OPTOELECTRONICS (I)

Chapter 5:
Losses in Optical Fibers

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5. Losses in Optical Fibers

- In an optical fiber, there are three fundamental **loss mechanisms**:

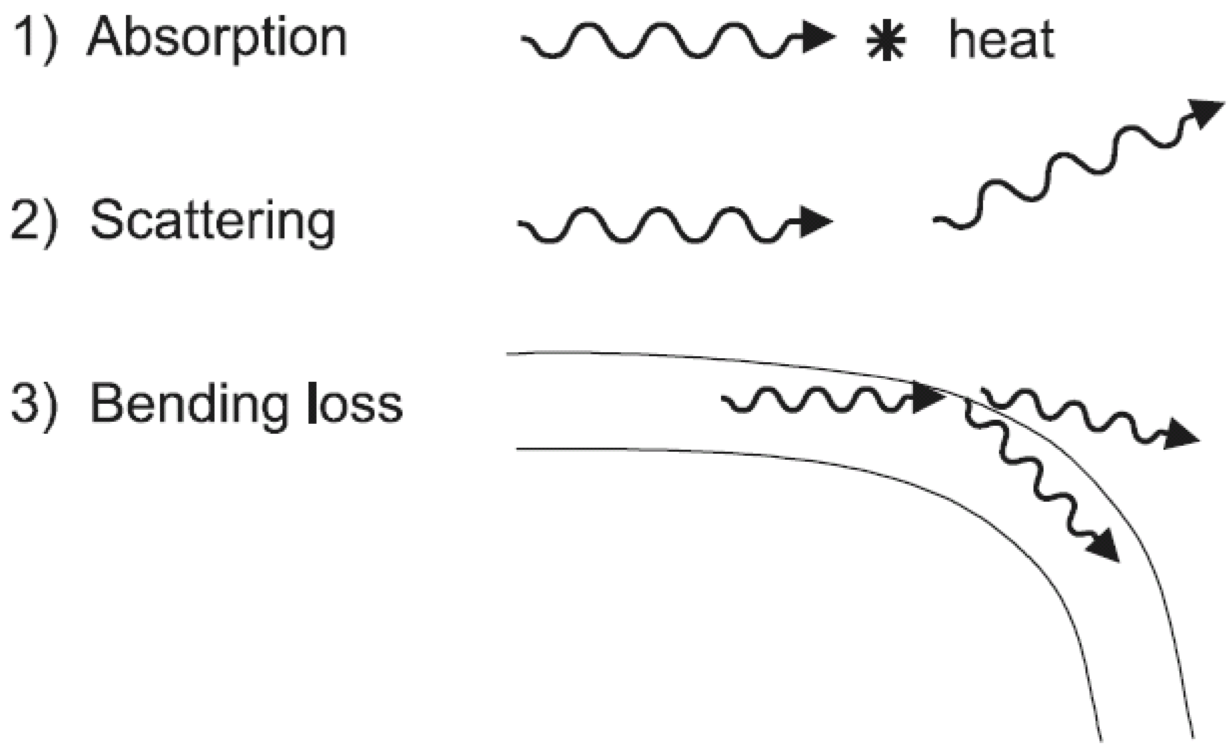


Figure 5-1 Loss mechanisms for light propating in optical fiber

5. Losses in Optical Fibers (2)

- Absorption results in the loss of a propagating photon, the photon's energy generally being converted into heat.

- In a scattering process, the photon does not disappear, but its direction (and possibly its energy) is changed.

- Absorption and scattering are fundamental materials properties, occurring both in **fibers** and in **bulk glass** (large uniform sections of glass).

- The third loss mechanism, bending loss, is unique to the fiber geometry, and relates to the requirement of total internal reflection (TIR) for lossless transmission down the fiber.

5-1 Absorption Loss (1)

➢ **Attenuation coefficient (α)** :as the fractional loss in light power **per unit length of propagation**.

➢ The **amount** of power lost in a thin slice of thickness dz is then $P\alpha dz$, where P is the power incident on the slice.

Beer's law:

$$P_{out} = P_{in}e^{-\alpha L} \quad (5\text{-}1)$$

α: absorption coefficient (cm^{-1})

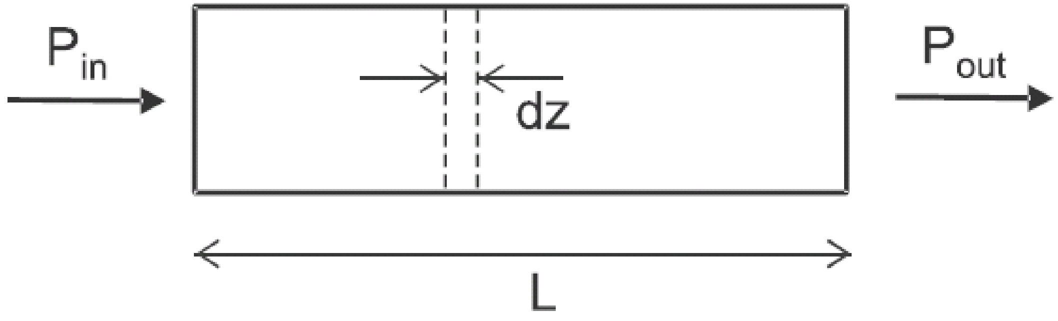


Figure 5-2 A fraction αdz of light power P is absorbed in slice of thickness dz.

5-1 Absorption Loss (2)

$$\text{dB loss} = 10 \log_{10}\left(\frac{P_{\text{in}}}{P_{\text{out}}}\right) = 10 \log_{10}(e^{\alpha L}) = 10\,\alpha L \log_{10} e \qquad (5\text{-}2)$$

or,

$$\boxed{\text{dB loss} = 4.34\,\alpha L} \qquad (5\text{-}3)$$

$$1\ \text{cm}^{-1} = 4.34 \times 10^{5}\ \text{dB/km}$$
$$1\ \text{dB/km} = 2.303 \times 10^{-6}\ \text{cm}^{-1} \qquad (5\text{-}4)$$

- In practice, the dB/km unit is usually used to describe losses in **optical fiber** systems.
- whereas the cm^{-1} unit is used when relating propagation losses to fundamental physical processes.

5-1 Absorption Loss (3)

window of transparency: $0.4 < \lambda < 2\mu m$

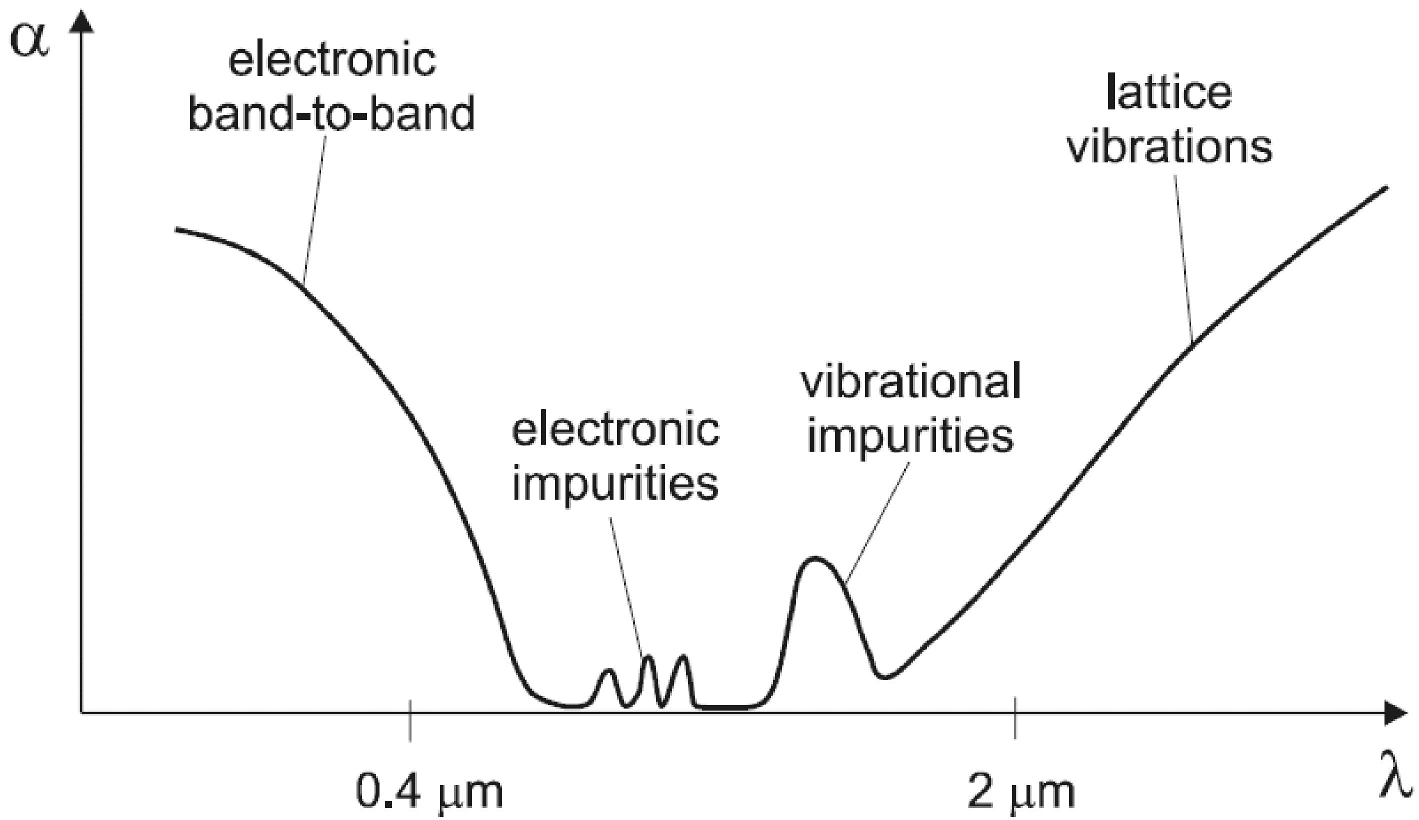


Figure 5-3 Absorption coefficient versus wavelength for optical fiber, showing electronic and vibrational loss mechanisms.

5-1 Absorption Loss (4)

- The presence of impurities introduces additional **electronic** and **vibrational** absorption, which can reduce the transparency in this window.
- Typical impurities include transition metal ions such as Cu^{2+}, Fe^{2+}, and Cr^{3+}, which introduce electronic transitions, and
- The hydroxyl ion OH^{-}, which introduces strong vibrational transitions at 1.4 and 2.8 μm.
- The transition at 1.4 μm is especially detrimental, being close to the important telecommunications wavelength 1.5 μm where the attenuation in silica fiber is a minimum.
- For the lowest-loss fibers, it is important to keep water **out during** the **manufacturing process**, to minimize the OH content.

5-1 Scattering

1. Rayleigh Scattering, 2. Brillouin Scattering, 3. Raman Scattering

1. Rayleigh Scattering

- The most important scattering loss in glass fibers is Rayleigh scattering, in which the wavelength of the **scattered light** remains unchanged.
- Rayleigh scattering **arises** from the interaction of the light wave with *stationary fluctuations* Δn in the **index of refraction** n.
- These fluctuations occur due to random thermal motion when the glass is in a *liquid state*, and are frozen in place when the glass makes the transition from liquid to solid at temperature T_F.
- The scattering process can be thought of as equivalent to the scattering of light from small spheres of diameter d and index n + Δn, embedded in a uniform medium of index n.

5-1 Scattering: (1. Rayleigh) -1

❖ If $d << \lambda$ (a good approximation here), α_R is found to be

$$\alpha_R \propto \frac{\langle(\Delta n)^2\rangle}{\lambda^4} \propto \frac{k_B T_F}{\lambda^4} \qquad \text{(Rayleigh scattering)} \tag{5-5}$$

$<(\Delta n)^2>$: average square of the refractive index fluctuation

k_B: Boltzmann's constant, T_F : Frozen Temperature

➢ why the sky is blue? Because light at shorter wavelengths, i.e. blue, is more strongly scattered into our eyes.

➢ Longer signal wavelengths will experience less loss.

❖ For the silica (SiO_2) glass typically used : **(0.8 can be made 0.6 or 0.7)**

λ: (μm)
α_R : (*dB/km*)

$$\alpha_R \simeq (0.8)\left(\frac{1\ \mu\text{m}}{\lambda}\right)^4 \text{dB/km} \qquad \text{(silica fiber)} \tag{5-6}$$

5-1 Scattering: (1. Rayleigh) -2

- First telecommunications window: $\lambda \approx 850$ nm → $\alpha_R = 1.5$ dB/km
- Second telecommunications window: $\lambda \approx 1.3$ μm → $\alpha_R = 0.28$ dB/km
- Third telecommunications window: $\lambda \approx 1.55$ μm → $\alpha_R = 0.14$ dB/km

❑ Whether the losses can be further reduced for wavelengths longer than 1.55 μm?

❖ Answer: for silica fiber is no, because at longer wavelengths the absorption of light by vibrational transitions of the host glass becomes more important than Rayleigh scattering.

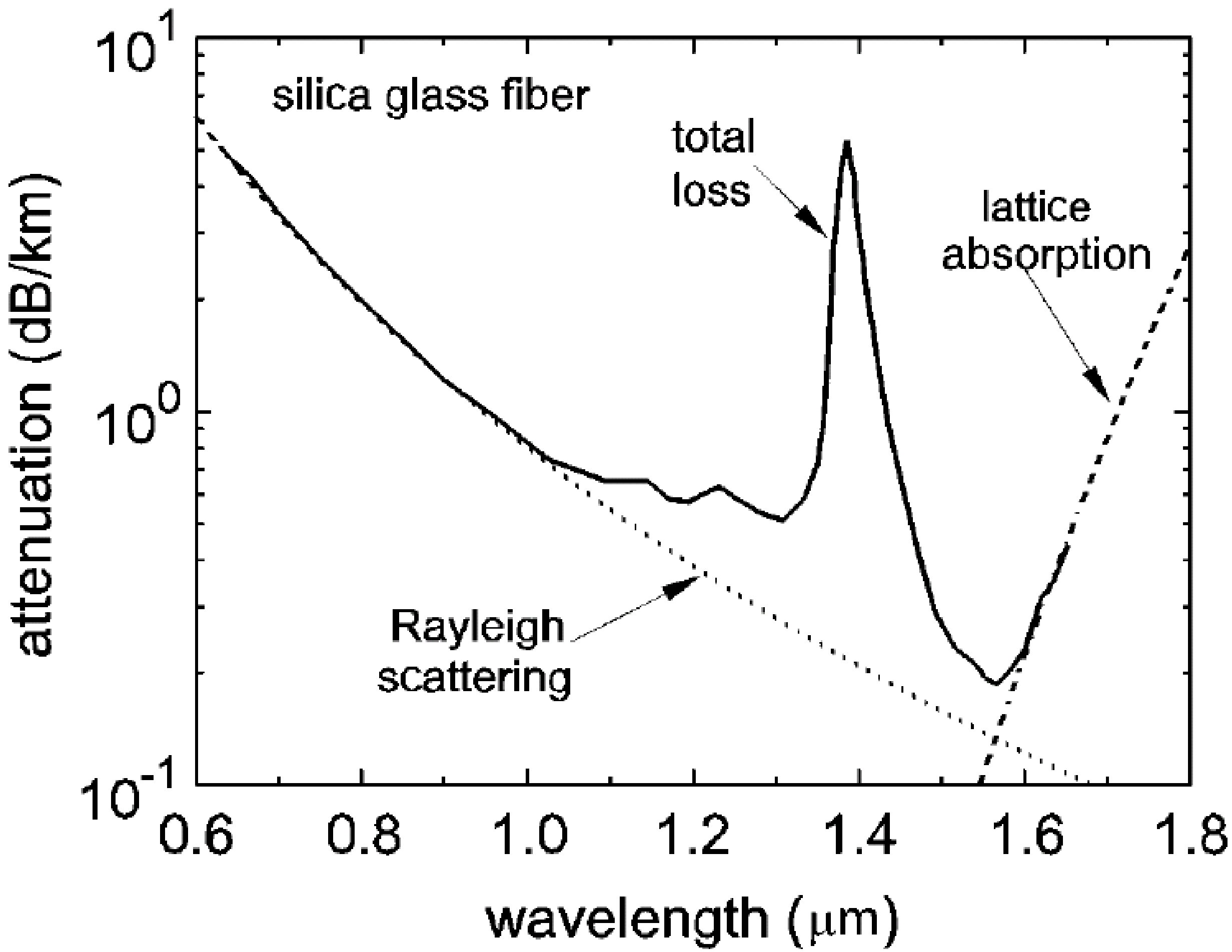
- The combination of Rayleigh scattering at shorter wavelengths and lattice absorption at longer wavelengths results in a V-shaped curve.

- In addition, there is a pronounced OH absorption peak at 1.4 μm, which creates local minima in the attenuation around 1.3 and 1.5 μm.

5-1 Scattering: (1. Rayleigh) -3

Figure 5-4
Typical attenuation spectrum for silica glass fiber, showing contributions from Rayleigh scattering and lattice absorption that result in a V-shaped curve.

For pure silica fiber:
minimum attenuation
≈ 0.15 dB/km



5-1 Scattering: (1. Rayleigh) -4

- The Rayleigh scattering can be reduced by **adding** small amounts of dopants such as Na_2O to the **silica** host, but the reduction is only a modest 20% (Saito et al. 1997).

- To reduce the lattice absorption: in the late 1980s there was much interest in ZrF_4-based, heavy-metal fluoride glasses for this purpose, since they have reduced absorption in the infrared compared with silica glass.

- However, the lowest loss so far in fluoride glass fibers is ~ 1 dB/km, due to problems with crystallization and other sources of loss.

- At present that for light propagating in a glass fiber, the ultimate practical minimum loss will be ~ 0.1 dB/km.

- To reduce the loss further would require that the **light propagate** not in glass, but in air. Recent developments that make this possible will be discussed in Chapter 8. (Photonic crystal)

5-1 Scattering: (2. Brillouin) -1

- Light will generally be scattered by any nonuniformity in a material's index of refraction (n).

- In the case of Rayleigh scattering in glass, the nonuniformity consists of "frozen in" when the liquid cooled into a solid.

- n can be thought of as nonuniform in a "lumpy" sort of way.

- Another way that the n can be nonuniform is via a sound (acoustic) wave, (نسبتا ناصاف) in which the density and pressure vary periodically inside the material.

- The varying density causes a varying n, resulting in "waves" of changing n, propagating at the speed of sound v_s in the material.

- The separation between planes of maximum index will be $d = v_s / f_a$, where f_a is the frequency of the acoustic wave.

- Light could scatter off acoustic waves in a process called Brillouin scattering.

5-1 Scattering: (2. Brillouin) -2

The change in optical frequency is

$$\boxed{\frac{\Delta\nu}{\nu} = 2\,\frac{v_{\text{along ray}}}{c/n} = \frac{2n}{c}\,v_s \sin\theta} \quad (5\text{-}٧)$$

n : *the average refractive index of the material*

θ : *the incident angle*

$$\boxed{\Delta\nu = f_a}$$

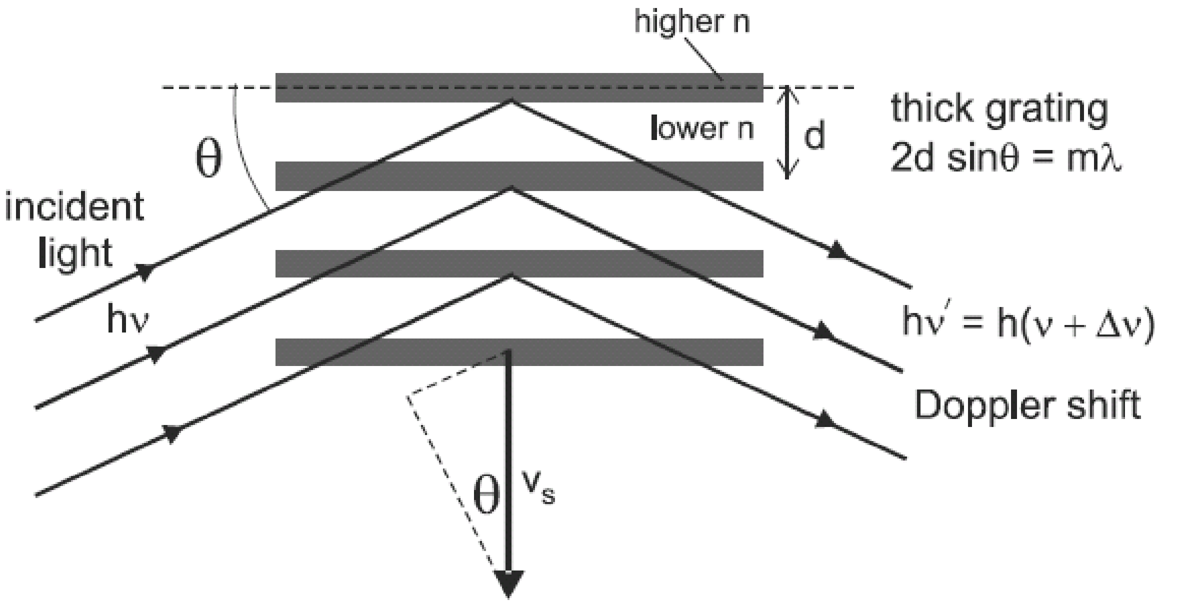


Figure 5-5 Brillouin scattering from acoustic waves.

5-1 Scattering: (2. Brillouin) -3

- **for glass**: $n = 1.5$ and $v_s = 5 \times 10^3$ m/s and setting $\sin\theta = 1$.

$\Rightarrow$ $\Delta\upsilon/\upsilon \approx 5 \times 10^{-5}$, which for 1500 nm light corresponds to $\Delta\upsilon = 10$ GHz or $\Delta\lambda = 0.075$ nm.

- The intensity of the scattered light is very weak for thermally generated acoustic waves.

- However, for externally applied sound waves of large amplitude, this scattering process can be efficient, and forms the basis for a practical way of deflecting laser beams, the acousto-optic deflector.

- In fibers, Brilluoin scattering is an important source of loss ***only*** when it becomes nonlinear. This occurs primarily for narrowband light, with spectral width $\Delta\upsilon < 10$ MHz.

5-1 Scattering: (3. Raman) -1

- The acoustic waves consist of the collective motion of a large number of atoms, with nearby atoms moving in nearly the **same direction**.
- Other types of vibrations: *localized vibrations* in which neighboring atoms are moving in **opposite directions**. (*Raman scattering*)
- For small-amplitude motion, this results in simple harmonic motion with vibrational frequency f_v given by:

$$\boxed{f_v = \frac{1}{2\pi}\sqrt{\frac{k}{m_r}}} \quad (5\text{-}8)$$

$m_r = m_1 \,.m_2 / (m_1 + m_2)$
(**reduced mass** of the system)

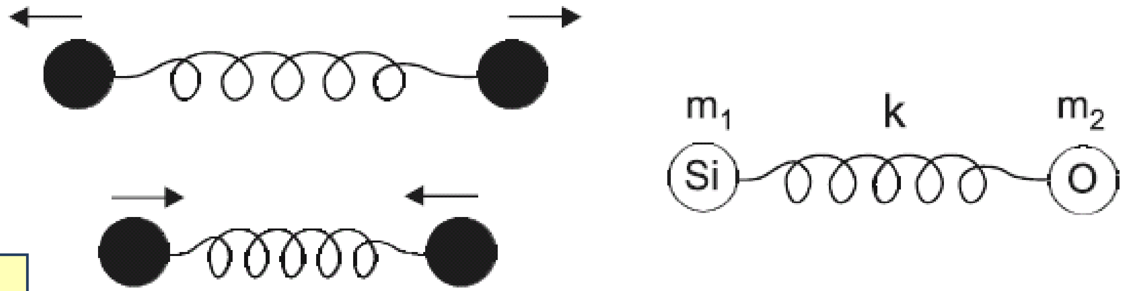


Figure 5-6 Molecular vibrations involved in Raman scattering can be modelled by masses and springs.

5-1 Scattering: (3. Raman) -2

- Energy is conserved in Raman scattering, just as for Brillouin scattering, and the new (scattered) photon energy *hύ* is

$$h\nu' = h\nu \pm hf_v \qquad \text{(Raman shift)} \qquad (5\text{-}9)$$

- *Stokes scattering* : When the scattered light is decreased in frequency.
- *Anti-Stokes scattering* : The converse process *takes vibrational energy out of the molecule to* increase the frequency of light.
- The ratio of anti-Stokes to Stokes scattering probabilities is less than one, and is temperature dependent.
- The magnitude of the frequency shift ύ – υ is much greater for Raman scattering than for Brillouin scattering because the localized vibrational frequency f_v is much larger than the typical acoustic frequency f_a.
- Typically, $f_v \sim 10 - 30$ THz, whereas $f_a \sim 10$ GHz.

5-1 Scattering: (3. Raman) -3

➢ Since the restoring force arises from changes in the spacing between adjacent atoms, the effective **spring constant** is reduced.

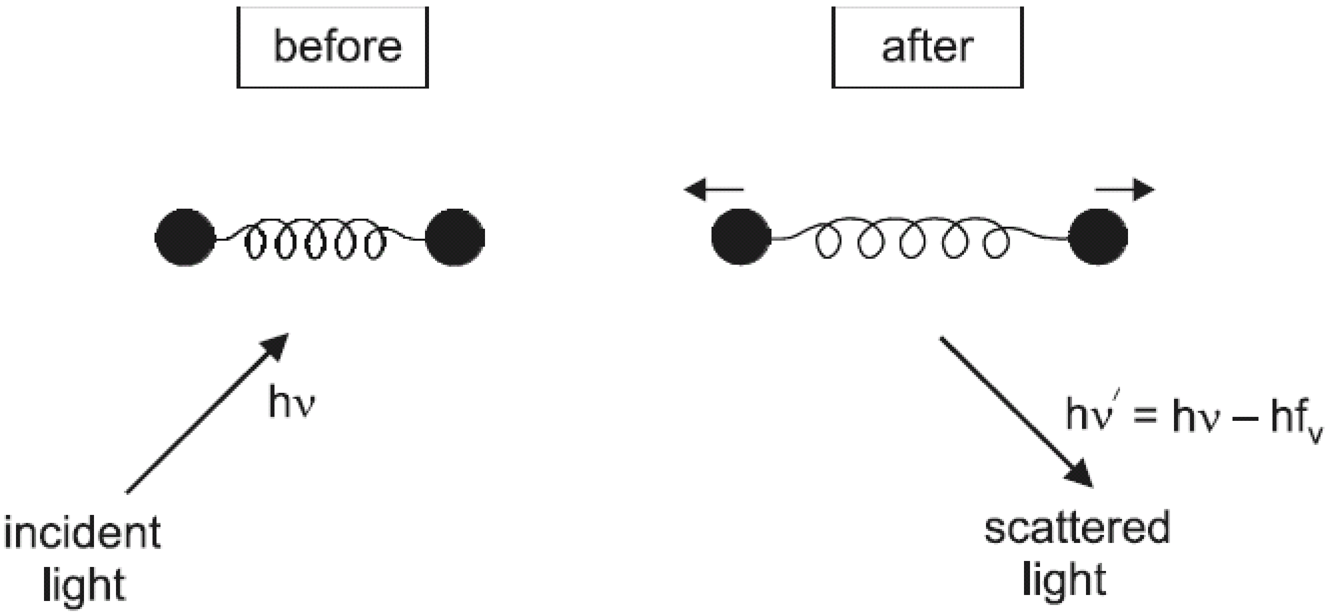


Figure 5-7 Some energy from the photon is **transferred** to molecular vibrational energy in Raman scattering.

5-1 Scattering: (3. Raman) -4

❖ Losses due to Raman scattering become important in single-mode fibers when nonlinear effects set in, typically at power levels > 500 mW.

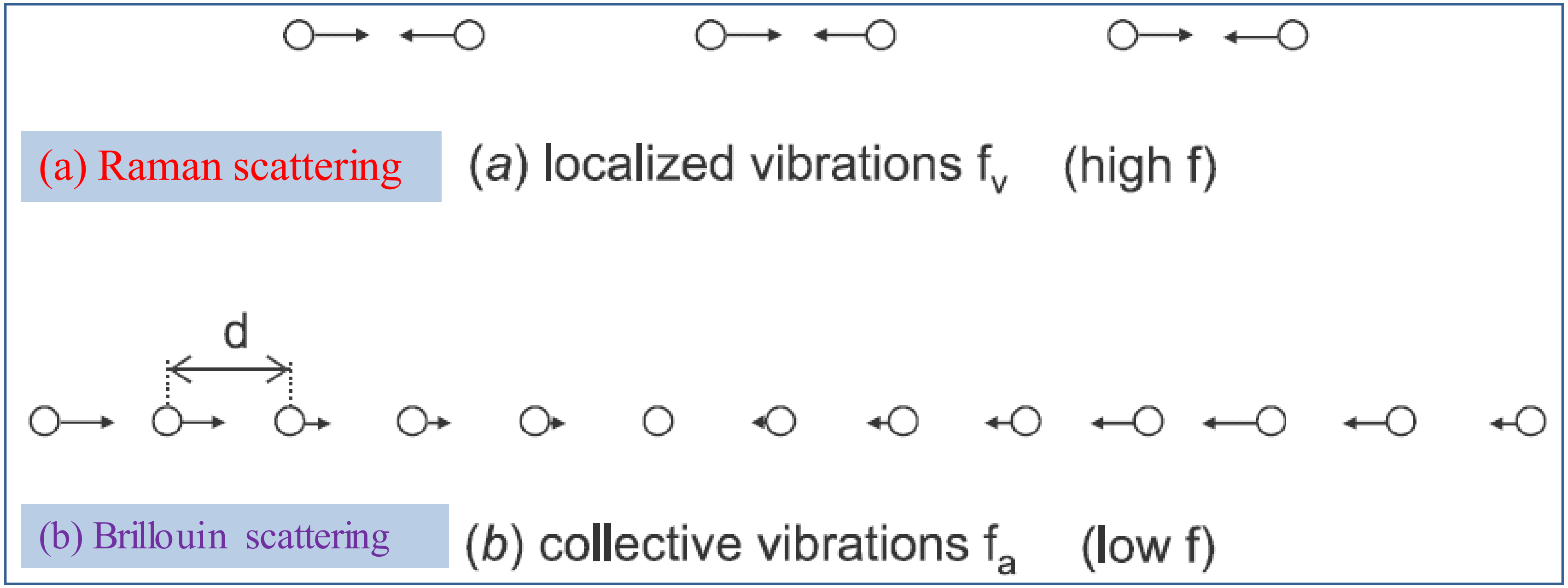


Figure 5-8 Vibrational patterns for (a) Raman scattering and (b) Brillouin scattering. Arrows show the relative displacement of the atoms.

EXAMPLE 5-1

❖ Light of free-space wavelength 1500 nm is incident on silica glass. Determine the frequency and wavelength of the Stokes-shifted, Raman-scattered light, assuming $f_v = 15$ THz.

Solution: The optical frequency of the incident light is

λ=1550 nm ⇒

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{1.5 \times 10^{-6} \text{ m}} = 2 \times 10^{14} \text{ Hz}$$

$h\nu' = h\nu \pm hf_v$ ⇒ frequency of scattered light is (ύ):

$$\nu' = (20 - 1.5) \times 10^{13} = 1.85 \times 10^{14} \text{ Hz}$$

which corresponds to

$$\lambda' = \frac{c}{\nu'} = \frac{3 \times 10^8 \text{ m/s}}{1.85 \times 10^{14} \text{ Hz}} = 1620 \text{ nm}$$

5-3 Bending Losses

➢ When an optical fiber is bent, light may become unguided, resulting in a loss of guided light power.

➢ Mode coupling: The **light** shift from one guided mode to **another** guided mode.

1. Geometrical Optics View **2. Physical Optics View**

1. Geometrical Optics View

If R is **too small**, $\theta < \theta_c$, and the ray will no longer be guided.

This occurs when: $$\boxed{R < \frac{a}{\Delta}} \quad (5\text{-}10)$$

(significant bending loss)

Where $\Delta \ll 1$ has been assumed.

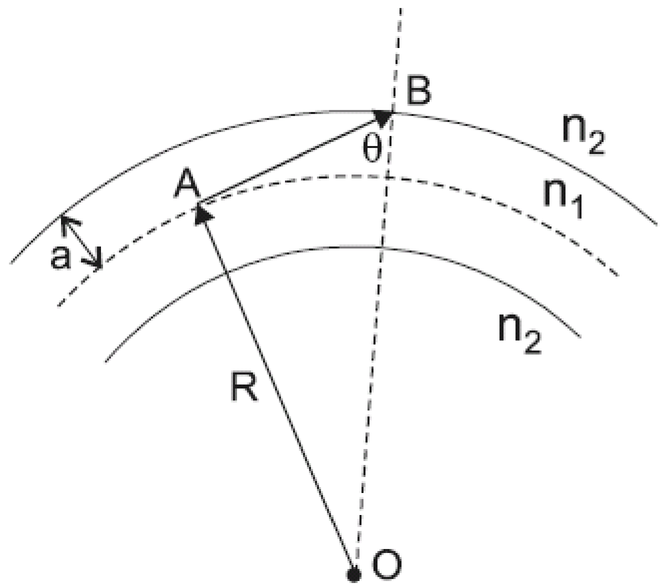


Figure 5-9 Ray optics picture of light loss due to fiber bending

5-3 Bending Losses (Geometrical Optics View)

- For example, if the core diameter is 100 μm and $\Delta = 0.01$, the bending loss will be significant for $R < 5\ mm$.

- The degree of bending loss depends not only on the bend radius, but also on which modes are propagating.

- The low-order modes are more stable and resistant to bending losses.

- Whereas the high-order modes are only marginally stable, and prone to *significant loss from even* small bends.

5-3 Bending Losses (Physical Optics View)

- As the wave moves along the arc, ***different parts*** of the wave must move at different speeds, in order for the wave to maintain the same shape as it propagates.

- At some distance r_{max} from the pivot, the evanescent wave in the cladding must be moving at a speed greater than the speed of light in the cladding material, c/n_2.

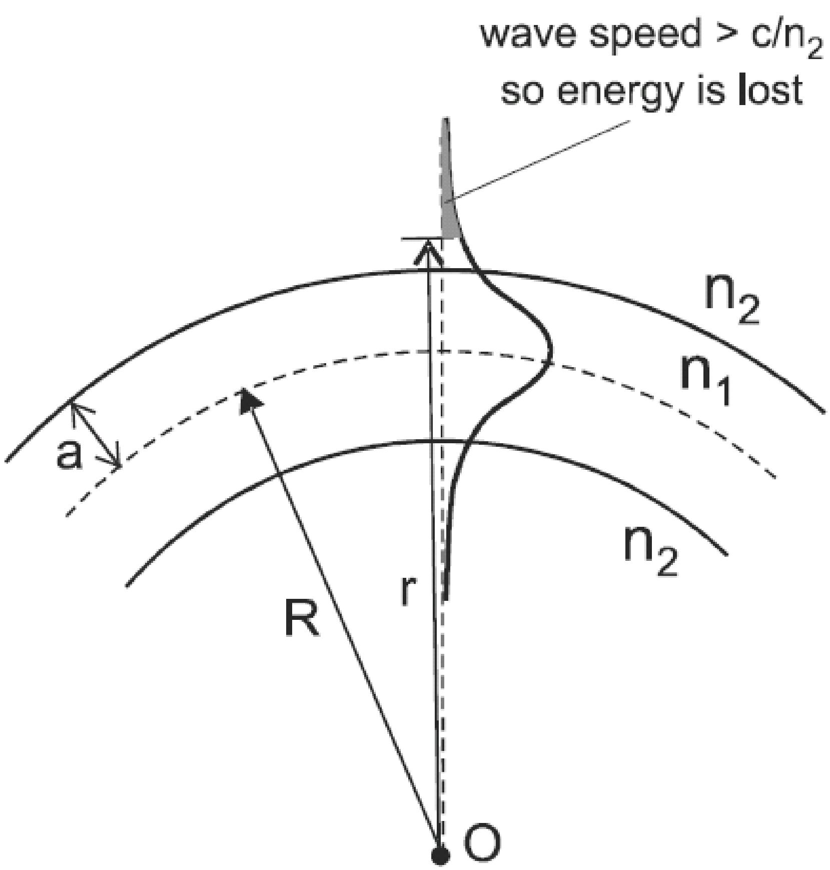


Figure 5-10 Wave optics picture of light loss due to fiber bending.

5-3 Bending Losses (Physical Optics View)

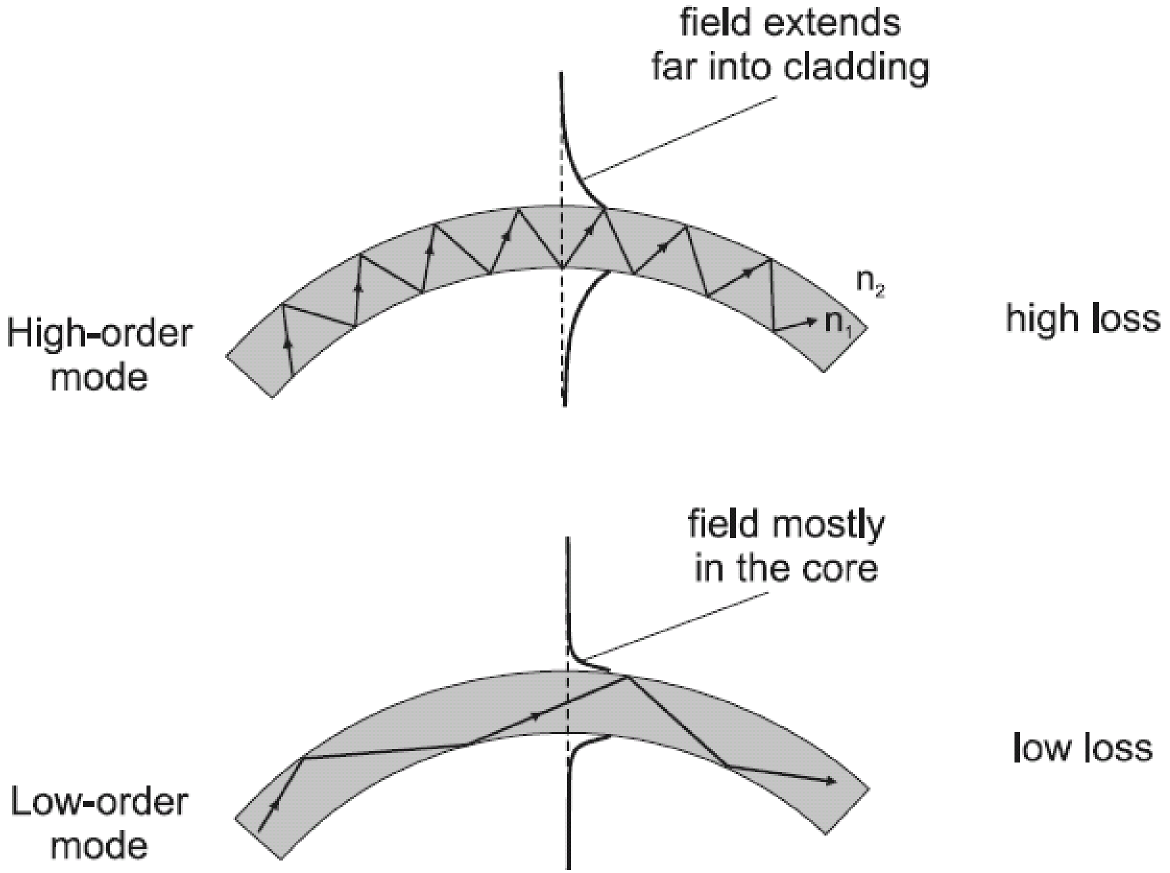


Figure 5-11 High-order modes are more lossy because more of the mode's energy is in the evanescent wave, where energy is lost due to bending.

5-3 Bending Losses (Length Scale for Bending Loss)

1. Macrobending 2. Microbending

- *Macrobending losses* are those caused by bends with R in the centimeter to meter range.

- These losses are usually small, affecting mostly the higher-order modes in a multimode fiber.

- Microbending losses are more difficult to control, arising from bends on the μm length scale.

- These microbends can be introduced by anything that crimps or stresses the fiber, including the packaging material that houses the fiber.

5-3 Bending Losses (Length Scale for Bending Loss) -2

- The protection from microbending is better with loose buffering, since there is more "wiggle room" for the fiber.

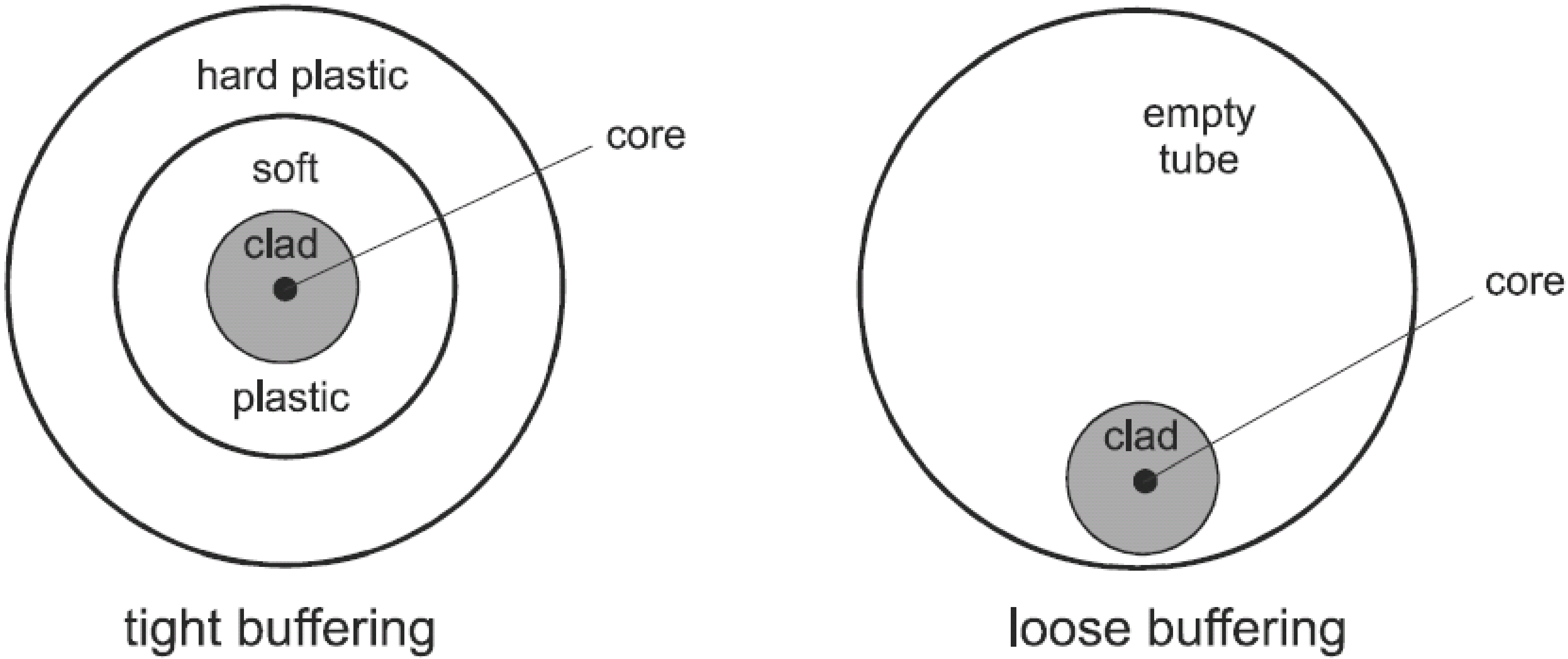


Figure 5-12 Two typical fiber-jacketing schemes. The method of containing the fiber in the cable can influence the degree of microbending loss.

5-3 Bending Losses (Mode Coupling)

➢ Mode coupling : light propagating in one guided mode can be scattered into another guided mode. This process of transferring energy from one mode to another is termed.

i. Low-order modes: Modes with the highest values

ii. High-order modes: Modes with the lowest values

1. Guided Mode 2. Radiation Mode 3. Cladding Mode

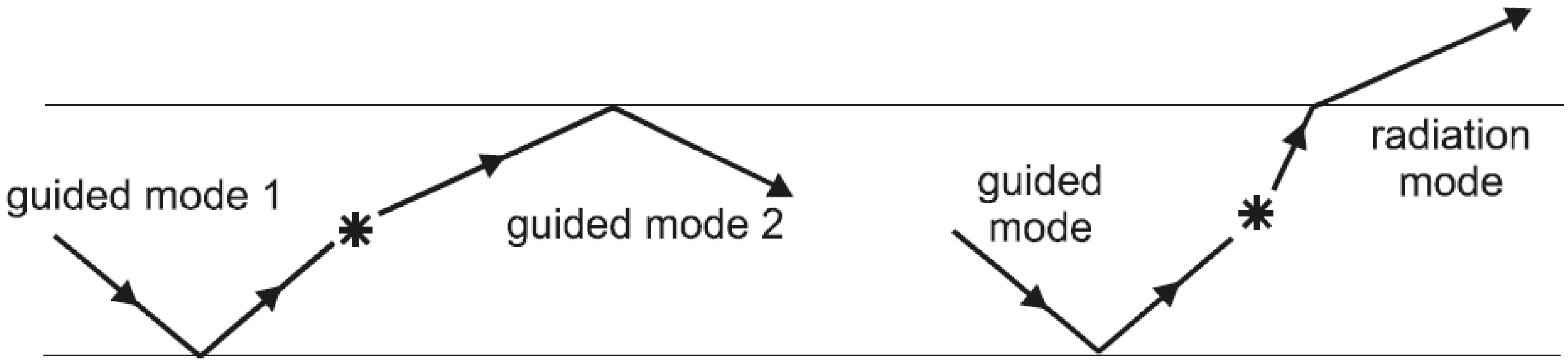


Figure 5-13 Scattering or fiber bending can couple light from one mode to another.

5-3 Bending Losses (Mode Coupling)

- **Radiation mode**: Light that is no longer guided ($\beta < n_2k_0$).
- In a radiation mode, although this is not a true mode of the fiber.

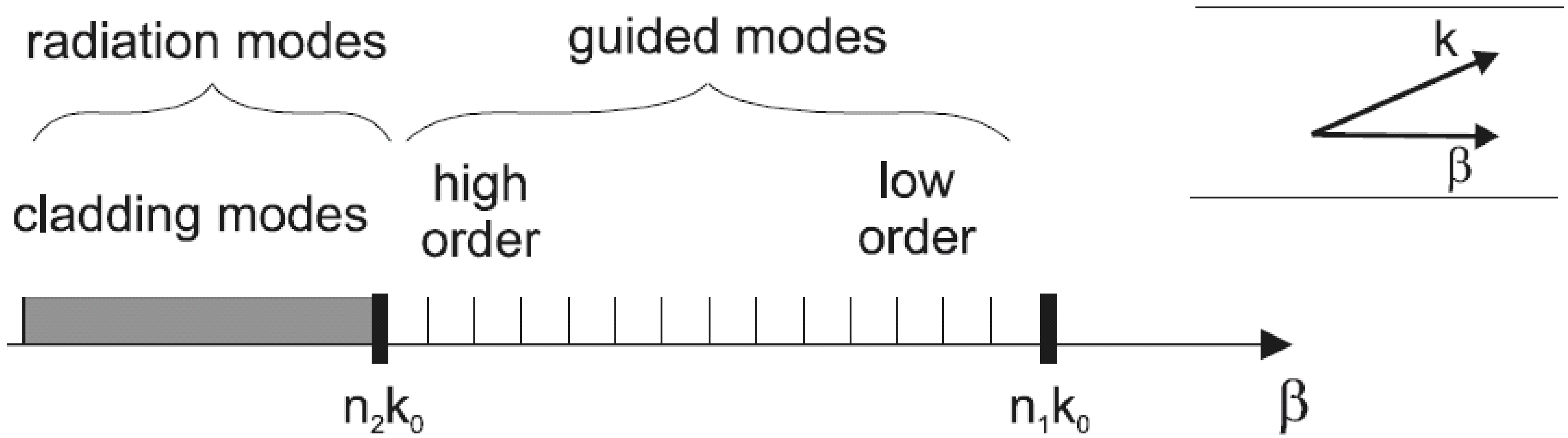


Figure 5-14 Distribution of fiber modes in β space, with discreet guided modes in the range $n_2k_0 < \beta < n_1k_0$, and continuous radiation modes for $\beta < n_2k_0$.

5-3 Bending Losses (Mode Coupling)

➢ The coupling of modes can be enhanced by forcing the fiber through a series of tight bends.

➢ Such a device is termed a *mode mixer*, and can be realized by simply sandwiching the fiber between pieces of sandpaper.

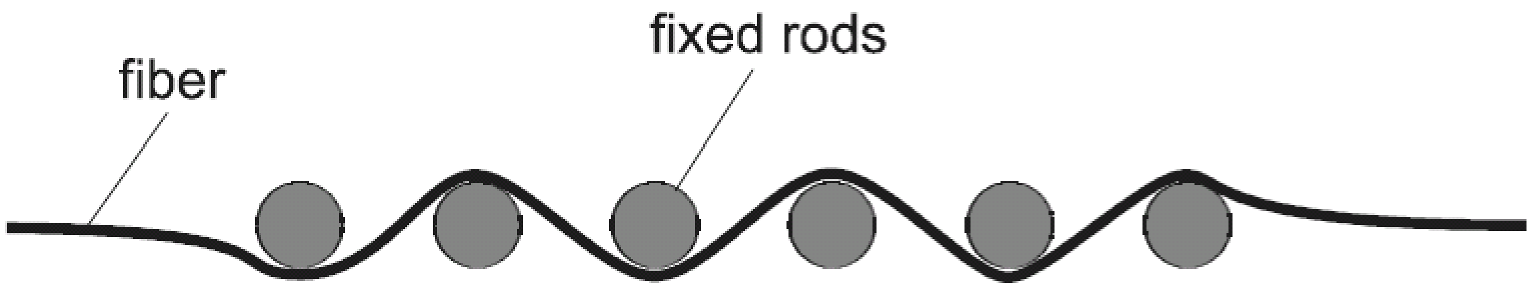


Figure 5-15 A mode mixer creates an equilibrium modal distribution.

5-3 Bending Losses (Cladding Modes)

- cladding mode: Light that is lost into radiation modes is no longer guided by the core, but it can still propagate some distance along the fiber.
- The mode stripper removes light from the cladding modes, leaving only true guided modes carrying the light energy.
- As the light propagates, some guided modes will continue to feed energy into the cladding modes by mode coupling.

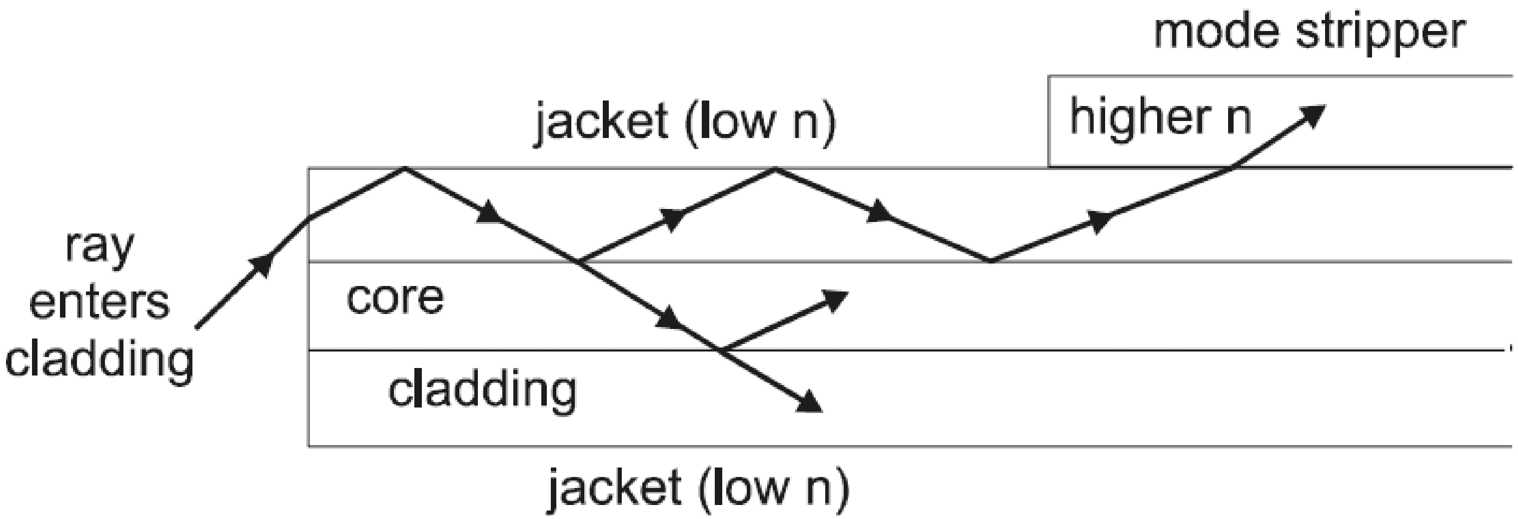


Figure 5-16 Cladding modes can be removed with a mode stripper.

Problems (chap.5): 2, 3, 6, 10, 12