

# Module 4 : Signal Distortion on Optical Fibers - Attenuation

## Lecture : Signal Distortion on Optical Fibers - Attenuation

### Objectives

In this lecture you will learn the following

- Signal distortion
- Condition for signal distortion-less transmission
- Special nature of Optical Signal
- Attenuation on Optical Fiber
- Material Loss
- Scattering Loss
- Micro-Bending Losses
- Radiation or Bending Loss

- **What is meant by signal distortion ?**

A signal is said to be undistorted if it is delayed in time and scaled version of the original signal. Let a system has input signal  $x(t)$  and output signal  $y(t)$ . Then for distortion-less system

$$y(t) = kx(t - \tau) \quad \text{----- (5.1)}$$

Where  $k$  is a scaling constant and  $\tau$  is the time delay.

- **What is the condition for signal distortion-less transmission ?**

To see the condition in the frequency domain let us take the Fourier transform of Eqn (5.1). If  $Y(\omega)$  is the Fourier transform of  $y(t)$  and  $X(\omega)$  is the Fourier transform of  $x(t)$ , we get,

$$Y(\omega) = k e^{-j\omega\tau} X(\omega) \quad \text{----- (5.2)}$$

That means if a system has a frequency response  $k e^{-j\omega\tau}$  then it does not produce any distortion of the signal. In other words for a system to be distortion-less, its frequency response must satisfy two conditions.

- (1) The amplitude response must be constant ( $k$  should be independent of frequency).
- (2) The phase response should be linear ( $\tau$  should be constant)

- **Why signal gets distorted while propagating on optical fiber ?**

- (1) The loss of optical fiber is wavelength dependent. That makes  $k$  a function of frequency. This is called the attenuation of the fiber.
- (2) Different wavelengths and different modes of the optical fiber travel with different speeds and therefore have delay which is wavelength dependent. This phenomenon is called the dispersion.

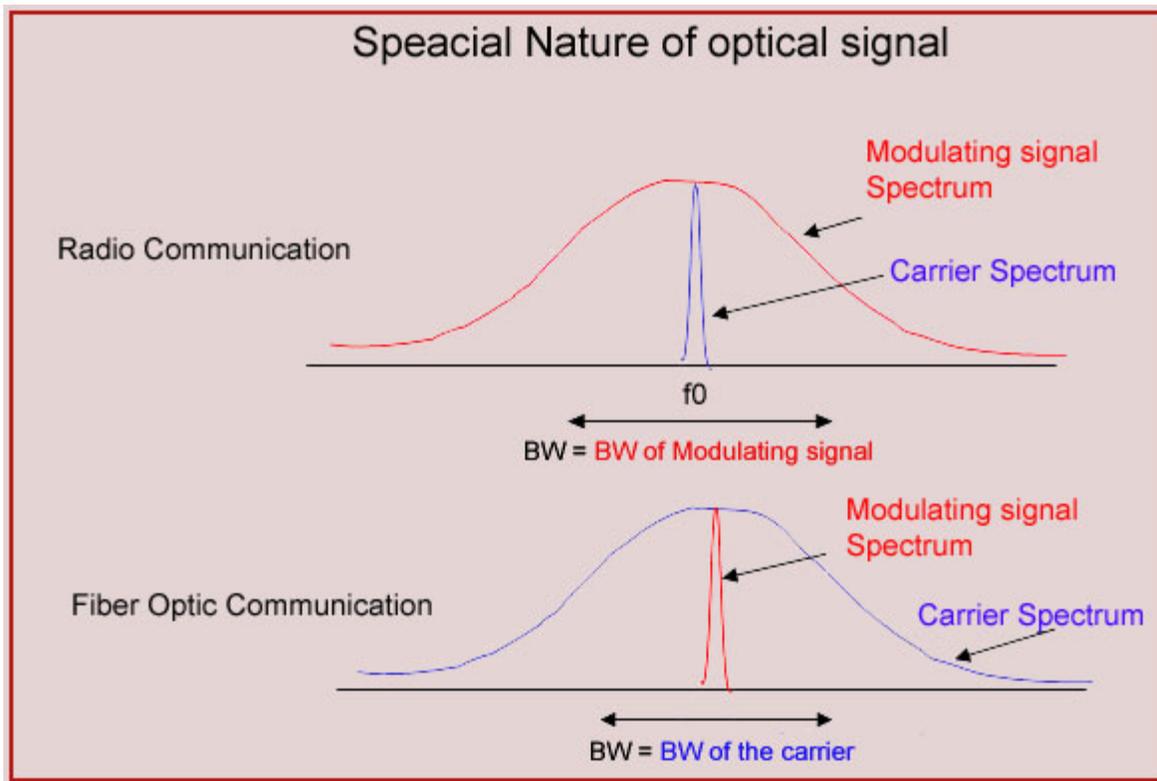
**So, in general the signals get distorted on an optical fiber because different**

- **frequency components undergo different attenuation and different delays.**

- For an optical communication link the highest data rate is about 10GHz. This translates approximately to a wavelength range of 0.1nm. For all practical purposes, the loss of the optical fiber can be assumed constant over a bandwidth of 0.1nm. Therefore, we note that uniform amplitude response condition is well satisfied for the optical fiber. The signal depending upon the loss may reduce in amplitude but there is no distortion of the signal due the loss.

The typical optical wavelength is about 1550nm and the signal bandwidth is about 0.1nm.

- That means the optical system is a very narrow band system, the fractional bandwidth is  $\ll 1$ . One would then wonder whether over such a narrow bandwidth the linearity of the phase response be violated! Or would the velocity differ significantly over such a narrow bandwidth to give substantial distortion! The answer to this would be 'NO'. However before we conclude this let us look at the special nature of the optical signals.



Look at the Figure. The Figure gives the spectra of modulating signal and the carrier for

- two types of communication, radio communication and the optical communication. There is marked difference between the two cases which can be summarized as follows:

- (1) For radio communication the intrinsic spectral width of the carrier is very small compared to the spectral width of the modulating signal. Therefore the bandwidth of the modulated signal is almost equal to the BW of the modulating signal. (twice if the signal is simple AM). Also the shape of the spectrum of the modulated signal is almost same as that of the modulating signal. So in radio communication, the spectrum of the modulating signal is preserved, except that it is shifted by the carrier frequency.
- (2) For optical communication the scenario is quite opposite. A typical optical source like LED has an intrinsic spectral width of 30-60nm (approximately 4000 to 8000GHz), and a source like a laser diode has a spectral width of 2-3nm (approximately 250 to 400 GHz). That means for optical communication the spectral width of the carrier is much greater than the spectral width of the data. The bandwidth of the modulated signal then is almost equal to the bandwidth of the carrier with hardly any signature of the data. So, in optical communication the spectrum cannot be used to recover the data. The demodulation therefore has to be done only in time domain. This is possible only by AM scheme where the signal can be recovered by a primitive technique of envelop detection.

The optical communication system hence cannot be treated on line similar to that used for

- normal radio communication link. Also since the modulated signal has a spectral width of few nm, the fractional bandwidth is not as small as it appeared earlier.

The optical communication system can be looked as a parallel multiple channel

- transmission of carriers spreading over the bandwidth of the carrier. One can then say that the distortion of the signal in optical communication is due to differential delay of the signal riding over different carriers within the spectral width of the carrier.

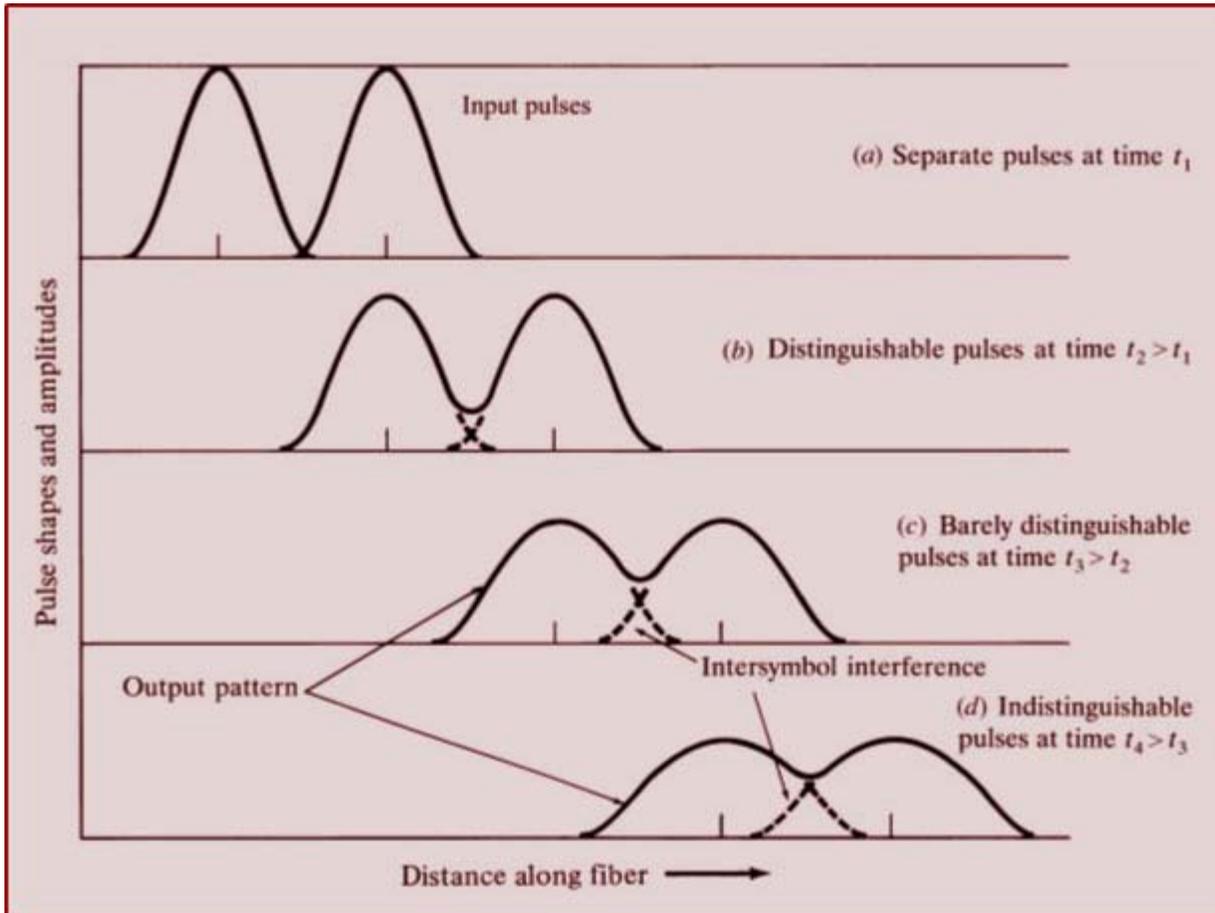
The signal pulse then goes on spreading as it travels along the optical fiber. The pulse

- broadening is proportional to the distance and it is also proportional to the spectral width

of the carrier. This phenomenon is the **dispersion** .

- So we conclude that when a signal pulse travels on an optical fiber it goes on broadening due to dispersion and goes on reducing in amplitude due to attenuation as shown in Fig. After certain distance the pulse shape is completely distorted not to resemble with the original pulse shape.

### Attenuation on Optical Fiber



- The signal on optical attenuates due to following mechanisms :

- (1) Intrinsic loss in the fiber material.
- (2) Scattering due to micro irregularities inside the fiber.
- (3) Micro-bending losses due to micro-deformation of the fiber.
- (4) Bending or radiation losses on the fiber.

The first two losses are intrinsically present in any fiber and the last two depend on the environment in which the fiber is laid.

### MATERIAL LOSS

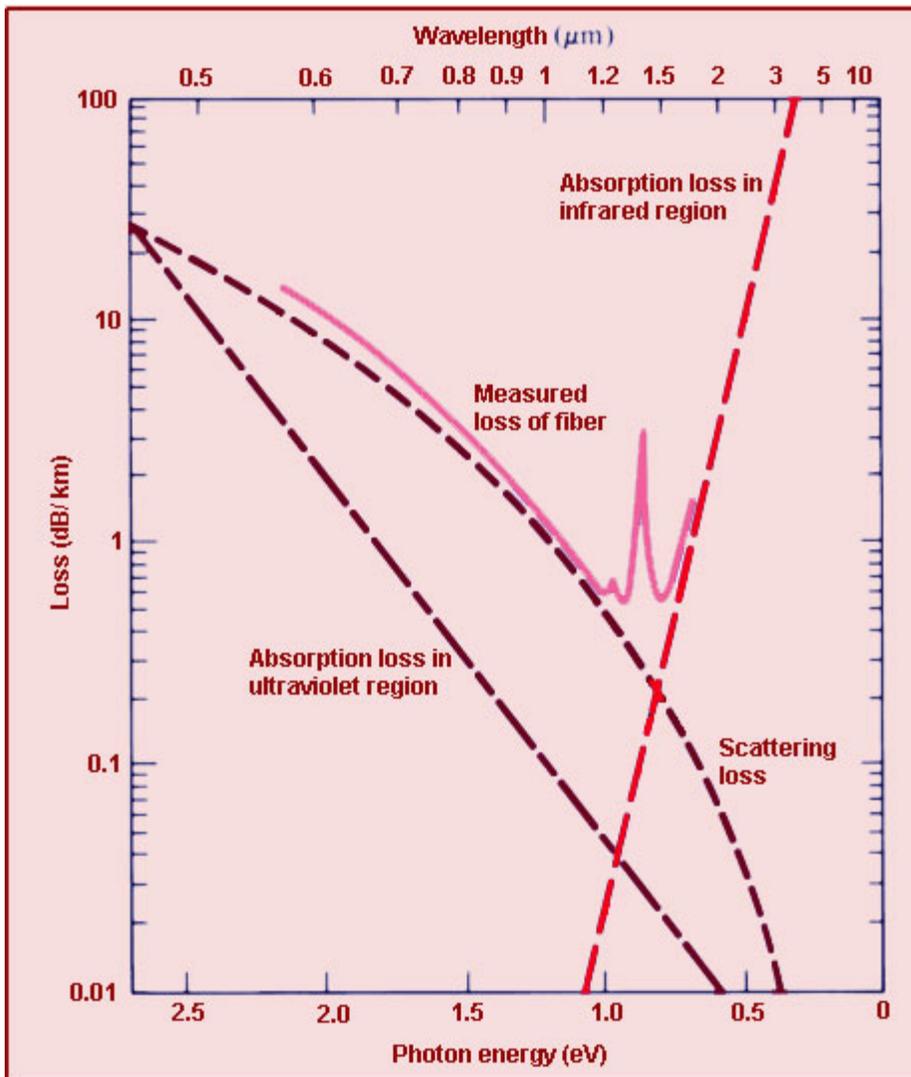
- (a) **Due to impurities:** The material loss is due to the impurities present in glass used for making fibers. In spite of best purification efforts, there are always impurities like Fe, Ni, Co, Al which are present in the fiber material. The Fig. shows attenuation due to various molecules inside glass as a function of wavelength. It can be noted from the figure that the material loss due to impurities reduces substantially beyond about 1200nm wavelength.
- (b) **Due to OH molecule:** In addition, the OH molecule diffuses in the material and causes absorption of light. The OH molecule has main absorption peak somewhere in the deep infra-red wavelength region. However, it shows substantial loss in the range of 1000 to 2000nm.
- (c) **Due to infra-red absorption :** Glass intrinsically is a good infra-red absorber. As we increase the wavelength the infra-red loss increases rapidly.

## SCATTERING LOSS

- The scattering loss is due to the non-uniformity of the refractive index inside the core of the fiber. The refractive index of an optical fiber has fluctuation of the order of  $10^{-4}$  over spatial scales much smaller than the optical wavelength. These fluctuations act as scattering centres for the light passing through the fiber. The process is, **Rayleigh Scattering**. A very tiny fraction of light gets scattered and therefore contributes to the loss.

- The Rayleigh scattering is a very strong function of the wavelength. The scattering loss varies as  $\lambda^{-4}$ . This loss therefore rapidly reduces as the wavelength increases. For each doubling of the wavelength, the scattering loss reduces by a factor of 16. It is then clear that the scattering loss at 1550nm is about factor of 16 lower than that at 800nm.

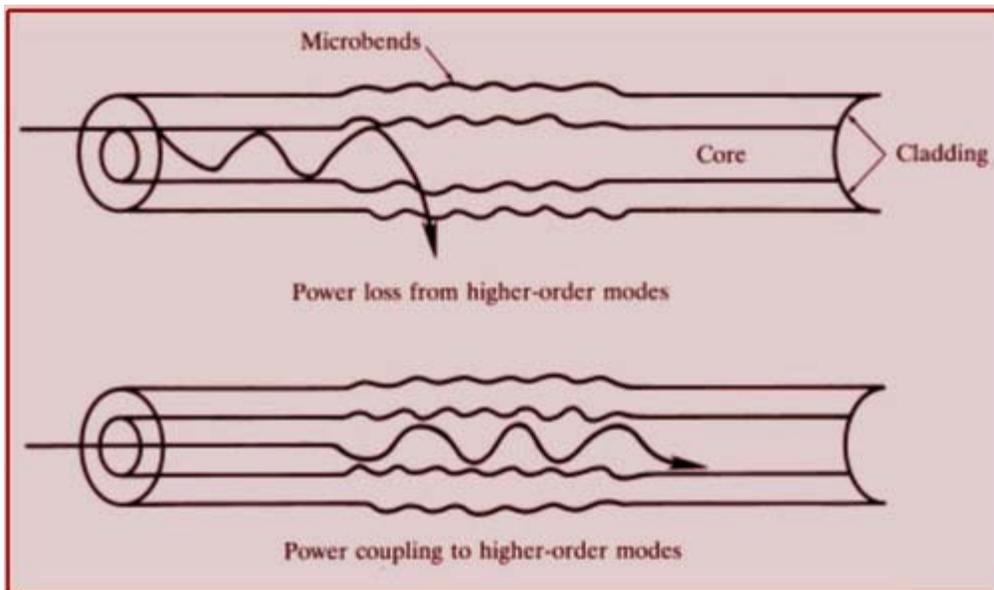
The following Fig. shows the infrared, scattering and the total loss as a function of wavelength.



- It is interesting to see that in the presence of various losses, there is a natural window in the optical spectrum where the loss is as low as 0.2-0.3dB/Km. This window is from 1200nm to 1600nm.
- There is a local attenuation peak around 1400nm which is due to OH absorption. The low-loss window therefore is divided into sub-windows, one around 1300nm and other around 1550nm. In fact these are the windows which are the II and III generation windows of optical communication.

### MICRO-BENDING LOSSES

- While commissioning the optical fiber is subjected to micro-bending as shown in Fig.



- The analysis of micro-bends is a rather complex task. However, just for basic understanding of how the loss takes place due to micro-bending, we use following arguments.

In a fiber without micro-bends the light is guided by total internal reflection (ITR) at the core-cladding boundary. The rays which are guided inside the fiber has incident angle greater than the critical angle at the core-cladding interface. In the presence of micro-bends however, the direction of the local normal to the core-cladding interface deviates and therefore the rays may not have angle of incidence greater than the critical angle and consequently will be leaked out.

- A part of the propagating optical energy therefore leaks out due to micro-bends.

Depending upon the roughness of the surface through which the fiber passes, the micro-bending loss varies.

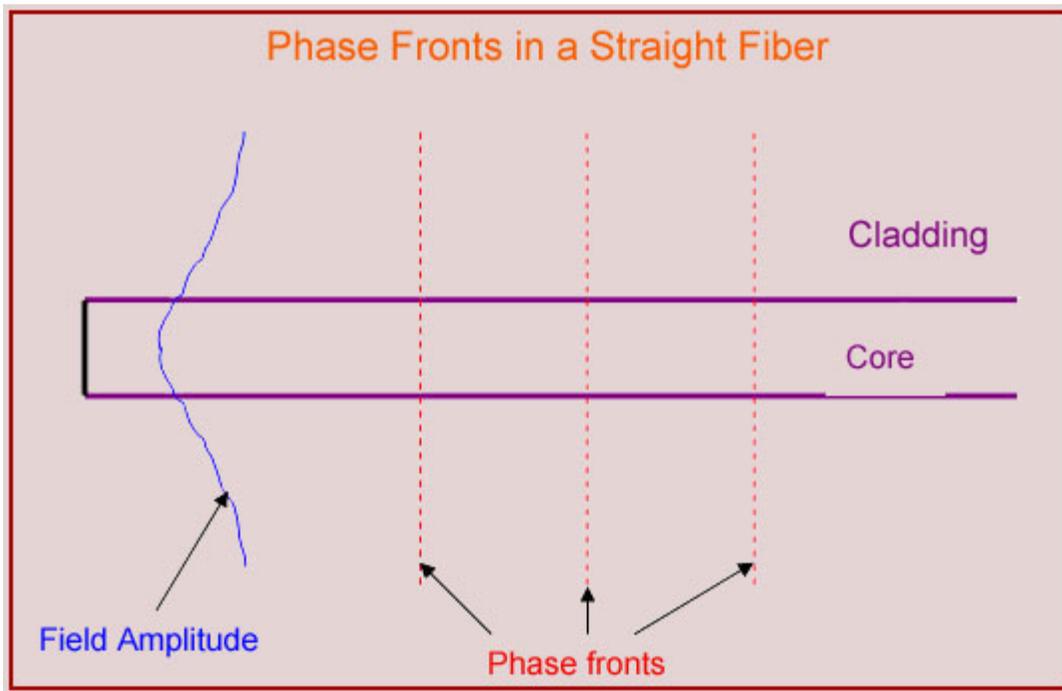
- Typically the micro-bends increase the fiber loss by 0.1-0.2 dB/Km.

## RADIATION OR BENDING LOSS

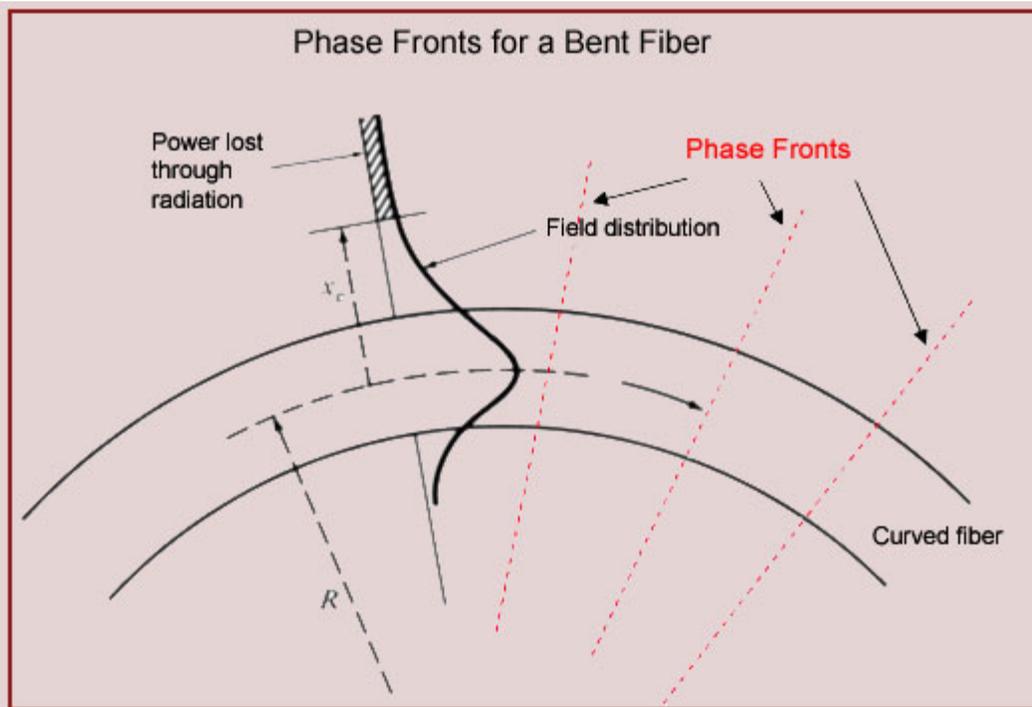
- While laying the fiber the fiber may undergo a slow bend. In micro-bend the bending is on micron scale, whereas in a slow bend the bending is on cm scale. A typical example of a slow bend is a formation of optical fiber loop.

- The loss mechanism due to bending loss can be well understood using modal propagation model.

- As we have seen, the light inside a fiber propagates in the form of modes. The modal fields decay inside the cladding away from the core-cladding interface. Theoretically the field in the cladding is finite no matter how far away we are from the core-cladding interface. Now look at the amplitude and phase distribution for the fibers which are straight and which are bent over an circular arc as shown in Fig.



- It can be noted that for the straight the phase fronts are parallel and each point on the phase front travels with the same phase velocity.



- However, as soon the fiber is bent (no matter how gently) the phase fronts are no longer parallel. The phase fronts move like a fan pivoted to the center of curvature of the bent

fiber (see Fig.). Every point on the phase front consequently does not move with same velocity. The velocity increases as we move radially outwards the velocity of the phase front increases. Very quickly we reach to a distance  $x_c$  from the fiber where the velocity tries to become greater than the velocity of light in the cladding medium.

- Since the velocity of energy can not be greater than velocity of light, the energy associated with the modal field beyond  $x_c$  gets detached from the mode and radiates away. This is called the bending or the radiation loss.

Following important things can be noted about the bending loss :

- (1) The radiation loss is present in every bent fiber no matter how gentle the bend is.
- (2) Radiation loss depends upon how much is the energy beyond  $x_c$ .
- (3) For a given modal field distribution if  $x_c$  reduces, the radiation loss increases. The  $x_c$  reduces as the radius of curvature of the bent fiber reduces, that is the fiber is sharply bent.
- (4) For a given  $x_c$  that is for a given fiber bent, if the field spreads more in cladding, the bend loss increases. We know from the modal field analysis that the lower order modes are more confined to the core, that is their fields decay rapidly in the cladding, and the higher order modes have more slowly decaying energy in the cladding . The higher order modes hence are more susceptible to the radiation loss compared to the lower order modes.
- (5) The number of modes therefore reduces in a multimode fiber in presence of bends.

## Recap

In this lecture you have learnt the following

- Signal distortion
- Condition for signal distortion-less transmission
- special nature of Optical Signal
- Attenuation on Optical Fiber
- Material Loss
- Scattering Loss
- Micro-Bending Losses
- Radiation or Bending Loss

Congratulations, you have finished Module 4. To view the next lecture select it from the left hand side menu of the page