘ηρ’ where ‘η’ is the efficiency factor of the material. That is,

\[ \text{Responsivity}, \rho = \frac{I_{\text{ph}}}{P_0} = \eta \frac{q}{h \nu} (1 - R)(1 - e^{-\alpha x}) \]  \hspace{1cm} (19.5)

Responsivity is a characteristic property of the photo-detector material and it increases inwards into the material. The generated electrons and holes are then collected in the device in the form of external circuit current. Thus if the nature of the relationship between the photo-current and the incident photonic flux power is accurately known, then based on the variation in the photo-current the incoming signal can be appropriately reproduced at the receiver end of the optical communication system.