Lecture: 10

Analysis of Signal Distortion in Optical Fiber
Material absorption and Scattering losses in an optical fiber are present in the optical fiber even before it is used for any application because these two losses are as result of the intrinsic materiality of glass. But along with these two, two other sources of loss also get illuminated once the fiber is laid as cables for communication purposes. These are the micro-bending and macro-bending losses. Micro-bending loss occurs due to deformation of the fiber in a micro scale and is already discussed earlier. In this section we discuss the macro-bending loss in detail.

When an optical fiber is subjected to a gentle bend over a large arch, light energy in the fiber starts to leak out of the optical fiber. This phenomenon is known as the macro-bending loss or the radiation loss in an optical fiber. When an optical fiber is laid, theoretically it must be laid in a perfectly straight line and any deformation in the form of micro or macro bends must be avoided. But in practice, fibers get deformed when laid into the system due to variety of reasons. In a straight fiber, the wave-fronts of the light energy propagating inside the fiber are parallel to each other and normal to the direction of propagation as shown in the figure below.

![Figure 10.1: Perfectly Straight Optical Fiber](image)

In this figure, every point on a particular wave-front moves with equal velocity and hence the overall mode propagates forward through the optical fiber. But when the optical fiber is gently bent over a large arch, the situations change drastically. This change in situation can be better understood with the help of the following figure (figure 10.2).

![Figure 10.2: Gently bent Optical Fiber](image)

In this case, the wave-fronts are no more parallel to each other and as a result, different points on a particular wave-front require different velocities to keep
up with the forward propagating mode. These velocities go on increasing as we move outwards along a particular wave-front (say from A to B). This increase very soon requires the velocity to increase beyond the intrinsic velocity of light in the medium. But this cannot happen and so these points in the wave-front are left behind and are detached from the propagating mode. It is this detached light energy is radiated out of the fiber causing loss of total light energy. This effect increases if the bend is sharper, i.e. if the radius of the bend decreases because, the requirement of a greater velocity then would occur at a point much earlier along the wave-front. Thus, no matter how large the radius of the bend is, there would always be some leakage of light energy from the optical fiber. In the following figure, the area of the curve in the shaded region is lost due to radiation.

![Phase Fronts for a Bent Fiber](image)

**Figure 10.3:** Radiated power on a bent optical fiber.

In the above figure, $x_c$ is distance from the axis of the fiber at which the velocity of the point on the wave-front requires to exceed the intrinsic velocity of light in the medium. If the radius of the bend decreases, $x_c$ decreases and more energy would be lost due to radiation because more area would come under the shaded region. So for zero radiation loss, the radius of curvature of the bend should be infinity, i.e. the fiber should be perfectly straight. If the fields of a particular mode are spread much more in the cladding, the radiation loss for that mode is also higher. From our earlier discussion on modal analysis, we find that higher order modes have much of their fields spread in the cladding. Therefore, for a given bend, higher order modes have higher radiation loss.

If we now perform some rigorous mathematical analysis, we find that the radiation loss in an optical fiber is a strong function of the radius of curvature of the bend. That means, sharper the bend more is the radiation loss. That is why, while laying optical fibers, one should be careful of not allowing any sharp bends or loops...
to be developed in the laid fibers in order to avoid radiation loss. Radiation loss also illuminates a very interesting notion about an optical fiber. If a fiber is laid perfectly straight, there would be no energy leaking from the fiber and so, just by externally looking at the fiber one would not be able to ascertain whether the fiber is illuminated or not. Presence of light inside the fiber can be ascertained by gently bending the optical fiber which would cause a leakage of light from the optical fiber due to radiation loss thereby confirming the presence of light in the optical fiber. This ease with which light can be made to leak out of optical fiber renders the optical fiber the vulnerability to tapping of optical signal by an external source. This causes a reduction in the signal security. But in practical optical fibers, this danger is averted by providing opaque sheaths over bare optical fibers which do not allow any radiated light to be tapped. This causes great difficulty in information tapping and hence provides great signal security.

Considering all the sources of signal distortion together, the optical fiber when laid into a system, gives a loss figure which is much higher than that which is due to the intrinsic nature of glass. If we now recall our discussion on the dispersion aspect of signal distortion in an optical fiber, we found that the material dispersion of glass cannot be manipulated but the waveguide dispersion can be manipulated as per our requirement by varying the different fiber parameters accordingly. Thus the total dispersion in an optical fiber, which is a combination of the material and the waveguide dispersions, can now be altered by altering the fiber parameters as per requirement. This illuminates a very interesting observation that, at operating wavelengths of about 1310nm the dispersion is almost zero whereas the loss figure is high, but at operating wavelengths of about 1550nm the dispersion is higher whereas the loss is lower. Hence we now have two operating options available with us to choose from. Either we choose to operate at high data rates with higher loss at 1310nm or we choose to operate at lower data rates at lower loss at 1550nm. But the characteristic of a good communication system requires a system that has both low loss as well as a large bandwidth. In our case we find that we can only have either large bandwidth with higher loss or smaller bandwidth with lower loss. However, the advancements in technology have made it possible to manipulate the total dispersion in an optical fiber in such a way that we no longer are in dilemma. So, by altering the different fiber parameters such as the refractive index profile, fiber radius, etc. we can actually manipulate the dispersion profile of the optical fiber. This flexibility induces an interrogation in the mind as to whether the zero dispersion point at 1310nm could be shifted to 1550nm. The reason behind this shifting is the low loss characteristics of the optical fiber at 1550nm coupled with the availability of a large bandwidth. The fiber manufacture technology now helps us in precise desing of optical fibers as per requirements and using such sophisticated technology the zero dispersion point has been shifted to almost 1550nm. These new type of optical fibers are hence called dispersion-shifted (DS) optical fibers. The dispersion profile of these fibers is shown in the figure 10.4 below. The figure shows the initial 1310nm optimized optical fiber and also the dispersion shifted optical fiber dispersion profile.
The above figure clearly shows how the dispersion profile of a single mode optical fiber has been shifted so as to shift the zero dispersion point from 1310nm to about 1550nm. This is done by favourably manipulating the refractive index profile and size of the fiber so as to change the waveguide dispersion profile so that the total dispersion profile, which actually is the sum of the material and the waveguide dispersion shifts altogether. This is the kind of optical fiber that is used in the modern optical communication system because this fiber gives both the advantages of a large bandwidth as well as low loss.

By the time these advancements in the fiber optic communication technology were brought to practice, the LASER technology as well as the optical fiber technology improved significantly. The developments in fiber manufacture technology helped the manufacturers to completely remove the OH$^{\text{+}}$ absorption peak that existed between the 2nd and 3rd windows of communication so that now we had a large band of low-loss operating wavelengths from about 1300nm to 1600nm. Since we are aware that 1nm width is equivalent to about 100GHz, the operating bandwidth now available is of the order of 300GHz. The advancements in the LASER technology made it possible that LASERs of any arbitrary wavelength in the above band could now be manufactured and hence sources are available too. The question now which comes to the mind is that can the dispersion profile of the fiber be manipulated in such a way that the optical fiber had very low dispersion over the entire band of operating wavelengths mentioned above? Precisely, that is what the engineers persevered and successfully manipulated the dispersion profile and obtained a profile as shown in the above figure 10.4. This new dispersion profile was termed as Dispersion-Flattened profile and the optical fibers manufactured with this
profile came to be known as dispersion flattened (DF) optical fibers. Due to the flattened dispersion profile of this new type of optical fiber, the fiber is compatible with all the existing 1300nm systems, the 1550nm systems and also with any system that uses any arbitrary operating wavelength from the entire band of operating wavelengths. So, we have finally arrived at the true wideband medium of communication that we were initially talking of. This medium has both low loss and large bandwidth over its entire operating range.

With the advancements in the fiber manufacturing technology, now we can create very accurate and complex refractive index profiles within the core. One should not here that we are talking of a single mode fiber core whose diameter is about 6-8microns. Within such a tiny diameter, the technology allows us to create very accurate and desired refractive index profiles to achieve the desired dispersion characteristics. The figure 10.5 below shows just a representation to indicate the complicacy of the refractive index profiles.

![Figure 10.5: Core Index Profiles of old and new Single Mode Optical Fibers](image)

In the optical systems used today we find wide use all the three types of fibers depending on the distances, bandwidths and the number of channels in the communication. A basic query that arises regarding these new types of fibers is that how to characterize these fibers? Earlier single mode fibers could be characterized in terms of V-number because we had two distinct regions of core and cladding. But in DS and DF fiber profiles, we find that the core itself is composed of multiply cladded complicated type structure which is evident from the figure 10.5. The V-number cannot be used to characterize these new types of optical fibers. So, this creates a necessity to define a new parameter to characterize the optical fibers.

![Figure 10.6: Field representation in SM optical fiber.](image)
Although the fiber index profile is modified in a very complicated manner, yet it is still a single mode optical fiber. A single mode optical fiber supports only one mode which is the LP$_{01}$ mode. LP$_{01}$ mode has a field distribution which has a maximum intensity at the axis of the fiber and the fields die down gradually as we move towards the periphery of the fiber core. A crude representation of this field behaviour is shown in the figure 10.6 above. The V-number of an optical fiber is very near to 2.4. One can now show that the field distribution shown in the figure 10.6 can be very closely approximated by a Gaussian distribution. The error in this approximation is very small. So the fields inside a single mode optical fiber follow a Gaussian distribution with a maximum at the axis of the optical fiber. This variation of the field is shown in figure 10.7 above. The radial distance at which the field magnitude reduces to about $e^{-1}$ times its maximum value is the effective radial distance upto which the field extends. In terms of power, the radial distance at which the power dies down to about $e^{-2}$ times the value at the axis of the fiber is the effective portion upto which the field of the mode extends. The diameter of this region is called the mode-field diameter of the optical fiber. So, for a complicated refractive index profiled single mode fiber, the mode field diameter is a more appropriate characteristic parameter than the V-number because V-number for such a fiber cannot be defined due to the complicated refractive index profile of the core. Just like the V-number in a simple single mode fiber, the mode field diameter also indicated the field distribution in the fiber. Mode field diameter of a fiber is important parameter, especially when we have to couple light from one fiber to another fiber which has different refractive index profile and also difference in other characteristics. But one can show that if the two fibers have equal mode field diameters, there is a very efficient optical coupling of light from one to the other and the two fibers are compatible with each other. So in making a joint of two fibers which may have different parameters, we simply enquire about one parameter and it is the mode field diameter of the two fibers. If this parameter is equal, then irrespective of all other differences in the parameters, an
efficient joint between these fibers can be made. In case if the mode field diameters are not equal, the joint would be lossy and this loss is given by:

$$\text{Loss in dB} = 20 \log_{10} \left[ \frac{2}{\left(\frac{\text{MFD}_1}{\text{MFD}_2}\right)^2 + \left(\frac{\text{MFD}_2}{\text{MFD}_1}\right)^2} \right] \quad (10.1)$$

MFD$_1$ and MFD$_2$ are the mode field diameters of the two fibers. If MFD$_1$=MFD$_2$, then this loss reduces to zero.

Along with the mode field diameter there are various other parameters that are used to characterize an optical fiber completely when it is laid into the system. One such important parameter is the ‘birefringence’ of an optical fiber. Any general linear polarization inside an optical fiber may be decomposed into horizontal and vertical components as shown in the figure 10.8 below. If the core of the optical fiber is perfectly circular, both of these orthogonal polarization components propagate through the fiber with the same phase constant and have equal phase velocities along the optical fiber so that at the output the linear polarization of the input light remains intact. But in practical fiber manufacturing processes, due to some errors, the manufactured fiber core sometimes has an elliptic nature. Due to this ellipticity, both the orthogonal polarization components, now, have different effective modal indices and propagate with different phase constants. So there is a net phase change between these two components which result in the initial linear polarization to turn elliptical. If we assume ‘n$_x$’ and ‘n$_y$’ be the effective modal refractive indices for the horizontal and vertical modes respectively, then the birefringence is defined as:

$$\text{Birefringence} = \beta_0 |(n_x - n_y)| \quad (10.2)$$

If the resultant phase-difference is 90° the polarization turns circular and for all other non-zero phase-differences the polarization would be elliptical. So, birefringence actually indicates the relative phase change that may occur in the optical fiber when used in the system. Birefringence causes the two orthogonal polarizations to travel with different phase velocities thereby creating a resultant
dispersion in the optical fiber. If we now observe the continuous changes in polarizations as the signal propagates through the fiber, we would see the following:

Figure 10.9: Change in polarization due to birefringence and beat length

As the figure shows, there is a cyclic change from linear to elliptical and back to linear but with different orientation. The length of the fiber at which this cycle completes is called the beat length of the fiber. Different fibers may have different beat lengths due to different birefringence values. The beat length of the optical fiber is given by:

\[ \text{Beat Length} = \frac{2\pi}{\beta_0 (n_x - n_y)} \]  

(10.4)

If we now talk in terms of group velocity, there is some kind of a birefringence in group velocity too. Due to this, the two orthogonal polarizations in the pulse separate out and results in a dispersion called as the polarization mode dispersion. Polarization mode dispersion is shown in the figure 10.10 below. The two separated polarizations are shown in the figure.
Pulses reach the output in different time intervals as shown in the figure (Δt) which causes the dispersion in the optical fiber. Also, the state of polarization of the output signal is different from the input signal. Polarization mode dispersion is a statistical quantity, i.e. there exists no definite pattern of dispersion inside the optical fiber. In fact, polarization mode dispersion is now becoming a bottleneck in high-speed optical communication because, at high data rates, this dispersion cannot be neglected. In normal systems, this dispersion has negligible effects on the communication, but at high speeds it causes a considerable dispersion leading to errors in communication.

Another important characteristic parameter of a practical optical fiber is the cut-off wavelength (λc). For an optical fiber to be a single mode optical fiber, the V-number of the fiber should be such that only one mode, the LP_{01} mode propagates through the optical fiber. Ideally, the V-number should be as away as possible from the cut-off V-number of the next higher mode, the LP_{11} mode, because if the V-number of the fiber is very close to this cut-off value, then even a slight imperfection in the fiber structure may result in the LP_{11} mode to get excited too and this would then lead to dispersion. So, the cut-off wavelength may be defined as the wavelength at which the next higher mode just starts getting excited.

To measure the cut-off wavelength quantitatively, certain standards have been laid down to ease the trouble of the designer. These standards are as follows:

Consider a practical optical fiber of about 2m in length and excite this fiber with a tuneable LASER source. A tuneable laser source is one which can be made to emit light of any arbitrary wavelength from a continuous band of wavelengths. This tuneable LASER should be such that it can excite both the LP_{01} and the LP_{11} modes in equal proportions. Lay the optical fiber in such a way that it forms a loop of about 3cm in diameter along its length. This set-up is shown in the figure 10.11 below.

![Figure 10.11: Experimental set-up for cut-off wavelength measurement](image)

The tuneable LASER source is capable of exciting both LP_{01} and LP_{11} modes in equal proportions. Using this LASER source a light of small wavelength is launched into the optical fiber and the output power corresponding to the LP_{01} + LP_{11} modes is measured using a photo-detector at the output side. When the wavelength is much smaller than the cut-off wavelength, then both, the first mode LP_{01} and the
next higher order $LP_{11}$ get excited in the fiber and both are far from cut-off. So both the modes are well guided and there is not much loss in the fiber. If we now increase the wavelength of operation, gradually the fields corresponding to $LP_{11}$ would start to lie more in the cladding and the radiation loss for it would, hence, increase at the loop, thereby giving a loss at the photo-detector. As the wavelength increases, the higher order $LP_{11}$ mode approaches cut-off and its energy spreads in the cladding. Due to radiation loss at the loop, this mode loses power and so, the power which reaches to the output is only the power with the first mode. The output then shows a higher loss. As the wavelength is increased further, the higher order mode does not get excited at all and the whole power is launched in the first mode which propagates without much loss. The loss on the fiber again reduces with the wavelength. The wavelength, at which the loss reduces to 0.2 dB, is called the cut-off wavelength of the fiber. If we plot a curve of the loss at the photo-detector as a function of the wavelength, we would get a curve as shown in the figure 10.12 below.

![Figure 10.12: Cut-Off wavelength measurement from loss curve.](image)

Cut-off wavelength is not as crucial parameter as the attenuation or dispersion. However its knowledge is useful in deciding the wavelength range of operation. If we take a typical 1310nm optical fiber, the cut-off wavelength lies about 20-30nm away from the wavelength of operation.

The above discussion, thus, explains the basic characteristic parameters of an optical fiber which help one to characterize different optical fiber on the basis of its utility to the particular desired application. A fiber manufacturer always specifies these parameters so that the designer can choose the appropriate optical fiber suitable for the application.