MODULE 2

CHAPTER 2

Transmission Characteristic of Optical Fiber

Syllabus

2.1 Dispersion in Optical fiber, types of dispersion, Dispersion compensation techniques and dispersion measurements, Time domain and Frequency Domain measurements. Dispersion management, Need for dispersion management and Post compensation techniques.

2.2 Transmission losses in the optical fiber, Attenuation, Absorption losses, radiation losses and linear scattering losses, Comparison of optical fibers. Measurement of attenuation: Insertion loss, Return loss, OTDR.

2.1 DISPERSION IN OPTICAL FIBER

UQ. Write short note on : Dispersion **MU – Q. 6(ii), Dec. 16, 5 Marks Q. 6(b), May 17, 10 Marks**

- **Definition :** Dispersion means spreading out of an optical pulse of light energy in time as it propagates down a fiber. It is also called as pulse spreading. Dispersion occurs because of the difference in the propagation time taken by the light rays that traverse different propagation paths within the fiber. If the pulse spreading is sufficiently severe, one pulse may interfere with another. Fig. 2.1.1 Shows dispersion.

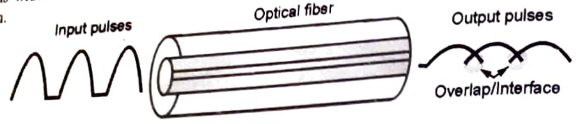


Fig. 2.1.1 : Dispersion

2.1.1 General Concept of Dispersion

Dispersion in a single-mode step-index fiber: The light rays propagating in a single-mode step-index fiber (diameter sufficiently small) is shown in Fig. 2.1.2.

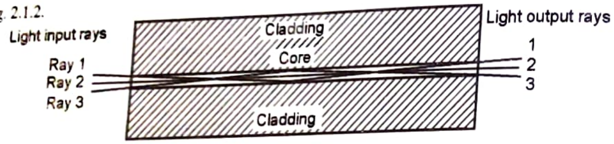


Fig. 2.1.2 : Light propagation in a single-mode step-index fiber

The following is observed:

1. Only a single transmission path is followed by all rays as they propagate through the fiber.
2. There is no intermodal dispersion and every light beam covers the same distance in a given amount of time.
3. The transmitted optical pulse is widened because a light pulse, despite propagating as a fundamental mode, has a variety of spectral components and that the fundamental mode's group velocity varies with frequency. This phenomenon is known as **intramodal,** or **group velocity dispersion** (GVD).

(I) ***Dispersion in a multimode step-index fiber:*** Dispersion occurs in a multimode step-index fiber. Consider three different light rays that propagate down a multimode step-index optical fiber as shown in Fig. 2.1.3.

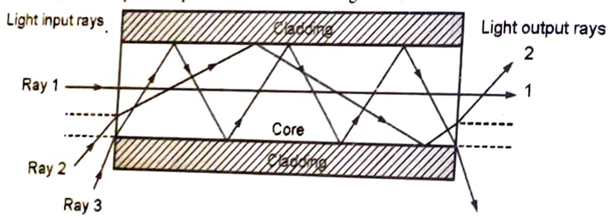


Fig. 2.1.3 : Light propagation in a Multi-mode step-index fiber

The following are the observation

- **Light ray-1 :** The lowest-order propagation mode takes path parallel to the central axis of the optical fiber.
- **Light ray-2 :** The middle-order propagation mode bounces several times at the interface till it reached propagates through fiber.
- **Light ray-2 :** The highest-order propagation mode bounces many times back and forth as it propagates the entire length. Hence light ray-3 has to travel more distance across the fiber as compared to ray1 and ray2.
- Hence when all the three rays are inject into fiber they will reach in different time at other end of the fiber. This means the propagated light energy would spread out with respect to time. This is called as intermodal or modal dispersion. Since pulse is stretched its amplitude get reduced at other end of fiber.

(II) **Dispersion in a multimode graded-index fiber:** Consider three different light rays traveling through a multimode graded-index fiber, as shown in Fig. 2.1.4.

Fig. 2.1.4 : Light propagation down a multimode graded-index fiber

Following are the observations

- All the three rays travel different mode and paths, time taken for propagating through the l optical fiber is approximately same. This is because the index of refraction decreases with radial distance from the center axis of the fiber core toward the cladding.
- Additionally, the refractive index has an inverse relationship with the speed of a beam. The rays 2 and 3 go further from the cable's core, propagate more quickly, and almost arrive at the end at the same time as ray 1.

2.2 TYPES OF DISPERSION

UQ. Discuss different types of Dispersion in optical fiber. **MU – Q. 2(b), Dec. 17, 5 Marks**

Signal dispersion in optical fibers can be broadly classified in three main categories, as shown if Fig. 2.2.1.

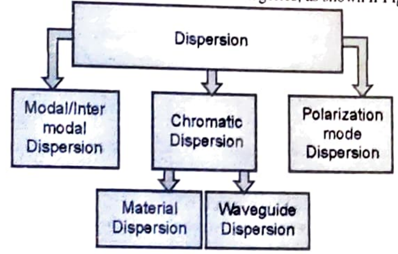


Fig. 2.2.1 : Types of Dispersion

2.2.1 Chromatic or Intramodal Dispersion

- It is results from the finite spectral linewidth of the optical source.
- Propagation delay differences between the different spectral components of the transmitted light signal causes broadening of each transmitted mode and hence collectively known as intramodal dispersion. Shown on Fig. 2.2.2.

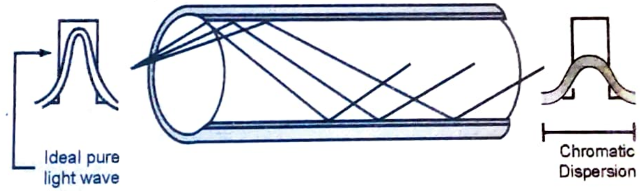


Fig. 2.2.2 : Chromatic or Intramodal dispersion

- It may occur in all types of optical fibers (single-mode , multimode, step-index and graded-index). It is caused by the dispersive properties of the fiber material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion).

2.2.2 Intermodal Dispersion or Mode Dispersion

- Modal dispersion is a distortion mechanism occurring in multimode fibers and other waveguides, in which the signal is spread in time because of different propagation velocity for all modes.
- Since light rays entering the fiber at different angles of incidence will go through different paths/modes. Some of these light rays will travel straight through the center of the fiber (axial mode) while others will repeatedly bounce off the cladding/core boundary to zigzag their way along the waveguide, as illustrated below with a step-index multimode fiber.
- Whenever there is a bounce off, modal dispersion (or intermodal dispersion) happens. The longer the path is, the higher the model dispersion will be.
- For example, the high-order modes (light entering at sharp angles) have more model dispersion than low-order modes (light entering at smaller angles).

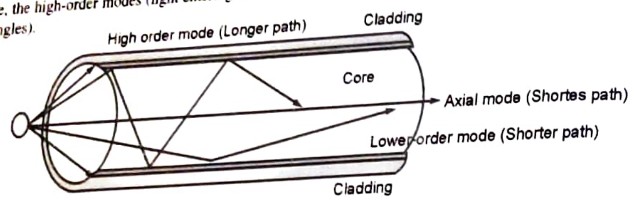


Fig. 2.2.3 : Intermodal or Mode dispersion

- Multimode fiber can support up to 17 modes of light at a time, suffering much modal dispersion. Whereas, if the fiber is a single mode fiber, there will be no modal dispersion since there is only one mode and the light enters along the fiber axis (enters in axial mode) without bouncing off the cladding boundary.
- However, things are different if one uses a graded-index multimode fiber. Although the light rays travel in different modes as well, the modal dispersion will be greatly decreased because of the various light propagation speeds.

For multimode step index fiber

In case of multimode step index fiber we will consider the two modes :

- These are fastest and slowest mode. The light ray which is passing along the axis of optical fiber is corresponding to the fastest mode. While the light ray which is incident at the interface of core cladding layer is having slowest mode.

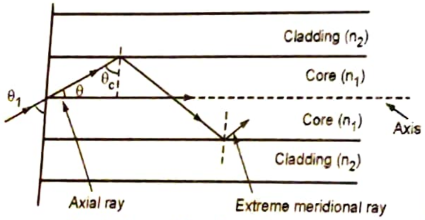


Fig. 2.2.4 : Axial and meridional rays

- This ray is making an incidence angle equals to the critical angle. This arrangement is as shown is Fig. 2.2.4. This ray making an angle equal to critical angle is called is extreme meridional ray.
- The axial ray requires less time to reach at the output. This time period is given by,

$$T_{min} = \frac{\text{distance}}{\text{velocity}}$$

$$T_{min} = \frac{L}{(c/n_1)} \quad \ldots(2.3.1)$$

Here, L = Length of fiber optic cable;
c = Speed of light
n_1 = Refractive index of core layer

- As compared to this fiber, the multimode graded index fiber is having less dispersion.

Overall dispersion in optical fiber

The overall dispersion in the fiber is the summation of intermodal and intramodal dispersion. The total rms pulse broadening σ_T is given by,

$$\sigma_T = \left[\sigma_c^2 + \sigma_n^2\right]^{1/2} \quad \ldots(2.3.2)$$

Here, σ_c = Intramodal broadening
σ_n = Intermodal broadening

2.2.3 Polarization Mode Dispersion (PMD)

- **Definition :** It is defined as the difference in the propagation times (that is, pulse broadening) between two orthogonally polarized components of the light pulse in a single-mode fiber.

- Due to variations in the fiber core diameter in a practical single- mode fiber, two orthogonal, linearly polarized modes are supported that are degenerate.

- The variations in the fiber core diameter may be due to the presence of non-uniform stress, bends, stress, etc. along the length of the fiber. Propagation times are different because of difference in the group velocities among light rays, which give rise to pulse broadening or pulse dispersion.
- Polarization mode dispersion (PMD) represents the polarization dependence of the propagation characteristics of light waves in optical fibers.
- In optical fibers, there is usually some slight difference in the propagation characteristics of light waves with different polarization states. When the light is defined as an energy wave or energy region, it possesses 2 mutually perpendicular axes, namely the electromotive force and magneto motive force(mmf).
- The moment the energy inside these two axes transfers at different speeds in a fiber, PMD occurs. Shown in Fig. 2.2.5.
- PMD has small effects for networks whose link speeds are lower than 2.5 Gbps even if the transmission distance is longer than 1000 km. However, as speeds increase, it becomes a more important parameter especially when the speeds are over 10 Gbps.
- In addition to the major inherent PMD caused by the glass manufacturing process, the PMD can be affected or caused by the fiber cabling, installation and the operating environment of the cable as well.
- If β_x and β_y are different propagation constants and λ is the optical wavelength then the modal birefringence (B_F) of fiber is given by,

$$B_F = \frac{\beta_x - \beta_y}{\frac{2\pi}{\lambda}}$$

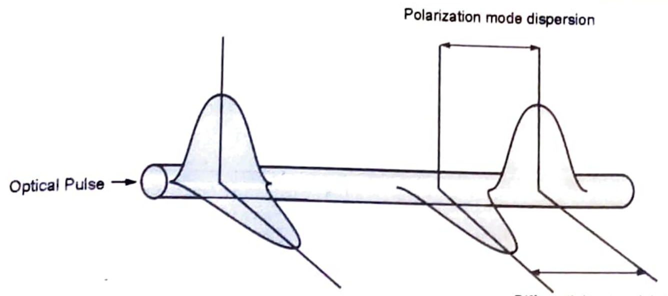


Fig. 2.2.5 : Polarization Mode Dispersion

2.2.4 Other Types of Dispersion

Two types of chromatic dispersion are :

1. Material dispersion as a function of wavelength
2. Waveguide dispersion or modal dispersion

(a) Material Dispersion

- Material dispersion is a delay-time dispersion caused by the fact that the refractive index of the glass material changes in accordance with the change of the signal frequency (or wavelength).
- Material dispersion is caused by the wavelength dependence of the index of refraction. It affects pulse broadening because each wavelength component of an initial pulse travels at a different group velocity.
- This phenomenon is observed due to variation of core refractive index [n(λ)] as a function of optical wavelength propagating in the fiber.
- Different modes travel in fiber with different group velocity (V_g) where V_g is dependent on refractive index [n(λ)].
- The source used in Tx has spectral width and hence, various spectral components of a given mode will travel at different velocities depending on the wavelength (λ).
- The propagation constant (β) of propagating wave is

$$\beta = \frac{2\pi n\,(\lambda)}{\lambda}$$

- Material Dispersion is denoted by D_m. It is given as,

$$D_m = \frac{\sigma_m}{L\,\sigma_\lambda} \quad \ldots(2.2.1)$$

Here, σ_m = Width of pulse spread because of material dispersion
L = Length of fiber optic cable
σ_λ = Spectral width of source

In terms of wavelength,

$$D_m = \frac{\lambda\,S_0}{4}\left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

Here S_0 = Zero dispersion slope
X_0 = Zero dispersion wavelength

It is also given by,

$$D_M = M_D = \frac{\lambda}{c}\left|\frac{d^2 n}{d\lambda^2}\right|,$$

Here λ = Operating wavelength
c = Speed of light
n = Refractive index of core

(b) Waveguide Dispersion

- In the optical waveguide, various modes are travelling together. Some rays are travelling along the axis in the fiber and other rays travel at different angles with respect to axis.
- The critical angle ray is extreme ray travelling in the fiber as shown below. They have different travel times over a fiber length L as some rays are following zig-zag path.
- Hence, different rays in a multimode fiber have different transmission time. The outer extreme ray takes maximum travel time (T_{max}) whereas the ray passing through axis takes minimum time (T_{min}).
- The time difference in the propogation over a length L is responsible for waveguide or model dispersion. This is negligible in Single Mode fiber but significant in Multi Mode fiber. Shown in Fig. 2.2.6.

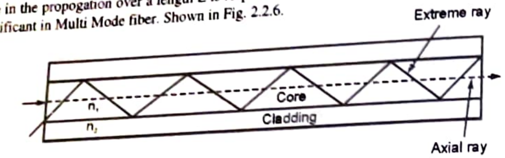


Fig. 2.2.6 : Wave Guide Dispersion

- In case of single mode fiber, the waveguide dispersion given as,

$$Dw = \frac{\sigma w}{L \cdot \sigma\lambda} \quad ...(2.2.2)$$

Here, σw = Width of pulse spread because of waveguide dispersion

L = Length of optic fiber $\quad \sigma\lambda$ = Spectral width of source

2.2.5 Comparison between Intra and Intermodal Dispersion

UQ. Compare between intermodal and intramodal dispersion.

MU - Q. 1(a), May 16, Dec. 16, Q. 1(a)(b), May 17, May 18, May 19 Dec. 18, 5 Marks

Sr. No.	Intermodal dispersion	Intramodal dispersion
1.	It takes place in all types of fibers.	It takes place only in multimode fibers.
2.	It is also called as material dispersion.	It is also called as modal dispersion.
3.	Less pulse broadening.	More pulse broadening.
4.	This type of dispersion occurs because different colors of light travel with different speed.	This type of dispersion occurs due to variation in group delay for individual mode at a single frequency.

2.3 DISPERSION COMPENSATION TECHNIQUES

- *Dispersion compensation plays a very significant role in controlling the overall chromatic dispersion of a system. It is used to avoid excessive temporal broadening of ultra-short pulses or the distortion of signals.*
- *Without dispersion compensation, each symbol gets broadened so much that it would strongly overlap with a number of neighbored symbols.*
- Dispersion bound the bandwidth or information carrying capacity of a fiber. The most commonly employed techniques for dispersion compensation are as follows:
  1. Dispersion Compensating Fibers (DCF)
  2. Fiber Bragg Grating (FBG)
  3. Electronic dispersion compensation (EDC)
  4. Optical Phase Conjugation Techniques
  5. Digital Filters Digital filters

2.3.1 Dispersion Compensating Fibers (DCF)

- The idea of utilizing dispersion compensating fibers (DCF) introduced in 1980.The components of DCF are not easily affected by temperature, wide bandwidth.
- DCF is a loop of fiber having a negative dispersion equal to the dispersion of the transmitting fiber. It can be put at either beginning or end known as pre compensation, post compensation, and symmetrical compensation.
- As the transmission bandwidth is fixed, allowable dispersion values are in inverse proportion to the square of transmission speed and therefore the faster the transmission bit rate speed, the more important the compensation of accumulated chromatic dispersion over transmission bandwidth.
- The very first technique was dsf (dispersion shifted fiber) which was used to compensate the dispersion at 1550 nm wavelength but in this window effects such as FWM (four wave mixing) and XPM (cross phase modulation) and FWM adversely affects the transmission.

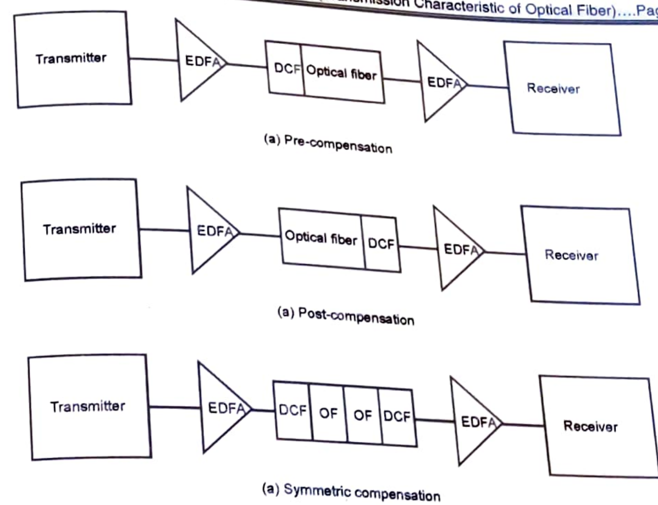


Fig. 2.3.1 : Types of Dispersion Compensation Fiber

- Then a new type of fiber established to compensate all the effects and was strong to nonlinear phase noise. This is known as dispersion compensation fiber (DCF). Shown in Fig. 2.3.1. This type of fiber can be employed before the optical fiber called pre-compensation or after the optical fiber called post compensation. When the DCF is employed between the amplifiers along with combination of both techniques called symmetrical compensation.
- The DCF technique is widely used with the WDM systems using single mode fiber having the large effective areas and low bit error rate. This is a very good and reliable technique but it gives high insertion loss and introduces nonlinear distortion when the input power is high. Other fibers like dispersion managed cables (DM) and reverse dispersion fiber (RDF) are employed which are similar to DCF.

2.3.2 Fiber Bragg Grating (FBG)

- A fiber Bragg grating (FBG) is an optical fiber in which the index of refraction within the core of the fiber changes along its length, from high-index to low-index.
- The modulation of the refractive index causes an FBG to act like a mirror that reflects certain wavelengths and transmits others. Shown in Fig. 2.3.2.

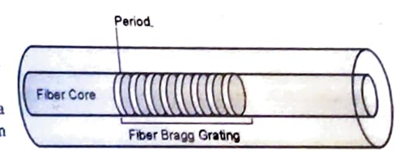


Fig. 2.3.2 : Fiber Bragg Grating

- The wavelength that an FBG reflects depends on the spacing between the high index and low index regions within the fiber.
- The distance between two high-index regions within the fiber is called the "period of the FBG", denoted as Δ . FBGs preferentially reflect light at the Bragg wavelength "λ_B", defined by

$$\lambda_B = 2n_{eff}\,\Delta,$$ where n_{eff} is the average effective refractive index of the fiber.

- A FBG is a periodic modulation of the refractive index in the core of an optical fiber. Often a FBG is visualized a 'barcode' like pattern with approximately 20,000 stripes inscribed over 10 millimeter fiber length.

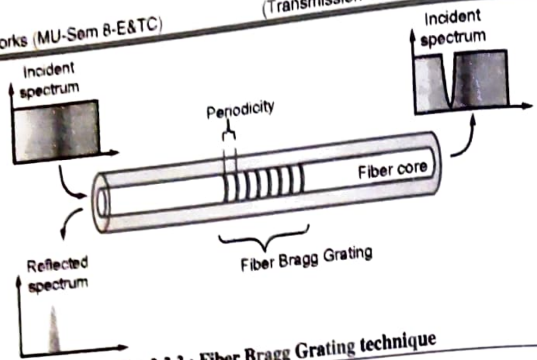


Fig. 2.3.3 : Fiber Bragg Grating technique

- The periodic pattern in the fiber (i.e. FBG) reflects a specific wavelength of light depending on the periodicity of the grating.
- Changing the periodicity, e.g. by elongating the fiber at the location of the FBG, will result in a shift of the reflected wavelength. Such an FBG is used to measure all different kinds of physical parameters, e.g. temperature, pressure, strain and is often used in harsh environments where conventional (electrical) sensors fail.
- The strength of the reflection depends on how large the index modulation is. This modulation of the refractive index within an FBG can be a steady periodic change or a variable "quasi-periodic" change.
- If an FBG contains regions with different periods, a single optical fiber can contain multiple "mirrors," causing different wavelengths of light to reflect from different positions along the fiber.
- The change in the period of the index modulation along the length of the fiber does not need to be abrupt. FBGs that feature a period that changes smoothly along the fiber length are called "chirped" FBGs or simply CFBGs. CFBGs can have elaborate period profiles.

2.3.3 Electronic Dispersion Compensation (EDC)

- The electronic signal processing used for distortion equalization in optical transmission systems started during 1991.
- Electronic dispersion compensation technique used the electronics in the optics for chromatic dispersion. There is a direct detection process in the receiver that the chromatic dispersion i.e. the linear distortion becomes nonlinear distortion after optic-electronic conversion. This technique is used in equalization circuits.
- Electronic equalization techniques are used in this method. Since there is direct detection at the receiver, linear distortions in the optical domain, e.g. chromatic dispersion, are translated into non linear distortions after optical-to-electrical conversion. It is due to this reason that the concept of nonlinear cancellation and nonlinear channel modeling is implemented.
- For this mainly feed forward equalizer (FFE) and decision feedback equalizers (DFE) structures are used. EDC slows down the speed of communication since it slows down the digital to analog conversion. A schematic of the EDC receiver is shown in Fig. 2.3.4.
- Block A contains the optical components. An AMZI biased at quadrature with a delay of 5 ps acts as a 200 GHz periodic filter, which is compatible with the ITU frequency grid.
- The outputs are detected by two 12GHz-bandwidth photodiodes, which generate the two different electrical signals V_1 and V_2, each dependent on the instantaneous frequency ($\Delta\omega$) and amplitude (A) of the received optical field. The functionality of blocks B, C and D may each be implemented using either analogue or digital electronics.
- Block B produces the two electrical signals

$$V_A = V_1 + V_2 \text{ and}$$

$$V_F = (V_1 - V_2)/(V_1 + V_2)$$

which are proportional to the power and instantaneous frequency of the received optical field.

- In Block C, a local oscillator is modulated in power and frequency using VA and VF respectively to give a replica of the received signal.
- Finally a dispersive transmission line equalizes the group delay. This is followed by square law detection and EFEC decoding which are used to recover the original signal from the electronic replica of the received signal.
- At the receiver, the signal was pre-amplified and filtered using a 42GHz-bandwidth third-order Gaussian optical filter.
- The amplified signal passed through the optical part of the receiver and the two voltages VA and VF were produced in blocks A and B.

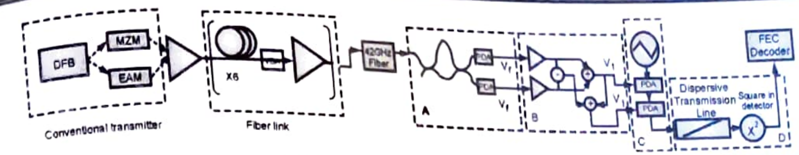
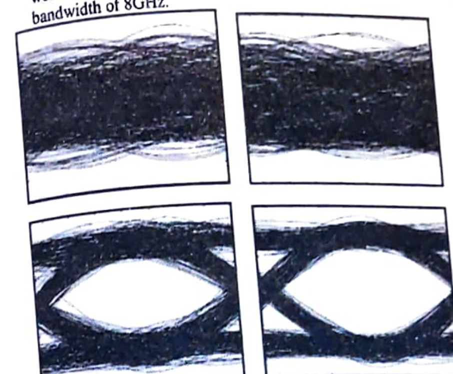


Fig. 2.3.4 : Electronics Dispersion Compensation

- Block C comprised a high frequency oscillator within the simulation bandwidth and ideal power and frequency modulators were used to generate the down-shifted signal. Linear dispersion and the overall circuit frequency response were implemented in Block D with a total single sided bandwidth of 8GHz.



(a) EYE Diagram before compensation
(b) EYE Diagram after compensation
Fig. 2.3.5

2.3.4 Optical Phase Conjugation Techniques

- The effective compensation of waveform distortion due to chromatic dispersion in a single mode fiber was demonstrated using an optical phase conjugate (OPC) wave generated by no degenerate forward four waves mixing in a zero dispersion single mode fiber.
- After transmission of 5 Gb/s and 6 Gb/s continuous phase FSK (CPFSK) signal through a dispersive single mode fiber, distortion compensation was confirmed by measuring bit error rate characteristics and observing heterodyne detected eye patterns.
- The schematic setup is combines transmitter, a fiber span consisting of two links, a mid span phase conjugator, and receiver. A 10 Gb/s NRZ data stream is sent over a first lossless fiber link where dispersion is set to D = 16 ps/nm/km. The peak power is set to – 3 dBm. After 1000 km the eye diagram shows a completely closed eye, due to the accumulation of chromatic dispersion.

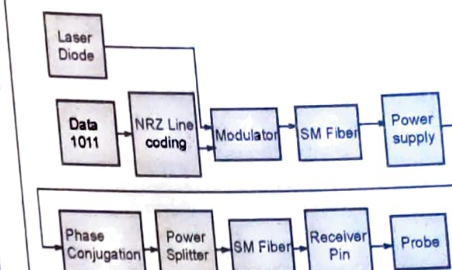
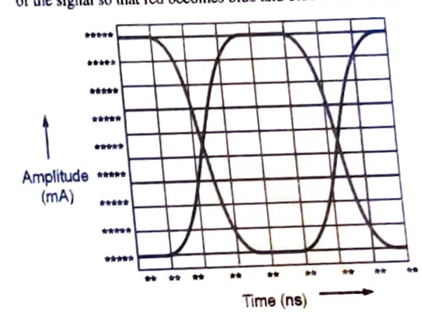
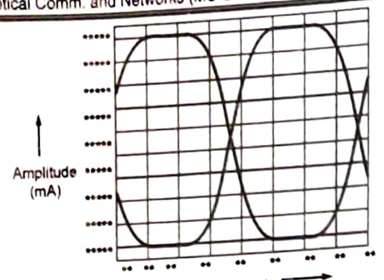


Fig. 2.3.6 : Schematic diagram of Optical phase conjunction techniques

- Then the signal goes through an OPC, and then to another 1000 km long fiber link. At the output of the second link the received eye is completely open. When a phase conjugator placed between two identical spools of fiber can completely compensate second order dispersion.
- The signal is being dispersed in the first half of the span resulting in distorted pulse shapes with the blue light leading the red light. This dispersed signal is then being phase conjugated. The OPC reverses or inverts the optical spectrum of the signal so that red becomes blue and blue becomes red.



(a) Eye diagram of transmitted signal
Fig. 2.3.7



(b) Eye diagram of received signal

Fig. 2.3.7

2.3.5 Digital Filters

- Digital filters using Digital Signal Processing (DSP) can be used for compensating the chromatic dispersion.
- They provide fixed as well as tunable dispersion compensation for wavelength division multiplexed system. Popularly used filter is lossless all-pass optical filters for fiber dispersion compensation, which can approximate any desired phase response while maintaining a constant, unity amplitude response.
- Other filters used for dispersion compensation are bandpass filter, Gaussian filters, Super-Gaussian filters, Butterworth filters and microwave photonic filter.
- The system of interest, as shown in Fig. 2.3.8, is based on a 10 Gb/s, non return to zero (NRZ) on off keying (OOK) pulse, optical source (λ_0) 1.55 μm, length of SMF (L) is 160 km with dispersion (D) is 17 ps/nm-km, square law detector and second order of Butterworth low pass filter.
- All pass filter (APF) can be used to equalize a phase of a signal without introducing any amplitude distortion. The design of an optical all pass filter (OAPF) is based on APF. From the transfer function of OAPF, the phase response of the OAPF can be made arbitrarily close to any desired phase response.
- If designed correctly, are potentially very important devices in optical transmission systems since they can be compensate any dispersion in very small structures with very low loss.

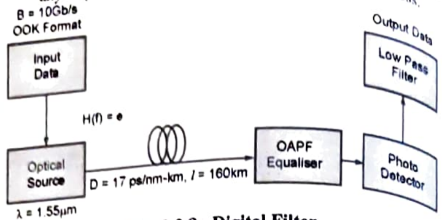


Fig. 2.3.8 : Digital Filter

- Since the OAPF response is periodic, the free spectral range (FSR) of OAPF can be chosen so that the OAPF response coincides with each channel passband providing dispersion compensation for multiple channels in a WDM system.
- OAPFs have the potential for providing the highly stable third order dispersion compensation in optical fiber transmission systems. However, there is a tradeoff between the maximum group delay and the bandwidth as well as the FSR.
- Performance may be improved by increasing the number of stages or designing the poles and zeros of OAPF closer to the unit circle, however this poses practical problem such as increased in fiber complexity, unacceptable losses and unacceptable ripple of GVD which OAPF produces. OAPF is a lossless device, but in cases where several stages are used the finite insertion loss in practical devices needs to be considered.
- In practice there will be loss associated to the OAPF in the form of coupling losses, however if the loss is small over the bandwidth of interest, then the degradation in the performance will be minimal. This paper considered the ideal lossless case. OAPFs are linear systems which have a unity magnitude response over all frequencies. The phase response of OAPFs varies with frequency.
- Fig. 2.3.9(a) and (b) shows the eye diagram at the receiver, at 160 km of SMF. The eye diagram of the system without the OAPF has an eye opening of 2% compared to a fully opened eye. The small eye opening will result in higher bit error rate (BER).

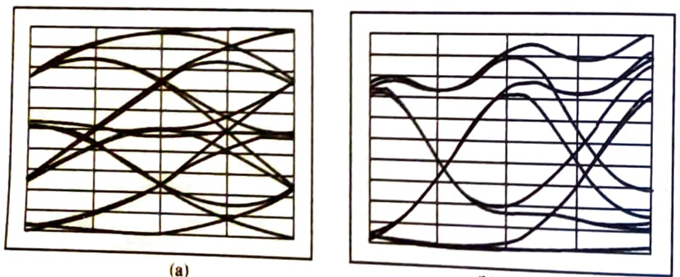


Fig. 2.3.9 : Eye Diagram at 160km

2.4 SOLVED PROBLEMS ON DISPERSION

Ex. 2.4.1 : Calculate the pulse spreading caused by material dispersion for a graded-index multimode fiber working at $\lambda = 850$ nm if the fiber's length is 100 km and the light source is an LED whose rms spectral width is 70 nm.

The given parameters are : Dispersion slope,

$S_0 = 0.097\ \text{ps/nm}^2\cdot\text{km}$ and $\lambda_0 = 1343$ nm. Is the dispersion value positive or negative in this example ? State the interpretation of negative sign.

Soln. :

Given : $\lambda = 850$ nm, L = 100 km ;

rms spectral width = 70 nm

S_0 = dispersion slope = $0.097\ \text{ps/nm}^2 \cdot \text{km}$.

$\lambda_0 = 1343$ nm

The unit of term λS_0 is $\text{nm}\cdot\dfrac{\text{ps}}{\text{nm}^2\cdot\text{km}} = \dfrac{\text{ps}}{\text{nm}\cdot\text{km}} = \dfrac{10^{-12}}{\text{nm}\cdot\text{km}}$

The total first order dispersion for the fiber at the wavelengths

$$\text{Dispersion (M)} = \frac{\lambda S_0}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

$$= \frac{850\times0.097\times10^{-12}}{4}\left[1-\left(\frac{1343}{850}\right)^4\right]$$

$$= \frac{8.5\times10^2\times9.7\times10^{-14}}{4}\left[1-(1.58)^4\right]$$

$$= \frac{8.5\times9.7\times10^{-12}}{4}\left[1-6.23\right]$$

$$= 20.6\times10^{-12}\left[-5.23\right]$$

$$= \mathbf{-107\ ps\ nm^{-1}\ km^{-1}}$$

The dispersion exhibits a negative sign due to influence of the waveguide dispersion.

RMS pulse broadening = Spectral width × L × M

$= 70\times100\ \text{km}\times107\ \text{ps nm}^{-1}\ \text{km}^{-1}$

$$\text{Pulse broadening /km} = \frac{70\times\cancel{100}\times107}{10\cancel{00}}\ \text{ps km}^{-1}$$

$= 749\ \text{ps km}^{-1} = \mathbf{0.749\ ns\ km^{-1}}$

Ex. 2.4.2 : A multimode graded index fiber exhibits total pulse broadening of 0.1 μs over a distance of 10 km. Assuming RZ format, estimate :

(i) The maximum possible bandwidth on the link assuming no intersymbol interference;

(ii) The pulse dispersion per unit length;

(iii) The bandwidth - length product for the fiber.

Soln. :

Given : Multimode graded index fiber pulse broadening = 0.1 μs over 10 km

(i) The maximum possible optical B.W. which is equivalent to the maximum possible bit rate [for RZ pulses] assuming no ISI may be obtained is

$$B_{opt} = B_T = \frac{1}{2\tau}$$

$$= \frac{1}{2\times0.1\times10^{-6}} = \mathbf{5\ MHz}$$

(ii) The dispersion / unit length $= \dfrac{0.1\times10^{-6}}{10}$

$= 10$ ns/km

(iii) The bandwidth length product length product

$B_{opt}\times L = 5\ \text{MHz}\times10\ \text{km}$

$= 50\ \text{MHz}\cdot\text{km}$

Ex. 2.4.3 : A multimode graded index fiber exhibits total pulse broadening of 0.1 μsec over a distance of 15 km. Calculate :

(i) The maximum possible bandwidth on the link assuming no inter symbol interference.

(ii) The pulse dispersion per unit length.

(iii) The bandwidth Length Product

Soln. :

Given : Pulse broadening = 0.1 μsec over 15 km

(i) The maximum possible bandwidth assuming no intersymbol interference

$$B_{opt} = B_T = \frac{1}{2\tau}$$

$$= \frac{1}{2\times0.1\times10^{-6}} = \mathbf{5\ MHz}$$

(ii) Dispersion / unit length $= \dfrac{0.1\times10^{-6}}{15} = \mathbf{6.66\ ns / km}$

(iii) The bandwidth length product

$B_{opt}\times L = 5\ \text{MHz}\times15\ \text{km}$

$= \mathbf{75\ MHz\cdot km}$

Ex. 2.4.4 : A multimode graded index fiber exhibits total pulse broadening of 0.1 μsec over a distance of 12 km.

Calculate :

(i) The maximum possible bandwidth on the link assuming no inter symbol interference;

(ii) The pulse broadening per unit length ;

(iii) The bandwidth-length product of the fiber.

Soln. :

Given : Multimode graded index fiber pulse

broadening = 0.1 μsec

distance = 12 km

(i) For no overlapping of light pluses down on an optical fiber link, the digital bit rate B_T must be equal to the reciprocal of broadened pulse duration (2τ).

$$B_{opt} = B_T = \frac{1}{2\tau}$$

$$= \frac{1}{2 \times 0.1 \times 10^{-6}} = \mathbf{5\ MHz}$$

(ii) The dispersion / unit length

$$= \frac{0.1 \times 10^{-6}}{12} = \mathbf{8.33\ ns/km}$$

(iii) The bandwidth length product

$$B_{opt} \times L = 5\ MHz \times 12\ km$$

$$= \mathbf{60\ MHz{\cdot}km}$$

Ex. 2.4.5 : Determine the maximum bit rate for RZ and NRZ encoding for the following pulse spreading constants and cable lengths.

(i) $\Delta t = 10$ ns/mm L = 100 m

(ii) $\Delta t = 20$ ns/m, L = 1000 m

(iii) Δt 2000 ns/m, L = 2 km

☑ **Soln. :**

To find maximum bit rate for RZ and NZR encoding.

(i) $\Delta t = 10$ ns / mm

Since 1 mm $= 10^{-6}$ km

$\therefore\ \Delta t = 10\ ns \times 10^{6}$ / km = 10 ms / km

Total dispersion for 100 m = 0.1 km is 1 ms

Thus pulse broadening of 1 ms over a distance of 100 m

The maximum possible optical bandwidth

= maximum possible bit rate for RZ is

$$B_{opt} = B_T = \frac{1}{2\tau}$$

$$= \frac{1}{1 \times 10^{-3}} = 1000\ MHz = \mathbf{1\ GHz}$$

For NRZ **500 MHz**

(ii) $\Delta t = 20$ ns / m

$1m = 10^{-3}$ km

$= 20\ ns / 10^{-3}$ km = 20 µs / km

Total dispersion for 1000 m or 1 km is 20 µs.

$$B_{opt} = B_T = \frac{1}{2\tau} = \frac{1}{20 \times 10^{-6}}$$

$$= \frac{100 \times 10^{4}}{20}$$

$$= 50 \times 10^{3} = \mathbf{50\ kHz}$$

For NZR – **25 kHz**

(iii) $\Delta t = 2000$ ns / m

$= 2000\ ns / 10^{-3}$ km = 2 ms / km

$\therefore$ Total dispersion over a length of 2 km is

$$\frac{2\ ms}{km} \times 2\ km = 4\ ms$$

$$\therefore B_{opt} = B_T = \frac{1}{2 \times 4 \times 10^{-3}} = \frac{10^3}{8} = 125$$

for NRZ = **62.5**

Ex. 2.4.6 : A 5 km optical link consists of multimode step index fiber with a core refractive index of 1.5 and a relative refractive index difference of 1%. Estimate :

(i) The delay difference between the slowest and fastest modes at the fiber output.

(ii) The rms pulse broadening due to intermodal dispersion on the link.

(iii) The maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion.

(iv) The bandwidth-length product corresponding to (iii).

☑ **Soln. :**

Given : Fiber link = 5 km

Multimode SIF $n_1 = 1.5$, $\Delta = 1\%$

(i) The delay difference is given by,

$$\delta_{TS} = \frac{L n_1 \Delta}{c}$$

$$= \frac{5 \times 10^{3} \times 1.5 \times 0.01}{3 \times 10^{8}} = \mathbf{250\ ns}$$

(ii) The rms pulse broadening due to intermodal dispersion is

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\,c}$$

$$= \frac{5 \times 10^{3} \times 1.5 \times 0.01}{2\sqrt{3} \times 3 \times 10^{8}} = \mathbf{72.25\ ns}$$

(iii) The maximum bit rate may be estimated by,

$$B_{T\,max} = \frac{0.2}{\sigma_s}$$

$$= \frac{0.2}{72.25\ ns} = \mathbf{2.77\ M\ bit/s}$$

(iv) Assuming RZ pulses, bandwidth length product is

$$B_{opt} \times L = 2.77\ MHz \times 5\ km$$

$$= \mathbf{13.85\ MHz \cdot km}$$

Ex. 2.4.7 : A multimode SIF has NA of 0.3 and a core R.I of 1.45. The material dispersion parameters for the fiber is 250 ps nm^{-1} km^{-1} which makes material dispersion the totally dominating intramodular dispersion mechanism.

Estimate :

(i) The total RMS pulse broadening per km when fiber is used with a LED source of RMS spectral width of 50 nm.

(ii) The corresponding BW length product for the fiber.

☑ **Soln. :**

Given : SIF, NA = 0.3 Core R.I. $n_1 = 1.45$,

$M_D = 250$ ps nm^{-1} km^{-1}

We have to find RMS pulse broadening/km rms spectral width = 50 nm and BW × L

(i)
$$\sigma_m (1km) \simeq \frac{\sigma_\lambda L \lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right| = \sigma_\lambda L M_D$$

$$= 50\ nm \times 1 \times 250\ ps\ nm^{-1}\ km^{-1}$$

$$= 12500\ ps \cdot km^{-1}$$

$$= \mathbf{12.5\ ns\ km^{-1}}$$

The rms pulse broadening per km due to intermodal dispersion

$$\sigma_s (1\ km) = \frac{L (N A)^2}{4\sqrt{3}\, n_1 c}$$

$$= \frac{10^{3} \times 0.09}{4\sqrt{3} \times 1.45 \times 3 \times 10^{8}}$$

$$= 29.898\ ns\ km^{-1}$$

$$\boldsymbol{\sigma_s (1\ km) = 29.9\ ns\ km^{-1}}$$

(ii) The total rms pulse broadening/km is

$$\sigma_T = (\sigma_m^2 + \sigma_s^2)^{1/2}$$

$$= (12.5^2 + 29.9^2)^{1/2}$$

$$\boldsymbol{\sigma_T = 32.4\ ns\ km^{-1}}$$

(iii) The bandwidth length product

$$B_{opt} \times L = \frac{0.2}{\sigma_T} = \frac{0.2}{32.4 \times 10^{-9}}$$

$$B_{opt} \times L = \mathbf{6.1728\ MHz \cdot km}$$

Ex. 2.4.8 : Consider an optical link consisting of a 10 km long step index fiber with a core index $\eta_1 = 1.49$ and relative refractive index difference = 1%.

(i) Find the delay difference at the fiber end between the fastest and the slowest modes.

(ii) Find the r.m.s. pulse broadening caused by intermodal dispersion.

(iii) Calculate the maximum bit rate B_T that can be transmitted on this fiber.

(iv) Assuming Max bit rate = Bandwidth, what is the BW distance product of this fiber.

☑ **Soln. :**

(i) The delay difference between fastest and slowest mode is,

$$\delta_{Tmod} = \frac{L n_1 \Delta}{c}$$

$$= \frac{10 \times 10^{3} \times 1.49 \times 0.01}{3 \times 10^{8}}$$

$$= \frac{1.49 \times 10^{2}}{3 \times 10^{8}} = \mathbf{496.67\ ns}$$

(ii) rms pulse broadening is,

$$\sigma_{pulse} = \frac{L n_1 \Delta}{2\sqrt{3}\,c}$$

$$= \frac{1}{2\sqrt{3}} \times \frac{10 \times 10^{3} \times 1.49 \times 0.01}{3 \times 10^{8}}$$

$$= \frac{1}{3.464} \times \frac{1.49 \times 10^{2}}{3 \times 10^{8}}$$

$$= \mathbf{143.37\ ns} \quad \ldots(1)$$

(iii) Maximum bit rate is,

$$B_{Tmax} = \frac{1}{2\tau} = \frac{1}{2\,\delta_{Tmod}}$$

$$= \frac{1}{2 \times 496\ ns} = \frac{10^{9}}{2 \times 496}$$

$$\mathbf{B_{Tmax} = 1.008\ Mb/s}$$

(iv) Using pulse broadening formula,

$$B_{Tmax} = \frac{0.2}{\sigma_s} = \frac{0.2}{143.4\ ns} = 1.39\ Mb/s$$

Bandwidth length product is,

$$B_{opt} \times L = 1.39\ MHz \times 10\ km$$

$$B_{opt} \times L = \mathbf{13.9\ MHz\ km}$$

UEx. 2.4.9 **MU - May 2013, 7 Marks**

A train of light pulses is transmitted through a 400 m fiber with $n_{core} = 1.4$ and $n_{clad} = 1.36$. Sketch the output pulses for

(i) A pulse rate of 10×10^{6} pulses per sec (10 Mb/s)

(ii) A pulse rate of 20×10^{6} pulses per sec (20 Mb/s)

Also find dispersion per km. for each assume that the input pulse is of near zero width.

☑ **Soln. :** Given : Length of fiber = 400 m

n_1 = core = 1.4, n_2 = cladding = 1.36

$\therefore\ \Delta$ = relative refractive index

$$= \frac{n_1^2 - n_2^2}{2 n_1^2} = \frac{1.96 - 1.849}{2 \times 1.96}$$

$$= \frac{0.111}{3.92} = 0.028$$

(i) The delay difference $\delta T_s = \frac{L n_1 \Delta}{C}$

$$= \frac{400 \times 1.4 \times 0.028}{3 \times 10^{8}}$$

$$= \frac{15.68}{3 \times 10^{8}} = \mathbf{52.57\ nsec.}$$

(ii) The rms pulse broadening due to intermodal dispersion is given by

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\, C} = \frac{400 \times 1.4 \times 0.028}{3 \times 10^5 \times 2 \times \sqrt{3}}$$

$\therefore$ σ_s = **15.176 nsec**

(iii) The bit rate = 10 Mb/s

The maximum bit rate B_T max $= \frac{0.2}{\sigma_s} = \frac{0.2}{15.176 \times 10^{-9}}$

B_T max = **13.17 Mbits/sec**

Thus is the maximum bit rate assuming no pulse overlap with 10 Mb/s there will be no pulse overlap but with 20 Mb/s, this rate is more than $B_{T\max}$ therefore there will be pulse overlap.

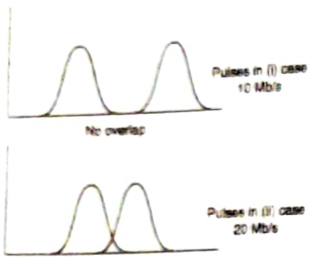


Fig. P. 2.4.9

(iv) Dispersion /km $= \frac{15.1 \times 10^{-9}}{400 \times 10^{3}}$

$= \frac{15.1 \times 10^{-9}}{400 \text{ km}}$ = **37.94 ns km^{-1}**

2.5 DISPERSION MEASUREMENT

- Dispersion measurements give an indication of the distortion to optical signals as they propagate down optical fibers.
- The delay distortion which, for example, leads to the broadening of transmitted light pulses limits the information-carrying capacity of the fiber.
- The measurement of dispersion allows the bandwidth of the fiber to be determined. Therefore, besides attenuation, dispersion is the most important transmission characteristic of an optical fiber. There are three major mechanisms which produce dispersion in optical fibers (material dispersion, waveguide dispersion and intermodal dispersion).
- The importance of these different mechanisms to the total fiber dispersion is dictated by the fiber type. For instance, in multimode fibers (especially step index), intermodal dispersion tends to be the dominant mechanism, whereas in single-mode fibers intermodal dispersion is nonexistent as only a single mode is allowed to propagate.
- In the single-mode case the dominant dispersion mechanism is chromatic (i.e. intramodal dispersion).
- The dominance of intermodal dispersion in multimode fibers makes it essential that dispersion measurements on these fibers are performed only when the equilibrium mode distribution has been established within the fiber, otherwise inconsistent results will be obtained.
- Therefore devices such as mode scramblers or filters must be utilized in order to simulate the steady state mode distribution.
- Dispersion effects may be characterized by taking measurements of the impulse response of the fiber in the time domain, or by measuring the baseband frequency response in the frequency domain.
- If it is assumed that the fiber response is linear with regard to power, a mathematical description in the time domain for the optical output power *Po*(*t*) from the fiber may be obtained by convoluting the power impulse response *h*(*t*) with the optical input power *Pi*(*t*) as:

$$P_o(t) = h(t) * P_1(t) \qquad \text{...(2.5.1)}$$

- where the asterisk * denotes convolution. The convolution of *h*(*t*) with *Pi*(*t*) shown in Eq. (2.4.1.) may be evaluated using the convolution integral where:

$$P_o(t) = \int_{-\infty}^{\infty} P_1(t-x)\, h(x)\, dx \qquad \text{...(2.5.2)}$$

- In the frequency domain the power transfer function *H*(ω) is the Fourier transform of *h*(*t*) and therefore by taking the Fourier transforms of all the functions in Eq. (2.5.2) we obtain:

$$P_o(\omega) = H(\omega)\, P_1(\omega) \qquad \text{...(2.5.3)}$$

2.5.1 Time Domain Measurement

- The most common method for time domain measurement of pulse dispersion in multimode optical fibers is illustrated in Fig. 2.5.1. Short optical pulses (100 to 400 ps) are launched into the fiber from a suitable source (e.g. A1GaAs injection laser) using fast driving electronics.
- The pulses travel down the length of fiber under test (around 1 km) and are broadened due to the various dispersion mechanisms. However, it is possible to take measurements of an isolated dispersion mechanism by, for example, using a laser with a narrow spectral width when testing a multimode fiber. In this case the chromatic dispersion is negligible and the measurement thus reflects only intermodal dispersion.

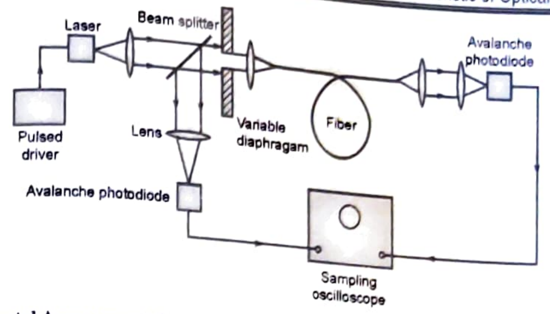


Fig. 2.5.1 : Experimental Arrangement for making multimode fiber dispersion measurement in the time domain

- The pulses are received by a high-speed photodetector (i.e. avalanche photodiode) and are displayed on a fast sampling oscilloscope. A beam splitter is utilized for triggering the oscilloscope and for input pulse measurement.
- After the initial measurement of output pulse width, the long fiber length may be cut back to a short length and the measurement repeated in order to obtain the effective input pulse width.
- The fiber is generally cut back to the lesser of 10 m or 1% of its original length. As an alternative to this cut-back technique, the insertion or substitution method similar to that used in fiber loss measurement can be employed. This method has the benefit of being nondestructive and only slightly less accurate than the cut-back technique.
- The fiber dispersion is obtained from the two pulse width measurements which are taken at any convenient fraction of their amplitude. If P_i (t) and P_o (t) of Eq. (2.5.1) are assumed to have a Gaussian shape then Eq. (2.6) may be written in the form:

$$\tau_o^2(3\text{ dB}) = \tau^2(3\text{ dB}) + \tau_i^2(3\text{ dB}) \qquad \text{...(2.5.4)}$$

- where τ_I (3 dB) and τ_o(3 dB) are the 3 dB pulse widths at the fiber input and output, respectively, and τ (3 dB) is the width of the fiber impulse response again measured at half the maximum amplitude. Hence the pulse dispersion in the fiber (commonly referred to as the pulse broadening when considering the 3 dB pulse width) in ns km−1 is given by:

$$\tau(3\text{ dB}) = \frac{(\tau_o^2(3\text{ dB}) - \tau_1^2(3\text{ dB}))^{1/2}}{L} \text{ ns km}^{-1} \qquad \text{...(2.5.5)}$$

where τ(3 dB), τ_I(3 dB) and τ_o(3 dB) are measured in ns and *L* is the fiber length in km.

- It must be noted that if a long length of fiber is cut back to a short length in order to take the input pulse width measurement, then *L* corresponds to the difference between the two fiber lengths in km.

2.5.2 Frequency Domain Measurement

- Frequency domain measurement is the preferred method for acquiring the bandwidth of multimode optical fibers. This is because the baseband frequency response H(ω) of the fiber may be obtained directly from these measurements using Eq. (2.5.1) without the need for any assumptions of Gaussian shape, or alternatively, the mathematically complex deconvolution of Eq. (2.5.1) which is necessary with measurements in the time domain.
- Thus the optical bandwidth of a multimode fiber is best obtained from frequency domain measurements.
- One of two frequency domain measurement techniques is generally used. The first utilizes a similar pulsed source to that employed for the time domain measurements shown in Fig. 2.5.2.
- However, the sampling oscilloscope is replaced by a spectrum analyzer which takes the Fourier transform of the pulse in the time domain and hence displays its constituent frequency components.
- The experimental arrangement is illustrated in Fig. 2.5.2. Comparison of the spectrum at the fiber output Po(ω) with the spectrum at the fiber input P_i (ω) provides the baseband frequency response for the fiber under test where:

$$H(\omega) = \frac{P_o(\omega)}{P_i(\omega)} \qquad \text{...(2.5.6)}$$

- The second technique involves launching a sinusoidally modulated optical signal at different selected frequencies using a sweep oscillator. Therefore the signal energy is concentrated in a very narrow frequency band in the baseband region, unlike the pulse measurement method where the signal energy is spread over the entire baseband region.

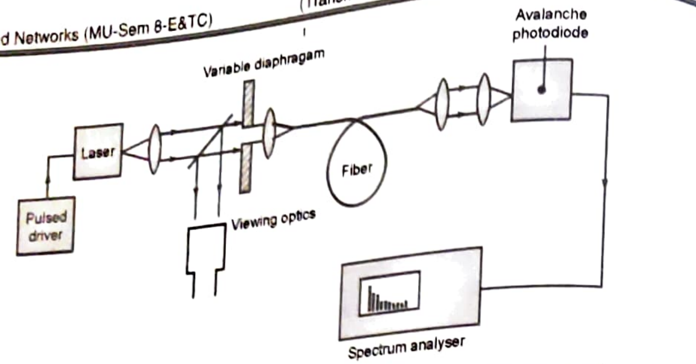


Fig. 2.5.2 : Experimental Setup for making fiber dispersion measurement in the frequency domain using a pulsed laser Source

2.6 DISPERSION AND PULSE BROADENING IN DIFFERENT OPTICAL CABLES

- The dispersion is related to the broadening of input signal at the output side. Because of this the considerable error is produced at the output side.

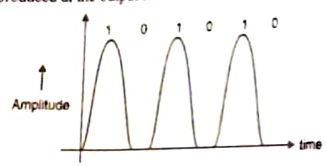


Fig. 2.6.1 : Input signal

- Consider the case of digital data transmission using fiber optic cable. The amplitude of input signal is as shown in Fig. 2.6.1. Here the input signal required to transfer is 101010. The amplitude levels and the time duration for each bit is as shown in Fig. 2.6.1.
- Now the widening of input signals takes place as these signals starts passing through an optical fiber. So at the output side the mixing of signals takes place. It is difficult at the output side to distinguish the different signal. Thus an interference of symbols takes place at the output side. This is called as inter symbol interference. This is as shown in Fig. 2.6.2.

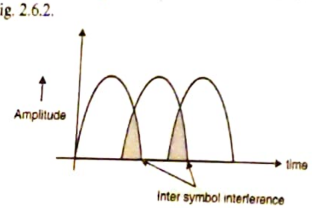


Fig. 2.6.2 : Output signal

- Now let 'T' be the duration of input pulse. Then if we want to avoid the dispersion taking place in an optical fiber then we will have to limit the bit rate (B_T). This is given by,

$$B_T \leq \frac{1}{2T} \quad ...(2.6.1)$$

- Here 2T represents the time period of broadened pulse when the dispersion occurs.
- Thus Equation (2.6.1) gives the value of maximum bit rate. Whenever an input signal is passing through an optical fiber then the dispersion depends on the distance between input and output side. The dispersion also depends on the time period.
- In case of multimode step index fiber, the dispersion is maximum. So the bandwidth is comparatively less. It is of the order of tens of megahertz.
- The dispersion in multimode graded index fiber is as shown in Fig. 2.6.3.

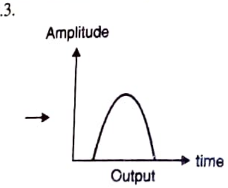


Fig. 2.6.3 : Dispersion is multimode step index fiber

- As compared to multimode step index fiber; in case of multimode graded index fiber less dispersion is obtained. This is shown in Fig. 2.6.4.
- The minimum dispersion occurs in case of single mode step index fiber. So higher transmission bandwidth are obtained. This bandwidth is in the range of gigahertz.
- The dispersion in case of single mode step index fiber is as shown in Fig. 2.6.5. We know that in order to transfer on electrical signal using fiber optic communication, it is necessary to convert this signal into optical signal.

- For this the light source is used. That means we are getting an optical signal corresponding to an electrical signal. Thus an electrical signal modulates an optical source. This modulated signal excites all the modes at an input of fiber optic cable.
- Each mode contain an optical component. And this optical component is equivalent to an electrical component of input signal. Whenever there optical components are travelling through the optical fiber then a time delay is produced for each optical component. Thus there is a group delay per unit length.
- This is denoted by (T_g)

$$\therefore T_g = \frac{L}{V_g} \quad ...(2.6.2)$$

Here L = Length of optical fiber, V_g = Group velocity

Here group velocity is the velocity with which the energy of pulse is passing through an optical fiber.

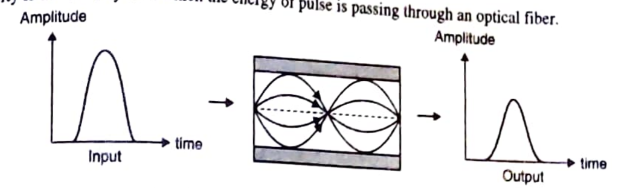


Fig. 2.6.4 : Dispersion in multimode graded index fiber

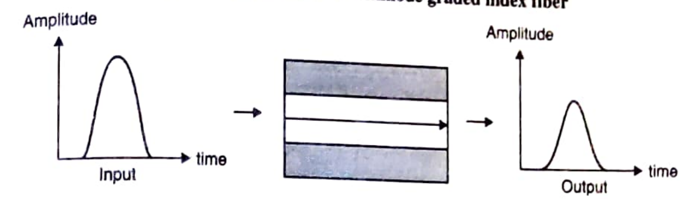


Fig. 2.6.5 : Dispersion for single mode step index fiber

This group velocity is given by

$$V_g = \frac{c}{\left(\frac{d\beta}{dk}\right)} \quad ...(2.6.3)$$

Here, c = Velocity of light in free space

$= 3 \times 10^8$ m/s

β = Propagation constant along axis of optical fiber

and K = Constant $= \frac{2\pi}{\lambda}$

Where, λ is the wavelength of optical signal.

- Since the group velocity given by Equation (2.6.3) contains the factor k; this velocity depends on the wavelength.
- Thus every spectral component takes different amount of time period to reach at the output. Because the group velocity depends on the wavelength. It means the group delay given by Equation (2.6.2) is also dependent of the wavelength.
- Thus all the spectral components are not reaching at the output at the same time. This gives spreading of pulse at the output side.
- The amount by which the spreading of optical signal takes place is called as dispersion. It is given by,

$$D = \frac{1}{L}\frac{d}{d\lambda}(T_g) \quad ...(2.6.4)$$

Here, L = Length of optical fiber,

λ = Wavelength of optical signal

T_g = Group delay.

2.6.1 Pulse Broadening in Multimode Fibers

UQ. Derive the expression for pulse spreading in intermodal dispersion. **MU – Q. 2(a), Dec. 16, 10 Marks**

- The intermodal distortion is dominant in multimode fibers. Basically, in multimode fibers, the maximum pulse broadening is the difference between the travel time of the highest mode (T_{max}) and the travel time of lowest mode (T_{min}).
- If L is the length of optical cable then the delay difference is given by,

delay difference = δ_{Tmod}

$$= T_{max} - T_{min} = \frac{L n_1^2}{c n_2} - \frac{L n_1}{c}$$

Here, n_1 = Refractive index of core layer

n_2 = Refractive index of cladding

and c = Speed of light

$$\delta_{Tmod} = \frac{L n_1}{c}\left[\frac{n_1}{n_2} - 1\right]$$

$$\delta_{Tmod} = \frac{L n_1}{c}\left[\frac{n_1 - n_2}{n_2}\right] \quad ...(2.6.5)$$

- Now, the relative refractive index difference is given by,

$$\Delta = \frac{n_1 - n_2}{n_2}$$

$$\delta_{Tmod} = \frac{n_1 \Delta L}{c} \quad ...(2.6.6)$$

- The numerical aperture is related to 'Δ' as,

$$NA = n_1\sqrt{2\Delta}$$

$$n_1^2 \cdot 2\Delta = (NA)^2$$

$$\Delta = \frac{(NA)^2}{2 n_1^2} \quad ...(2.6.7)$$

- Putting Equation (2.6.7) in Equation (2.6.6) we get,

$$\delta_{Tmod} = \frac{n_1 L}{c}\left[\frac{(NA)^2}{2 n_1^2}\right]$$

$$\delta_{Tmod} = \frac{L (NA)^2}{2 n_1 c} \quad ...(2.6.8)$$

- The rms pulse broadening due to intermodal dispersion is given by,

$$\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}\, c} \quad ...(2.6.9)$$

- The maximum bit rate is given by,

$$B_{Tmax} = \frac{0.2}{\sigma_s} = \frac{1}{2\,\delta_{Tmod}} \quad ...(2.6.10)$$

- The rms pulse broadening due to material dispersion is,

$$\sigma_m = \frac{\sigma_\lambda L}{c\lambda}\left|\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right| \quad ...(2.6.11)$$

Here L = Length of optical cable

λ = Operating wavelength

n_1 = Refractive index of core layer

σ_λ = rms spectral width of source

- *In terms of dispersion parameter (M_D) it is given by,*

$$\sigma_m = \sigma_\lambda L M_D \quad ...(2.6.12)$$

2.6.2 Bandwidth Distance Product

- The manufactures normally specify bandwidth of optical cable as the bandwidth length product. It is expressed in terms of MHz · km or GHz · km.
- This parameter can be used to predict the effective bandwidth for other fiber lengths. This parameter is also useful for comparing the performance of different types of fiber optic cables.
- The amount of pulse dispersion per unit length gives limit for bit rate of optical cable. The broadening of pulse increases with increase in the length of optical cable; that means the bandwidth of fiber optic cable is inversely proportional to the length.
- For multimode step index and graded index fibers, ideal values of bandwidth length product are 20 MHz · km and 1 GHz · km respectively.
- For optical cables; bandwidths are usually specified over 1 km length of cable and it is optical bandwidth.
- Optical bandwidth is slightly greater than electrical bandwidth.

2.7 DISPERSION MANAGEMENT

- Dispersion management is a somewhat wider term than **dispersion compensation**, even though both are often used in the same way.
- Strictly, dispersion compensation is a method for canceling the **chromatic dispersion** of some optical element(s). While dispersion management more broadly refers to the application of customized dispersion qualities to improve a function.

2.7.1 Need of Dispersion Management

UQ. Explain SPM and how it is mitigated by GVD. **MU - Q. 4(a), Dec. 16, 8 Marks**

- Dispersive and non-linear factors frequently cause fiber-optic communication systems' performance to be constrained. Although optical amplifiers used as in-line amplifiers throughout the fiber link do compensate for fiber losses, the dispersion issue is only made worse.
- The degradation of the transmitted optical signals due to dispersion gets accumulated when cascaded arrangement of in-line optical amplifiers is employed along the fiber-optic transmission link. Dispersion-induced pulse broadening imposes the serious limitations on the system performance.

Limitation on System Performance

- Let understand limitations on limiting bit rate and fiber bandwidth.
- For example, in 50 km length of the optical fiber cable, the transmitted bit rate is limited to about 2 Gbps due to dispersion.

- In fact, it is the available bandwidth of the fiber that delivers the dispersion-limited transmitted bit rate. The 3-dB fiber bandwidth is given by

$$f_{3dB} = \frac{0.188}{|D|\, L\sigma_\lambda}$$

where, | D | denotes the dispersion parameter, expressed in ps/(km–nm);

L represents the length of the in km, and σ_λ represents the root-mean-square value of the spectral width of the optical source in nanometers.

When $\sigma_\lambda = 0$, the optical source spectral width very much smaller than the bit rate.

- At typical values of σ_λ = 1 nm or 5 nm, the bit rate reduces with fiber length for given value of D = 16 ps/(km–nm).
- Let us denote $\sigma_\lambda \cong |D|\, L\, \sigma_\lambda$ which signifies the extent to which the optical pulse is broadened due to dispersion. Then, we can write

$$f_{3dB} = \frac{0.188}{\sigma_D}$$

- The bit rate R_B is related with 3-dB fiber bandwidth by the relationship, $R_B \le 1.33\, f_{3dB}$. This implies that the bandwidth of the optical fiber gives a rough estimate of the maximum transmitted bit rate that is possible in a typical optical fiber communication link which is dispersion-limited.
- If a laser is used having narrow linewidth as the optical source, then it is possible to minimize the effects of Group-Velocity Dispersion (GVD) considerably.
- Even if we operate it at the wavelength closer to the fiber's specified zero-dispersion wavelength, λ_{ZD}, then also the effects of GVD can be minimized.
- Practically, it is not always possible to operate the system at zero-dispersion wavelength.
- Because the 'standard' single-mode fiber (SMF) has λZD = 1310 nm, whereas 3G terrestrial fiber–optic systems (which use distributed feedback laser as optical source) operate near λ = 1550 nm.
- In this optical band of standard single-mode fiber (SMF), the specified dispersion parameter is about 16 ps/(km–nm). In case the transmitted bit rate exceeds 2 Gbps, then the **Group Velocity Dispersion(GVD)** severely limits the system performance.

Reasons also that justify the need for dispersion management such as:

(a) For a directly-modulated distributed-feedback (DFB) laser, the relationship between the bit rate (R_B) and maximum transmission distance (L) can be expressed as

$$L < \frac{1}{4 R_B |D| \sigma_\lambda}$$

where, σ_λ is the RMS spectral width of the dispersion-induced (mainly due to frequency chirping) optical pulse.

For Example :

Let σ_λ = 0.25 nm, D = 10 ps/(nm–km), then L = 42 km only is obtained at operating bit rate R_B = 2.5 Gbps. Since optical amplifiers can be spaced at a much larger spacing than L = 42 km, for dispersion-limited fiber-optic systems, dispersion management technique must be employed.

(b) The use of an external modulator along with DFB laser can significantly improve the system performance. This helps to minimize spectrum broadening of transmitted pulse, if any, due to frequency chirping.

The $\sigma_\lambda = 0$ provides the upper limit of the dispersion provided standard fibers are used with this type of optical transmitters. The upper limit of the transmission distance L is then given by

$$L < \frac{1}{16\,|\beta_2|\,R_B^2}$$

where, β_2 represents the GVD coefficient and is related with D such that

$$\beta_2 = -D\frac{\lambda^2}{2\pi c}$$

- Typical value of β_2 = –20 ps2/km at l = 1550 nm. Then, for required bit rate R_B = 2.5 Gbps, L < 500 km. This shows a considerable improvement over directly modulated DFB laser ($L \approx$ 42 km only).

The following observations can be made:

- When in-line optical amplifiers are used along with the optical fiber, then even this amount of dispersion is quite considerable.
- When the transmitted bit rate RB is increased beyond 2.5 Gbps (10 Gbps, say), then the GVD limited transmission distance decreases to 30 km only which is extremely less as envisaged for the use of in-line optical amplifiers.

Conclusion

- It is concluded that the standard single-mode fibers have relatively considerable amount of GVD which may result into degradation in the performance of 1550 nm fiber-optic systems at higher bit rate (usually 10 Gbps or more).
- For improving the overall performance of optical fiber communications networks, dispersion-management techniques must be implemented.

2.7.2 Pre Compensation Dispersion Management

- Pre-compensation dispersion management techniques are implemented prior to the occurrence of the dispersion. Since the dispersion occurs within the optical fiber as the optical signals propagate through them, it implies that these techniques are applied at the optical transmitter end.
- In pre-compensation, the characteristics of optical pulses are suitably modified (changing the spectral amplitude) before they are launched into the optical fiber.

- The nature and extent of modification is to counter the impact of GVD (within the fiber) exactly, and the shape of the output optical pulse will be retained as that of the input optical pulse. Fig. 2.7.1 shows a functional block schematic of pre-compensation dispersion management technique.

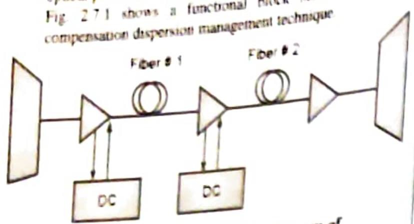


Fig. 2.7.1 : Functional Block diagram of Pre-Compensation Dispersion(DC)

2.7.3 Post Compensation Dispersion Management

- In post-compensation dispersion management techniques, actual implementation is carried out at the optical receiver end so as to cancel out the phase factor which is responsible for dispersion-induced degradation of the optical signal during its propagation in the fiber.
- Fig. 2.7.1 shows a functional block schematic of post-compensation dispersion management technique.
- Various post-compensation techniques are discussed below :
  - Electronic Equalization
  - Opto-Electronic Equalization
  - Optical Equalization

(a) Electronic Equalization

- Electronic equalization is the most practical dispersion compensation approach for coherent fiber-optic communication systems in which direct detection is used at the receiver end. Group-velocity dispersion (GVD) within the optical receiver can be compensated by employing electronic equalization techniques.
- It is assumed that the optical fiber behaves like a linear system. GVD-degraded optical signal can be equalized at the receiver. The compensation for dispersion is relatively easy when a heterodyne receiver detects the received optical signal.
- In a heterodyne receiver, the received optical signal is first converted into an intermediate frequency while preserving the amplitude and phase information of the signal.
- The original signal is recovered by passing it through a microwave bandpass filter.
- GVD cannot be compensated using a linear electronic equalization technique, because photodetector reacts to an optical signal power only, and all phase information is lost. Hence a linear electronic equalization circuit cannot retrieve a spread optical pulse.
- In order to achieve this the use of the non-linear equalization technique. The dispersion-degraded optical signal can be recovered by it.
- For example, the decision threshold at the receiver is changed as per the preceding bit. The analog waveform is examined over number of bit intervals around the bit under consideration before making a decision about a given bit.
- The major drawbacks of electronic equalization techniques are :
- The requirement of electronic logic devices and circuits operating at the required bit rate.
- Exponential increase in their complexity as the number of bits representing spread optical pulse increases. This happens due to resultant GVD-induced spreading of the optical pulse.
- Due to this, there is a restriction to operation for transmission distance (limited up to a few dispersion lengths) as well as transmission bit rate (relatively quite low) with electronic equalization post-compensation dispersion management techniques.

(b) Opto-Electronic Equalization

- An opto-electronic equalization technique for post dispersion management is based on a *transversal filter*.
- In opto-electronic equalization, the received optical signal is split into several branches by a power splitter used at the optical receiver. Each branch uses fiber-optic delay lines that introduce variable delays.
- Photodetectors having variable sensitivity are used in each branch, which convert the optical signal into corresponding photocurrent. The photocurrent from each branch is then summed and applied to the decision-making circuit for final recovery of the signal.
- Using this technique, the transmission distance can be extended three-fold for a fiber-optic communication system operating at 5 Gbps.

(c) Optical Equalization

- We know that the optical signal is affected by GVD through the spectral phase. So, an optical equalization filter, having its transfer function such that it cancels the phase and suitable for compensating the GVD exactly, will be able to restore back the original optical signal.
- But there cannot be such an ideal optical filter. However, there can be an arrangement of using an optical filter along with an optical amplifier in such a way that both GVD as well as fiber attenuation can be compensated together.
- If the bandwidth of an optical filter is much smaller than bandwidth of optical amplifier, then amplifier noise can also be reduced. Interferometry optical filter and fiber gratings filters are two most popular methods of optical equalization for dispersion managements

2.8 TRANSMISSION LOSSES IN OPTICAL FIBER

- Various types of optical signal transmission losses in optical fiber cables result in less output power than required, thereby reducing the overall system capacity, net transmission bandwidth, transmission data rate, and operating efficiency.
- Losses in optical fibers result from attenuation in the material itself and from scattering, which causes some of the light to strike the intersection of the fiber and the cladding at an incidence angle less than the desired critical angle of incidence so as to produce total internal reflection, so vital for propagation of optical signals within the optical fiber cable.
- Some parts of the incident light may get refracted from the core-cladding interface and enter into the cladding, which does not contribute to the transmission of optical signals through the optical fiber cable.

2.8.1 Types of Transmission Losses

- There are many factors are influenced by the waveguide structure, and the composition of the basic material (including preparation and purification) used for the fiber core and cladding which lead to attenuation and losses in the fiber.
- Some of the major transmission losses in optical fiber cables may be categorized as follows :
  1. Absorption loss
  2. Scattering (Linear and non-linear) losses
  3. Bending losses
  4. Coupling losses

2.8.2 Absorption Losses

(MU - May 2011, May 2013, May 2014)

- During the fabrication process of fiber optic cable; some of the transmitted light is dissipated as heat. It is called as material absorption loss.
- Absorption loss is directly related with the actual composition of the material and the manufacturing process used. It is analogous to power dissipation in copper cables when electric current flows through it. Fig. 2.8.1 shows absorption losses in fiber.
- The major factors responsible for material absorption loss are as follows :

(i) Intrinsic absorption due to basic atoms of fiber material.

(ii) Extrinsic absorption due to impurity atoms.

(iii) Absorption due to atomic detects in the glass material.

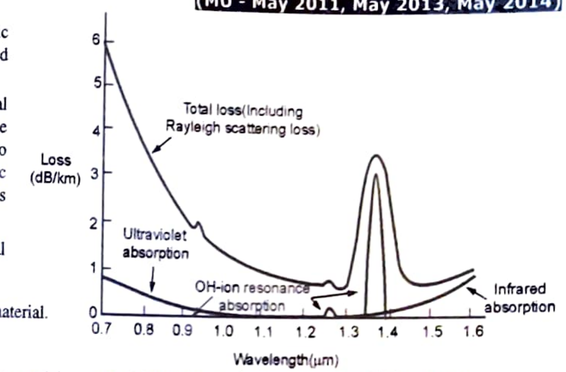


Fig. 2.8.1 : Absorption losses in optical fiber cables

2.8.3 Intrinsic Absorption

- Optical fibers are normally made of silica-based glass material. As light energy passes through the fiber, it may be partially absorbed by this material itself. This is called intrinsic absorption.
- It is mainly caused by the interaction with major components of the fiber material.
- Two factors cause intrinsic losses – Material resonances in UV and IR regions, and Rayleigh scattering. Silica displays heavy absorption in the UV and IR regions and is wavelength-dependent.
- Rayleigh scattering occurs because the EM field excites the irregularities of the molecules of SiO2. There are three factors that contribute to the intrinsic absorption in optical fibers: ultraviolet absorption, infrared absorption, and ion resonance absorption.
- **Ultraviolet absorption.** Ultraviolet absorption is caused by valence electrons in the silica material from which fibers are manufactured. Light ionizes the valence electrons into conduction. The ionization contributes to the transmission losses of the fiber.
- **Infrared absorption.** Infrared absorption occurs due to the absorption of photons by the atoms of the glass core molecules. The absorbed photons are converted to random mechanical vibrations typical of heating.
- **Ion resonance absorption.** During the manufacturing of optical fiber cables, water molecules may get trapped in the glass process. This results in OH– ions in the material, which cause ion resonance absorption. Iron, copper, and chromium molecules also cause ion resonance absorption.
- Fig. 2.8.2 shows attenuation spectra for intrinsic losses in a pure glass.

- In near infrared region, the intrinsic absorption takes place due to the basic fiber material properties.
- Usually, pure silica glass shows low intrinsic absorption.
- At the short wavelengths (ultraviolet region), intrinsic absorption is more dominant.
- In IR region, the absorption peaks are present around the operating wavelength range 700 nm to 1200 nm.
- Basically an interaction between vibrating SiO band and electromagnetic field of optical region takes place and it produces intrinsic absorption.

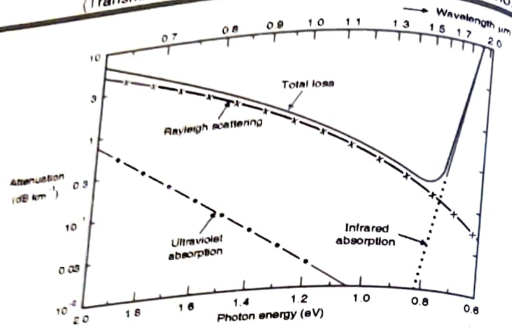


Fig. 2.8.2 : Attenuation spectrum

2.8.4 Extrinsic Absorption

- There may be some impurities within the fiber material which may absorb some part of light energy. This is called **extrinsic absorption**. Common metallic ion impurities in glasses are Cr^{3+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Ni^{2+}, Mn^{3+}, which absorb light energy strongly in the wavelength range of 600–1600 nm.
- Optical fibers are manufactured using melting techniques. During this process, the metallic ions like Cu^{2+}, Fe^{2+}, Ni^{2+} etc. gets deposited. These are metal element impurities, which causes absorption of incoming photons and it is called as extrinsic absorption.
- Another source of extrinsic absorption is the presence of hydroxyl ions, OH-. These molecules enter the silica in the form of water vapor during the manufacturing process.
- Basically OH ions form SiOH bond and it has fundamental absorption at 2700 nm. But the harmonics of these fundamental frequencies at 1380 nm, 1250 nm and 950 nm also produces extrinsic absorption.
- This type of absorption can be reduced by reducing amount of impurities and by reducing the level of OH.

2.9 SCATTERING LOSSES

UQ. Explain the Linear and Nonlinear scattering in optical fiber. **(MU – Q. 2(a), May 19, 10 Marks)**

- Due to the non-uniformities in fiber optic cable; a straight line path of light rays gets deviated. It is referred as scattering. Scattering loss occurs due to transfer of the optical power available within one guided propagation mode into a different mode of propagation.
- The scattering may happen when a light beam propagating within the fiber strikes at an imperfection in a core material and then changes its direction. This scattering effect prevents attainment of desired total internal reflection at the intersection of the fiber core and the cladding. This may result in a power loss.
- Even very minute variation in the specified value of the core refractive index can be considered as an optical obstacle by a propagating light beam. In case of optical cable; some of the optical power from one propagating mode gets transferred to another mode.
- This transfer of power takes place through the leaky or radiation mode. This leaky mode does not continue to propagate within the fiber core, but it is radiated out from the fiber. It produces the scattering loss.
- These losses are mainly caused by interaction of light with density fluctuations within a fiber. This density fluctuations occur when the fiber is produced.
- Basically the glass is composed of randomly connected network of molecules, which is made up of several oxides and it increases the compositional fluctuations.
- In case of multimode fibers, there is a higher dopent concentration and greater compositional fluctuations. Thus scattering losses are more.
- The scattering losses are classified as follows :

Scattering
- Linear scattering
  - Rayleigh scattering
  - Mie scattering
- Non-Linear scattering
  - Stimulated Brillouring scattering
  - Raman scattering

Fig. 2.9.1 : Types of Scattering

2.9.1 Linear Scattering

UQ. Explain linear and non-linear scattering losses in optical fiber. **(MU – Q. 2(a), Dec. 2019, 10 Marks)**

In case of linear scattering; optical power gets transferred from one mode to another mode. But there is no change of frequency on the scattering.

Linear Scattering
- 1. Rayleigh Scattering
- 2. Mie Scattering

Fig. 2.9.1(a) : Linear scattering

2.9.1(a) Rayleigh Scattering

- Intrinsic loss mechanism occurs because of core refractive index fluctuations due to density and compositional variations in the glass lattice on cooling.
- During manufacturing of optical fibers, glass is drawn into long fibers of very small diameter. During this process, the glass is in a plastic state (not liquid and not solid).
- The tension applied to the glass causes the cooling glass to develop permanent submicroscopic irregularities. When light rays propagating down a fiber strike one of these impurities, they are diffracted. Diffraction causes the light to disperse or spread out in many directions.
- Some of the diffracted light continues down the fiber, and some of it escapes through the cladding. The light rays that escape represent a loss in light power.
- The light from the sun is scattered in atmosphere to give the sky color blue. Rayleigh scattering in the glass is having same phenomenon and this scattering takes place in all directions.
- The Rayleigh scattering produces attenuation in the light rays and this attenuation is proportional to $\frac{1}{\lambda^4}$; where λ is optical wavelength. Thus if we transmit the data through the fiber optic cable at lower wavelength; the scattering is minimized.
- The Rayleigh scattering coefficient is denoted by γ_R and it is given by,

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} \cdot n^8 \cdot P^2 \cdot \beta_c \cdot K \cdot T_F$$

Here
λ = Optical wavelength
n = Refractive index of the medium
P = Average photoelastic coefficient
β_c = Isothermal compressibility of fictive temperature
K = Boltzmann's constant
T_F = Fictive temperature

- The temperature at which the glass can reach a state of thermal equilibrium is called as fictive temperature.
- The transmission loss factor is called as transmissivity of the fiber.

It is denoted by ψ and it is related to Rayleigh coefficient as,

$$\psi = e^{-\gamma_R L}$$

where L = Length of optical cable

2.9.1(b) Mie Scattering

Meaning : Scattering of light that occurs because of the presence of some imperfections in the waveguide structure is known as Mie scattering. It can result into considerable attenuation in optical fiber.

- The scattering caused by homogenetics which are comparable in size with guided wavelength; are called as Mie scattering.
- This is a linear scattering, which is always in forward direction.
- The different factors, responsible for Mie scattering are as follows :
  (i) The cylindrical structure of optical cable is not perfect.
  (ii) Imperfections or irregularities in the core cladding interface.
  (iii) Core-cladding refractive index differences, along the fiber are not uniform.
  (iv) There are fluctuations in the core diameter.
  (v) There can be presence of bubble or strain in the fiber material.
- When the dimension of the scattering inhomogeneity exceeds λ/10, then the effect of Mie scattering may be very large, mainly in the forward direction.
- Thus, Mie scattering can cause significant attenuation in optical signal, depending on the fiber material, manufacturing process and design.
- Mie scattering can be reduced by performing following steps :
  (i) Removing imperfections during glass manufacturing process.
  (ii) Controlling the coating of fiber.
  (iii) Increasing the relative refractive index difference between core and cladding.

2.9.2 Non Linear Scattering

UQ. Explain linear and non-linear scattering losses in optical fiber. **(MU – Q. 2(a), Dec. 2019, 10 Marks)**

- When the optical power is transferred from one mode to another mode or same mode, but at different frequencies; then it is called as non linear scattering. This scattering takes place either in forward or backward direction.
- The non-linear scattering mechanism actually produces optical gain but there is a shift in frequency. A non-linear optical effect is one when its parameters are functions of optical signal intensity. Non-linear scattering is also called stimulated scattering when light power essentially increases.
- Stimulated scattering means transfer of light energy from the incident wave to scattered wave at longer wavelength, with the small energy difference being released in the form of phonons.
- A phonon is an elementary particle analogous to a photon but differs from a photon in its quantum properties. Scattered optical waves are also known as Stokes' optical waves.
- Stimulated scattering increases fiber losses at a high level of transmitted optical power (negligible at low power levels).

Stimulated scattering is characterized by three major parameters, namely,

- Threshold power : It is the power of incident light at which loss due to stimulated scattering is 3 dB over fiber length L. The intensity of scattered light goes exponentially when the power of incident light exceeds threshold power.
- Gain coefficient : It refers to peak gain of stimulated scattering at given L. Spectral Bandwidth : Range of frequencies within which scattering is effective.
- When the light is transmitting through the fiber optic cable at a specific wavelength then due to nonlinear scattering there is change in frequency, so it produces attenuation.
- There are two types of nonlinear scattering as follows :

Non Linear Scattering
1. Stimulated Brillouin Scattering (SBS)
2. Stimulated Raman Scattering (SRS)

Fig. 2.9.2 : Non linear scattering

2.9.2(a) Stimulated Brillouin Scattering (SBS)

- When the laser light beam is travelling in optical cable; there are variations in an electric field of this beam. These variations in electric field produces acostic vibrations in the optical cable.
- That means incident photon produces a phonon (vibrational quanta) of acostic frequency as well as it produces a scattered photon.
- This type of scattering is called as stimulated Brillouin scattering and this scattering is usually in opposite direction to that of incoming beam.
- The scattered light looks like upper and lower sidebands, which are separated from the incident light by the modulation frequency.
- During this scattering, a frequency shift is produced which varies with the scattering angle. This frequency shift is maximum in the backward direction.

2.9.2(b) Stimulated Raman Scattering (SRS)

- Raman scattering basically represents inelastic scattering of photons. When a laser light is travelling through optical cable; the spontaneous scattering takes place. In this process; some of the photons are transferred to the near frequencies.
- When the scattered photons lose their energy then it is called as stokes shift and when the scattered photons gain the energy then it is called as **antistoke shift.**
- But if the photons of other frequencies are already present then the scattering of such photons takes place and in this case the two photons are generated. It is called as stimulated raman scattering.

- This scattering is similar to **Stimulated Brillouin Scattering** (SBS) but in SRS instead of acoustic photon, a high frequency optical phonon is created.
- The SRS can occur in both forward and backward direction.
- In SRS, optical threshold power is higher than SBS and it is given by,

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha$$

Here d = Diameter of core layer (in μm)

λ = Operating wavelength

α = Attenuation in dB/km

2.10 BENDING LOSSES

MU - May 2011, May 2012, May 2013, May 2014, May 2015, May 2016

- Bending an optical fiber too sharply can increase fiber losses by causing some of the light to meet the intersection to the fiber core and the cladding at less than the critical angle of incidence, thereby preventing the desired phenomenon of total internal reflection. The Fig. 2.10.1 shows how bending losses happen.

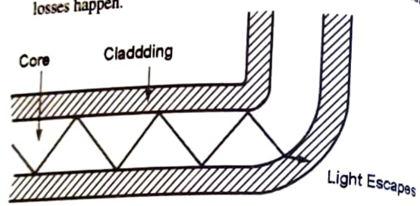


Fig. 2.10.1 : Bending an optical fiber

Losses vary greatly with the type of fiber. For example,

- Plastic fiber may have losses of several hundred decibels per kilometer. Graded-index multimode glass fiber has attenuation figure of about 2–4 dB/km, while single-mode glass fiber has attenuation figure of about 0.4 dB/km or less.
- If there is abrupt change in the radius of curvature of fiber, then the radiation loss takes place from the fiber. If there is sharp bend of the fiber then there is a probability of mechanical failure of optical cable.
- Usually the higher order modes are not tightly bound to the core layer; so due to the sharp bends, the radiation losses of such modes take first. ***There are two types of fiber bending losses shown in Fig. 2.10.2*** :

Fiber Bending Losses
1. Macroscopic bending losses
2. Microbending losses or mode coupling losses

Fig. 2.10.2 : Fiber Bending losses

2.10.1 Macroscopic Bending Losses

UQ. What is macro bending loss ? **MU – Q. 3(a), Dec. 15, Q. 4(c), Dec. 17, 5 Marks**

- There is a radiation loss, when the radius of curvature of bend is greater than the diameter of fiber. Such losses are also called as large radius losses. As the radius of curvature of bend decreases, such losses increase exponentially.
- There is a certain critical value of radius of curvature upto which such losses can be observed. In optical cable; the wavefront perpendicular to the direction of propagation must be maintained; to achieve this the part of mode, which is on the outside of bend has to travel faster.
- It indicates that, the light rays travelling through cladding; should travel faster. It is not possible, so the energy associated with that part is lost through radiation. The macroscopic bending loss is shown in Fig. 2.10.2(a).

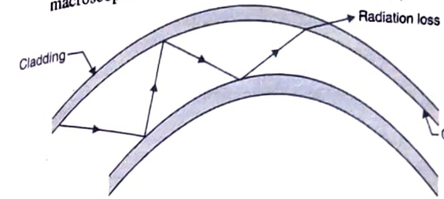


Fig. 2.10.2(a) : Macroscopic Bending Losses

- If R is the radius of curvature bend then, the radiation loss is expressed as,

$$\alpha_R = C_1 e^{(-C_2 R)} \quad ...(2.10.1)$$

Here α_R = Radiation attenuation coefficient

C_1 and C_2 = Constants independent of R

- In case of multimode fibers, at a particular value of radius of curvature; large bending losses occur. This radius of curvature (R_C) is,

$$R_C = \frac{3 n_1^2 \lambda}{4\pi \left(n_1^2 - n_2^2\right)^{3/2}} \quad ...(2.10.2)$$

Here n_1 = Refractive index of core

and n_2 = Refractive index of cladding

- This loss can be reduced if the fiber has large refractive index difference $(n_1 - n_2)$ and if such fibers are operated at shorter wavelengths.
- In case of single mode fibers; the radius of curvature, for which large bending loss occurs is,

$$R_{CS} = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left[2.748 - 0.996 \frac{\lambda}{\lambda_c}\right]^{-3} \quad ...(2.10.3)$$

Here λ_C = Cutoff wavelength for single mode fiber

2.10.2 Micro Bending Losses or Mode Coupling Losses

UQ. Explain with neat diagram. Explain how to minimize microbending losses. **(MU – Q. 3(a), Dec. 15, 5 Marks)**

UQ. What are the sources of micro bending loss ? How it can be overcomed ? **MU – Q. 4(a), May 16, 5 Marks**

UQ. What is micro bending loss ? Explain how to minimize the losses with neat sketch. **MU – Q. 5(b), Dec. 16, 8 Marks**

- **Definition** : It is a minor geometric imperfection present along the fiber axis that actually represents a discontinuity at which Rayleigh scattering can occur.
- Microbends may occur due to differences in the thermal contraction rates for the materials used for the fabrication of the fiber core and the cladding.
- Microbends, sometimes called constant-radius bends, result in radiation losses in the fiber.
- Microbends may also refer to some imperfections in the geometry of the interface boundary between the fiber core and the cladding, as shown in the Fig. 2.10.3.

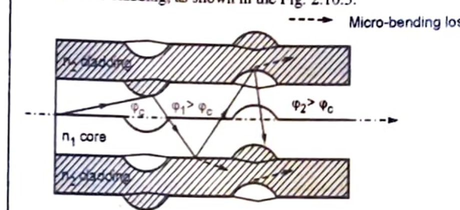


Fig. 2.10.3 : Micro Bending

- The beam, which initially travels at the critical propagation angle, after being reflected at these imperfection points, will change the angle of propagation.
- This results in partial refraction and will leak out of the core, which is called microbending loss. The condition of total internal reflections will not be met at microbends.
- **To minimize the losses following precautions are taken**

(i) While manufacturing the cable; a precise control of core diameter is maintained.

(ii) A compressible jacket is fitted over the fiber, so that when the external pressure is applied then the deformation of jacket takes place and there will not be creation of microbends in the core layer of fiber.

2.11 SOLVED PROBLEMS ON BENDING LOSSES

Ex. 2.11.1 : Estimate the critical bend radius of curvature at which large bending losses would occur for a 62.5/125 μm MMSI fiber with core refractive index of 1.5 relative refractive index difference Δ = 3% and operating wavelength of 820 nm.

☑ Soln. : Relative refractive index difference is given by,

$$\Delta = \frac{n_1^2 - n_2^2}{2 n_1^2}$$

$$\therefore 2 n_1^2 \Delta = n_1^2 - n_2^2$$

$$\therefore n_2^2 = n_1^2 - 2\Delta n_1^2$$

$$= 2.25 - 0.06 \times 2.25$$

$$\therefore n_2^2 = 2.115$$

For multimode fiber, radius of curvature is,

$$R_C = \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{3/2}} \quad \text{...(From Equation (2.10.2))}$$

$$= \frac{3 \times 2.25 \times 820 \times 10^{-9}}{4 \times \pi \times [(1.5)^2 - 2.115]^{3/2}}$$

$$\therefore R_C = 8.879\ \mu m$$

Ex. 2.11.2 : A multimode fiber has a core and clad refractive indices of 1.46 and 1.45 respectively. The critical radius of curvature at which large bending losses occur is 84 μm when the fiber is transmitting light of a particular wavelength. Determine the wavelength of the transmitted light.

☑ Soln. : In multimode fibers, large bending losses occur at a critical radius of curvature R_C.

$$R_C = \frac{3 n_1^2 \lambda}{4\pi \left(n_1^2 - n_2^2\right)^{3/2}}$$

Given, $n_1 = 1.46$; $n_2 = 1.45$;

$$\therefore n_1^2 = 2.13 ; n_2^2 = 2.10$$

$$\text{Now} \quad R_C = \frac{3 n_1^2 \lambda}{4\pi \left(n_1^2 - n_2^2\right)^{3/2}}$$

$$\therefore \lambda = \frac{R_C \times 4\pi \left(n_1^2 - n_2^2\right)^{3/2}}{3 n_1^2}$$

$$= \frac{84 \times 10^{-6} \times 4 \times \pi \times [2.13 - 2.10]^{3/2}}{3 \times 2.13}$$

$$\therefore \lambda = \frac{5486.2 \times 10^{-9}}{6.39}$$

$$\therefore \lambda = 858.5\ nm \simeq \mathbf{859\ nm}$$

2.12 COUPLING TRANSMISSION LOSSES

In optical fiber cables, coupling losses can occur at any of the following **three types of optical junctions:**

1. connections between light source and the fiber at the transmitter end (source-to-fiber power launching)
2. fiber-to-fiber interconnections (to extend the length of the optical fibers)
3. connections between the fiber and the photodetector at the receiver end

- Coupling the fiber to sources and detectors creates losses, especially when it involves mismatches in numerical aperture or in the size of optical fibers.
- In an optical fiber communication system, the losses in splices and connectors can easily be more than in the fiber cable itself. Coupling losses are normally caused by the imperfect physical connections in optical fiber communication system. Junction losses are most often caused by one of the following alignment problems:

1. Lateral or axial misalignment
2. Gap misalignment
3. Angular misalignment
4. Imperfect surface finishes

1. Lateral or axial misalignment

- Lateral or axial misalignment or displacement is the lateral or axial displacement between two pieces of adjoining fiber cables. The Fig. 2.12.1 shows lateral misalignment in optical fibers.

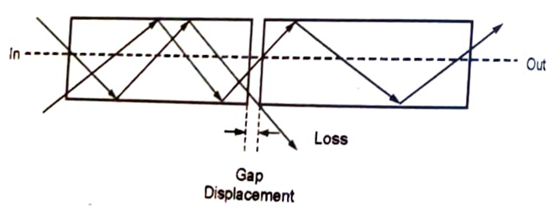


Fig. 2.12.1 : Lateral misalignment in optical fibers

- The amount of coupling loss may vary from a tenths of a dB to several dBs. This loss is generally negligible if the fiber axes are aligned to within 5% of the smaller fiber's diameter.

2. Gap misalignment

- Gap misalignment or displacement occurs when splices are made in optical fibers, and the optical fibers should actually touch. If the fibers are kept far apart, there will be more loss of optical signal. The Fig. 2.12.2 shows gap misalignment in optical fibers.

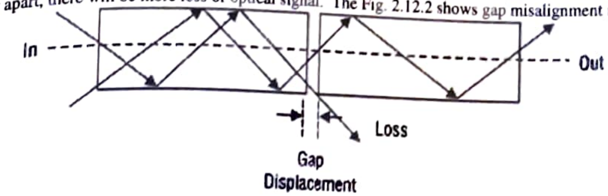


Fig. 2.12.2 : Gap misalignment in optical fibers

- If two fibers are joined with a connector, the ends should not touch because the two ends rubbing against each other in the connector could cause damage to either or both fibers.

3. Angular misalignment :

- Angular misalignment or displacement is shown in Fig. 2.12.3. If the angular displacement is less than 2°, the loss will typically be less than 0.5 dB.

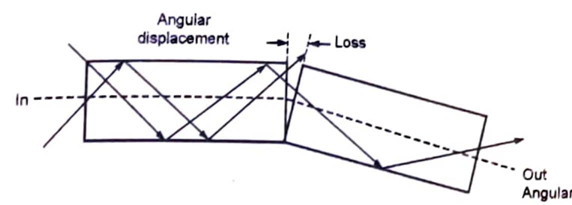


Fig. 2.12.3 : Misalignment in optical fibers

2. **Imperfect surface finish.** Imperfect surface finish is shown in Fig. 2.12.4

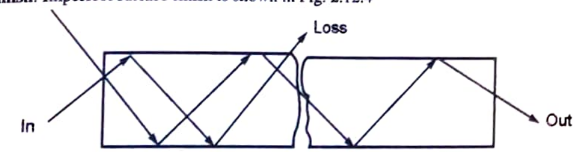


Fig. 2.12.4 : Imperfect surface finish in optical fibers

- If the fiber ends are less than 3° off from perpendicular, the losses will typically be less than 0.5 dB. The ends of the two adjoining fibers should be highly polished and fit together squarely.

2.13 ATTENUATION

(MU - May 2012, Dec. 2013, May 2017

- Basically, attenuation represents the reduction in amplitude of signal. In case of fiber optic cable, attenuation is also called as the transmission loss and it represents the reduction in intensity of light rays propagating through it.
- This attenuation is measured with respect to the distance travelled by light rays in optical cable. Thus, attenuation is basically related to the losses in the signal and in case of fiber optic cable, attenuation is caused due to scattering and absorption of light rays.
- Attenuation is usually expressed in decibel (dB). Let input power launched into the fiber is P_i and the fiber output is P_o then attenuation in dB is,

$$\text{Attenuation } (\alpha) = 10 \log_{10} \frac{P_i}{P_o}$$

- In case of optical cable, attenuation is expressed in terms of decibels per unit length that means dB/km

$$\therefore \alpha_L = 10 \log_{10} \frac{P_i}{P_o}$$

Here α = Attenuation of signal per unit length

L = Length of fiber optic cable

- The signal attenuation produces losses in the system. The different factors responsible for attenuation are as follows :
  (i) Material absorption losses
    (a) Intrinsic (b) Extrinsic
  (ii) Linear scattering losses
  (iii) Losses due to non-linear scattering
  (iv) Losses due to stimulated Raman scattering
  (v) Fiber bending losses
  (vi) Dispersion
    (a) Chromatic dispersion
    (b) Material dispersion
    (c) Waveguide dispersion
    (d) Intermodal dispersion
    (e) Polarized mode dispersion

2.13.1 Attenuation Coefficient

- In the optical fiber, attenuation loss is expressed in terms of decibels per kilometre (dB/km). It is called as attenuation coefficient of optical cable and is given by,

$$\alpha = \frac{10}{z\,(km)} \log\left[\frac{P(0)}{P(z)}\right] \quad ...(2.13.1)$$

- Here $P(z)$ is optical power at a position z from the starting point and $P(0)$ is the power at the starting point.
- For a length 'L' of optical cable if P_{in} is the input power launched into the cable and P_{out} is the output power then,

$$P_{out} = P_{in} e^{-\alpha L} \quad ...(2.13.2)$$

2.13.2 Solved Problems of Attenuation

Ex. 2.13.1 : When the optical power launched into a 10 km length fiber is 100 μW, the optical power at fiber output is 5 μW.

Calculate : (i) Overall signal attenuation in dB.

(ii) Signal attenuation per km

(iii) The overall signal attenuation for a 12 km optical link using same fiber with splices at 1 km interval, each giving attenuation of 0.5 dB.

☑ Soln. :

Length of the fiber = 10 km

Optical power = 100 μW (input)

Optical power = 5 μW (output)

$P_o = 100\ \mu W$, $P(z) = 5\ \mu W$, $z = 10$ km

(i)
$$\alpha = 10 \log \frac{P(0)}{P(z)}$$
$$= 10 \log \frac{5 \times 10^{-6}}{100 \times 10^{-6}}$$
$$\therefore \boldsymbol{\alpha = 13.01\ dB}$$

(ii) α dB / km can also be found by

$$\alpha = \frac{10}{z} \log \frac{P(0)}{P(z)}$$
$$= \frac{10}{10} \log \frac{5 \times 10^{-6}}{100 \times 10^{-6}}$$
$$\therefore \boldsymbol{\alpha = 1.3\ dB / km}$$

(iii) 12 km optical link,

$\therefore$ 11 splices at 1 km interval

$\therefore$ Total splices attenuation = 11×0.5 dB = 5.5 dB

Since = 1.3 dB / km

1.3×12 = 15.6 dB

$\therefore$ Total attenuation = 15.6 + 5.5 = **21.1 dBs**

Ex. 2.13.2 : For a 30 km long fiber attenuation 0.8 dB/km at 1300 nm. If a 200 μW power is launched into the fiber, find the output power.

☑ Soln. :

Given : Fiber length = 30 km, attenuation = 0.8 dB/km, λ = 1300 nm, input power = 200 μW

We have,

$$\alpha = \frac{10}{z} \log\left[\frac{P(0)}{P(z)}\right],$$
$$\therefore 0.8 = \frac{10}{30} \log\left[\frac{200\ \mu W}{P(z)}\right]$$
$$\therefore \log\left[\frac{200\ \mu W}{P(z)}\right] = 2.4$$
$$\therefore \frac{200 \times 10^{-6}}{P(z)} = 10^{2.4}$$
$$\therefore \boldsymbol{P(z) = 0.7962\ \mu W}$$

UEx. 2.13.3 MU : Dec. 2011, 7 Marks

A continuous 12 km long optical fiber link has a loss of 1.5 dB/km : (a) What is the minimum optical power level that must be launched into the fiber to maintain an optical level of 0.3 μW at the receiving end. (b) What is the required input power if the fiber has a loss of 2.5 dB/km.

☑ Soln. :

Given : L = 12 km, $P_o = 0.3\ \mu W$, α_{dB} = loss = 1.5 dB/km

(a) $\alpha_{dB} L = 1.5 \times 12 = \mathbf{18\ dB}$

$$\text{Signal attenuation} = 10 \log_{10} \frac{P_o}{P_z}$$
$$\therefore 18 = 10 \log_{10} \frac{P_o}{0.3 \times 10^{-6}}$$

$$= 10 \log_{10} \frac{P_o}{0.3 \times 10^{-6}}$$
$$\therefore \boldsymbol{P_o = 18.92\ \mu W}$$

(b) if α_{dB} = 2.5 dB/km

$\alpha_{dB} L = 2.5 \times 12 = 30$ dB

$$\text{Signal attenuation} = 10 \log_{10} \frac{P_o}{P_z}$$
$$\therefore 30 = 10 \log_{10} \frac{P_o}{0.3 \times 10^{-6}}$$
$$\therefore \boldsymbol{P_o = 300\ \mu W}$$

UEx. 2.13.4 MU - Dec. 2011, 3 Marks

An optical signal at specific wavelength has a loss of 55% of its power after traveling 3.5 km of fiber. What is the attenuation in dB/km in this fiber.

☑ Soln. :

Given : Power loss = 55% at output

$\therefore$ P (z) = 45% P (o)

P (z) = 0.45 P (o), L = 3.5 km

$$\text{Signal attenuation} = 10 \log_{10} \frac{P(o)}{P(z)}$$
$$= 10 \log_{10} \frac{P_o}{0.45\, P_o}$$

$\alpha_{dB} L$ = 3.46 dB

$\therefore$ Attenuation in dB/km = $\frac{3.46}{3.5}$

α_{dB} = **0.988 dB/km**

UEx. 2.13.5 MU - Dec. 2012, 7 Marks

A 15 km optical fiber link uses fiber with a loss of 1.5 dB/km. The fiber is jointed every kilometer with connectors which give an attenuation of 0.8 dB each. Determine the minimum mean optical power which must be launched into the fiber in order to maintain a mean optical power level of 0.3 μW at the detector.

Soln. :

(i) Connector loss = 0.8 dB/km

$\therefore$ For 15 km length the loss = 0.8 dB/km (15 km)

= 12 dB

(ii) Fiber loss = 1.5 dB/km

$\therefore$ For a length of 15 km, the loss = (1.5 dB/km) (15 km)

= 22.5 dB

Total loss = 12 dB + 22.5 dB

= 34.5 dB

Optical power level at the detector P (z) = 0.3 μW

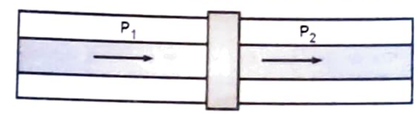
Optical power to be launched into the fiber P (o).

$$x\ dB = 10 \log \frac{P(o)}{P(z)}$$
$$\therefore 34.5 = 10 \log \frac{P(o)}{0.3\ \mu W};$$
$$\log \frac{P(o)}{0.3\ \mu W} = 3.45$$
$$\therefore \frac{P(o)}{0.3\ \mu W} = 2818.3;$$
$$P(o) = 8.455 \times 10^{-4}\ W$$
$$= 0.8455\ mW$$

2.14 MEASUREMENT OF ATTENUATION

2.14.1 Insertion Loss

Fig. 2.14.1 shows the basic concept of insertion loss measurement for a fiber joint or any 2-port optical component.



Insertion loss in dB = $-10 \log_{10} \left(\frac{P_2}{P_1}\right)$

Fig. 2.14.1 : Basic concept of insertion loss

- Insertion loss measurement is carried out using an optical source at the input and an optical power meter at the output. Measured insertion loss values for fiber connectors are usually very small (0.1–0.5 dB).
- Any variations in the optical source output or/and test leads will directly affect the loss measurements. Ideally an optical source is used having a stability ten times better than the lowest value to be measured.
- An optical splitter may be used with a power meter to monitor the reference power output continuously for very high stability.
- It is recommended to use high quality clean test leads with a test-jig fixture for test lead adapters.

- Fig. 2.14.2 shows a typical test set-up for the measurement of an insertion loss of an optical component, such as an optical fiber, 3-dB optical coupler, or any other optical device using optical spectrum analyzer.

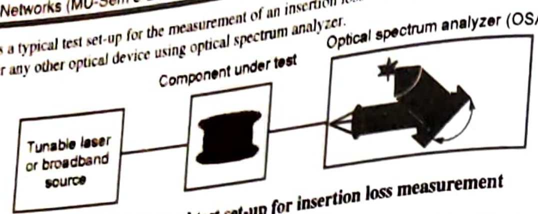


Fig. 2.14.2 : A typical test set-up for insertion loss measurement

- Basically, an optical spectrum analyzer contains a tunable bandpass filter as well as an optical power meter.
- An optical power meter (a calibrated optical to electrical converter without having any wavelength information) can also be used in place of an optical spectrum analyzer provided the output power level of optical source is known.
- The attenuation of the optical fiber and the associated connectors is then given by,

$$A_{dB} = 10 \log \left(\frac{P_1 (\lambda)}{P_2 (\lambda)} \right)$$

where, $P_1(\lambda)$ and $P_2(\lambda)$ represents the launch-power level and received power level, respectively.

- Fig. 2.14.3 depicts insertion loss versus wavelength measurement for component under test with power meter (PM) and optical spectrum analyzer (OSA).
- The test set-up consisting of tunable laser source and power meter (PM) can provide a large measurement range but of fine wavelength resolution (< 200 nm). The major limitation of such a set-up is the presence of broadband noise from the tunable laser source.
- On the other hand, the test set-up comprising of tunable laser source and optical spectrum analyzer (OSA) can provide additional filtering of the broadband noise emission, thereby exhibiting better performance with narrow spectral width.

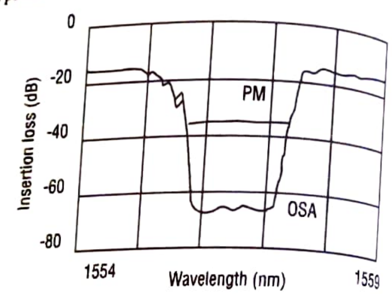


Fig. 2.14.3 : Insertion loss vs wavelength measurement

Note: A measurement test set-up consisting of broadband optical source such as tungsten lamp emitter (that can cover entire wavelength range of optic-fiber communications) along with narrowband high power optical amplifier and optical spectrum analyzer can provide wide wavelength range coverage, fast measurement speed and moderate measurement range.

2.14.2 Return Loss Measurements

- Optical return-loss (RL) measurement is equivalent to optical reflection measurements.
- These measurements can be made using either a dedicated return loss test set-up (for RL ≥ 60 dB), or an Optical time-domain reflectometer (for coarse measurements). It may be noted that inherent RL of the test set-up must be at least 15–20 dB better than the best RL value to be measured. Fig. 2.14.4. illustrates a dedicated test set-up for measurement of optical return-loss.

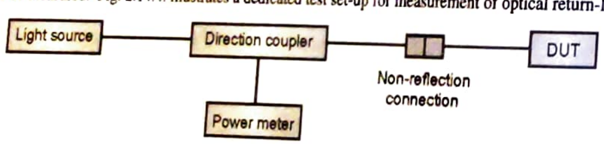


Fig. 2.14.4 : A test set-up for measurement of return loss

- The output of an optical source is first applied to a 3-dB optical directional coupler, then to an optical device under test. The directional coupler separates the reflected signal from the incident signal.
- The optical return loss is measured with the help of optical power meter by comparing the forward and reverse signal levels. Fig. 2.14.5 depicts the return–loss versus wavelength for an optical source such as a tunable laser.
- For measurement of large values of optical return–loss, it is recommended to use an optical time domain reflectometer (OTDR) technique instead of optical power meter.
- This is because of the fact that the locations of the reflecting surfaces become critical.
- Fig. 2.12.6 shows a test set-up using a high resolution OTDR (consisting of a Michelson interferometer and a broadband optical source to locate reflections with 20 microns accuracy) measurement technique. The resultant display to measure the return loss (dB) is also shown.

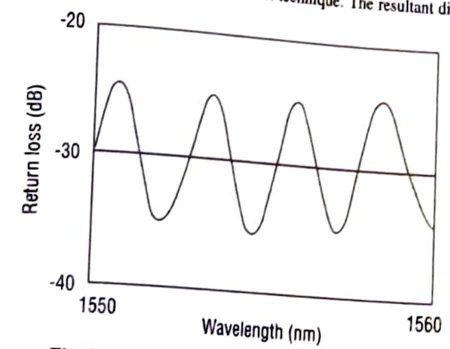


Fig. 2.14.5 : Measurement of optical reflection

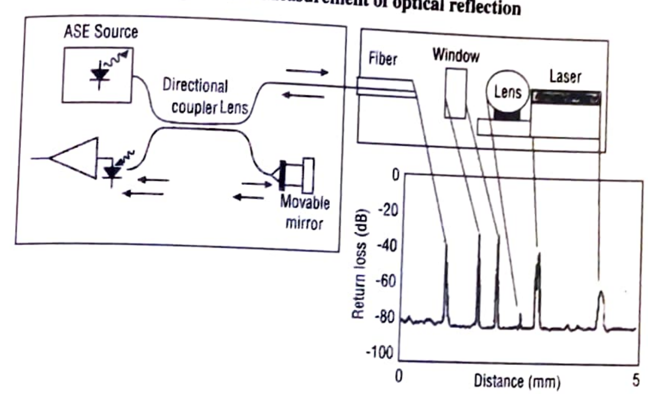


Fig. 2.14.6 : OTDR measurement of optical reflection

- It should be noted that the characterization of optical device/component requires very fine resolution in distance parameter (usually in the millimeter to micron range).
- OTDR is more accurate but expensive, provides more information and is widely used to detect faults in optical fiber systems.

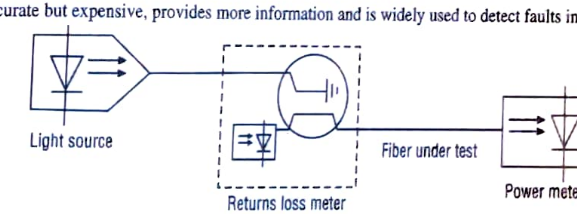


Fig. 2.14.7 : Integrated test set-up for IL and RL measurements

2.14.3 Cut-Back technique of Attenuation Measurement

UQ. Draw and explain block diagram of cutback method of attenuation measurement **(MU - Q. 5(b), Dec. 2019, 10 Marks)**

- Fiber attenuation measurement techniques have been developed in order to determine the total fiber attenuation of the relative contributions to this total from both absorption losses and scattering losses.
- The overall fiber attenuation is of greatest interest to the system designer, but the relative magnitude of the different loss mechanisms is important in the development and fabrication of low-loss fibers.
- Measurement techniques to obtain the total fiber attenuation give either the spectral loss characteristic or the loss at a single wavelength (spot measurement).
- A commonly used technique for determining the total fiber attenuation per unit length is the cut-back or differential method. Fig. 2.14.8 shows a schematic diagram of the typical experimental setup for measurement of the spectral loss to obtain the overall attenuation spectrum for the fiber. It consists of a 'white' light source, usually a tungsten halogen or xenon arc lamp. The focused light is mechanically chopped at a low frequency of a few hundred hertz. This enables the lock-in amplifier at the receiver to perform phase-sensitive detection.
- The chopped light is then fed through a monochromator which utilizes a prism or diffraction grating arrangement to select the required wavelength at which the attenuation is to be measured. Hence the light is filtered before being focused onto the fiber by means of a microscope objective lens. A beam splitter may be incorporated before the fiber to provide light for viewing optics and a reference signal used to compensate for output power fluctuations.
- When the measurement is performed on multimode fibers it is very dependent on the optical launch conditions. Therefore unless the launch optics are arranged to give the steady-state mode distribution at the fiber input, or a dummy fiber is used then a mode scrambling device is attached to the fiber within the first meter.
- The fiber is also usually put through a cladding mode stripper, which may consist of an S-shaped groove cut in the Teflon and filled with glycerin. This device removes light launched into the fiber cladding through radiation into the index-matched (or slightly higher refractive index) glycerin. A mode stripper can also be included at the fiber output end to remove any optical power which is scattered from the core into the cladding down the fiber length. This tends to be pronounced when the fiber cladding consists of a low-refractive-index silicone resin.

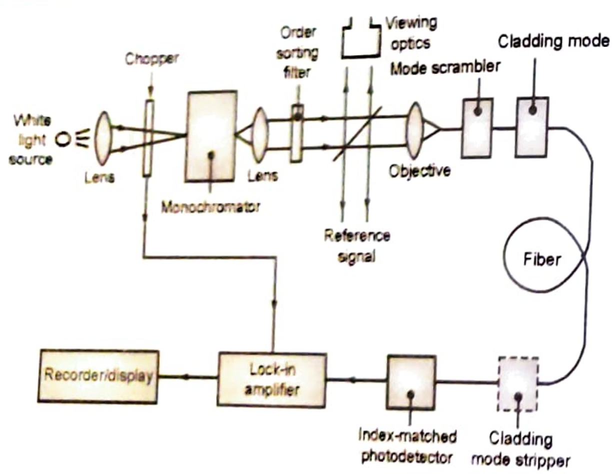


Fig. 2.14.8 : A typical experimental arrangement for the measurement of spectral loss in optical fibers using the cut-back technique

- The optical power at the receiving end of the fiber is detected using a *p-i-n* or avalanche photodiode. In order to obtain reproducible results the photo detector surface is usually index matched to the fiber output end face using epoxy resin or an index-matching gell. Finally, the electrical output from the photo detector is fed to a lock-in amplifier, the output of which is recorded.
- The cut-back method* involves taking a set of optical output power measurements over the required spectrum using a long length of fiber (usually at least a kilometer). This fiber is generally uncabled having only a primary protective coating. Increased losses due to cabling do not tend to change the shape of the attenuation spectrum as they are entirely radiative, and for multimode fibers are almost wavelength independent.
- The fiber is then cut back to a point 2 m from the input end and, maintaining the same launch conditions, another set of power output measurements is taken.

$$\alpha_{dB} = \frac{10}{L_1 - L_2} \mathrm{Log}_{10} \frac{P_{02}}{P_{01}}$$

Where L_1 and L_2 are the original and cut-back fiber lengths respectively, and P_{01} and P_{02} are the corresponding output optical powers at a specific wavelength from the original and cut-back fiber lengths.

Hence when L_1 and L_2 are measured in kilometers, α_{dB} has units of dB km^{-1}.

$$\alpha_{dB} = \frac{10}{L_1 - L_2} \mathrm{Log}_{10} \frac{V_2}{V_1}$$

where V_1 and V_2 correspond to output voltage readings from the original fiber length and the cut-back fiber length respectively.

Note : The cut-back technique for fiber attenuation measurement is regarded as the reference test method by the CCITT and EIA standards. It is also outlined in Fiber Optic Test Procedures (FOTP) for single-mode as well as multimode fibers as FOTP-78 and FOTP-46 standards, respectively.

2.15 FIBER DISPERSION MEASUREMENTS

- The characterization of the minimum fiber dispersion wavelength is important in the design of high-speed WDM networks. For DWDM, dispersion influences cross-talk. Dispersion compensation management requires an accurate measurement of dispersion parameters.
- Dispersion specifications are a key differentiator for single-mode fiber. Precise compensation for chromatic dispersion needs its accurate measurement. The measurement of chromatic dispersion in an optical fiber is accomplished by analyzing the group delay as function of wavelength of the optical signal propagating through it.
- Fig. 2.15.1 shows a typical test set-up for measurement of the chromatic dispersion of optical fiber or any two-port optical device.

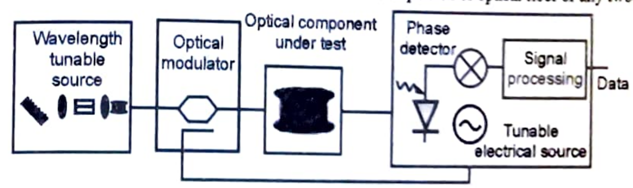


Fig. 2.15.1 : Test set-up for chromatic dispersion measurement

- The measurement procedure involves transmission of intensity-modulated signal from a wavelength tunable optical source and then comparing the phase of the detected modulation signal with that of the transmitted modulation signal.
- The phase comparison is repeated many times after varying the wavelength of the tunable source, resulting in the phase delay. Group delay can then be computed from the phase delay. Fig. 2.15.2 depicts the result for the measurement of the group delay versus wavelength of tunable laser source.
- Polarization of an optical signal refers to the orientation of the electric field component. Insertion loss as well as group delay of an optical fiber or any two-port optical device vary as a function of the polarization of the incident optical signal. Polarization-mode dispersion (PMD) varies randomly with time.

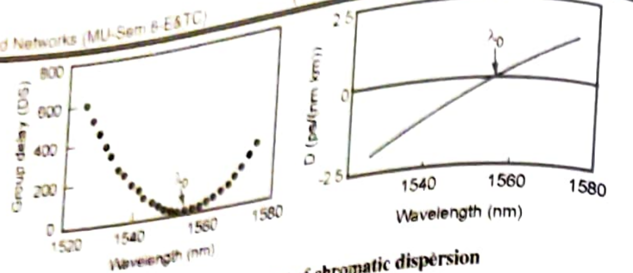


Fig. 2.15.2 : Measurement of chromatic dispersion

- So its measurement is relatively difficult and moreover successive measurements may differ by as much as 20%. To measure the polarization state of the optical signal propagating through the fiber or optical device, polarization analyzer is used, as shown in Fig. 2.15.3.

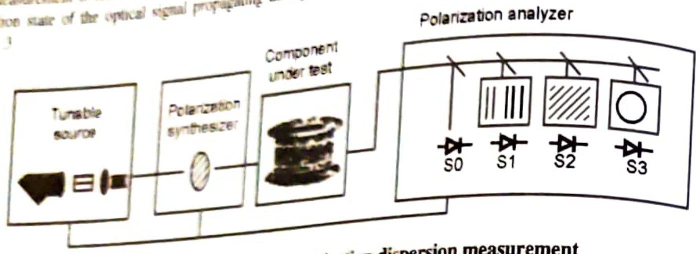


Fig. 2.15.3 : Test set-up for polarization dispersion measurement

- As shown, three well-known polarization states of the optical signal from a tunable laser source is applied to optical fiber or any other optical component under test by using polarization synthesizer. The resultant output polarization state (i.e., polarization transfer function) is characterized in the polarization analyzer. Table 2.15.1. gives typical PMD values for different bit rates for a 1-dB power penalty.

Table 2.15.1 : Typical PMD parameters

	Bit rate	Maximum PMD	PMD coefficient for 400 km link ($ps/km^{1/2}$)
STM-16	2.5 Gbits/s	40	<2
STM-64	10 Gbits/s	10	<0.5
STM-256	40 Gbits/s	2.5	<0.125

- This necessitates that polarization analyzer must have at least 0.05–80 ps range with less than 30 seconds measurement time, having high accuracy up to 1% and about 50 dB dynamic range. Thus, it is a special and expensive test equipment.

2.16 OPTICAL TIME DOMAIN REFLECTOMETER (OTDR)

UQ. Explain OTDR with neat sketch and mention its advantages and applications.
MU - Q. 3(b), Dec. 15, 5 Marks Q. 2(b), May 16, 10 Marks

UQ. Explain OTDR working principle in detail. Mention its limitations.
MU - Q. 2(a), May 17, 10 Marks

- Optical Time-Domain Reflectometer is also known as OTDR. It is a testing device used for determining the characteristics of the optical fiber cable.
- OTDR is known to be similar to the electronic time-domain reflectometer. In fiber-optic communication, a signal is transmitted inside an optical fiber. A measurement technique which is far more sophisticated and which finds wide application in both the laboratory and the field is the use of optical time domain reflectometry (OTDR).
- This technique is often called the backscatter measurement method. It provides measurement of the attenuation on an optical link down its entire length giving information on the length dependence of the link loss. When the attenuation on the link varies with length, the averaged loss information is inadequate.

- During transmission, if there are some impurities or defects in the cable, a part of the signal is reflected back causing distortion and signal attenuation. This is where OTDR is used. It transmits a laser signal into an optical fiber cable then captures the reflected signal from the same end of the cable.
- The power of the reflected signal is measured and integrated as a function of time. Timed measurement of the reflected signal is performed. The scattering of signal/light from optical fiber occurs due to a phenomenon known as Rayleigh backscatter.
- OTDR also allows splice and connector losses to be evaluated as well as the rotation of any faults on the link. It relies upon the measurement and analysis of the fraction of light which is reflected back within the fiber's numerical aperture due to Rayleigh scattering.

2.16.1 Working Principle of OTDR

- Optical Time-Domain Reflectometer, OTDR, works on the same principle as that of Radar. Radar is a detection system, that uses radio waves to determine the range, position, or velocity of the objects.
- The transmitter generates the radio waves towards the object. These waves when come across the object get reflected back towards the transmitter. A receiver gathers these reflected waves and extracts information about the object's position and speed.
- OTDR works on the same principle as radar. Here, instead of radio waves, a laser is used. Laser is transmitted inside the optical fiber whose characteristics have to be determined. Some of the laser signals get reflected back due to defects present in the fiber.
- A receiver present at the same side of the transmitter gathers the reflected rays and extracts information about the defects present in the optical fiber. This is also known as the Backscatter measurement method. The power of the reflected rays is calculated and plotted against a time graph to know about the defects or distortions present in the cable.

2.16.2 OTDR Block Diagram

The different types of equipment used in the design of the OTDR are shown in the Fig. 2.16.1.

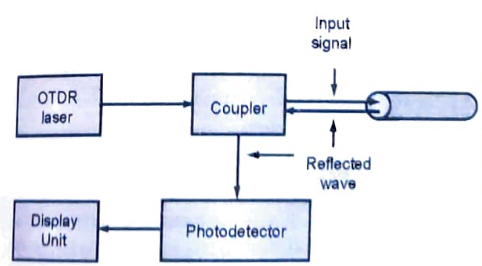


Fig. 2.16.1 : OTDR Block Diagram

OTDR Laser

Optical i.e. light source is used in the construction of OTDR. Here the light source used is a " "Laser ". These laser pulses are applied to the fiber optic cable under test through a coupler. Laser pulses are short and of the intense beam.

Fiber Coupler

A fiber coupler is a fiber device used for coupling light from one or more input fibers with one or more output fibers. These are also used to direct the light from free space into a fiber cable. But coupler can cause wastage of transmitted signal. To avoid this one can opt for a circulator. Circulators provide good directional property which can increase the dynamic range of the OTDR. One of the drawbacks of using a circulator is it increases the overall cost of the OTDR system.

Photodetector

The photodetector connected to the circuit detects the reflected signals and provides information about the power of signals to the next stage. The signal passed through the fiber cable can undergo reflection either due to Rayleigh scattering, splicers inside fiber bend in fiber, or variations in the refractive index of light.

Display

Here, the display is used to display the time-based plot of OTDR which gives information about the type of defect causing the reflection of transmitted light in the fiber.

2.16.3 Working of OTDR

- An optical time domain reflectometer is test equipment used to evaluate the loss of signal inside an optical fiber by transmitting laser pulses inside the fiber and measures the scattered light signal.
- As shown the Fig. 2.16.1. that an optical time domain reflectometer contains a light source (mainly a laser) and a receiver along with a coupler or circulator. The coupler is connected with the fiber under test through a front panel connector.
- The laser produces a short and intense light beam. These pulses are directed into the fiber link under test through a fiber optic coupler. A coupler splits the transmitted light pulse into two halves. Due to this, not all the transmitted pulse is directed inside fiber.
- However, despite using a coupler if we use a circulator then this wastage of transmitted signal can be avoided. As **circulators are highly directional devices** that direct the overall light signal into the fiber as well as sends the reflected or scattered light signal into the detector.
- By inserting circulators in the operational unit of OTDR, the dynamic range of the equipment can be improved. However, it also causes the overall cost of the system to increase considerably as circulator is highly expensive in comparison to couplers.

- So, during the propagation of light pulses inside the fiber due to absorption and Rayleigh scattering, some losses in the transmitted pulse occurs. Also, some losses are introduced due to splicers connected inside the fiber or the bends inside it.
- Sometimes variation in the refractive index also causes the light energy to get reflected. This reflected energy reaches the OTDR and in this way, it detects the characteristics of the fiber link.

2.16.4 Specifications of OTDR

The specifications of OTDR are :

OTDR Trace

The reflected light is traced on the display screen of the reflectometer. The figure below represents the trace of the reflected power on the screen of OTDR.

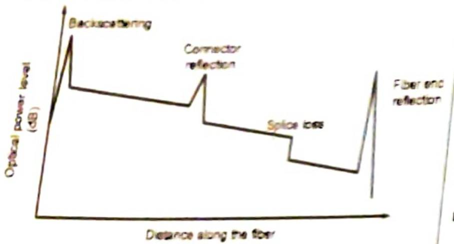


Fig. 2.16.2 : Representation of Trace of OTDR

- As we can see that in the above Fig.2.16.2 that the y-axis represents the optical power level of the reflected signal. While the x-axis represents the distance between the measurement points of the fiber link.
- Now, on observing the trace of the OTDR, we can list the features of the reflected wave :
- The positive spikes in the trace are the result of Fresnel reflection at the joints of the fiber link and the imperfections in the fiber.
- The shifts in the curve are due to losses that occur due to fiber joints. A deteriorated tail in the curve is the outcome of Rayleigh scattering. As Rayleigh scattering is the result of fluctuations in the refractive index of the fiber and is the major reason for the attenuation of the signal inside the fiber.

OTDR Dead Zone

- The dead zone of an OTDR is a crucial parameter. It is the distance in the fiber cable at which the defects cannot be measured properly.
- Now the question arises why a dead zone occurs in an OTDR? In case a very major portion of the transmitted signal is reflected then the received power at the photodetector is highly greater than the backscattered power level.
- This saturates the OTDR with the light and hence it needs some duration to overcome the saturation. In this recovery duration, the reflectometer is unable to detect the backscattered reflection. Thereby leading to generate a dead zone in the trace of OTDR.

2.16.5 Performance Parameters of OTDR

The parameters on which the performance of the OTDR depends. Those are as follows :

- **Dynamic range** : This is basically the difference between the backscattered optical power at the front connector and the peak of the noise level at the other end of the fiber. By evaluating the dynamic range one can get an idea about the maximal measured loss inside the fiber link and the time needed for such a measurement.
- **Accuracy** : The difference between the measured value and the true value of the measured event gives the accuracy of the device.
- **Measurement range** : The measurement range is nothing but provides the distance up to which splice or connection points can be detected by the OTDR. Its value relies on the width of the transmitted pulse and the attenuation.
- **Instrument Resolution** : It is a measure of how close two events can be calibrated and still be measured as two separate events. Shorter the pulse duration, shorter the sampling interval, better the instrument resolution.

2.16.6 Advantages and Disadvantages

Advantages

- A number of optical time domain reflectometers are commercially available for operation over the entire wavelength range.
- These instruments are capable of carrying out tests over single or dual wavelengths for multimode and for single-mode optical fiber links.
- Although the OTDR functionality is provided, these instruments are also often capable of performing a number of other optical system and network tests (e.g. optical loss, dispersion measurement etc.).
- Such instruments are usually referred as universal or optical network test systems rather than simply optical time domain reflectometers.

Disadvantages

The main disadvantage of OTDR is the occurrence of a dead zone during measuring the defects.

2.16.7 Applications

- An Optical Time Domain Reflectometer (OTDR) is an important instrument used by organizations to certify the performance of new fiber optics links and detect problems with existing fiber links.

- OTDRs are also used for maintaining fiber plant performance. An OTDR allows to see more detail impacted by the cabling installation. An OTDR maps the cabling and can illustrate termination quality, location of faults.
- An OTDR provides advanced diagnostics to isolate a point of failure that may hinder network performance.
- An OTDR allows discovery of issues along the length of a channel that may affect long term reliability.
- OTDRs characterize features such as attenuation uniformity and attenuation rate, segment length, location and insertion loss of connectors and splices, and other events such as sharp bends that may have been incurred during cable installation.

2.17 SOURCES OF LOSS AT A FIBER JOINT

UQ. Explain the sources of loss at a fiber joint. **MU – Q. 3(b), May 16, 10 Marks**

Loss Mechanisms at Joints

(I) Fresnel Reflection

i. Optical Loss encountered at the interfaces even when two fiber ends are smooth, perpendicular to fiber axes and perfectly aligned.

ii. A small proportion of light may be reflected back into transmitting fiber causing attenuation at the joint.

iii. Light that is reflected back into the source fiber is lost. This reflection loss, called Fresnel reflection, occurs at every fiber interface.

iv. Fresnel reflection is caused by a step change in the refractive index that occurs at the fiber joint.

v. Can be reduced to a very low level using index matching fluid in the gap between jointed fibers.

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

R is the fraction of the incident light reflected at the fiber

n_1: R.I. of core

n: R.I. of interfacing medium (= 1 for air) Loss in decibel due to FR at single interface

$$Loss_{Fres} = -10\log_{10}(1-r)$$

Index matching gel reduces the step change in the refractive index at the fiber interface, reducing Fresnel reflection.

Deviation in Geometrical & Optical Parameters:

All light from one fiber is not transmitted to another fiber; Because of mismatch of mechanical dimension Three major cases:

(a) Core mismatch
(b) NA mismatch
(c) Index Profile

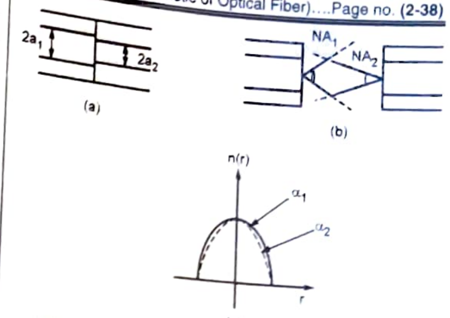


Fig. 2.17.1 : Deviation in Geometrical and Optical Parameters

(II) Intrinsic Losses

Minimized using fibers manufactured with lowest tolerance i.e.(same fiber). Losses due to Fresnel Reflection, Deviation in Geometrical & Optical parameters. Intrinsic coupling losses are limited by reducing fiber mismatches between the connected fibers.

(III) Extrinsic Losses

Extrinsic coupling losses are caused by jointing techniques. Fiber-to-fiber connection loss is increased by the following sources of intrinsic and extrinsic coupling loss:

1. Reflection losses
2. Fiber separation
3. Lateral misalignment
4. Angular misalignment
5. Core and cladding diameter mismatch
6. Numerical aperture (NA) mismatch
7. Refractive index profile difference
8. Poor fiber end preparation
9. Losses due to some imperfection in splicing
10. Caused by Misalignment

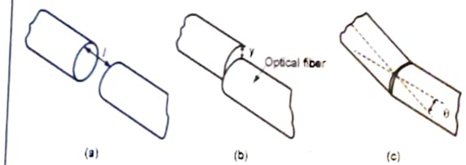


Fig. 2.17.2 : Loss caused by Misalignment

Three possible types of misalignment at joint :

(a) Longitudinal misalignment
(b) Lateral misalignment;
(c) Angular misalignment

2.18 MATERIAL ATTENUATION IN OPTICAL FIBER COMMUNICATION

UQ. Explain material attenuation in optical fiber communication **MU - Q. 3(a), Dec. 16, 6 Marks**

- The extremely low attenuation or transmission loss of optical fibers is one of the most important factors in bringing its wide acceptance as a medium of transmission.
- Signal transmission within optical fibers, as with metallic conductors, is usually abbreviated as dB. The decibel (dB) is a convenient way of comparing two divergent power levels, say, P_1 and P_2. This is defined as

$$\text{Attenuation in dB} = 10 \log_{10} \frac{P_2}{P_1}$$

- Optical fiber attenuation is the measurement of light loss between input and output. Total attenuation is the sum of all losses.
- So it is the sum of material absorption, Rayleigh scattering in the fiber and waveguide imperfections.
- There are other factors which could also cause light loss, such as light leakage when the fiber is under microbending.
- Attenuation limits how far a signal can travel through a fiber before it becomes too weak to detect.

Material Absorption

Material absorption can be divided into two categories. Intrinsic absorption losses correspond to absorption by fused silica (material used to make fibers) whereas extrinsic absorption is related to losses caused by impurities within silica.

(A) Intrinsic Absorption

- Any material absorbs at certain wavelengths corresponding to the electronic and vibrational resonances associated with specific molecules.
- For silica molecules, electronic resonances occur in the ultraviolet region (wavelength < 0.4um), whereas vibrational resonances occur in the infrared region (wavelength > 7μm).
- Because of the amorphous nature of fused silica, these resonances are in the form of absorption bands whose tails extend into the visible region.
- The following picture shows that intrinsic material absorption for silica in the wavelength range 0.8-1.6μm is below 0.1dB/km. In fact, it is less than 0.03dB/km in the 1.3 to 1.6μm wavelength range which are commonly used for lightwave systems.

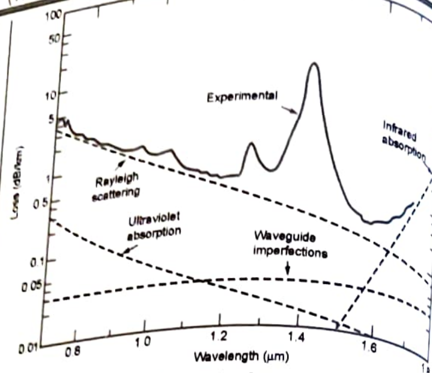


Fig. 2.18.1 : Intrinsic absorption Loss

(B) Extrinsic Absorption

- Extrinsic absorption results from the presence of impurities. Transition-metal impurities such as Fe, Cu, Co, Ni, Mn, and Cr absorb strongly in the wavelength range 0.6~1.6μm. Their amount should be reduced to below 1 part per billion to obtain a loss level below 1dB/km. Such high-purity silica can be obtained by using modern techniques.
- The main source of extrinsic absorption in state-of-the-art silica fibers is the presence of water vapors. A vibrational resonance of the OH ion occurs near 2.73μm. Its harmonic and combination tones with silica produce absorption at the 1.39μm, 1.24μm and 0.95μm wavelengths.
- The three spectral peaks seen in above figure occur near these wavelengths and are due to the presence of residual water vapor in silica.
- In new kind of glass fiber, known as *dry fiber*, the OH ion concentration is reduced to such low levels that the 1.39μm peak almost disappears.
- This is show in the below picture. Such fibers are used to transmit WDM (Wavelength Division Multiplexer) signals over the entire 1.30μm to 1.65μm wavelength range.

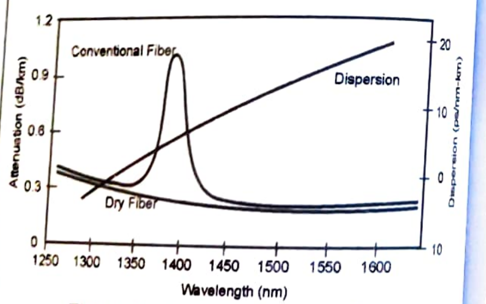


Fig. 2.18.2 : Extrinsic Absorption Loss

2.19 SIGNAL ATTENUATION IN OPTICAL FIBERS

UQ. Explain Signal Attenuation in optical fibers and plot the three windows. **(MU - Q. 2(b), May 18, 10 Marks)**

- Attenuation of light signal as it propagates along a fiber is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance between a transmitter and a receiver or in-line amplifier.
- The longer the fiber is and the farther the light has to travel, the more the optical signal is attenuated. Consequently, attenuation is measured and reported in decibels per kilometer (dB/Km) also known as attenuation rate or attenuation coefficient.
- Attenuation varies depending upon the fiber type and the operating wavelength.
- Fig. 2.19.1 shows three optical windows which offer minimum signal attenuation and also relationship between attenuation and wavelength.

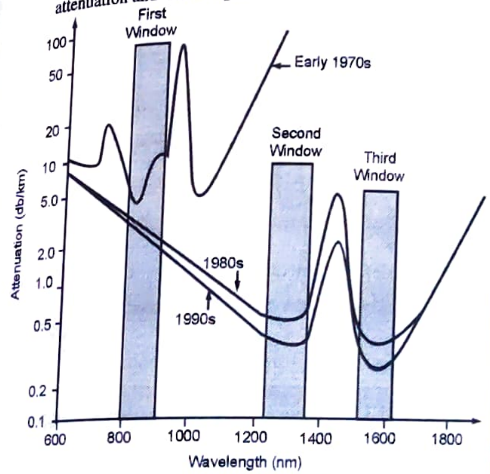


Fig. 2.19.1 : Operating Window

- The first optical window is defined from 800-900nm, where the minimum signal loss is 4dB/km. In early 1970's this window was used for operation of optical sources and detectors.
- By reducing the concentration of hydroxyl ions and metallic impurities in the fiber material, in 1980's manufacturers were able to fabricate optical fibers with very low loss in the 1100-1600nm region. This spectral band is called long wavelength region.
- The second optical window is centered at 1310nm also called O-band, which offers 0.5dB/km.
- The third optical window is centered at 1550nm also called C-band, which gives the loss of 0.2dB/km.
- Hence while designing optical systems for long distance applications the 1550nm wavelength is preferred because loss offered at this wavelength is minimum than any other wavelength.
- For silica based optical fibers, single mode fibers have lower attenuation than multimode fibers. The higher the wavelength the lower is the attenuation. This is true over the typically 800-1600nm operating wavelength range for conventional datacom and telecom optical fibers.

Causes of Attenuation

The basic attenuation mechanism in a fiber is;

- **Absorption:** This is related to fiber material.
- **Scattering:** It is associated with both the fiber material with structural imperfections in optical waveguide.
- **Bending (radiative losses):** Attenuation owing to radiative effects originates from perturbation in fiber geometry (both microbending and macrobending)
- **Dispersion:** Due to the modes.

2.20 SELF-PHASE MODULATION

UQ. Define self phase modulation. **(MU - Q. 4(c), May 18, 5 Marks)**

Due to the **Kerr effect**, high **optical intensity** in a medium (e.g. an **optical fiber**) causes a **nonlinear phase** delay of the propagating **light**. That phase delay which has the same temporal shape as the optical intensity. In simple models, the effect is described as a nonlinear change in the **refractive index**:

$$\Delta n = n_2 I$$

with the **nonlinear index** n_2 and the optical intensity I. In the context of self-phase modulation, the emphasis is on the *temporal* dependence of the phase shift, whereas the transverse dependence for some **beam** profile leads to the phenomenon of **self-focusing**.

Of course, the nonlinear phase delay comes *in addition* to the linear phase delay.

> **Note :** The description of self-phase modulation with a time-dependent refractive index is somewhat simplified, and accurate only for not too short pulses. In more extreme situations, extended models are required, which also take into account the effect of self-steepening – a change of the temporal pulse shape even in the absence of chromatic dispersion. That may be interpreted as a nonlinear modification of the **group velocity**. There can also be higher-order nonlinear effects, leading to more complicated propagation phenomena.

In **optical fibers**, SPM can be the dominant effect on an ultrashort pulse if the **peak power** is high (leading to strong SPM) while the chromatic dispersion is weak, so that the **pulse duration** remains approximately constant.

Fig. 2.20.1 shows an example case where that assumption is well fulfilled within the first 30 mm of fiber; here, the overall spectral width rises about linearly with the propagation distance. Thereafter, it grows faster because anomalous dispersion leads **to pulse compression** and thus to an increased **peak power** and an enhanced nonlinear interaction.

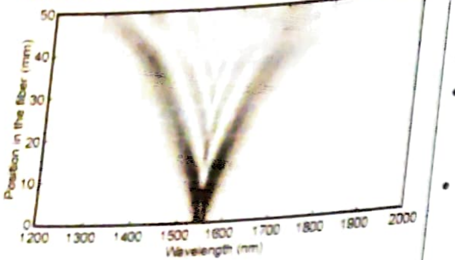


Fig. 2.20.1

Propagation of an ultrashort pulse in a fiber, where self-phase modulation is the dominant effect on the pulse within the first 30 mm of propagation distance. The numerical simulation (which takes into account chromatic dispersion, SPM, self-steepening and stimulated **Raman scattering**) has been done with the **RP Fiber Power** software.

In optical fibers with anomalous **chromatic dispersion**, the chirp from self-phase modulation may be compensated by dispersion; this can lead to the formation of **solitons**. In the case of fundamental solitons in a lossless fiber, the spectral width of the pulses stays constant during propagation, despite the SPM effect.

In optical fibers with normal dispersion, a **modulational instability** can occur. That can also contribute to pulse break-up in **supercontinuum generation**.

2.21 SOLITONS

UQ. Write short note on Solitons. **(MU - Q. 6(iii), Dec. 2019, 5 Marks)**

- Group velocity dispersion (GVD) causes most pulses to broaden in time as they propagate through an fiber.
- A 'solitons' are pulses that travel along the fiber without change in shape or amplitude or velocity.
- Soliton, takes advantage of non-linear effects in silica, particularly self phase modulation (SPM) resulting from the Kerr non-linearity, to overcome the pulse-broadening effects if GVD.

The term "soliton" refers to special kinds of waves that can propagate undistorted over long distances and remain unaffected after collision with each other.

- In an optical communication system, solitons are very narrow, high intensity optical pulses that retain their shape through the interaction of balancing pulse dispersion with the non-linear properties of an optical fiber.
- In an relative effects of SPM and GVD are controlled just right, and the appropriate pulse shape is chosen, the pulse compression routing from SPM can exactly offset the pulse broadening effect of GVD.
- **Fundamental Solitons-** The family of pulse that do not change in shape are called fundamental solitons.

1. Solitons Pulse

- When a pulse transverse a medium with a positive GVD parameter β2 for the constituent frequencies, the leading part of the pulse is shifted toward a longer wavelength (lower frequencies) so that the speed in that portion increases.
- In the trailing half, the frequency arises. So the speed decreases. This causes the trailing edge to be further delayed.

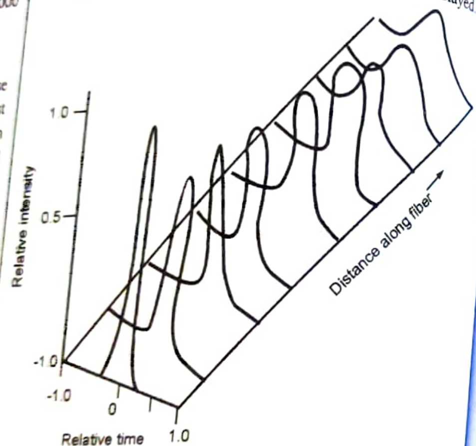


Fig. 2.21.1 : Temporal Change in a Narrow High Intensity Pulse

- When a narrow high-intensity pulse traverse a medium with a negative GVD parameter for the constituting frequencies, GVD counteracts the chirp produced by SPM.
- GND retards the low frequencies in the front end of the pulse and advances the high frequencies at the back. The result is that the high-intensity sharply peaked soliton pulse changes neither its shape nor its spectrum as it travels along the fiber.
- To derive the evolution of the pulse shape required for sodium transmission, one needs to consider the non-linear schrodinger (NLS) equation

$$-j\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + N^2 |u|^2 u - j(\alpha/2)u \qquad ...(2.21.1)$$

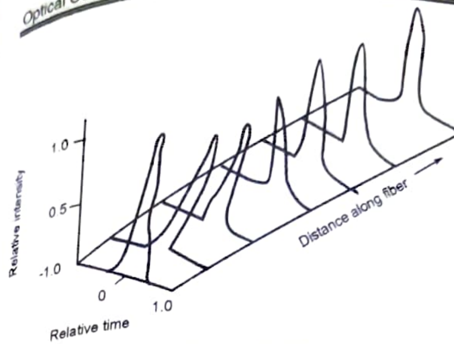


Fig. 2.21.2 : Characteristics of High Intensity Sharply Peaked Solitions Pulse

Special soliton units to eliminate scaling constants.

The Three Right-Hand Terms in Equation (2.21.1)

(1) The first term represents GVD effects of the fiber.

(2) The second non-linear term denotes the fact that the refractive index of the fiber depends on the light intensity.

Through the self-modulation process, this physical phenomenon broadens the frequency spectrum of a pulse.

(3) The third term represents the effects of energy loss or gain.

2. Solitons Parameters

(a) Full-Width Half-Maximum (FWHM)

The full-width Half-maximum (FWHM) is a pulse is defined as the full width of the pulse at its half-maximum power level.

The FWHM Ts of the fundamental soliton pulse in normalized time is found from the relationship

$$\text{Sech}^2(\tau) = \frac{1}{2}$$

Where $\tau = \frac{\tau_s}{(2T_o)}$

To is the basic normalized time unit

$$T_o = \frac{T_s}{2\cosh^{-1}\sqrt{2}} = \frac{T_s}{1.7627} \approx 0.567\ T_S \qquad ...(2.21.2)$$

(b) Dispersion Length (Ldisp)

The normalized distance parameter (also called dispersion length) **Ldisp** is a characteristic length for the effects of the dispersion term.

L_{disp} is a measure of the period of a soliton

$$L_{disp} = \frac{2\pi c}{\lambda^2}\frac{T_o^2}{D} = \frac{1}{[2\cosh^{-1}\sqrt{2}]^2}\frac{2\pi c}{\lambda^2}\frac{T_s^2}{D}$$

$$= 0.322\frac{2\pi c}{\lambda^2}\frac{T_s^2}{D} \qquad ...(2.21.3)$$

Where c is the speed of light,

λis the wavelength in vaccum,

D is the diperion of the fiber,

L_{disp} is measured in km.

The solution to equation (2.21.3) for the fundamental solution is given by

$$u(z,t) = \text{sech}(t)\exp(jz/2) \qquad ...(2.21.4)$$

Where sech (t) is the hyperbolic secant function. This is a bell-shaped pulse.

- The phase term exp (jz/2) in equation (2.21.4) has no influence on the shape of the pulse, the soliton is independent of z and hence is non-dispersive in the time domain.
- For the NLS equation, to find the first-order effects of the dispersive and non-linear terms are just complementary phase shifts.
- For a given by equation (2.21.4), these phase shifts are

$$d\phi_{non\text{-}line} = |u(t)|^2 dz = \text{sech}^2(t)\,dz$$

For the non-linear process, and

$$d\phi_{disp} = \left(\frac{1}{2u}\frac{\partial^2 u}{\partial t^2}\right)Dz = \left[\frac{1}{2} - \text{sech}^2(t)\right]dz \qquad ...(2.21.5)$$

- Dispersion and non-linear phase shifts of a soliton pulse which sum is constant, which yields a common phase shift of z/2 for the entire pulse.
- Since such a phase shift changes neither the temporal nor the spectral shape of a pulse, the soliton remains completely non-dispersive in both the temporal and frequency domain.

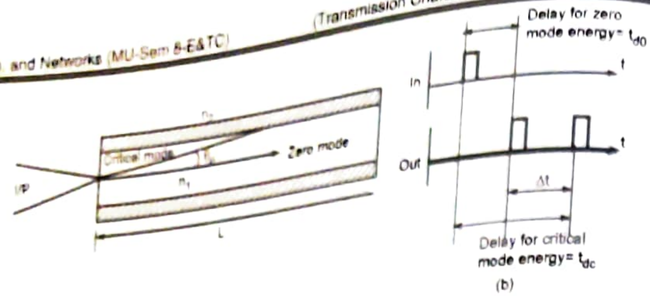
2.22 TIME DELAY IN INTERMODAL DISPERSION

UQ. Derive an expression for Time Delay in Intermodal Dispersion **(MU - Q. 2(b), May 17, 5 Marks)**

- The dispersion which is caused by the delay between different modes is called inter model dispersion.

  Or

- It is dispersion between the modes, caused by difference in propagation time for different modes.
- Let us consider two extreme modes propagating along the fiber axis shown as :
- In Fig. 2.22.1(a) the critical model propagating at angle θc and another mode is zero mode because here propagation angle is zero.



(a) Inter modal dispersion

Fig. 2.22.1

- A pulse of light launched into the fiber will propagate along the fiber in both modes.
- For mode 0, travel time will be minimal and can be expressed by

$t_{d0} = L/(c/n_1)$

$t_{d0} = L(n_1/c)$ ...(2.22.1) Min. Propagation delay

where

L = fiber length

n_1 = core refractive index

c/n_1 = Speed of light in fiber

- For any travelling at angle θc, the delay will be maximum and can be expressed by

$t_{dc} = (L/\cos\theta_c)/(c/n_1)$

$t_{dc} = (L/\cos\theta_c)/(n_1/c)$

$t_{dc} = Ln_1/C\cos\theta_c$ ...(2.22.2) Max. Propagation delay

- The difference between shortest delay (t_{d0}) and largest delay (t_{dc}) is the time during which pulse energy will arrive at the fiber output, which represents the pulse width at output

so

pulse width = $\Delta t = t_{dc} - t_{d0}$ put from (2.22.1) and (2.22.2)

since $\cos\theta_c = \frac{n_2}{n_1}$ Therefore

$$\Delta t = \frac{Ln_1}{C\frac{n_2}{n_1}} - \frac{Ln_1}{C} = \frac{Ln_1n_1}{Cn_2} - \frac{Ln_1}{C}$$

$$= \frac{Ln_1}{C}\left(\frac{n_1}{n_2} - 1\right)$$

$$\Delta t = \frac{Ln_1}{C}\left(\frac{n_1 - n_2}{n_2}\right) \quad ...(2.22.3)$$

Where n_1 = refractive index of core

n_2 = refractive index of cladding

since $\Delta = (n_1 - n_2)/n_2$ = relative refractive difference

Now for $\Delta << 1$, the denominator can be n1 or n_2

Therefore put in (2.22.3)

$$\Delta = (n_1 - n_2)/n_2$$

$$\Delta t = \frac{Ln_1}{C}\Delta \quad ...(2.22.4)$$

$$N.A = n_1\sqrt{2\Delta}$$

Since $\Delta = \frac{(N.A)^2}{2 \times n_1^2}$ put in (2.22.4) we get This is the equation for amount of pulse broadening in terms of N. Aperture

$$\Delta t = \frac{Ln_1}{C}\frac{(N.A)^2}{2 \times n_1^2}$$

$$\Delta t = \frac{L(N.A)^2}{2Cn_1} \quad ...(2.22.5)$$

For brodening per unit length of fiber equation (2.22.5) becomes

$$\frac{\Delta t}{L} = \frac{(N.A)^2}{2 \times n_1^2} \quad ...(2.22.6)$$

2.22.1 Factors Responsible for Attenuation and Dispersion in Optical Fiber

UQ. What are the **different** factors responsible for attenuation and dispersion in optical fiber.
MU - (Q. 3(a), Dec. 2019, 10 Marks)

An optical signal becomes increasingly distorted as it travels along the fiber. Following are the factors responsible for attenuation and dispersion is optical fiber.

I. Dispersion

- Dispersion is the broadening of actual time-width of the pulse due to material properties and imperfections.
- As pulse travels down the fiber, dispersion causes pulse spreading. This limits the distance travelled by the pulse and

the bit rate of data on optical fiber.

- In a fiber three distinct types of distortion are observed:

1. Intramodal dispersion

- Pulse broadening within a single mode is called as intramodal dispersion or chromatic dispersion.
- The two main causes of intramodal dispersion are as follows:

a. Material dispersion

- It is the pulse spreading due to the dispersive properties of material.
- It arises from variation of refractive index of the core material as a function of wavelength.

b. Waveguide dispersion

- It occurs because a single mode fiber confines only about 80% of the optical power to the core.
- Dispersion thus arises since the 20% light propagating in the cladding travels faster than light confined to the core.

2. Intermodal dispersion

- Dispersion caused by multipath propagation of light energy is referred to as intermodal dispersion.
- In digital transmission, we use light pulse to transmit bit 1 and no pulse for bit 0. When the light pulse enters fiber it is breakdown into small pulses carried by individual modes.
- At the output individual pulses are recombined and since they are overlapped receiver sees a long pulse causing pulse broadening.

3. Polarization mode dispersion

- Birefringence is the optical property of a material having refractive index that depends on the polarization and propagation direction of light.
- Varying birefringence along the length of the fiber causes each polarization mode to travel at slightly different velocity and polarization orientation changes with distance.
- The resulting difference in the propagation time between the orthogonally polarized modes causes pulse spreading and this leads to polarization mode dispersion.

II. Attenuation

- When the light travels in the optical fiber then due to transmission characteristics it gives signal loss.
- Different factors are responsible for signal attenuation inside the fiber.

1. Bending loss

1. Once fiber is laid as cables for communication purpose bending losses occur.
2. Optical fibers suffer radiation losses at bends or curves on their paths.

a. Macrobending loss

- Fiber is subjected to gentle bend over a large arc, this bend causes failure of total internal reflection condition of a optical signal at the core-cladding interface which leads to leakage of optical signal from the fiber.
- This causes macrobending loss. Refer Fig. 2.10.2 Macroscopic bending Losses.

b. Microbending losses

- Microbends are caused either by non-uniformities in the manufacturing of the fiber or by non-uniform lateral pressures created during the cabling or packaging losses.
- When a light beam strikes these imperfections in the fiber, the condition of total internal reflection is not attained and the beam leaks out of the core causing microbending losses. Refer Fig. 2.10.3 Micro Bending

2. Absorption loss

Absorption is caused by three different mechanism :

i. Intrinsic absorption by basic constituent atoms of fiber material

ii. Extrinsic absorption by impurity atoms in silica material

iii. Absorption by atomic defects in the composition of glass

3. Scattering loss

Scattering losses in glass arise from microscopic variations in the material density, from compositional fluctuations and from structural inhomogeneties or defects occurring during fiber manufacture.

Chapter Ends...

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