The distortion of optical signal in an optical fiber is a very important issue for analysis. This distortion to the optical signals may come from mainly two sources - dispersion and attenuation. Dispersion and attenuation may result due to a variety of factors such as the material properties, modal propagation of light, etc. But the dispersion inside an optical fiber is a weak phenomenon and so, the different types of dispersion can be separately analysed. The discussion on the issue of material dispersion led us to the an expression which showed that material dispersion is directly proportional to the wavelength as well as to the second derivative of the refractive index function. This expression for the material dispersion is given below:

\[ D_{\text{material}} = -\frac{\lambda}{c} \frac{d^2 n(\lambda)}{d\lambda^2} \]  \hspace{1cm} (9.1)

We had also seen the experimentally plotted \( n(\lambda) \) graph, which showed a change of curvature at around 1270nm wavelength. At this wavelength of operation the material dispersion becomes almost zero. The different windows of optical communication and there corresponding material dispersions are tabulated below:

<table>
<thead>
<tr>
<th>Wavelength (( \lambda )) (nm)</th>
<th>( D_{\text{material}} ) (ps/Km/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>85</td>
</tr>
<tr>
<td>1310</td>
<td>0.1</td>
</tr>
<tr>
<td>1550</td>
<td>-20</td>
</tr>
</tbody>
</table>

In the above table we see that, for wavelength of about 1550nm, the material dispersion value goes negative. Dispersion indicates the amount of broadening that a light pulse undergoes while propagating through an optical fiber. The question then comes to the reader’s mind is that, does the negative sign indicates the shrinking or narrowing of the optical pulse? The answer to this query is a clear ‘no’. To understand the reason for this answer, let us refer back to the fundamental expression for the material dispersion.

\[ D = \frac{dt_d}{d\lambda} \]  \hspace{1cm} (9.2)

This equation shows that the material dispersion is actually the derivative of the group delay (per unit length) with respect to the wavelength. So when the sign of material dispersion is negative, it merely indicates a decreasing group delay per unit length for an increasing value of wavelength. Since the group delay is related inversely to the group velocity inside the optical fiber, a decrease in the group delay with wavelength indicates an increase in the group velocity with increasing wavelength. This means longer wavelengths (or lower frequencies) travel with higher velocities as compared to the shorter wavelengths (or higher frequencies). On the contrary, positive sign, thus, indicates that shorter wavelengths (or higher frequencies) travel faster than the longer wavelengths (lower frequencies). From this discussion, we can say that unless one is interested in finding out the actual pattern...
in which the different frequencies (or wavelengths) travel inside an optical fiber, the sign of the material dispersion does not matter because both the signs indicate pulse broadening, irrespective of the pattern of the frequencies in the broadened pulse. That is why, we generally use the absolute value of the material dispersion in our calculations.

Let us now move on to calculate the waveguide dispersion in an optical fiber. For this, we assume the material dispersion to be zero and the fiber has distinct core and cladding regions (observe that the infinite nature of the fiber medium assumed in the calculation of material dispersion has been given up in this assumption for waveguide dispersion). Waveguide dispersion is due to the modal nature of light inside the optical fiber. We are actually interested in finding out the group velocity of a mode inside our assumed wave-guiding structure of the optical fiber. From the group velocity we would then be in a position to calculate the dispersion caused due to the modal propagation of light inside the optical fiber. We would try to express this wave-guide dispersion in terms of the b and V parameters of the optical fiber. The b-V diagram of optical fiber suggests that the variation of propagation constant with frequency is not linear and so we can expect that there would be some kind of dispersion created due to this wave-guiding nature of the optical fiber. While investigating the dispersion due to the modal nature of light, we assume the material dispersion to be zero inside the fiber. From the analysis of the derivation of the field behaviour inside the optical fiber we have:

\[ \text{Normalized propagation Constant, } b = \frac{\beta_1^2 - \beta_2^2}{\beta_1^2 - \beta_2^2} \] (9.3)

Here \( \beta_1 \) and \( \beta_2 \) are the propagation constants in the core and the cladding material of the optical fiber. The value of \( b \) ranges between 0 and 1. The V-number of an optical fiber is related to the frequency by the following relation:

\[ V = \frac{a}{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda N.A.} \] (9.4)

Here \( \omega \) = Angular frequency of the mode.

\( a \) = Radius of the optical fiber.

\( n_1 \) = Refractive Index of core.

\( n_2 \) = Refractive Index of Cladding.

\( \lambda \) = Wavelength of the light.

N.A. = Numerical Aperture of the fiber.

For a practically used optical fiber we have the difference in the refractive indices of the core and cladding to be very small, typically of the order of \( 10^{-3} \) to \( 10^{-4} \).
Based on this, we also defined a quantity ‘\( \Delta \)’ under the weakly guiding approximation, which is given as:

\[
\Delta = \frac{n_1 - n_2}{n_2} \approx \frac{n_1 - n_2}{n_2} \quad (\text{Since } n_1 \approx n_2) \quad (9.5)
\]

Here \( n_1 \) and \( n_2 \) are the core and cladding refractive indices respectively. During the above discussion about the field behaviour inside the optical fiber we also bounded the range of the values of the propagation constant \( \beta \), whose bounds are represented by:

\[
\beta_2 < \beta < \beta_1 \quad \Leftrightarrow \quad n_2 \beta_0 < \beta < n_1 \beta_0 \quad (9.6)
\]

Since the values of \( n_1 \) and \( n_2 \) are very close to each other, the range of values of \( \beta \) is hence largely narrowed and so the equation 9.3 can be reduced to:

\[
b = \frac{\beta - \beta_1}{\beta_1 - \beta_2} \quad (9.7)
\]

If we rearrange the terms in the above equation, we may write the phase constant \( \beta \), for a mode in general, as:

\[
\beta = \beta_1 + b(\beta_1 - \beta_2)
\]

\[
\Rightarrow \beta = \beta_2(1 + \Delta b)
\]

\[
\Rightarrow \beta = \frac{\omega}{c} n_2(1 + \Delta b)
\]

(9.8)

To find the group delay ‘\( t_g \)’, we simply differentiate equation 9.8 with respect to the angular frequency \( \omega \) (note here, ‘\( b \)’ is a function of \( \omega \)):

\[
t_g = \frac{d\beta}{d\omega} = \frac{n_2}{c} \{1 + \Delta b\} + \frac{\omega n_2}{c} \Delta \frac{db}{d\omega} \quad (9.9)
\]

Since we are interested in expressing the dispersion in terms of \( b \) and \( V \) parameters, we modify the equation 9.9 as given below. The reason behind this modification is that, once we have the \( b-V \) diagram for an optical fiber, we can only find quantities in terms of \( b \) and \( V \), and so we want to express our quantity of interest also in terms of \( b \) and \( V \) so that it can be calculated from the \( b-V \) diagram easily.

\[
t_g = \frac{db}{d\omega} = \frac{n_2}{c} \{1 + \Delta b\} + \frac{\omega n_2}{c} \Delta \frac{db}{dV} \cdot \frac{dv}{d\omega} \quad (9.10)
\]

From equation 9.4, we can find the value of \( \frac{dv}{d\omega} \) by simply differentiating it with respect to \( \omega \) as:
\[ \frac{dV}{d\omega} = \frac{a}{c} (N. A.) = \frac{V}{\omega} \quad (9.11) \]

Substituting equation 9.11 in equation 9.10, we shall have,

\[ t_g = \frac{d\beta}{d\omega} = \frac{n_2}{c} \left\{ 1 + \Delta b + \Delta V \frac{db}{dV} \right\} \]

or,

\[ t_g = \frac{d\beta}{d\omega} = \frac{n_2}{c} \left\{ 1 + \Delta \frac{d}{dV} (bV) \right\} \quad (9.12) \]

Equation 9.12 above has a very interesting fact to observe. The term ‘\(n_2/c\)’ is actually a constant group delay which any light pulse would inevitably undergo inside the cladding and it is independent of frequency or wavelength. The only term that gives rise to a differential delay (and thus gives rise to dispersion) is the second term within the parentheses. This term is explicitly expressed in terms of the \(b-V\) diagram parameters. The only step now left to find the waveguide dispersion is to differentiate \(t_g\) with respect to the wavelength. Differentiating equation 9.12 with respect to wavelength, we get:

\[ \text{Waveguide Dispersion} \quad D_{wg} = \frac{dt_g}{d\lambda} = \frac{n_2 \Delta}{c} \frac{d}{d\lambda} \left( \frac{d}{dV} (bV) \right) \]

\[ \Rightarrow D_{wg} = \frac{n_2 \Delta}{c} \frac{d}{dV} \left( \frac{d}{dV} (bV) \right) \frac{dV}{d\lambda} \quad (9.13) \]

This time we differentiate equation 9.4 with respect to ‘\(\lambda\)’ to get the value of the derivative in the above equation and then we may re-write the above equation as:

\[ D_{wg} = \frac{n_2 \Delta}{c} \left( \frac{d}{dV} (bV) \right) \left( -\frac{V}{\lambda} \right) \]

\[ \Rightarrow D_{wg} = \frac{n_2 \Delta}{c} \frac{V}{\lambda} \frac{d^2}{dV^2} (bV) \quad (9.14) \]

With the help of the \(b-V\) diagram of an optical fiber, we are now in a position to ascertain the waveguide dispersion in the optical fiber using equation 9.14. But, the \(b-V\) diagram of an optical fiber has no analytical expression from which the second derivative (which is required in equation 9.14) can be calculated. So the above equation has to be solved numerically and so we must have considerably accurate \(b-V\) diagram of the optical fiber. Although the waveguide dispersion can be calculated from equation 9.14, yet, one does not get any idea of the operating wavelength range in order to get minimum waveguide dispersion. So the next task is to find out the operating wavelength range for minimum dispersion, which again has to be approached and solved numerically from the \(b-V\) diagram. If we do so, we observe the following facts:
At 800nm, $D_{\text{material}} >> D_{\text{wg}}$

At 1300nm $D_{\text{material}} < < D_{\text{wg}}$

$D_{\text{wg}}$ peaks around a V-number of 1.2

So if we want to operate at a minimum dispersion range, either this range has to be much higher than V-number 1.2 or it has to be much lower than V-number 1.2. But, if we operate at a range much lower than 1.2, it causes considerable reduction in V-number which in turn leads to unacceptably low launching efficiencies. So the only option available to us is to operate at much higher V-numbers than 1.2. But in this case too there is a limitation that the V-number of operation cannot exceed 2.4. Otherwise the optical fiber would no longer remain a single mode optical fiber. Thus we realise that we have further reduced the allowable range of the propagation constant by the above limitations. Hence to reduce waveguide dispersion, we must operate at V-number as close as possible to 2.4 but neither greater nor equal to it. Of course, the dispersion here is not so reduced that it can be acknowledged, but is almost 20% of the peak which would occur at $V=1.2$. The total dispersion in the single mode optical fiber is thus the sum of the material dispersion and the waveguide dispersion. Since these dispersions in the single mode optical fiber is due to its finite bandwidth, we call the total dispersion as the chromatic dispersion of the optical fiber. Thus,

**Chromatic Dispersion = Material Dispersion + Waveguide Dispersion.**

The material dispersion in an optical fiber cannot be varied. Material dispersion is a property of the glass as a material and will always exist irrespective of the structure of the optical fiber. The only quantity that is a structure dependent quantity is the waveguide dispersion. Waveguide dispersion depends upon the radius, numerical aperture etc. of the optical fiber which are structure related parameters. Hence by altering these parameters, we can manipulate the waveguide dispersion which in turn manipulates the chromatic dispersion. If we now plot a curve indicating the total dispersion in a single mode optical fiber, we would find a curve as shown in the figure 9.1 below. The red dashed curve indicates the response of the material dispersion as a function of wavelength and the dot-dashed blue curve shows the variations of the waveguide dispersion as a function of the wavelength. If both of these curves are added point-by-point, we obtain another curve as the one shown by the violet continuous curve in the figure 9.1. Since the material dispersion of a single mode optical fiber can be varied, its curve can be hence manipulated. The waveguide dispersion curve can be either flattened or shifted altogether. But we shall see these manipulations in later discussions. If we now recall our discussion on material dispersion of glass, we found that material dispersion of glass goes to zero at a wavelength of about 1270nm. This situation is now can be clearly seen from the curve of the material dispersion in the figure 9.1 below. If we observe the total dispersion curve shown in the figure below, we see that it crosses zero at a
wavelength of about 1310 nm. Thus if a single mode optical fiber is operated at a wavelength of about 1310 nm, the total dispersion in this fiber would be almost zero at this wavelength of operation. The word 'almost' is used because when the fiber is operated at around 1310 nm wavelength, the incident light does not contain only a single wavelength of 1310 nm but consists of a small band of wavelengths centred around 1310 nm. These wavelengths would have their own corresponding dispersions and hence the total dispersion will not be zero although it might be very small. In other words, at an operating wavelength of around 1310 nm, the single mode optical fiber would support very large bandwidth or very high data rates. If this operating wavelength is shifted to 1550 nm, the dispersion in the fiber is very large and consequently the bandwidths and the data rates are low at 1550 nm operation. Primarily this was the reason for the 1310 nm optical window to be the most immediately accepted window of operation in optical communication.

Let us now recall our discussion on the causes of distortion on an optical fiber and go into the details of the distortion caused by the attenuation of the optical signal inside the optical fiber. As is evident from the figure 8.3, there are many sources of attenuations that may occur inside an optical fiber. Material absorption, scattering, micro and macro bending losses, etc. constitute the main sources in this category. Material absorption is an intrinsic property of a material to absorb light of one or more wavelengths and hence this property of glass may cause some amount of attenuation in the signal as it propagates along the optical fiber. Yet, the more
significant loss is the scattering loss which causes greater loss of optical power from
the optical signal.

When we discussed about the constructional details of the optical fiber, we
stated that in an optical fiber there are two distinct regions of core and cladding
having distinct refractive indices and each of these regions are homogeneous
throughout its length and width. But during the manufacturing process of the optical
fiber, there remain tiny regions inside the optical fiber which have refractive index
different than the medium in which they lie. These types of tiny regions are called
micro-centres and are responsible for the scattering of light. The dimensions of
these micro-centres are much smaller compared to the wavelength of the light and
they scatter the light as shown in the figure 9.2

Figure 9.2: Rayleigh Scattering in Optical Fiber

When light is launched into an optical fiber, it travels along the length of the
optical fiber by virtue of multiple total internal reflections at core cladding boundary.
This light while travelling along the optical fiber encounter the micro-centres in the
fiber and sees it as a small perturbation in the refractive index. This causes the light
to get scattered almost in the same way as the scattering of atmospheric microwave
signals by rain-drops. This type of scattering is called as Rayleigh scattering. Due to
Rayleigh scattering, a very small amount of light is lost and as a result the light signal
is attenuated. This loss of light is called as the scattering loss. Rayleigh scattering is
a very strong function of the wavelength as it varies indirectly to $\lambda^4$, where $\lambda$ is the
wavelength of light. This means that, if we double the wavelength of operation, the
Rayleigh scattering loss would reduce by a factor of 16 (i.e. $2^4$). Close observation
would reveal that this might be the reason behind the low loss characteristic of the
optical fiber at 1550nm as compared to 800nm (as seen in figure 2.1) because the
ration between the two wavelengths is almost double. If we plot the Rayleigh scattering loss as function of wavelength, we would obtain a curve as shown in figure 9.3.

![Figure 9.4: Rayleigh Scattering Loss in optical fiber](image)

The above figure clearly shows the trend in which the scattering loss decreases as the wavelength of operation increases. However for glass, there is another type of loss which is termed as the infrared-loss which occurs due to the intrinsically bad conductivity of glass to infrared wavelengths. This loss is a rapidly increasing function of wavelength. So any infrared wavelength gets rapidly attenuated inside glass. This loss of glass is also shown in the above figure. So as we move our wavelength of operation more towards the infrared region, the loss profile of glass gets dominated by the infrared loss of glass. This transfer from a Rayleigh scattering loss to a infrared loss in the loss profile of glass creates a valley like region in the overall loss profile of glass. This region is indicated by the region inside the circle in the above figure.

During the process of purification glass, some water molecules remain inside glass even after glass has been carefully purified. Water molecules may also get diffused into glass directly from the atmosphere if glass is directly subjected to the atmosphere for prolonged periods of time. This OH$^{1-}$ radical of these water molecules render glass with, yet another absorptive loss which causes absorption peaks in the loss profile of glass. One such absorption peak coincides with the valley...
region as shown in the figure 9.4. However purification and manufacturing technologies have been considerably improved and modified to reduce these absorption peaks to a considerably low level. It is this peak in the valley region that gives rise to two distinct minima in the loss profile of glass causing two different windows of optical communication. This is the peak that appeared in the loss profile of glass between 1300nm and 1500nm. If we magnify the region inside the circle, we would find the following curve which we had already studied as figure 2.1.

![Diagram of attenuation vs. wavelength with peaks and valleys indicating loss windows.](image)

The material absorption and the scattering losses are due to intrinsic properties of glass and hence would always remain in the optical fiber even in the ideal condition when the fiber is not laid into the system. But along with these losses, there are two other sources which are not due to intrinsic nature of glass. These losses are due to deformations produced in the optical fiber while laying the fiber for application.

![Diagram illustrating micro bending and power losses.](image)

**Figure 9.5:** Micro Bending in Optical Fibers
This deformation may be microscopic or even macroscopic. Microscopic deformations are referred to as micro-bending and the loss is called as micro-bending loss. The other type of loss is called as macro-bending loss. Micro bending loss in a fiber can be caused even by a slight application of pressure onto the fiber by the hand while holding the fiber. One can see this loss in the laboratory by gently applying pressure onto the fiber by holding the fiber between the fingers. These deformations are shown in the figure 9.5 above which clearly show the otherwise straight fiber deformed due to micro-bending. Micro-bending creates local normal to be established which cause the critical angle condition to be invalid for the propagating rays and hence these rays refract out of the fiber as shown in the figure. This causes loss of light energy and leads to attenuation of the light signal.