Attenuation in fibers

Transmission characteristics of optical fibers

- The transmission characteristics of most interest: **attenuation (*loss*)** and **bandwidth**.

- Now, *silica-based* glass fibers have losses less than 0.2 dB/km (i.e. 95 % launched power remains after 1 km of fiber transmission). This is essentially the *fundamental lower limit* for attenuation in silica-based glass fibers.

- **Fiber bandwidth** is limited by the *signal dispersion* within the fiber. Bandwidth determines the number of bits of information transmitted in a given time period. Now, fiber bandwidth has reached many 10's Gbit over many km's per wavelength channel.

Attenuation

- Signal attenuation within optical fibers is usually expressed in the logarithmic unit of the decibel.

The decibel, which is used for comparing two *power* levels, may be defined for a particular optical wavelength as the *ratio* of the output optical power P_o from the fiber to the input optical power P_i.

$$\text{Loss (dB)} = -10 \log_{10} (P_o/P_i) = 10 \log_{10} (P_i/P_o)$$

$$(P_o \leq P_i)$$

*In *electronics*, $\text{dB} = 20 \log_{10} (V_o/V_i)$

Attenuation in dB/km

*The logarithmic unit has the advantage that the operations of *multiplication* (*and division*) reduce to *addition* (*and subtraction*).

In numerical values: $P_o/P_i = 10^{[-\text{Loss(dB)}/10]}$

The attenuation is usually expressed in decibels per unit length (i.e. dB/km):

$$\gamma L = -10 \log_{10} (P_o/P_i)$$

γ (dB/km): signal attenuation per unit length in decibels

L (km): fiber length

dBm

- dBm is a specific unit of power in decibels when the reference power is 1 mW:

$$\text{dBm} = 10 \log_{10} (\text{Power}/1 \text{ mW})$$

e.g. 1 mW = 0 dBm; 10 mW = 10 dBm; 100 μW = - 10 dBm

=> Loss (dB) = input power (dBm) - output power (dBm)

e.g. Input power = 1 mW (0 dBm), output power = 100 μW (-10 dBm)

$$\Rightarrow \text{loss} = -10 \log_{10} (100\ \mu\text{W}/1 \text{ mW}) = 10 \text{ dB}$$

$$\text{OR} \quad 0 \text{ dBm} - (-10 \text{ dBm}) = 10 \text{ dB}$$

Fiber attenuation mechanisms

1. Material absorption
2. Scattering loss
3. Nonlinear loss
4. Bending loss
5. Mode coupling loss

- ***Material absorption*** is a loss mechanism related to both *the material composition* and the *fabrication process* for the fiber. The optical power is lost as *heat* in the fiber.

- The light absorption can be *intrinsic* (*due to the material components of the glass*) or *extrinsic* (*due to impurities introduced into the glass during fabrication*).

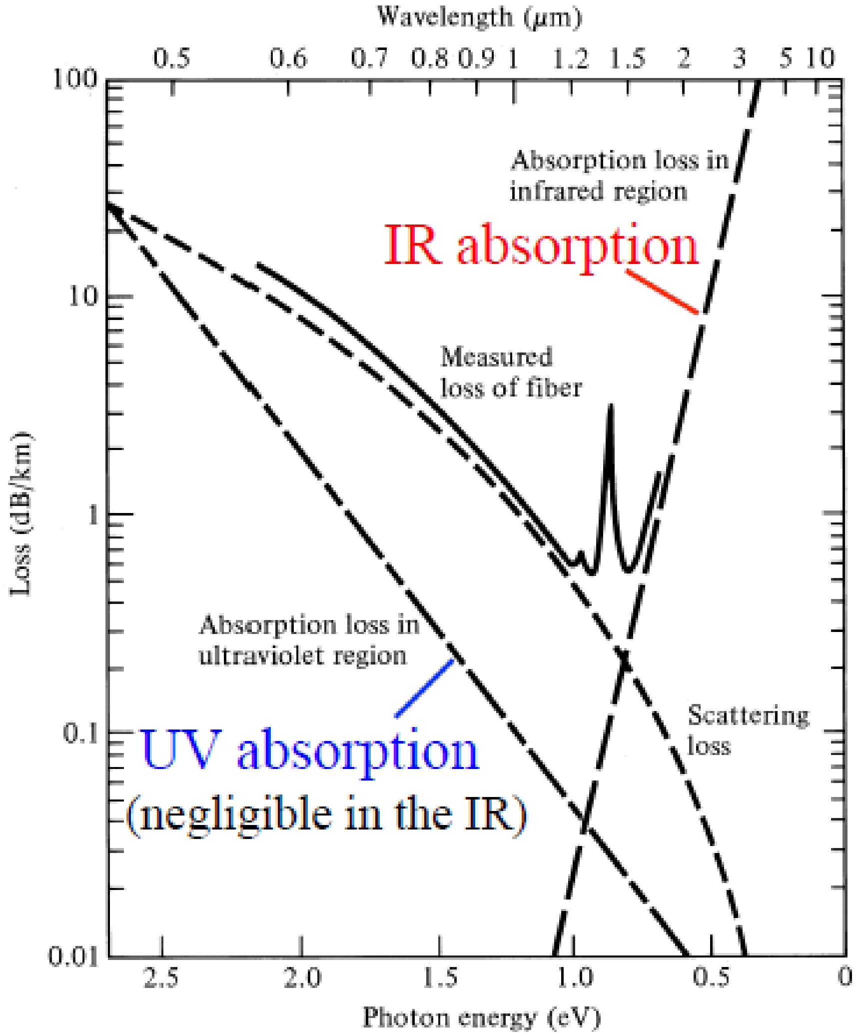
Intrinsic absorption

- 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.

Fundamental fiber attenuation characteristics



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.

Electronic and molecular absorption

- ***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

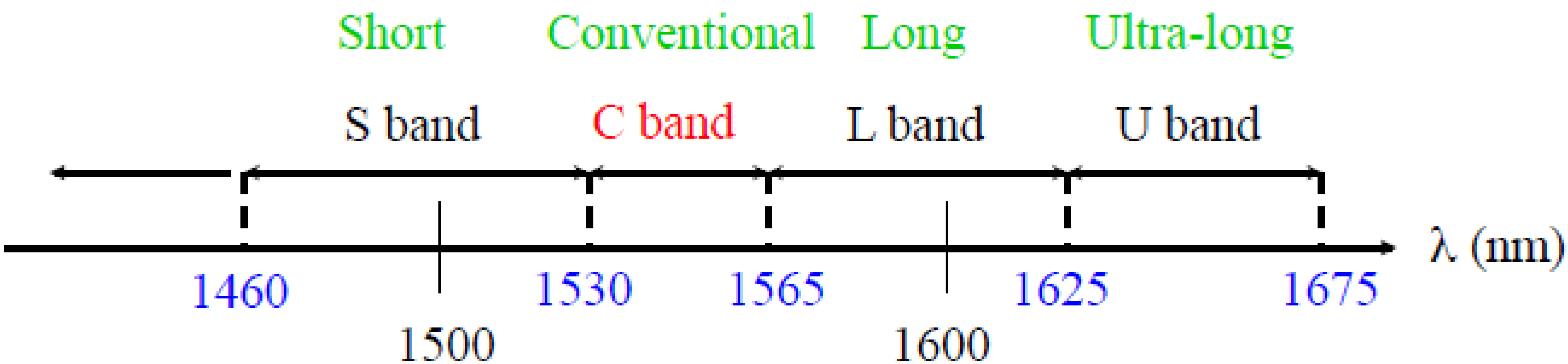
- ***Impurity absorption***: most impurity ions such as OH^-, Fe^{2+} and Cu^{2+} form absorption bands in the *near infrared* region where both electronic and molecular absorption losses of the host silica glass are very low.
- Near the peaks of the impurity absorption bands, an impurity concentration 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.

Three major fiber transmission spectral windows

The 1st window: 850 nm, attenuation 4 dB/km
The 2nd window: 1300 nm, attenuation 0.5 dB/km
The 3rd window: 1550 nm, attenuation 0.2 dB/km

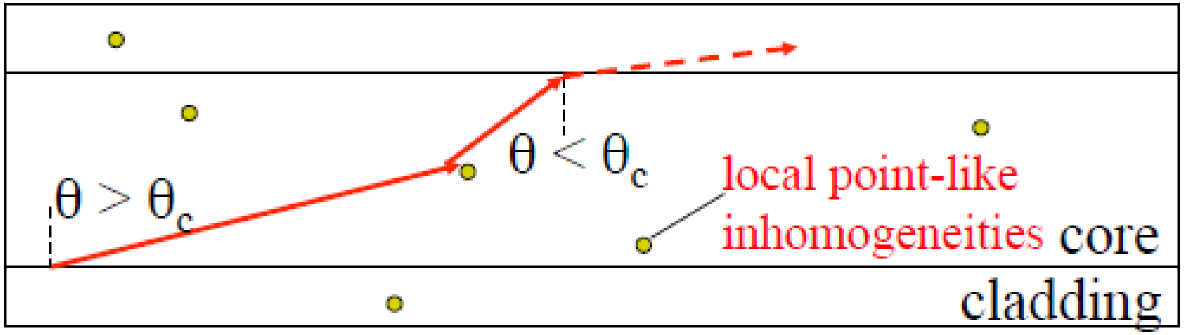
1550 nm window is today's standard **long-haul** communication wavelengths.



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.

$$\bullet \ll \lambda$$

- 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

- ***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.

Nonlinear losses

- Because light is confined over long distances in an optical fiber, ***nonlinear optical effects*** can become important even at a relatively moderate optical power.
- Nonlinear optical processes such as *stimulated Brillouin scattering* and *stimulated Raman scattering* can cause significant attenuation in the power of an optical signal.
- Other nonlinear processes can induce *mode mixing* or *frequency shift*, all contributing to the loss of a particular guided mode at a particular frequency.
- Nonlinear effects are *intensity dependent*, and thus they can become very important at high optical powers.

Dispersion in fibers

Dispersion in fibers

- Dispersion is the primary cause of limitation on the optical signal transmission bandwidth through an optical fiber.

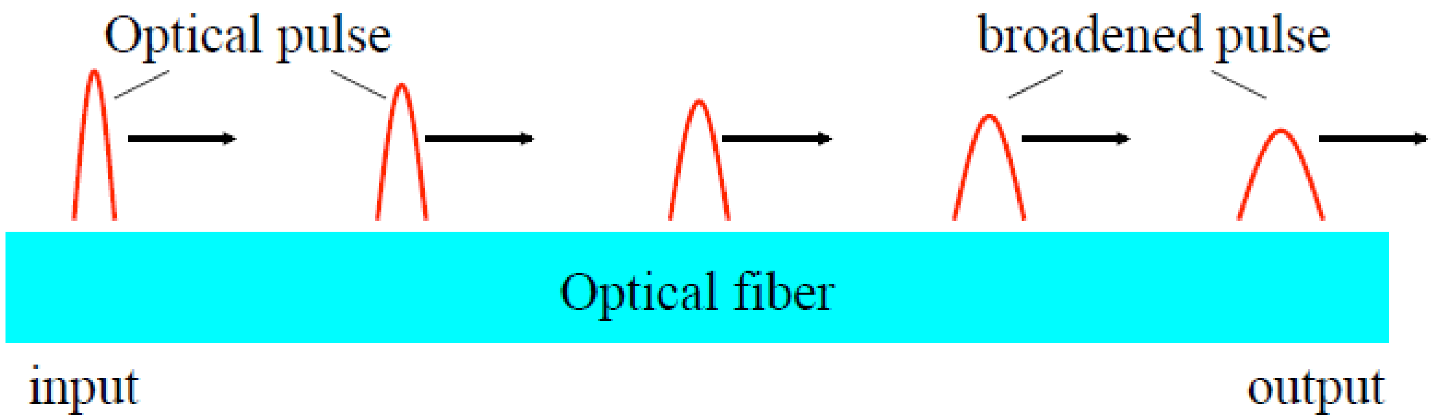
- Both material dispersion and waveguide dispersion are examples of *chromatic dispersion* because both are frequency dependent.
- *Waveguide dispersion* is caused by frequency dependence of the propagation constant β of a specific mode due to the waveguiding effect. (*recall the b vs. V plot of a specific mode*)
- The combined effect of material and waveguide dispersions for a particular mode alone is called *intramode dispersion*.

Modal dispersion

- ***Modal dispersion*** is caused by the variation in propagation constant between different modes; it is also called *intermode dispersion*. (*recall the b vs. V plot at a fixed V*)
- Modal dispersion appears only when *more than one* mode is excited in a multimode fiber. It exists even when chromatic dispersion disappears.
- *If only one mode is excited in a fiber*, only intramode chromatic dispersion has to be considered even when the fiber is a multimode fiber.

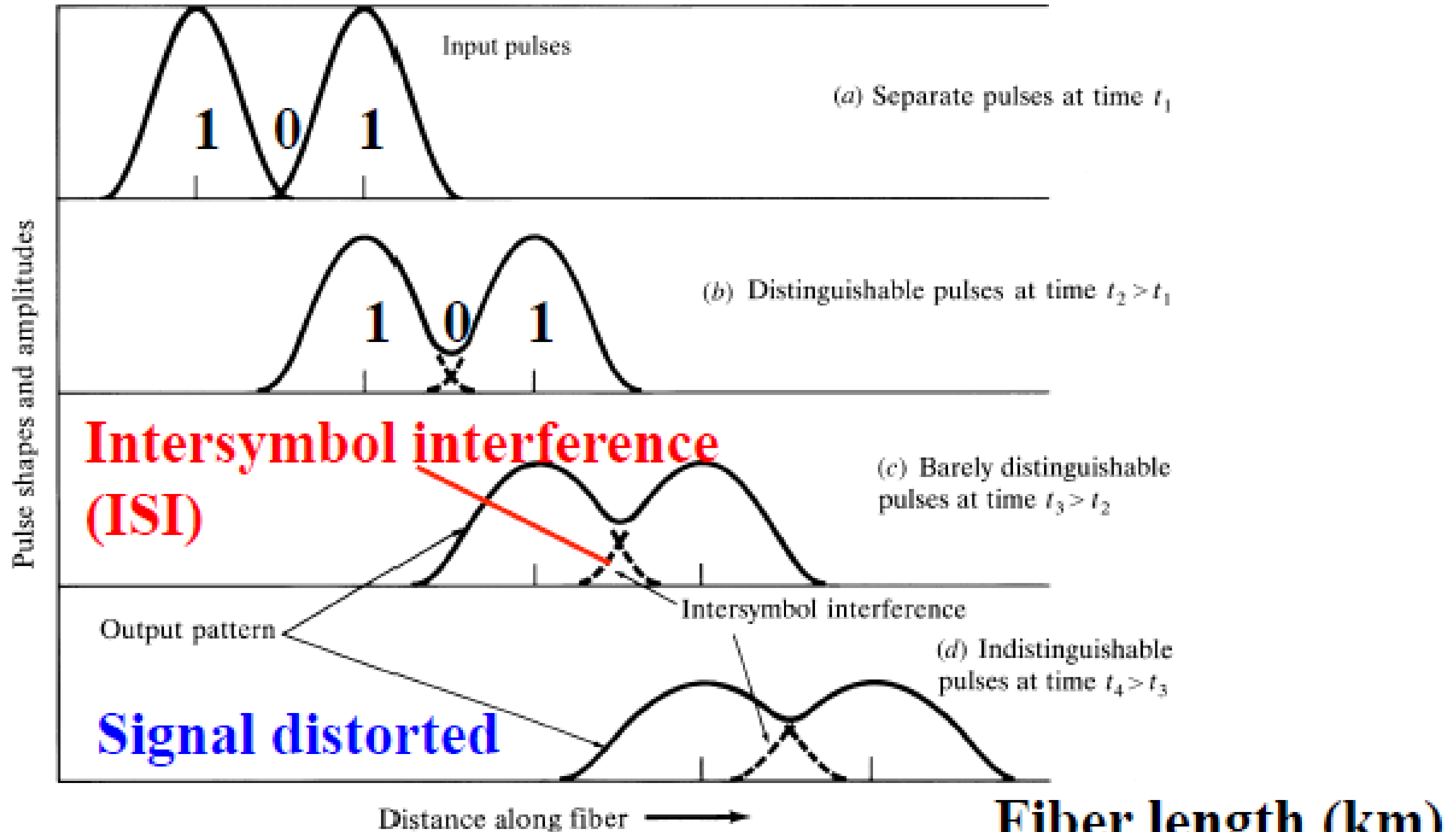
Fiber dispersion

- Fiber dispersion results in *optical pulse broadening* and hence *digital signal degradation*.



Dispersion mechanisms: 1. Modal (or *intermodal*) dispersion
2. Chromatic dispersion (CD)
3. Polarization mode dispersion (PMD)

Pulse broadening limits fiber bandwidth (data rate)



- An *increasing number of errors* may be encountered on the digital optical channel as the ISI becomes more pronounced.

Modal dispersion

- When numerous waveguide modes are propagating, they all travel with different velocities with respect to the waveguide axis.

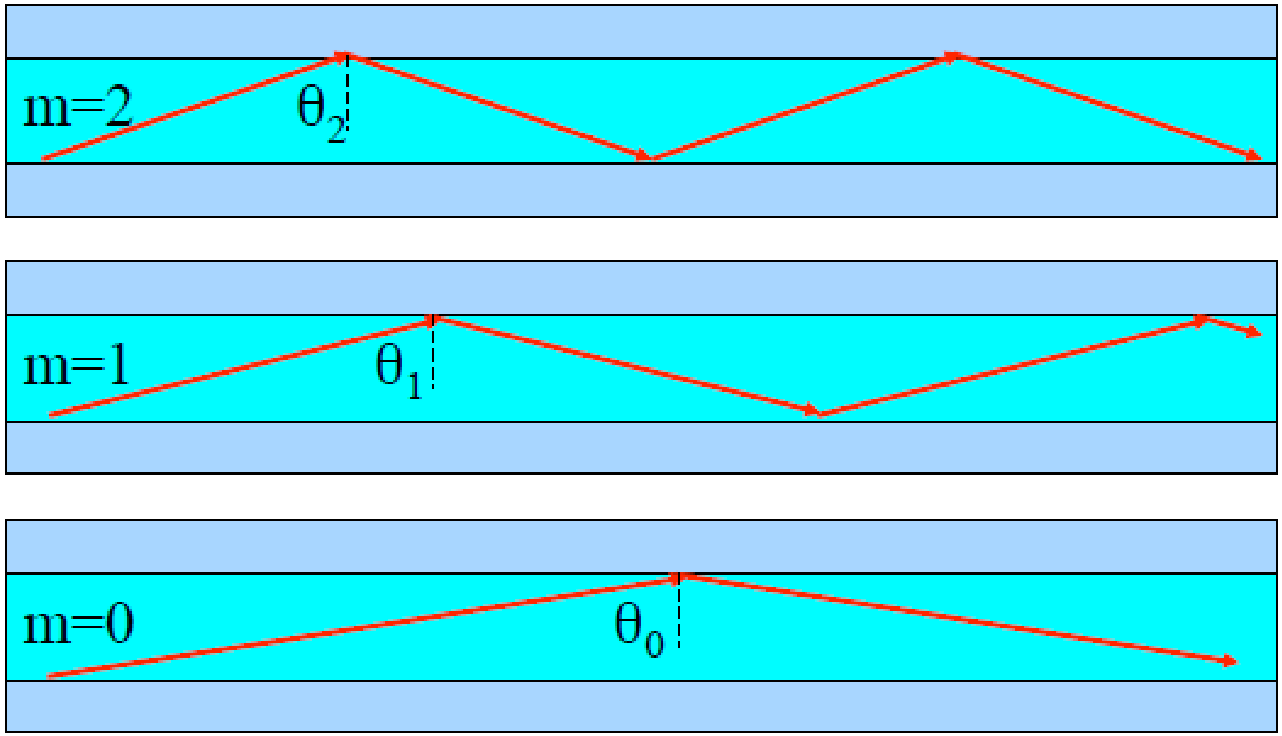
- An input waveform distorts during propagation because its energy is distributed among several modes, each traveling at a different speed.

- Parts of the wave arrive at the output before other parts, spreading out the waveform. This is thus known as multimode (modal) dispersion.

- Multimode dispersion does *not* depend on the source linewidth (even a *single* wavelength can be simultaneously carried by *multiple modes* in a waveguide).

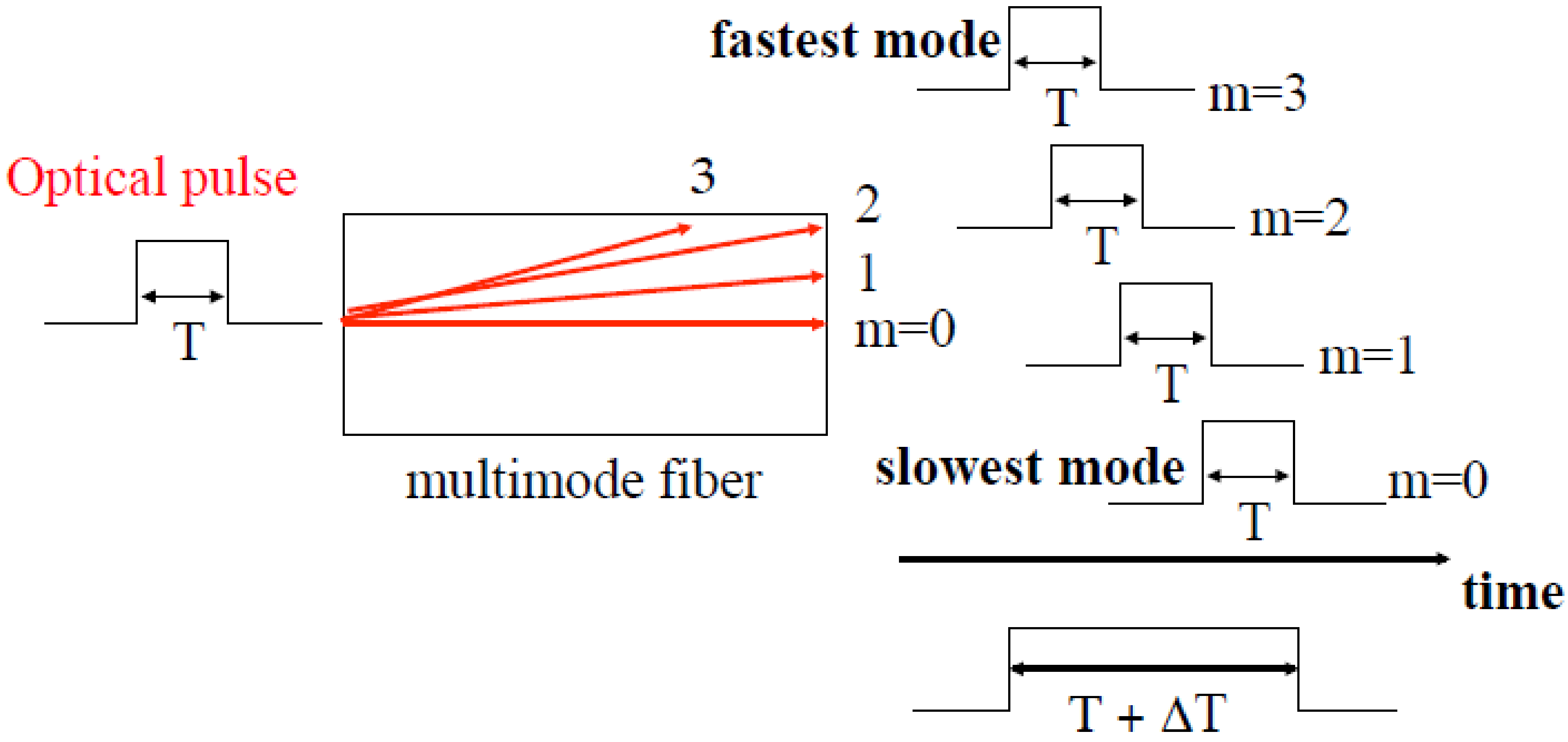
- Multimode dispersion would *not* occur if the waveguide allows *only* one mode to propagate - the advantage of *single*-mode waveguides!

Modal dispersion in multimode waveguides



The carrier wave can propagate along all these different "zig-zag" ray paths of *different path lengths.*

Modal dispersion results in pulse broadening

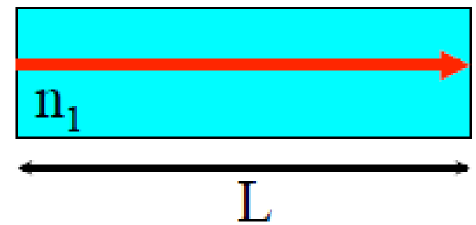


modal dispersion: different modes arrive at the receiver with different delays => pulse broadening

Estimate modal dispersion pulse broadening using phase velocity

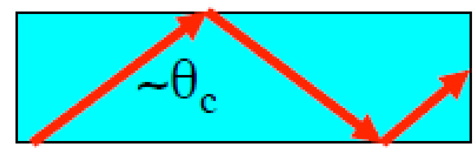
- A zero-order mode traveling near the waveguide axis needs time:

$t_0 = L/v_{m=0} \approx Ln_1/c \qquad (v_{m=0} \approx c/n_1)$



- The highest-order mode traveling near the critical angle needs time:

$t_m = L/v_m \approx Ln_2/c \qquad (v_m \approx c/n_2)$



=> the *pulse broadening* due to modal dispersion:

$$\Delta T \approx t_0 - t_m \approx (L/c)(n_1 - n_2)$$

$$\approx (L/2cn_1)\,NA^2 \qquad (n_1 \sim n_2)$$

How does modal dispersion restricts fiber bit rate?

e.g. How much will a light pulse spread after traveling along 1 km of a step-index fiber whose NA = 0.275 and $n_{core} = 1.487$?

Suppose we transmit at a low bit rate of 10 Mb/s

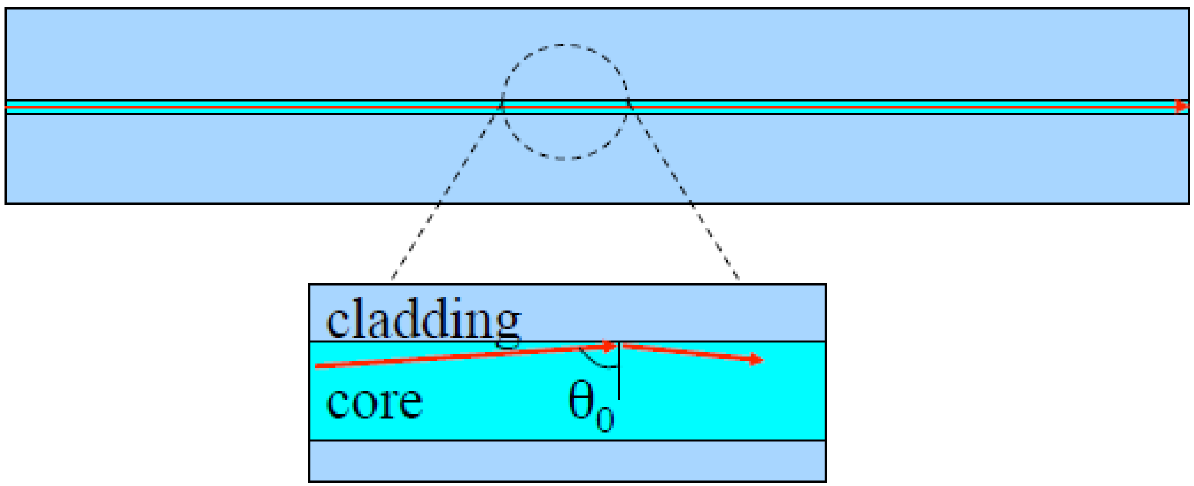
=> Pulse duration = $1 / 10^7$ s = 100 ns

Using the above e.g., each pulse will spread up to ≈ 100 ns (i.e. ≈ pulse duration !) every km

⇒The broadened pulses overlap! (**Intersymbol interference** (ISI))

*Modal dispersion limits the bit rate of a km-length fiber-optic link to ~ 10 Mb/s. (a coaxial cable supports this bit rate easily!)

Single-mode fiber eliminates modal dispersion

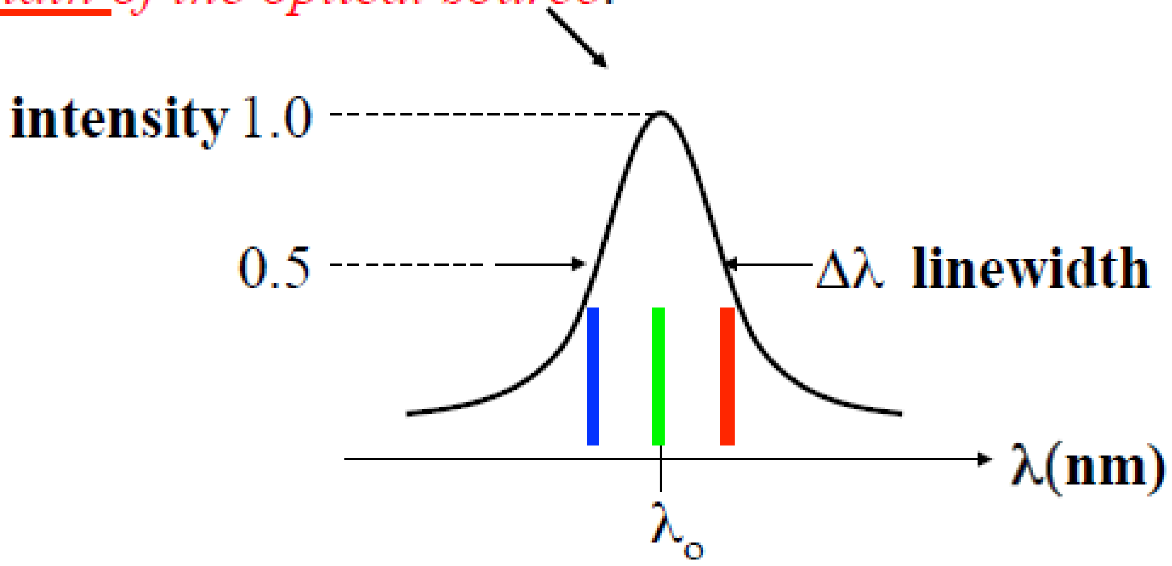


- The main advantage of *single*-mode fibers is to propagate *only one mode* so that *modal dispersion is absent.*

- However, *pulse broadening does not disappear altogether*. The *group velocity* associated with the fundamental mode is *frequency dependent* within the pulse *spectral linewidth* because of <u>chromatic dispersion</u>.

Chromatic dispersion

- Chromatic dispersion (CD) may occur in *all* types of optical fiber. The optical pulse broadening results from the *finite spectral linewidth of the optical source*.



*In the case of the semiconductor laser $\Delta\lambda$ corresponds to only a fraction of % of the centre wavelength λ_o. For LEDs, $\Delta\lambda$ is likely to be a significant percentage of λ_o.

Spectral linewidth

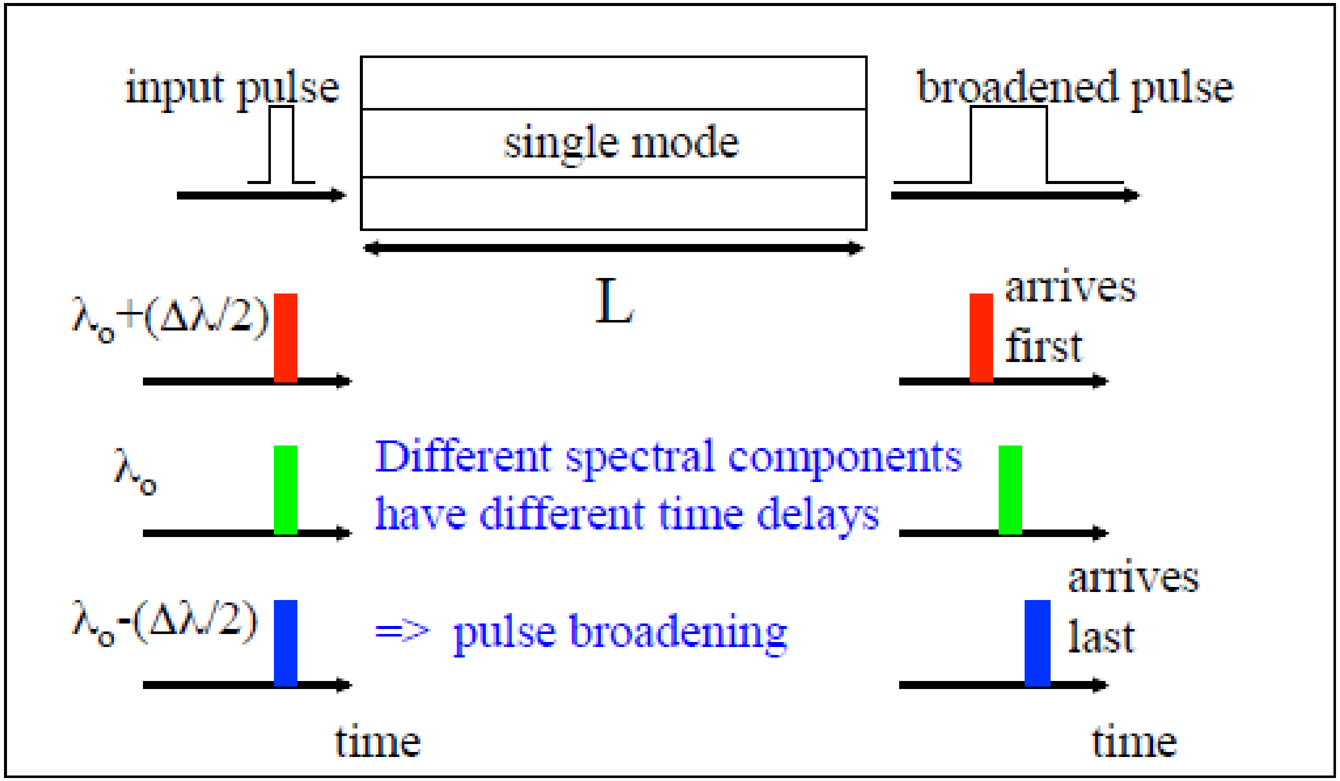
- Real sources emit over a range of wavelengths. This range is the *source linewidth* or *spectral width*.

- The smaller is the linewidth, the smaller the spread in wavelengtl or frequencies, the more *coherent* is the source.

- A perfectly coherent source emits light at a *single* wavelength. It has *zero* linewidth and is *perfectly* monochromatic.

Light sources	**Linewidth (nm)**
Light-emitting diodes	20 nm – 100 nm
Semiconductor laser diodes	1 nm – 5 nm
Nd:YAG solid-state lasers	0.1 nm
HeNe gas lasers	0.002 nm

Chromatic dispersion



- Pulse broadening occurs because there may be *propagation delay differences* among the *spectral components* of the transmitted signal.
- **Chromatic dispersion (CD):** Different spectral components of a *pulse* travel at different *group velocities*. This is also known as *group velocity dispersion* (GVD).

Light pulse in a dispersive medium

When a *light pulse* with a spread in frequency $\delta\omega$ and a spread in propagation constant δk propagates in a *dispersive* medium $n(\lambda)$, the group velocity:

$$v_g = (d\omega/dk) = (d\lambda/dk)\,(d\omega/d\lambda)$$

$k = n(\lambda)\, 2\pi/\lambda \quad \Rightarrow \quad dk/d\lambda = (2\pi/\lambda)\,[(dn/d\lambda) - (n/\lambda)]$

$\omega = 2\pi c/\lambda \quad \Rightarrow \quad d\omega/d\lambda = -2\pi c/\lambda^2$

Hence $\quad v_g = c\,/\,[n - \lambda(dn/d\lambda)] = c\,/\,n_g$

Define the **group refractive index** $n_g = n - \lambda(dn/d\lambda)$

Waveguide dispersion

In fact there are <u>two</u> mechanisms for chromatic dispersion:

(a) Silica refractive index *n is wavelength dependent* (i.e. $n = n(\lambda)$)

=> different wavelength components travel at different speeds in silica

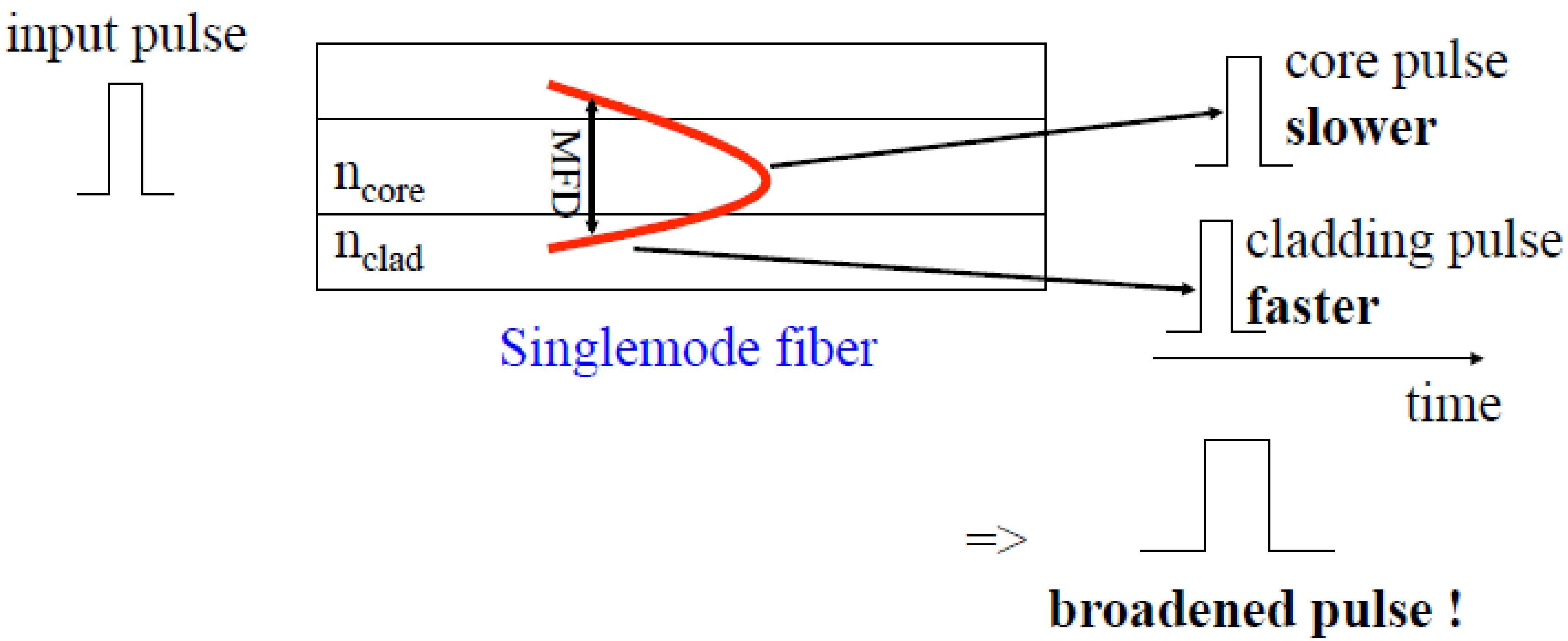
This is known as **<u>material dispersion</u>**.

(b) Light energy of a mode propagates *partly in the core and partly in the cladding*. The mode power distribution between the core and the cladding *depends on λ*. (*Recall the mode field diameter*)

This is known as **<u>waveguide dispersion</u>.**

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

Waveguide dispersion in a single-mode fiber



Waveguide dispersion depends on the *mode field distribution in the core and the cladding*. (i.e. the fiber V number)