□ Transmission Characteristics of Optical Fibers

- Fiber attenuation
- Fiber dispersion
- Group velocity
- Material dispersion
- Waveguide dispersion
- Chromatic dispersion compensation
- Polarization mode dispersion
- Polarization-maintaining fibers

Reading: Senior 3.1-3.4, 3.6, 3.8-3.13
Keiser 3.1 – 3.3

Transmission characteristics of optical fibers

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

- Now, *silica-based* glass fibers have losses about 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/s 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*, $\text{dB} = 20 \log_{10} (V_o/V_i)$

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

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

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

Fibre Loss

- attenuates power reaching receiver
  $\rightarrow$ limits transmission length

Attenuation Coefficient

Power attenuation in fibre $$\frac{dP}{dz} = -\alpha P$$

α = attenuation coefficient
P = optical power

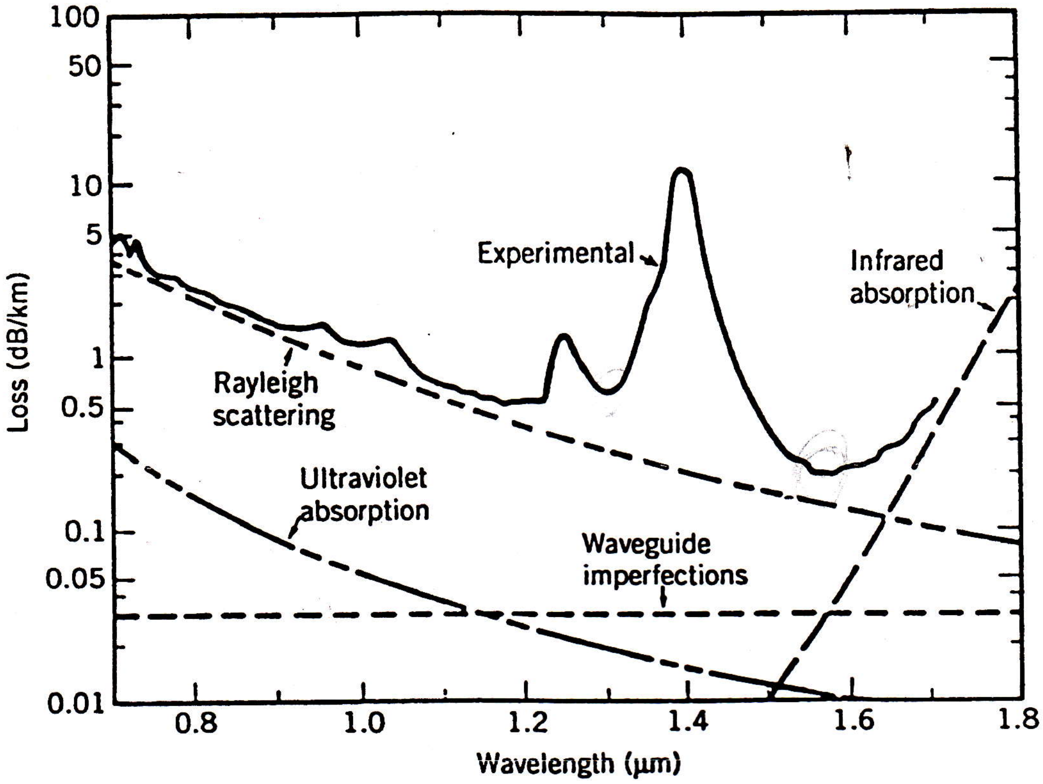
Output power after fibre length L for launched power P_{in}

$$P_{out} = P_{in} e^{-\alpha L}$$

More commonly express α in dB/km

$$\alpha\,(\mathrm{dB/km}) = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Fibre loss is wavelength dependent.



Minimum loss	0.2 dB/km	@ 1.55 μm (close to fundamental limit of 0.15 dB/km of silica fibres)
Low loss	0.5 dB/km	@ 1.3 μm (this is also wavelength of minimum dispersion)
Short wavelength	~ 2 dB/km	@ 0.85 μm (low cost lasers)

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)

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

OR 0 dBm – (-10 dBm) = 10 dB

The dBm Unit

Example 3.2 As Sec. 1.3 describes, optical powers are commonly expressed in units of *dBm*, which is the decibel power level referred to 1 mW. Consider a 30-km long optical fiber that has an attenuation of 0.4 dB/km at 1310 nm. Suppose we want to find the optical output power P_{out} if 200 μW of optical power is launched into the fiber. We first express the input power in dBm units:

$$P_{in}(\text{dBm}) = 10 \log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right]$$

$$= 10 \log\left[\frac{200 \times 10^{-6}\ \text{W}}{1 \times 10^{-3}\,\text{W}}\right] = -7.0\ \text{dBm}$$

From Eq. (3.1*c*) with $P(0) = P_{in}$ and $P(z) = P_{out}$ the output power level (in dBm) at $z = 30$ km is

$$P_{out}(\text{dBm}) = 10 \log\left[\frac{P_{out}(\text{W})}{1\,\text{mW}}\right]$$

$$= 10 \log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right] - \alpha z$$

$$= -7.0\ \text{dBm} - (0.4\ \text{dB/km})\,(30\ \text{km})$$

$$= -19.0\ \text{dBm}$$

In unit of watts, the output power is

$$P(30\ \text{km}) = 10^{-19.0/10}(1\ \text{mW}) = 12.6 \times 10^{-3}\ \text{mW}$$

$$= 12.6\ \mu\text{W}$$

e.g. When the mean optical power launched into an 8 km length of fiber is 120 μW, the mean optical power at the output is 3 μW.

Determine:

(a) the overall signal attenuation (or loss) in decibels through the fiber assuming there are no *connectors* or *splices*

(b) the signal attenuation per kilometer for the fiber

(c) the overall signal attenuation for a 10 km optical link using the same fiber with *splices* (i.e. fiber connections) at 1 km intervals, each giving an attenuation of 1 dB

(d) the output/input power ratio in (c).

(a) signal attenuation = $-10 \log_{10}(P_o/P_i)$ = 16 dB

(b) 16 dB / 8 km = 2 dB/km

(c) the loss incurred along 10 km fiber = 20 dB.

With a total of 9 *splices* (i.e. fiber connections) along the link, each with an attenuation of 1 dB, the loss due to the splices is 9 dB.

=> the overall signal attenuation for the link = 20 + 9 dB = 29 dB.

(d) $P_o/P_i = 10^{(-29/10)} = 0.0013$

fiber attenuation mechanisms:

1. Material absorption
2. Scattering loss
3. Bending loss
4. Radiation loss (due to mode coupling)
5. Leaky modes

1. Material absorption losses in silica glass fibers

- 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).

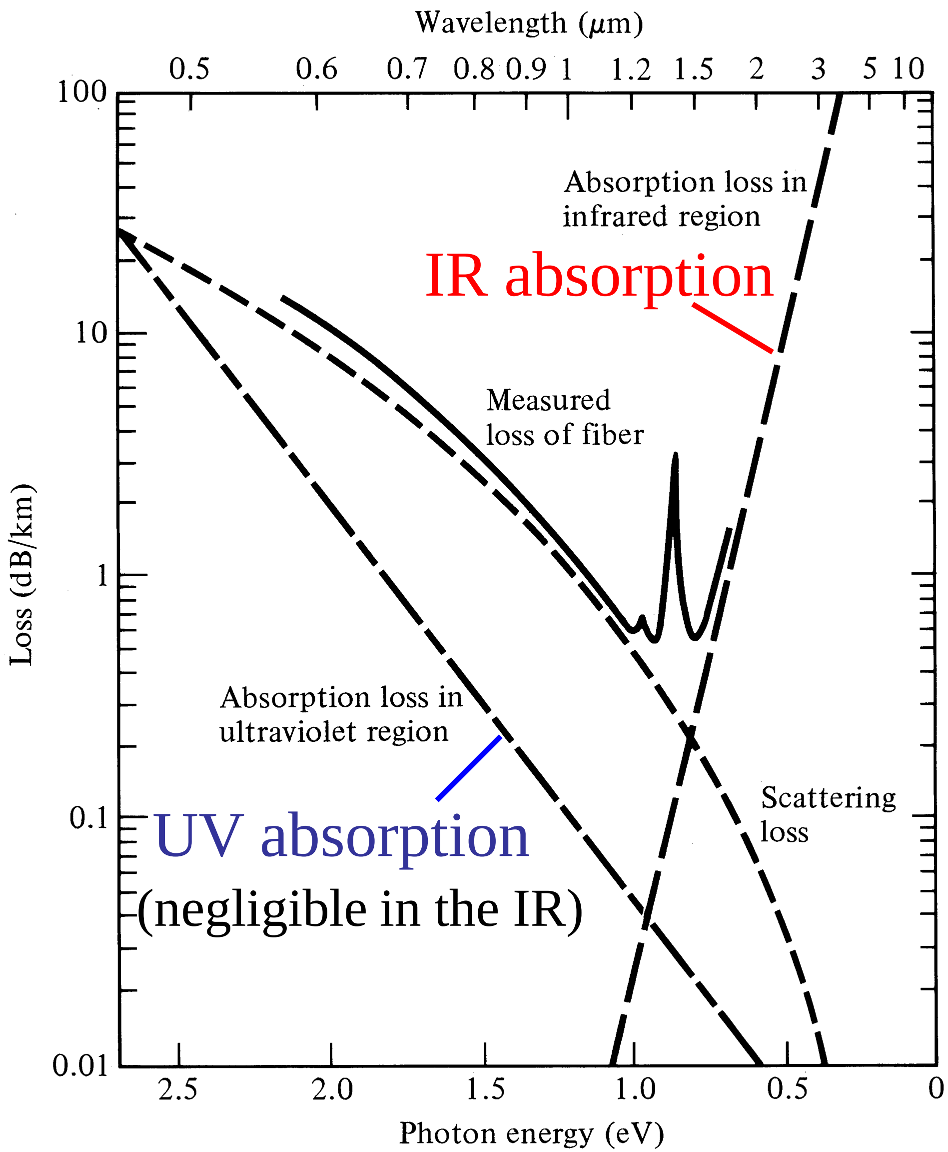
Intrinsic absorption

- 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



Extrinsic absorption

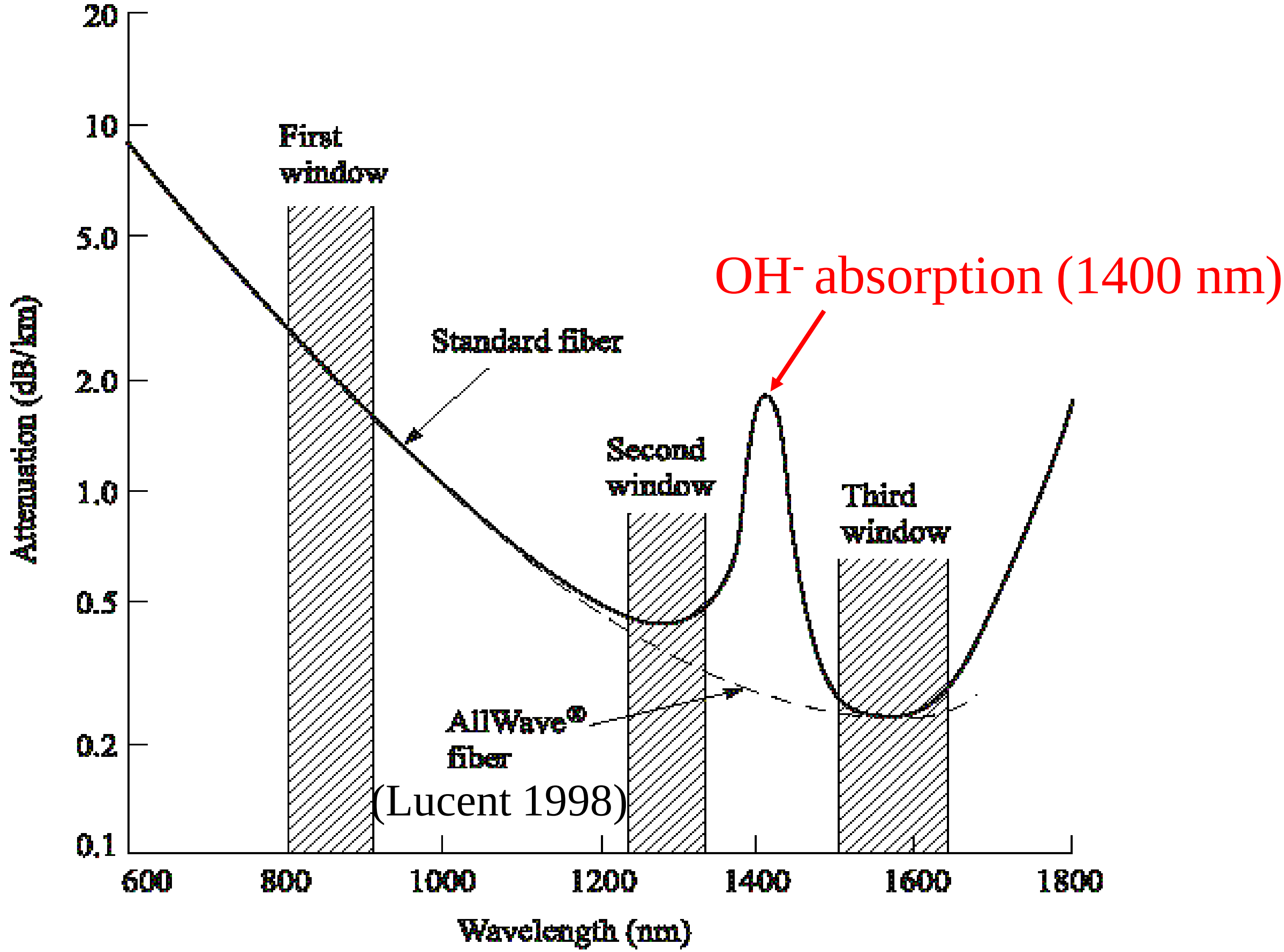
- Major extrinsic loss mechanism is caused by absorption due to water (*as the hydroxyl or OH^- ions*) introduced in the glass fiber during *fiber pulling by means of oxyhydrogen flame*.

- These OH^- ions are bonded into the glass structure and have absorption peaks (due to *molecular vibrations*) at 1.38 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.

1400 nm OH^- absorption peak and spectral windows



OFS AllWave fiber: example of a "low-water-peak" or "full spectrum" fiber. Prior to 2000 the fiber transmission bands were referred to as "windows."

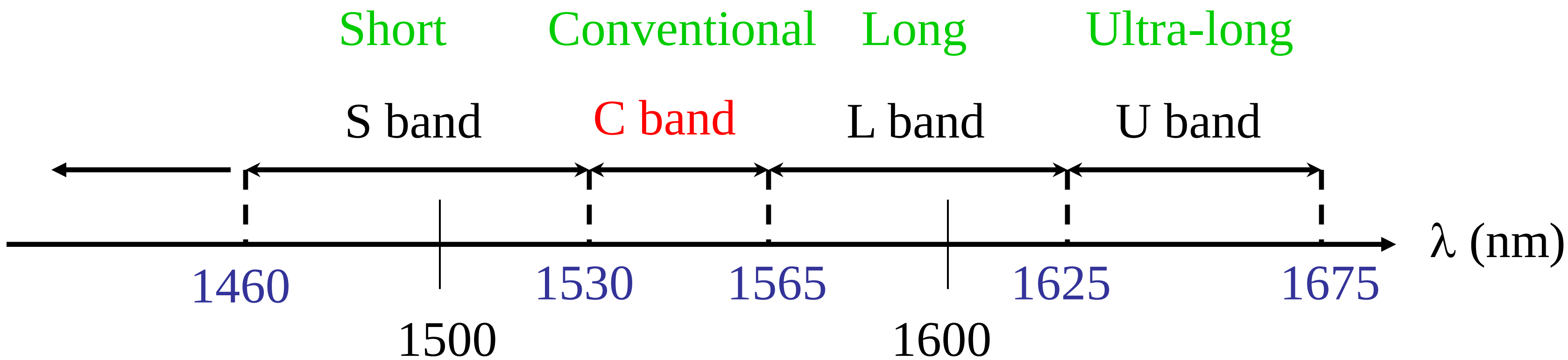
Three major spectral windows where fiber attenuation is low

The 1st window: 850 nm, attenuation 2 dB/km

The 2nd window: 1300 nm, attenuation 0.5 dB/km

The 3rd window: 1550 nm, attenuation 0.3 dB/km

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



Absorption Losses of Impurities

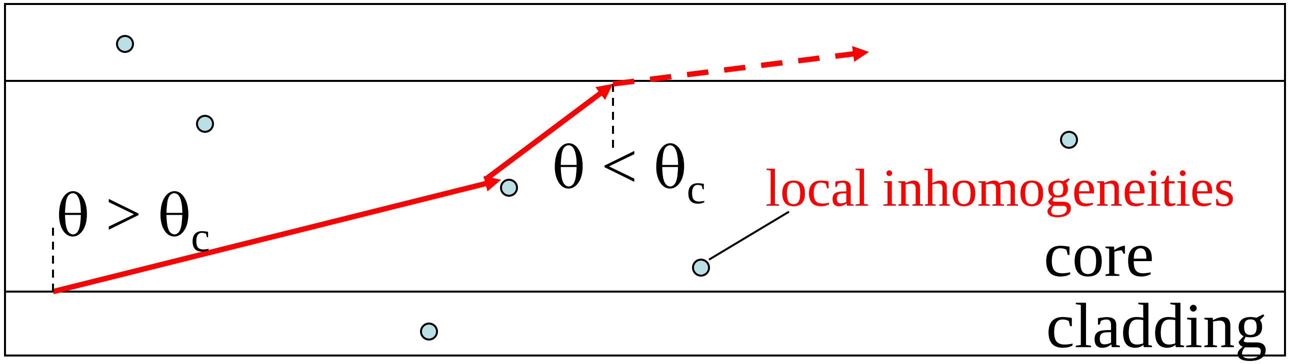
Table 3.1 *Examples of absorption loss in silica glass at different wavelengths due to 1 ppm of water-ions and various transition-metal impurities*

Impurity	*Loss due to 1 ppm of impurity (dB/km)*	*Absorption peak (nm)*
Iron: Fe^{2+}	0.68	1100
Iron: Fe^{3+}	0.15	400
Copper: Cu^{2+}	1.1	850
Chromium: Cr^{2+}	1.6	625
Vanadium: V^{4+}	2.7	725
Water: OH^{-}	1.0	950
Water: OH^{-}	2.0	1240
Water: OH^{-}	4.0	1380

2. 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*.



Silica glass is amorphous.

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

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

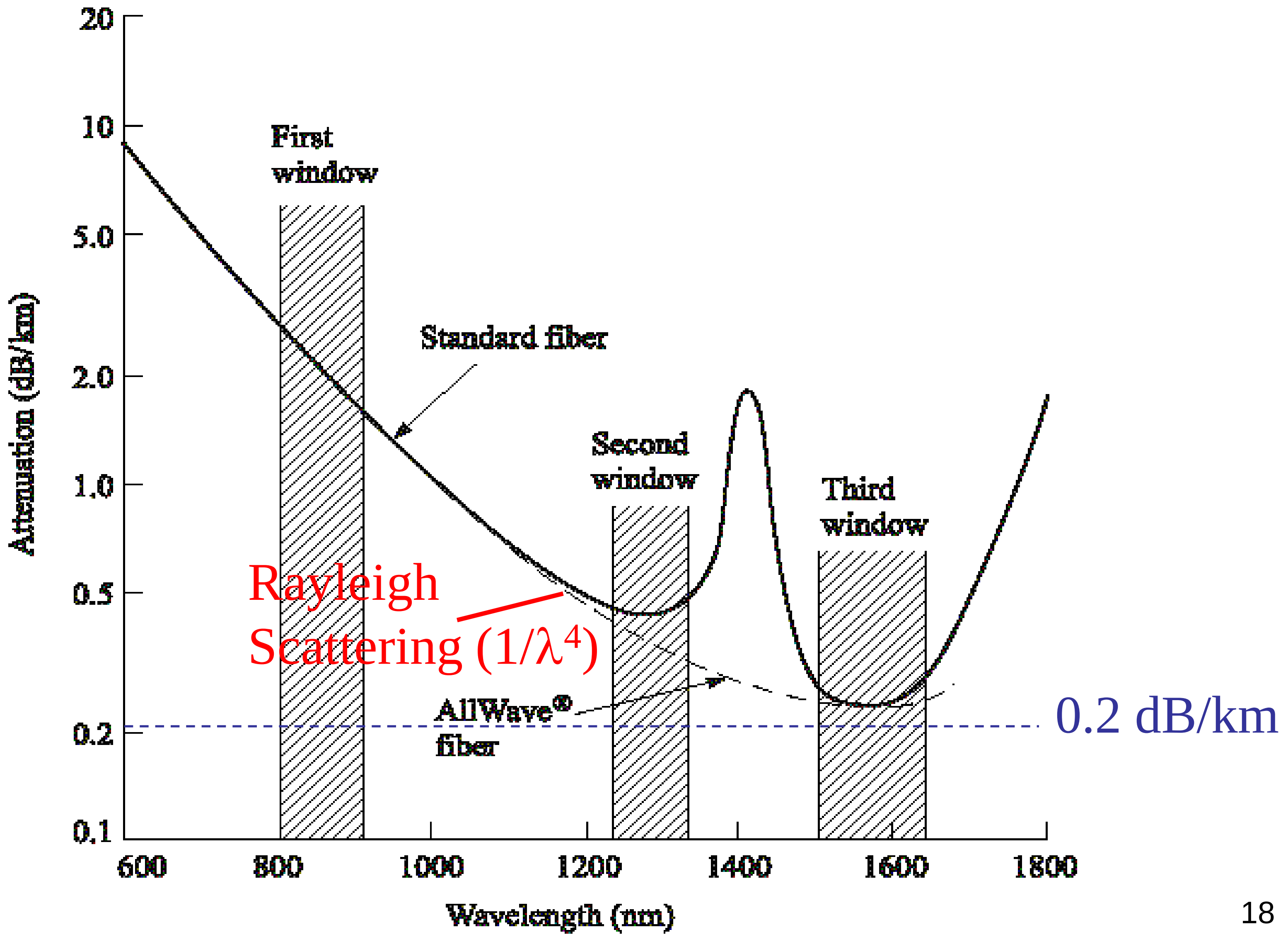
$$\circ \ll \lambda$$

• 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* !

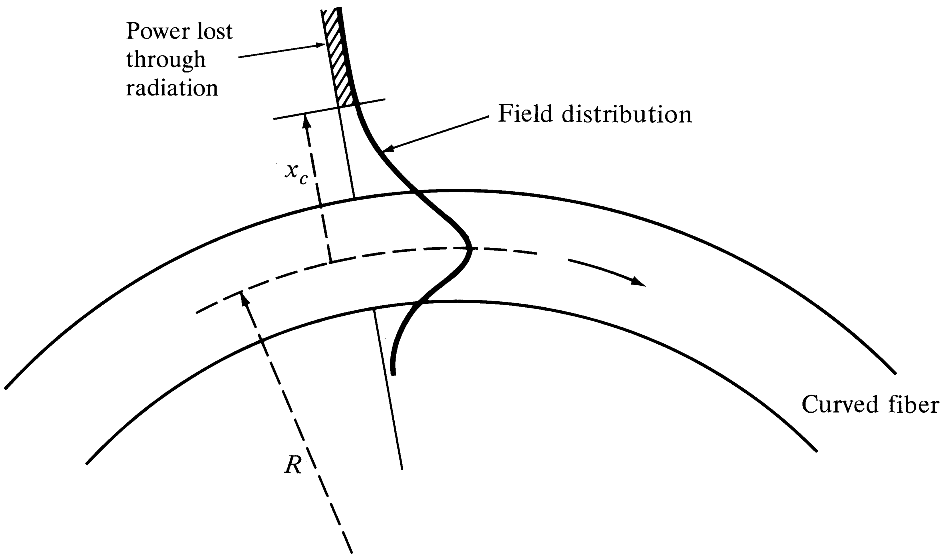
Rayleigh scattering results in an attenuation (dB/km) $\propto 1/\lambda^4$

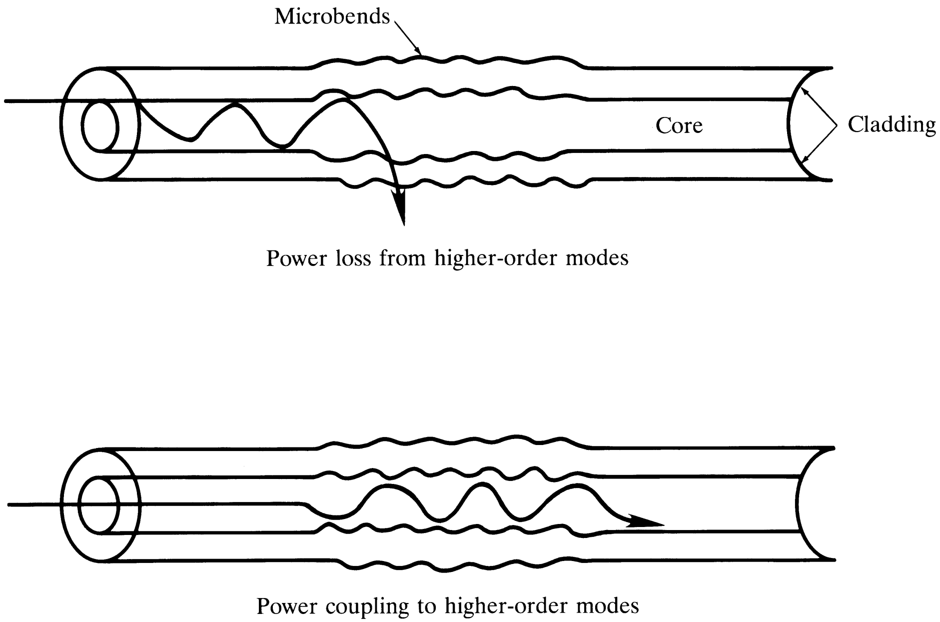
Where else do we see Rayleigh scattering?

Rayleigh scattering is the dominant loss in today's fibers



Fiber bending loss and mode-coupling to higher-order modes





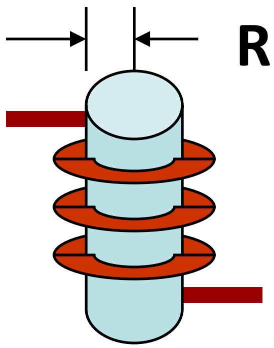
"macrobending"

(*how do we measure bending loss*?)

"microbending" – power coupling to higher-order modes that are more lossy.

Bending Losses in Fibers (1)

- Optical power escapes from tightly bent fibers
- Bending loss increases at longer wavelengths
  - Typical losses in 3 loops of standard 9-µm single-mode fiber (from: *Lightwave*; Feb 2001; p. 156):
  - 2.6 dB at 1310 nm and 23.6 dB at 1550 nm for R = 1.15 cm
  - 0.1 dB at 1310 nm and 2.60 dB at 1550 nm for R = 1.80 cm
- Progressively tighter bends produce higher losses
- Bend-loss insensitive fibers have been developed and now are recommended
- Improper routing of fibers and incorrect storage of slack fiber can result in violations of bend radius rules



Test setup for checking bend loss: N fiber loops on a rod of radius R

Bending Losses in Fibers (2)

The total number of modes that can be supported by a curved fiber is less than in a straight fiber.

$$M_{\text{eff}} = M_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2kR}\right)^{2/3}\right]\right\}$$

Example 3.6 Consider a graded-index multimode fiber for which the index profile $\alpha = 2.0$, the core index $n_1 = 1.480$, the core-cladding index difference $\Delta = 0.01$, and the core radius $a = 25\ \mu m$. If the radius of curvature of the fiber is $R = 1.0$ cm, what percentage of the modes remain in the fiber at a 1300-nm wavelength?

Solution: From Eq. (3.7) the percentage of modes at a given curvature R is

$$\frac{M_{\text{eff}}}{M_{\infty}} = 1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2kR}\right)^{2/3}\right]$$

$$= 1 - \frac{1}{.01}\left[\frac{2(25)}{10000} + \left(\frac{3(1.3)}{2(1.465)2\pi(10000)}\right)^{2/3}\right]$$

$$= 0.42$$

Thus 42 percent of the modes remain in this fiber at a 1.0-cm bend radius.