Transmission Characteristics

- The transmission through an optical fiber is limited by attenuation (or loss) and dispersion.
- In 1970s, it was realized that the attenuation was largely due to absorption in the glass caused by impurities such as iron, copper, manganese etc. Hence, research was stimulated towards a new generation of "pure" glasses for use in optical fiber communication. It lead to silica based glass fibers with losses less than 0.2 dB/km.
- The other characteristic is bandwidth which is mostly limited by signal dispersion within the fiber. It determines the number of bits of transmission transmitted in a given time period.

ATTENUATION

❖ Attenuation determines the maximum transmission distance prior to signal restoration. OFC became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors. (< 5 db/km)

❖ Signal attenuation in optical fibers (or that of metallic cable) is usually expressed in the units of decibel. Decibel is used for comparing two power levels.

$$dB = 10\log_{10}\frac{P_i}{P_o}$$

For a particular optical wavelength,

P_i → input (transmitted) optical power

P_o → output (received) optical power

In OFC, attenuation is usually expressed in dB per unit length (dB/km)

$$\alpha_{dB}L = 10\log_{10}\frac{P_i}{P_o}$$

α_{dB} → signal attenuation/length

L → Fiber length

MATERIAL ABSORPTION LOSSES IN SILICA GLASS FIBERS

❖ This loss mechanism is related to material composition and the fabrication process for the fiber. Absorption of light may be :

Intrinsic: caused by the interaction with one or more of the major components of the glass

Extrinsic: caused by impurities within the glass

Intrinsic absorption

- Pure silica-based glass has *two* major intrinsic absorption mechanisms at optical wavelengths:

(1) a *fundamental UV absorption* edge, the peaks are centered in the *ultraviolet wavelength region*. This is due to the *electron transitions* within the glass molecules. The tail of this peak may extend into the the shorter wavelengths of the fiber transmission spectral window.

(2) A fundamental *infrared and far-infrared absorption edge*, due to *molecular vibrations* (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

Electronic and molecular absorption

- ***Electronic absorption***: the bandgap of fused silica is about 8.9 eV (~140 nm). This causes strong absorption of light in the UV spectral region due to electronic transitions across the bandgap.

  In practice, the bandgap of a material is not sharply defined but usually has ***bandtails*** extending from the conduction and valence bands into the bandgap due to a variety of reasons, such as *thermal vibrations of the lattice ions* and *microscopic imperfections of the material structure*.

  An *amorphous* material like fused silica generally has very long bandtails. These bandtails lead to an absorption tail extending into the visible and infrared regions. Empirically, the absorption tail at photon energies below the bandgap falls off exponentially with photon energy.

- ***Molecular absorption***: in the infrared region, the absorption of photons is accompanied by transitions between different *vibrational modes* of silica molecules.

- The *fundamental vibrational transition* of fused silica causes a very strong absorption peak at about 9 μm wavelength.

- *Nonlinear effects* contribute to important harmonics and combination frequencies corresponding to minor absorption peaks at 4.4, 3.8 and 3.2 μm wavelengths.

=> a long absorption tail extending into the near infrared, causing a sharp rise in absorption at optical wavelengths longer than 1.6 μm.

Extrinsic absorption

- Major extrinsic loss mechanism is caused by absorption due to water (*as the hydroxyl or OH^- ions*) introduced in the glass fiber during *fiber pulling by means of oxyhydrogen flame*.

- These OH^- ions are bonded into the glass structure and have absorption peaks (due to *molecular vibrations*) at 1.39 μm. The fundamental vibration of the OH^- ions appear at 2.73 μm.

- Since these OH^- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH^- absorption.

- The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 μm at about 0.2 dB/km, approaching the *minimum possible attenuation* at this wavelength.

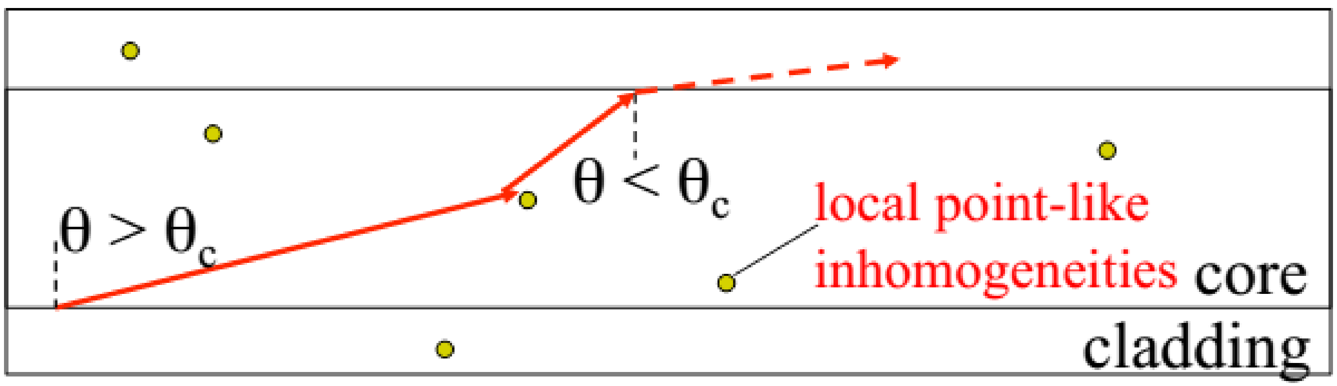
Impurity absorption

- ***Impurity absorption***: most impurity ions such as OH^-, Fe^{2+} and Cu^{2+} form absorption bands in the *near infrared* region where both electronic and molecular absorption losses of the host silica glass are very low.
- Near the peaks of the impurity absorption bands, an impurity concentration as low as *one part per billion* can contribute to an absorption loss as high as 1 dB km^{-1}.
- In fact, fiber-optic communications were not considered possible until it was realized in 1966 (Kao) that most losses in earlier fibers were caused by impurity absorption and then ultra-pure fibers were produced in the early 1970s (Corning).
- Today, impurities in fibers have been reduced to levels where losses associated with their absorption are negligible, with the exception of the OH^- radical.

Scattering loss

Scattering results in attenuation (*in the form of radiation*) as the scattered light may not continue to satisfy the total internal reflection in the fiber core.

One major type of scattering is known as *Rayleigh scattering*.



The scattered ray can escape by refraction according to Snell's Law.

Rayleigh scattering

- *Rayleigh scattering* results from random *inhomogeneities* that are small in size compared with the wavelength.

$$\circ \quad \ll \quad \lambda$$

- These inhomogeneities exist in the form of *refractive index fluctuations* which are frozen into the *amorphous* glass fiber upon fiber pulling. Such fluctuations *always exist and cannot be avoided* !

Rayleigh scattering results in an attenuation (dB/km) $\propto 1/\lambda^4$

Waveguide scattering (Mie Scattering)

- ***Imperfections in the waveguide structure*** of a fiber, such as nonuniformity in the size and shape of the core, perturbations in the core-cladding boundary, and defects in the core or cladding, can be generated in the manufacturing process.

- Environmentally induced effects, such as stress and temperature variations, also cause imperfections.

- The imperfections in a fiber waveguide result in additional scattering losses. They can also induce coupling between different guided modes.

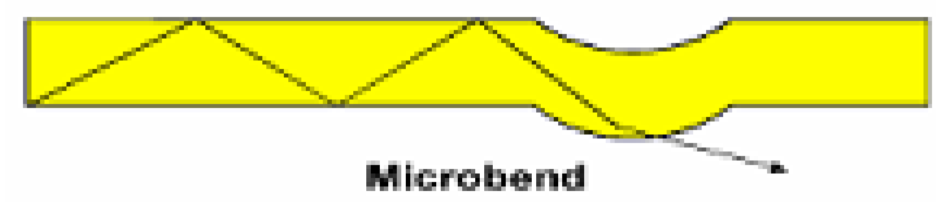
Bending loss

- At a bend the propagation conditions alter and light rays which would propagate in a straight fibre are lost in the cladding.

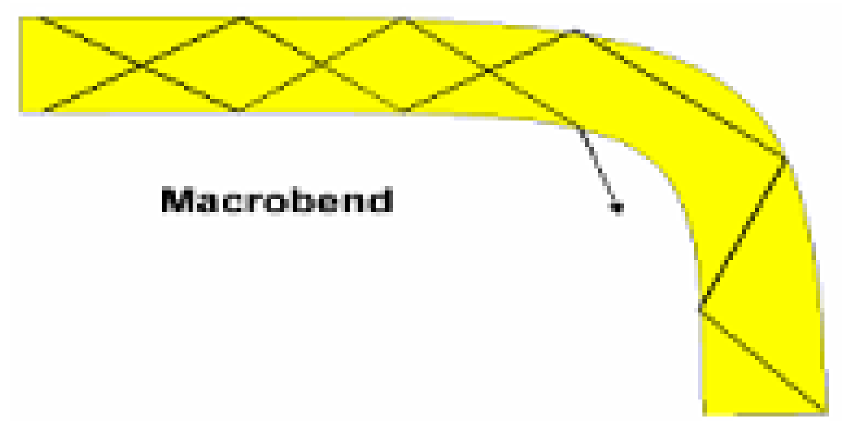
- Macrobending, for example due to tight bends

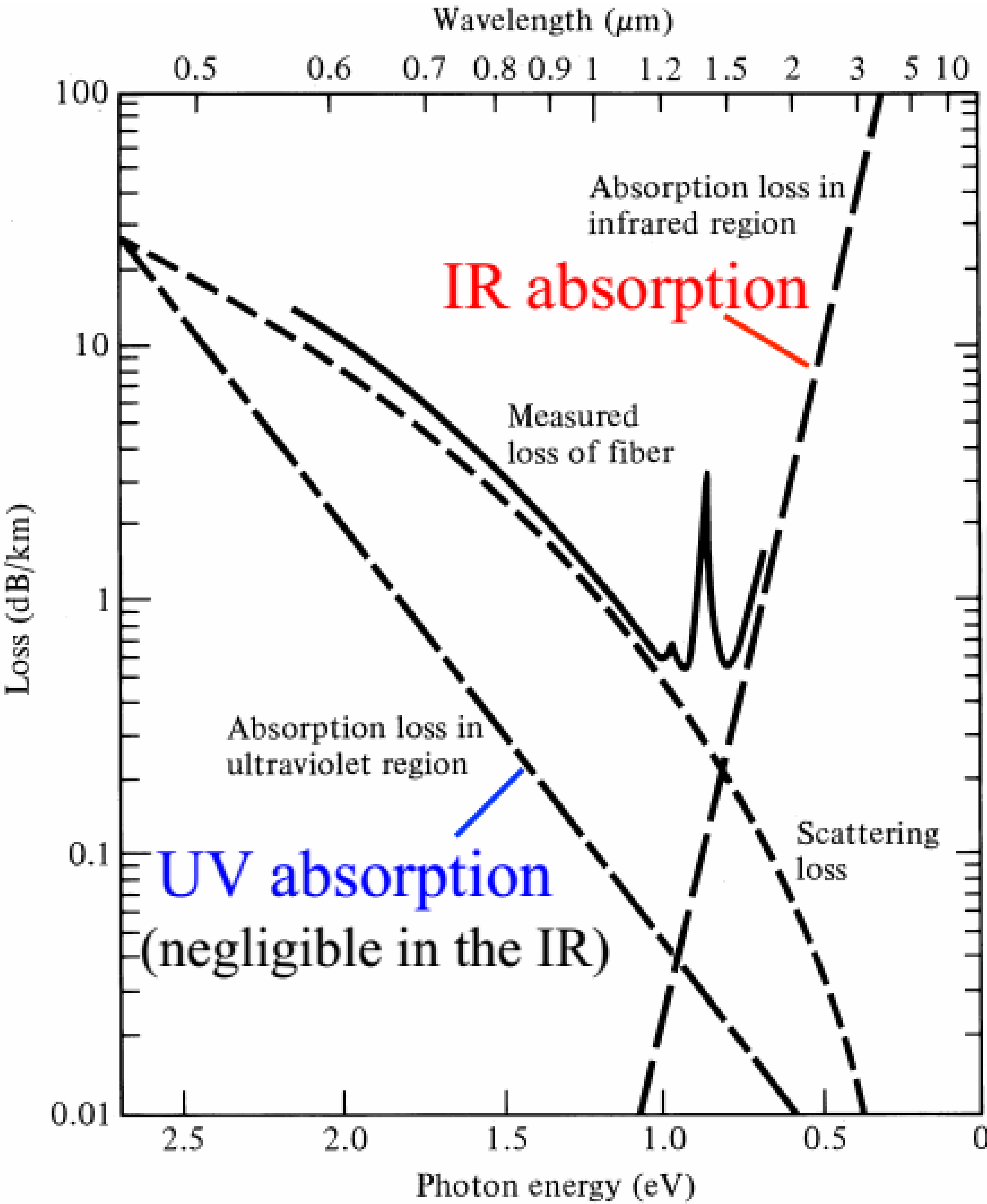
- Microbending, due to microscopic fibre deformation, commonly caused by poor cable design

Microbending is commonly caused by poor cable design



Macrobending is commonly caused by poor installation or handling

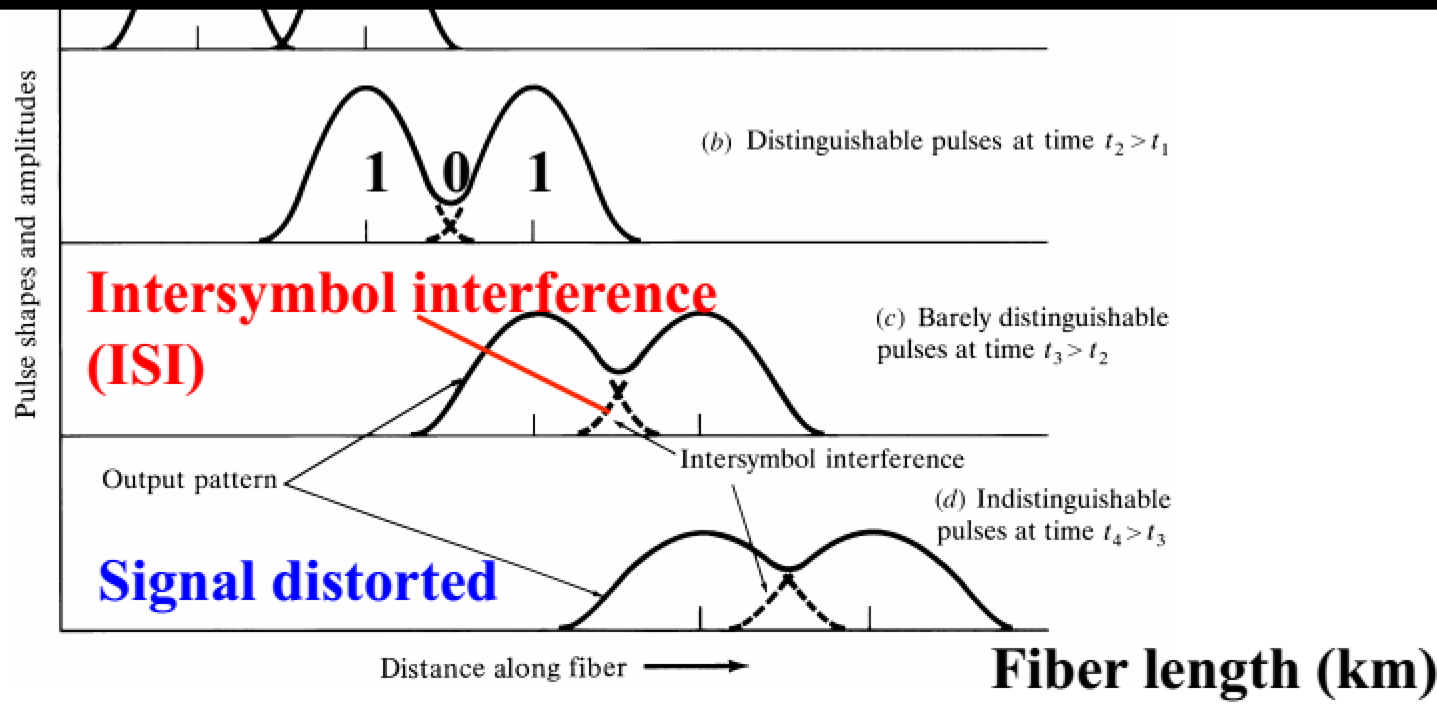




Attenuation spectra for fused silica based glass

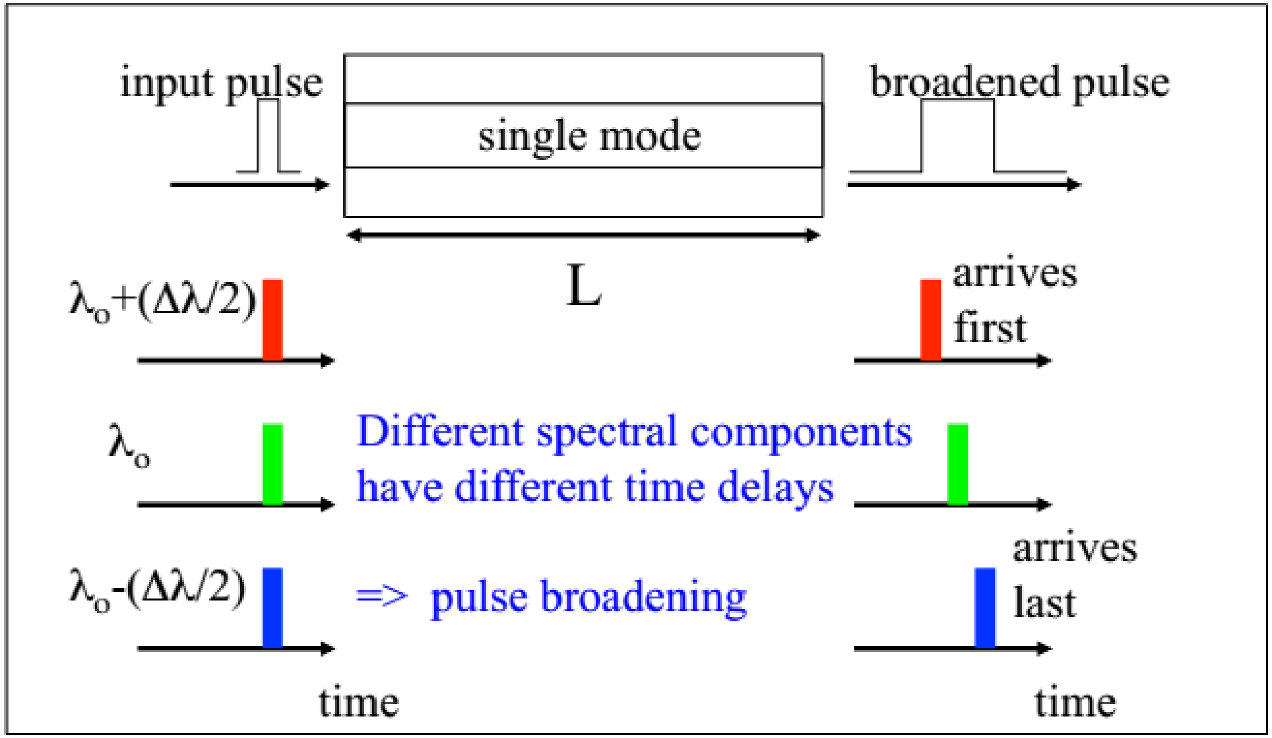
DISPERSION

Hence, the number of optical signal pulses which may be transmitted in a given period and therefore the information carrying capacity of the fiber, is restricted by the amount of pulse dispersion per unit length. The pulse broadening increases linearly with fiber length and thus the bandwidth is inversely proportional to distance.



Intramodal (Chromatic) dispersion

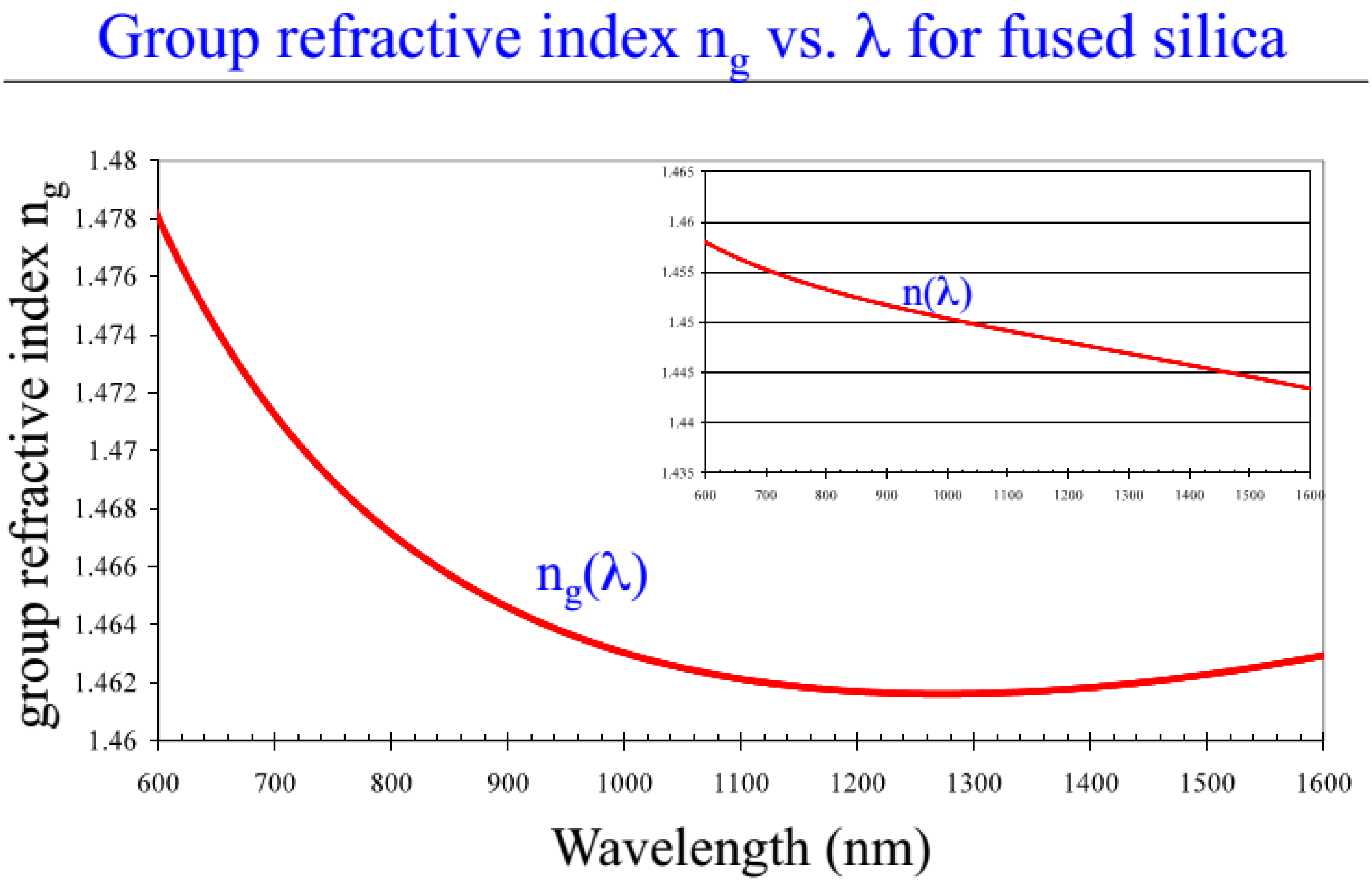
- Results from the finite spectral linewidth of the optical source.
- Optical light sources do not emit just a single frequency but a band of frequencies. Hence, there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion.



- The delay differences may be caused by:
  - Dispersive properties of the waveguide material **(material dispersion)**
  - Guidance factors within the fiber structure **(waveguide dispersion)**

Material Dispersion

❖ Results when different spectral components of a pulse travel at different group velocities.

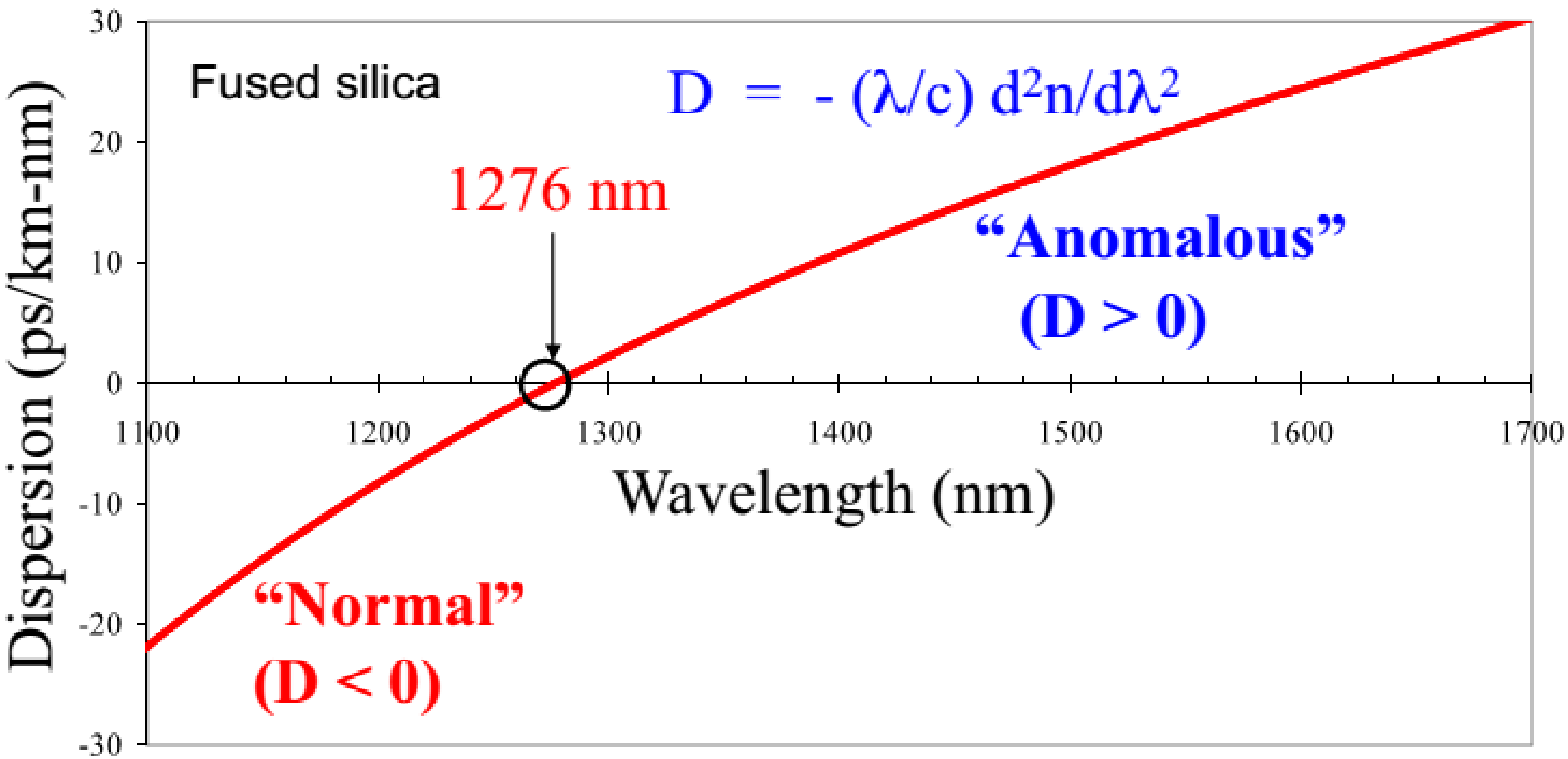


❖ A material is said to exhibit material dispersion when the 2^{nd} order refractive index of core with respect to wavelength is not equal to zero.

$$\boxed{\frac{d^2n}{d\lambda^2} \neq 0}$$

❖ Material dispersion $D(\lambda)$ is given by:

$$\boxed{D(\lambda) = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2}}$$



Material dispersion $D_{mat} = 0$ at $\lambda \sim 1276$ nm for fused silica.

This λ is referred to as the ***zero-dispersion wavelength*** $\boldsymbol{\lambda_{ZD}}$.

Chromatic (or *material*) dispersion $D(\lambda)$ can be zero;
or
negative => longer wavelengths travel *faster* than shorter wavelengths;
or
positive => shorter wavelengths travel *faster* than longer wavelengths.

Waveguide Dispersion

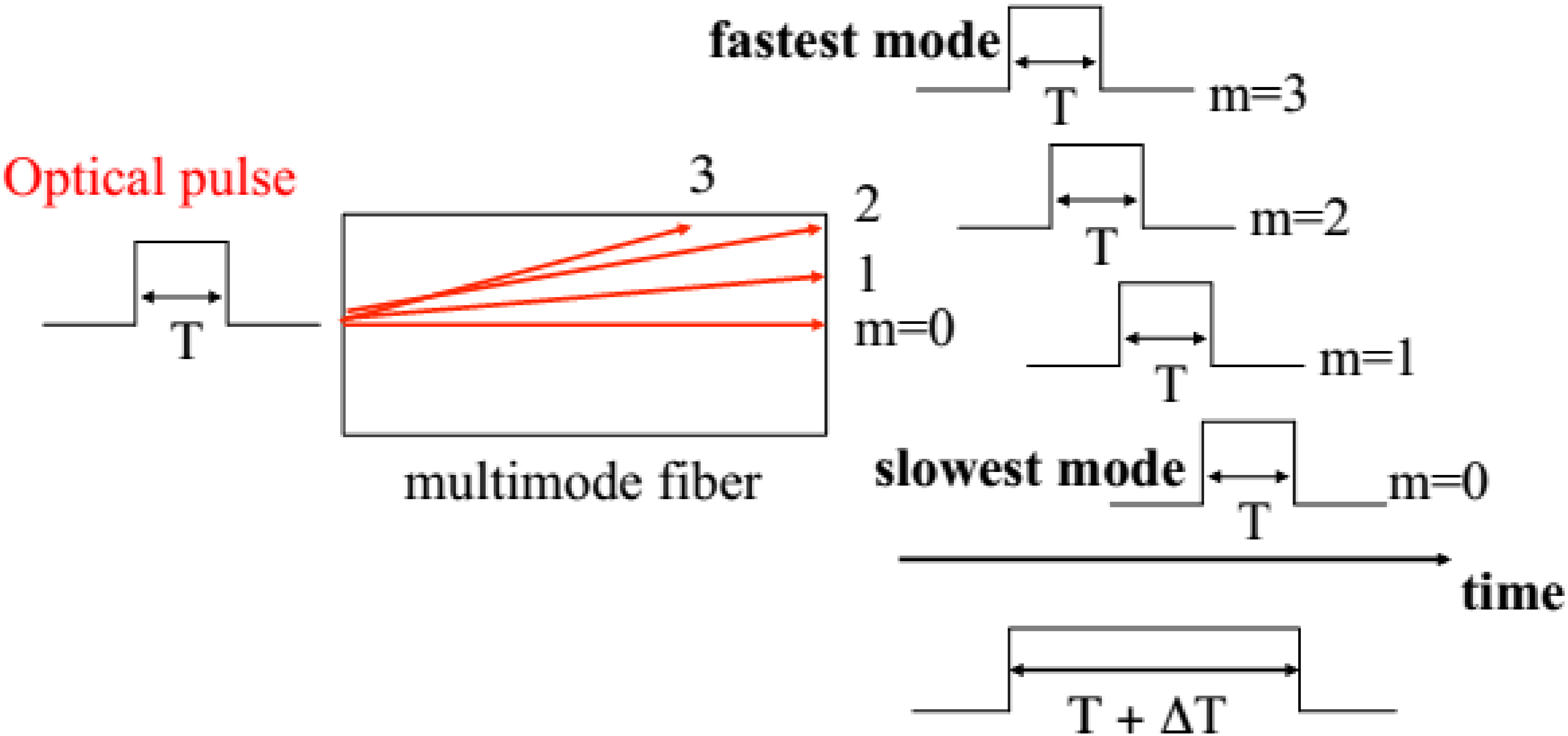
- Results from the variation in group velocity with wavelength for a particular mode.
- Angle between the ray and the fiber axis varies with wavelength which subsequently leads to a variation in the transmission times for the rays, hence dispersion.
- More prominent in case of single mode fibers than in the multimode fibers.

$$\Rightarrow D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda)$$

Intermodal dispersion

- Sometimes referred to as Modal (or mode) dispersion.
- When numerous waveguide modes are propagating, they all travel with different group velocities.
- Parts of the wave arrive at the output before other parts, spreading out the waveform. Hence, it is also known as multimode dispersion.
- It is independent of the source linewidth.
- It does not occur in a single mode fiber.

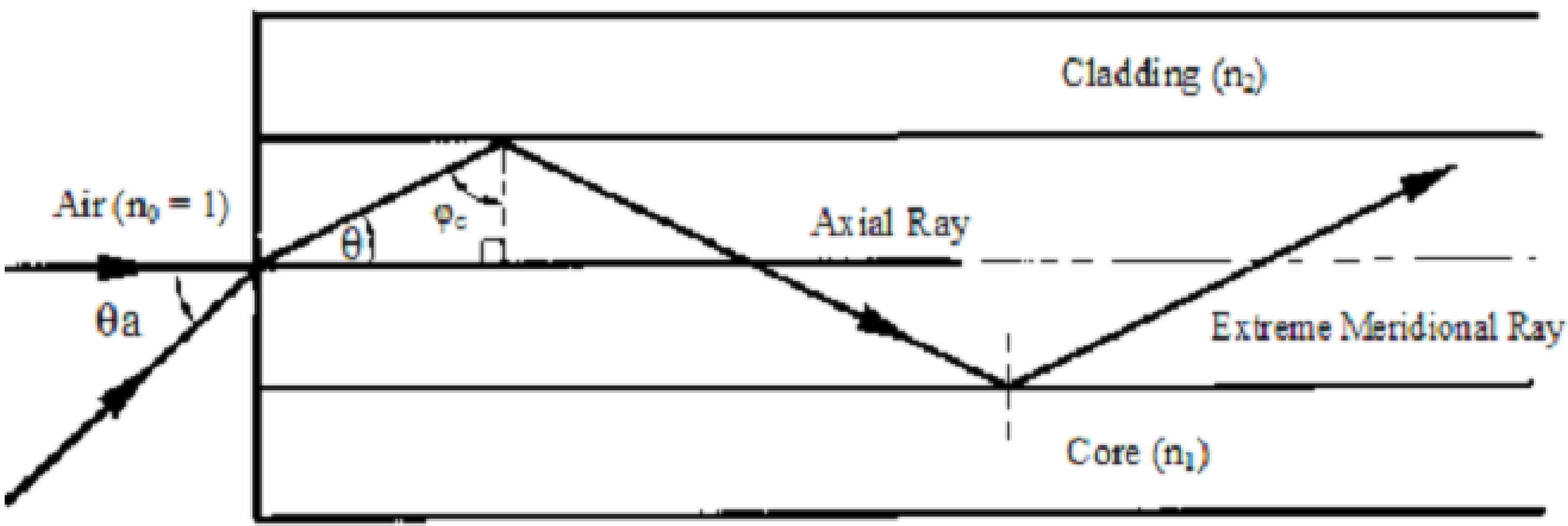
Modal dispersion results in pulse broadening



modal dispersion: different modes arrive at the receiver with different delays => pulse broadening

Multimode step index fiber

Paths taken by the axial and an extreme meridional ray in a perfect multimode step index fiber is shown here.



T_{Min} → Minimum delay time (time taken for the axial ray to travel along a fiber of length L)

T_{Max} → Maximum delay time (time taken for the meridional ray to travel along a fiber of length L)

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

$$T_{Max} = \frac{L/\cos\theta}{(C/n_1)} = \frac{Ln_1}{C\cos\theta}$$

$$\sin\phi_c = \frac{n_2}{n_1} = \cos\theta$$

$$T_{Max} = \frac{Ln_1^2}{Cn_2}$$

$$\delta T_s = T_{Max} - T_{Min} = \frac{Ln_1^2\,\Delta}{Cn_2} \cong \frac{Ln_1\Delta}{C} \cong \frac{L(NA)^2}{2n_1 C}$$

Delay difference for $\Delta \ll 1$

Optical Sources

- Optical source is often considered to be the active component in an optical fiber communication system
- Fundamental function is to convert electrical energy into optical energy (light)

Three main types of optical sources

- Wide band **continuous spectra source** (incandescent lamp)
- Monochromatic **incoherent** sources (**Light Emitting Diodes LED**)
- Monochromatic **coherent** sources (**Laser**)

Characteristics of optical sources for OFC

- ❖ Light output should be highly directional.
- ❖ Most accurately track the electrical input signal to minimize distortion and noise. Ideally, the source should be linear.
- ❖ Should emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient.
- ❖ Should have a very narrow spectral linewidth in order to minimize dispersion in the fiber.