6. Dispersion

Dispersion is the spreading of a light pulse as it travels down the length of an optical fiber. Dispersion ultimately limits the information-carrying capacity of a fiber. In fiber-optic communications, there are two major types of dispersions, namely,

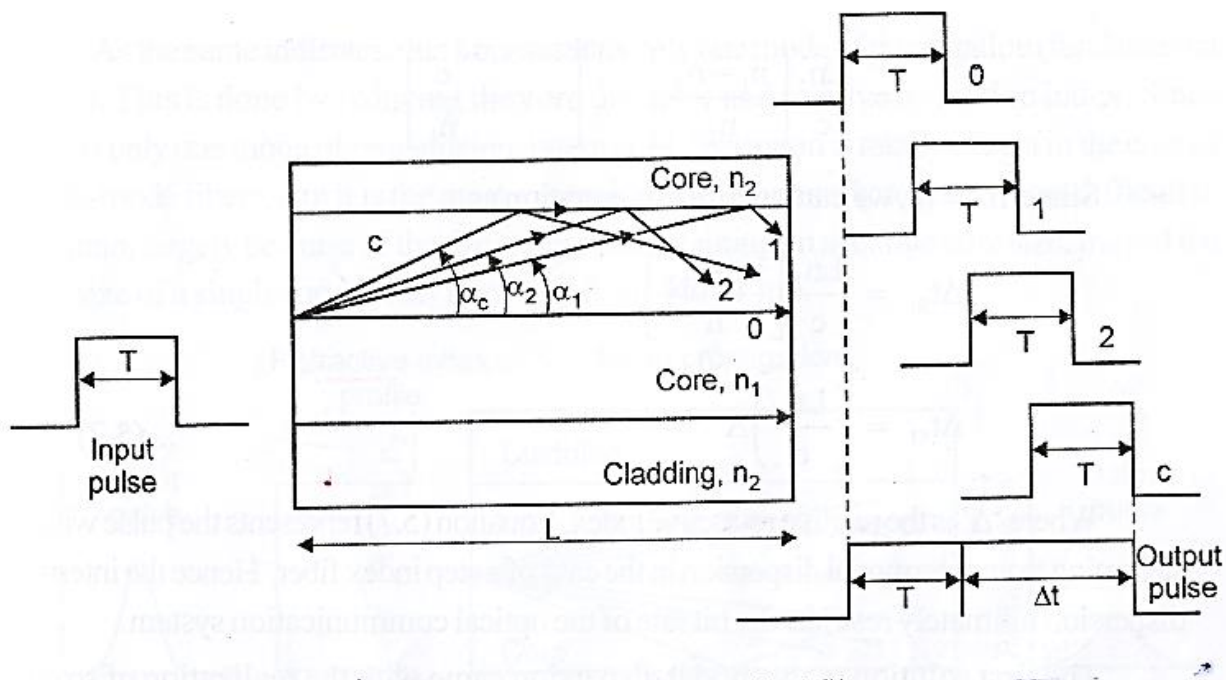
1. Intermodal dispersion and
2. Intramodal dispersion

6.1 Intermodal Dispersion

When an optical pulse is launches into a fiber, the optical power in the pulse is distributed over all of the modes of the fiber. *The propagation of light within the fiber can be described in terms of a set of guided electromagnetic waves called the* '***modes***'. Roughly, we can say that a mode is the path taken by the light ways while entering into the fiber. Hence different modes will travel with different propagation angles, the range being zero (corresponding to the fundamental mode) to the critical value, α_c (corresponding to the critical mode). These modes take different routes but travel with the same velocity and hence, at the end of the fiber, they arrive at different timings. This ultimately causes the pulse widening. This is called *intermodal dispersion* or simply *modal dispersion* since it is the dispersion that arises with the different modes of a single pulse.

Measuring Intermodal Dispersion

Consider a beam propagating inside a fiber, taking into account the mode concept, as in below Figure. For digital transmission, a light pulse represent logic 1, and no light pulse represent logic 0. Such light pulses, radiated by light source, enter a fiber, where each pulse breaks down into a set of small pulses carried by an individual mode. At the fiber output, individual pulses recombine and, since they are overlapping, the receiver sees one long light pulse whose rising edge is from the fundamental mode and whose falling edge is from the critical mode. This explanation is depicted in below Figure, where four modes are shown as an example.



Modes in an optical fiber

To ascertain why these individual pulses arrive at the receiver end at different times, let us do a simple calculation. A zero-order mode travelling along the fiber axis needs time, to reach the receiver end.

$t_0 = {}^{L}/_{v}$; Here, L is the link length and v $\left(= \frac{c}{n_1}\right)$ is

the light velocity within the core having refractive index n_1. 'c' is the speed of light in vacuum. The highest order mode propagating at the critical angles needs time,

$$t_c = \frac{L}{(v \cos \alpha_c)}$$

to complete the path. Therefore the pulse widening due to intermodal dispersion is,

$$\Delta t_{SI} = t_c - t_0 = \frac{L}{(v\cos\alpha_c)} - \frac{L}{v}$$

$$\Delta t_{SI} = \frac{L}{v}\left[\frac{1}{\cos\alpha_c} - 1\right]$$

$$= \frac{L}{v}\left[\frac{n_1}{n_2} - 1\right] \qquad \left[\because \cos\alpha_c = \frac{n_2}{n_1}\right]$$

$$= \frac{L}{v}\left[\frac{n_1 - n_2}{n_2}\right] \qquad \left[\because v = \frac{c}{n_1}\right]$$

Since $n_2 \approx n$, we can rewrite this equation as,

$$\Delta t_{SI} = \frac{L\,n_1}{c}\left[\frac{n_1 - n_2}{n}\right]$$

$$\Delta t_{SI} = \left(\frac{L\,n_1}{c}\right)\Delta \qquad \ldots(1)$$

When 'Δ' is the relative refractive index. Equation (1) represents the pulse widening stemming from the intermodal dispersion in the case of a step index fiber. Hence the intermodal dispersion ultimately restricts the bit rate of the optical communication system.

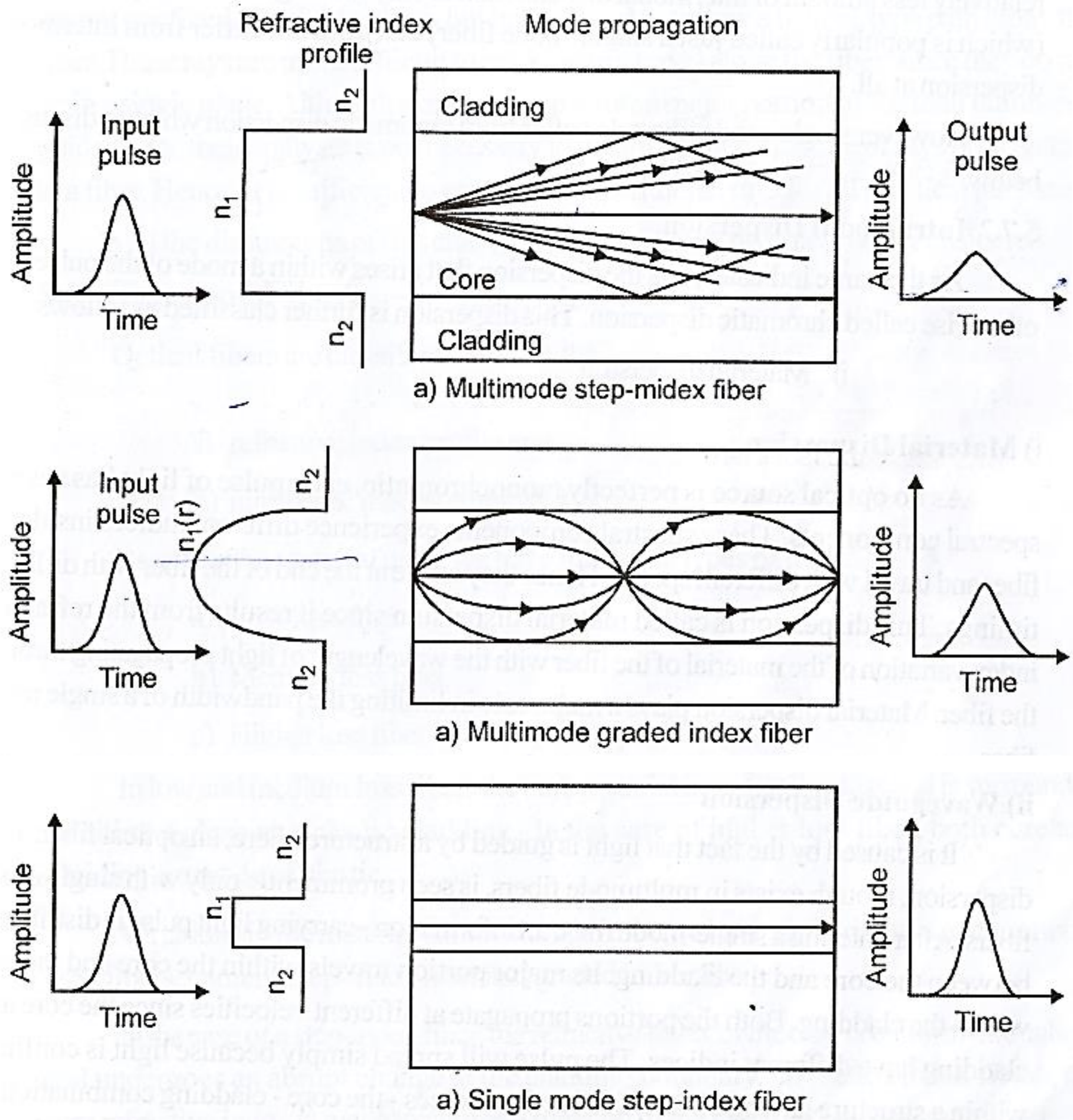
The first solution to the modal dispersion came with the realization of so called *graded-index fiber* and the physics behind reducing intermodal dispersion using graded-index fibers is as follows:

It should be recalled at this stage that intermodal dispersion arises in a step index fiber owing to the fact that different beams travel at the same velocity, but over different distances and hence arrive at the receiver end at different times.

A clever modification in the refractive index profile has considerably reduced the intermodal dispersion. Such a fiber is called *graded-index fiber*. In this fiber, refractive index is maximum (say, n_1) at the axis of the core and decreases radially until it meets the core-cladding boundary. Hence the mode propagating along the centerline of this fiber – the shortest distance – travels at the lowest speed because it meets the highest refractive index. The mode traveling closer to the fiber cladding – the longer distance – propagates at the higher speed because it meets a lower refractive index. These are clearly shown in the Figure below (next page). Hence the fractions of an input pulse delivered by the different modes arrive at the receiver end more or less simultaneously. Therefore, intermodal dispersion will be relatively less and bit rate can be increased. It has been estimated that a graded-index fiber has a modal dispersion $\Delta/8$ times less than that of a step-index fiber. However graded index fibers are relatively expensive when compared to step-index fibers because of the requirement of complex index profile.

Though a graded-index fiber exhibit relatively less intermodal dispersion, this dispersion is not totally absent. Hence a complete solution for the intermodal dispersion was thought of and subsequently realized too. Such a fiber is called *single-mode fiber*.

As the name indicates, this fiber sustains only one mode of propagation (fundamental mode). This is done by reducing the core diameter and relative refractive index. Since there is only one mode of propagation, intermodal dispersion is totally absent in the case of single-mode fibers. But it is the most expensive fiber to manufacture and most difficult to maintain, largely because of the difficulty in maintaining an accurate core size. Indeed the core size of a single mode fiber may vary from 4 to 11 μm.



Schematic diagram for pulse broadening due to intermodal dispersion in all the three types of fibers

While step-index and graded-index fibers are used for short and intermediate-distance networks, single mode fibers are the most popular type of link, particularly for long-distance communications.

From the above Figure, it is clear that a multimode step-index fiber, which is generally called a step-index fiber, suffers from the maximum intermodal dispersion. It is seen that a multimodal graded-index fiber, which is generally called a graded-index fiber, suffers from relatively less amount of intermodal dispersion. It is only the single mode step-index fiber (which is popularly called just a single-mode fiber) that does not suffer from intermodal dispersion at all.

However single-mode fibers do suffer from chromatic dispersion which is discussed below.

6.2 Intramodal Dispersion

As the name indicates, it is the dispersion that arises within a mode of the pulse. It is otherwise called chromatic dispersion. This dispersion is further classifies as follows:

i) Material dispersion
ii) Waveguide dispersion

i) Material Dispersion

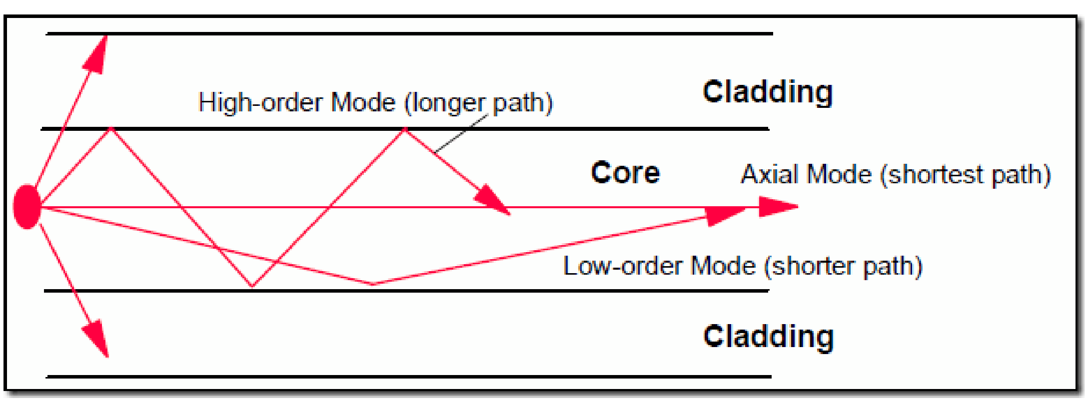
As no optical source is perfectly monochromatic, each pulse of light has several spectral components. These spectral components experience different indices inside the fiber and travel with different speeds. Hence they arrive at the end of the fiber with different timings. This dispersion is called material dispersion since it results from the refractive index variation of the material of the fiber with the wavelength of light propagating through the fiber. Material dispersion plays a major role in limiting the bandwidth of a single mode fiber.

ii) Waveguide Dispersion

It is caused by the fact that light is guided by a structure – here, an optical fiber. This dispersion, though exists in multimode fibers, is seen prominently only with single mode fibers. After entering a single-mode fiber, an information – carrying light pulse is distributed between the core and the cladding. Both the portions propagate at different velocities since the core and cladding have different indices. The pulse will spread simply because light is confined within the structure having different relative indices – the core – cladding combination of fiber. This dispersion is called *waveguide dispersion*. However, waveguide dispersion in a single-mode fiber is relatively small compared with material dispersion. It should be noted that multimode fibers also suffer from chromatic dispersion. However modal dispersion is the major factor limiting multimode fiber bandwidth.

6.3 Meridional and Skew beams

All beams (modes) propagating within an optical fiber is divided into two categories: ***meridional*** *beams* and ***skew*** *beams*. Meridional beams are those that intersect the centerline of the fiber or fiber axis during every reflection at the core cladding boundary. The below figure show the paths of rays in step-index fiber.



In this, three rays are entering at different angles of incidence with the axis. All these 3 rays travel in different path lengths and emerge out at different times. It is obvious from the figure that an input pulse gets widened as it travels along the fiber.

The light rays propagate through it in the form of skew rays or helical rays. They Skew beams propagate without intersecting the fiber's central axis. Skew rays are not confined to a single plane, so they cannot be tracked easily. The acceptance angle for skew rays is larger than the acceptance angle of meridional rays. Analyzing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays lead to greater power loss. Although skew rays constitute a major portion of the total number of guided rays, their analysis is not necessary to obtain a general picture of rays propagating in a fiber. Hence, it is sufficient to consider the meridional rays for all practical purposes.