Optical Communication-KEC 058

Section-V EC-2

Lecture 11

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Lecture Objective

In this lecture you will learn the following

- Chromatic dispersion
- Intermodal Dispersion
- Modal Noise
- Over all Dispersion
- Kerr Effect

Chromatic dispersion

Chromatic or intramodal dispersion may occur in all types of optical fiber and results from the finite spectral linewidth of the optical source.

- There may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence **intramodal dispersion**.
- The delay differences may be caused by the dispersive properties of the waveguide material (**material dispersion**) and also guidance effects within the fiber structure (**waveguide dispersion**).

- **Material dispersion**

- Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source.
- It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero ie $d^2n/d\lambda^2 \neq 0$)

- The pulse spread due to material dispersion may be obtained by considering the group delay τg in the optical fiber which is the reciprocal of the group velocity υg

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$

- The pulse delay τm due to material dispersion in a fiber of length L is therefore:

$$\tau_m = \frac{L}{c}\left(n_1 - \lambda\frac{dn_1}{d\lambda}\right)$$

- For a source with rms spectral width σλ and a mean wavelength λ, the rms pulse broadening due to material dispersion σm may be obtained from the above expansion in a Taylor series about λ where

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{2d^2\tau_m}{d\lambda^2} + \ldots$$

- As the first term in above Eq. usually dominates, especially for sources operating over the 0.8 to 0.9 μm wavelength range, then

$$\sigma_m \simeq \sigma_\lambda \frac{d\tau_m}{d\lambda}$$

- Hence the pulse spread may be evaluated by considering the dependence of τm on λ

$$\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c}\left[\frac{dn_1}{d\lambda} - \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda}\right] \quad = \frac{-L\lambda}{c}\frac{d^2n_1}{d\lambda^2}$$

- rms pulse broadening due to material dispersion is given by:

$$\sigma_m \simeq \frac{\sigma_\lambda L}{c}\left|\lambda\frac{d^2n_1}{d\lambda^2}\right|$$

material dispersion parameter $$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2 n_1}{d\lambda^2}\right|$$

Waveguide dispersion

▪ The waveguiding of the fiber may also create chromatic dispersion. This results from the variation in group velocity with wavelength for a particular mode.

▪ It is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays and hence dispersion.

▪ For a single mode whose propagation constant is β, the fiber exhibits waveguide dispersion.

▪ **Multimode fibers, where the majority of modes propagate far from cutoff, are almost free of waveguide dispersion and it is generally negligible compared with material dispersion**

$$d^2\beta/d\lambda^2 \neq 0$$

Intermodal dispersion

- Pulse broadening due to intermodal dispersion (sometimes referred to simply as **modal or mode dispersion**) results from the propagation delay differences between modes within a multimode fiber.
- As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest modes.
- Multimode step index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in multimode fibers may be reduced by adoption of an optimum refractive index profile which is provided by the near-parabolic profile of most graded index fibers. Hence, the overall pulse broadening in multimode graded index fibers is far less than that obtained in multimode step index fibers (typically by a factor of 100). Thus graded index fibers used with a multimode source give a tremendous bandwidth advantage over multimode step index fibers.
- **Under purely single-mode operation there is no intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion mechanisms**

- **For Multimode Step Index fiber**

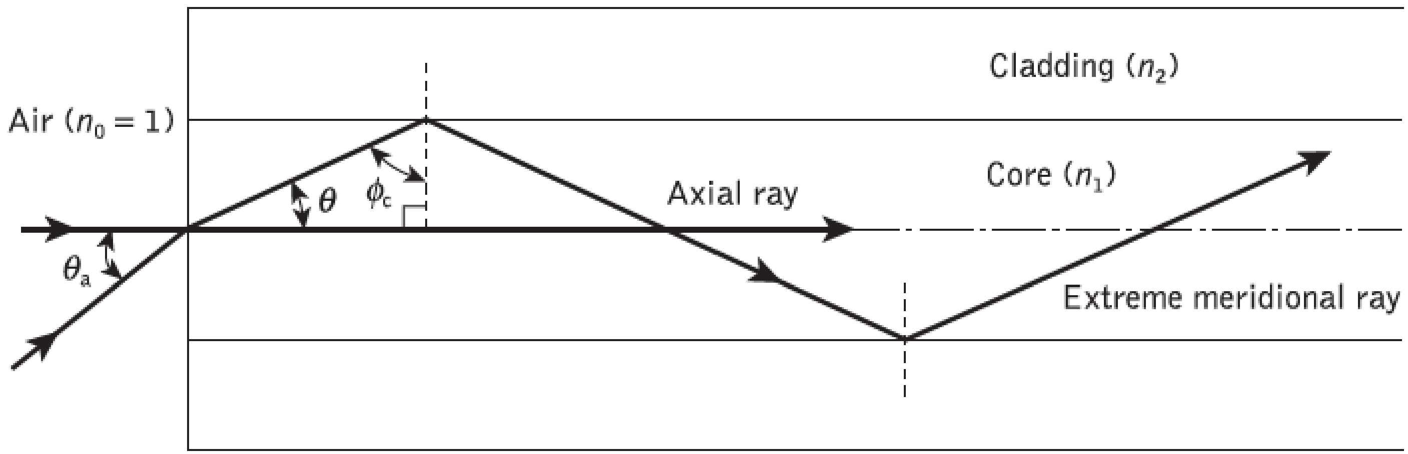


Figure The paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber

- The time taken for the axial ray to travel along a fiber of length L gives the minimum delay time

$$T_{\text{Min}} = \frac{\text{distance}}{\text{velocity}} = \frac{L}{(c/n_1)} = \frac{Ln_1}{c}$$

- The extreme meridional ray exhibits the maximum delay time

$$T_{\text{Max}} = \frac{L/\cos\theta}{c/n_1} = \frac{Ln_1}{c\cos\theta}$$

- Using Snell's law of refraction at the core–cladding interface

$$\sin \phi_c = \frac{n_2}{n_1} = \cos \theta \qquad T_{\text{Max}} = \frac{Ln_1^2}{cn_2}$$

- The delay difference δTs between the extreme meridional ray and the axial ray

$$\delta T_s = T_{\text{Max}} - T_{\text{Min}} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

$$= \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right)$$

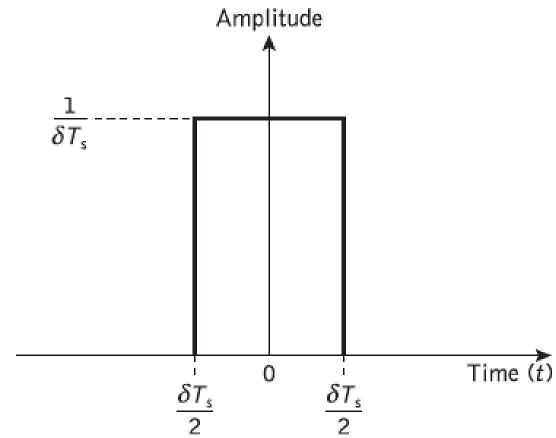
$$\simeq \frac{Ln_1^2\Delta}{cn_2} \quad \text{when } \Delta \ll 1$$

$$\Delta \simeq \frac{n_1 - n_2}{n_2} \qquad \delta T_s = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right) \simeq \frac{Ln_1\Delta}{c}$$

$$\delta T_s \simeq \frac{L(NA)^2}{2n_1 c}$$

- When the optical input to the fiber is a pulse pi(t) of unit area

$$\int_{-\infty}^{\infty} p_i(t)\,dt = 1$$



It may be noted that $p_i(t)$ has a constant amplitude of $1/\delta T_s$ over the range:

$$\frac{-\delta T_s}{2} \le p(t) \le \frac{\delta T_s}{2}$$

The rms pulse broadening at the fiber output due to intermodal dispersion for the multimode step index fiber σ_s (i.e. the standard deviation) may be given in terms of the variance σ_s^2 as

$$\sigma_s^2 = M_2 - M_1^2$$

where M_1 is the first temporal moment which is equivalent to the mean value of the pulse and M_2, the second temporal moment, is equivalent to the mean square value of the pulse. Hence:

$$M_1 = \int_{-\infty}^{\infty} t p_i(t)\,dt \qquad \text{and:} \qquad M_2 = \int_{-\infty}^{\infty} t^2 p_i(t)\,dt$$

The mean value M_1 for the unit input pulse of Figure is zero, and assuming this is aintained for the output pulse, then

$$\sigma_s^2 = M_2 = \int_{-\infty}^{\infty} t^2 p_i(t)\,dt$$

$$\sigma_s^2 = \int_{-\delta T_s/2}^{\delta T_s/2} \frac{1}{\delta T_s} t^2 \, dt$$

$$= \frac{1}{\delta T_s} \left[\frac{t^3}{3} \right]_{-\delta T_s/2}^{\delta T_s/2} = \frac{1}{3} \left(\frac{\delta T_s}{2} \right)^2$$

$$\sigma_s \simeq \frac{L n_1 \Delta}{2\sqrt{3} c} \simeq \frac{L (NA)^2}{4\sqrt{3} n_1 c}$$

The pulse broadening is directly proportional to the relative refractive index difference Δ and the length of the fiber L

Q. A 6 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

a) the delay difference between the slowest and fastest modes at the fiber output;

b) the rms pulse broadening due to intermodal dispersion on the link;

c) the maximum bit rate that may be obtained without substantial errors on the link assuming only intermodal dispersion;

d) the bandwidth–length product corresponding to (c).

$$\delta T_s \simeq \frac{Ln_1\Delta}{c} = \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$
$$= 300 \text{ ns}$$

$$\sigma_s = \frac{Ln_1\Delta}{2\sqrt{3}c} = \frac{1}{2\sqrt{3}} \frac{6 \times 10^3 \times 1.5 \times 0.01}{2.998 \times 10^8}$$
$$= 86.7 \text{ ns}$$

$$B_T(\max) = \frac{1}{2\tau} = \frac{1}{2\delta T_s} = \frac{1}{600 \times 10^{-9}}$$
$$= 1.7 \text{ Mbit s}^{-1}$$

$$B_T(\max) = \frac{0.2}{\sigma_s} = \frac{0.2}{86.7 \times 10^{-9}}$$
$$= 2.3 \text{ Mbit s}^{-1}$$

$$B_{opt} \times L = 2.3 \text{ MHz} \times 6 \text{ km} = 13.8 \text{ MHz km}$$

Modal noise

- The intermodal dispersion properties of multimode optical fibers create another phenomenon which affects the transmitted signals on the optical channel.
- It is exhibited within the speckle patterns observed in multimode fiber as fluctuations which is known as **modal or speckle noise**. The speckle patterns are formed by the interference of the modes from a coherent source when the **coherence time of the source is greater than the intermodal dispersion time δT** within the fiber. The coherence time for a source with uncorrelated source frequency width δf is simply 1/δf. Hence, modal noise occurs when $\delta f \gg \frac{1}{\delta T}$
- Disturbances along the fiber such as vibrations, discontinuities, connectors, splices and source/detector coupling may cause fluctuations in the speckle patterns and hence modal noise.

Conditions of Modal Noise generation

a. a coherent source with a narrow spectral width and long coherence length (propagation velocity multiplied by the coherence time);
b. disturbances along the fiber which give differential mode delay or modal and spatial filtering;
c. phase correlation between the modes.

Condition to reduce Modal Noise: modal-noise-free transmission may be obtained by the following:

a. The use of a broad spectrum source in order to eliminate the modal interference effects. This may be achieved by either

   - increasing the width of the single longitudinal mode and hence decreasing its coherence time

   -by increasing the number of longitudinal modes and averaging out of the interference patterns.

b. It is found that fibers with large numerical apertures support the transmission of a large number of modes giving a greater number of speckles, and hence reduce the modal noise generating effect of individual speckles.

c. The use of single-mode fiber which does not support the transmission of different modes and thus there is no intermodal interference.

d. The removal of disturbances along the fiber. This has been investigated with regard to connector design in order to reduce the shift in speckle pattern induced by mechanical vibration and fiber misalignment.

Overall fiber dispersion

- **For Multimode fibers:** The overall dispersion in multimode fibers comprises both chromatic and intermodal terms. The total rms pulse broadening σT is given

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{\frac{1}{2}}$$

where σc is the intramodal or chromatic broadening and σn is the intermodal broadening caused by delay differences between the modes

- **For Single Mode Fiber:** The pulse broadening in single-mode fibers results almost entirely from chromatic or intramodal dispersion as only a single-mode is allowed to propagate.
- The transit time or specific group delay τg for a light pulse propagating along a unit length of single-mode fiber may be given

$$\tau_g = \frac{1}{c}\frac{d\beta}{dk}$$

- The total first-order dispersion parameter or the chromatic dispersion of a single-mode fiber, DT, is given by

$$D_T = \frac{d\tau_g}{d\lambda} \qquad D_T = -\frac{\omega}{\lambda}\frac{d\tau_g}{d\omega} = -\frac{\omega}{\lambda}\frac{d^2\beta}{d\omega^2}$$

- The rms pulse broadening caused by chromatic dispersion down a fiber of length L is given by

$$\text{Total rms pulse broadening} = \sigma_\lambda L \left| \frac{d\tau_g}{d\lambda} \right|$$

$$= \frac{\sigma_\lambda L 2\pi}{c\lambda^2}\frac{d^2\beta}{dk^2}$$

KERR EFFECT

- When an optical wave is within a fiber medium incident photons may be scattered, producing a phonon emitted at acoustic frequencies by exciting molecular vibrations, together with another photon at a shifted frequency.
- This process can be described as the molecule absorbing the photon at the original frequency while emitting a photon at the shifted frequency and simultaneously making a transition between vibrational states.
- The scattered photon therefore emerges at a frequency shifted below or above the incident photon frequency with the energy difference between the two photons being deposited or extracted from the scattering medium

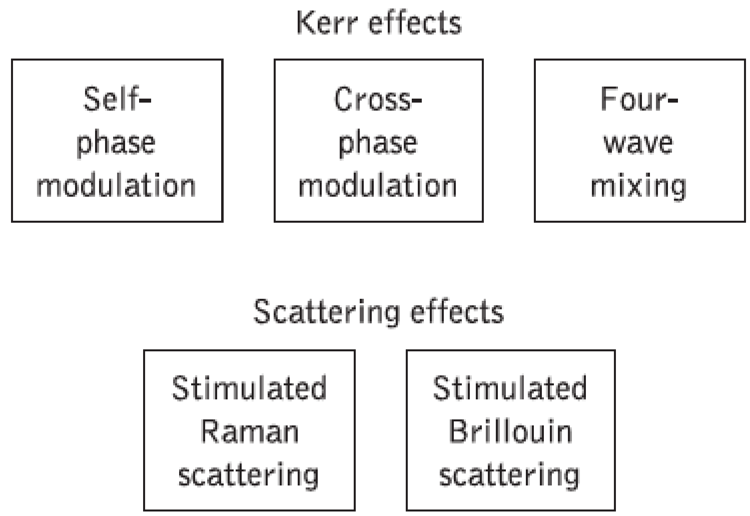


Figure Block schematic showing the fiber nonlinear effects

- The Kerr effect is due to the non-linear response of the material. It means that the index of the silica is now depending on the optical field propagation through it.
- The power dependence of the refractive index is responsible for the Kerr-effect.
- Depending upon the type of input signal, the Kerr-nonlinearity has three different effects such as **Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM).**
- The nonlinearity in refractive index is known as Kerr nonlinearity.
- This nonlinearity produces a carrier induced phase modulation of the propagating signal, which is called Kerr Effect.

  Self Phase Modulation (SPM) : If an intensity modulated signal propagates in the fibre, the intensity modulation induces an index modulation of the fibre and in return a phas modulation to the signal. The signal modulates itself The SPM induced phase modulation broadens the signal spectrum.
- **Self-phase modulation (SPM) is a fiber nonlinearity caused by the** nonlinear index of refraction of glass. The index of refraction varies with optical power level causing a frequency chirp which interacts with the fiber's dispersion to broaden the pulse.

$$n = n + n_2\left(\frac{P}{A_{eff}}\right)$$

Where:

- n = Ordinary refractive index of material
- n_2 = Nonlinear index coefficient
- P = Optical Power
- A_{eff} = Effective mode area

The numerical value of $n_2 = 2.6 \times 10^{-20}\ m^2/W$

- **Cross Phase Modulation (XPM) :** In the case of a multi–channel propagation, the index modulation induced by the Kerr–effect modulates the other channels and vice-versa.
- **Four Wave Mixing (FWM) :** In the case of a multi–channel propagation and under phase matching conditions, new frequencies are generated in the fibre causing crosstalk and power depletion.
- The easiest way to obtain FWM in a fibre is to propagate two waves at angular frequencies w1 and w2 that will create new waves at frequencies w3 and w4 such as:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

- This phenomenon is strongly dependent on channel spacing and chromatic dispersion.
- The generated waves may cause crosstalk if they are at the same wavelength as incident channels.