Optical and Photonic Glasses

Lecture 25:

Optical Fibers C: Fiber Loss

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Fiber losses

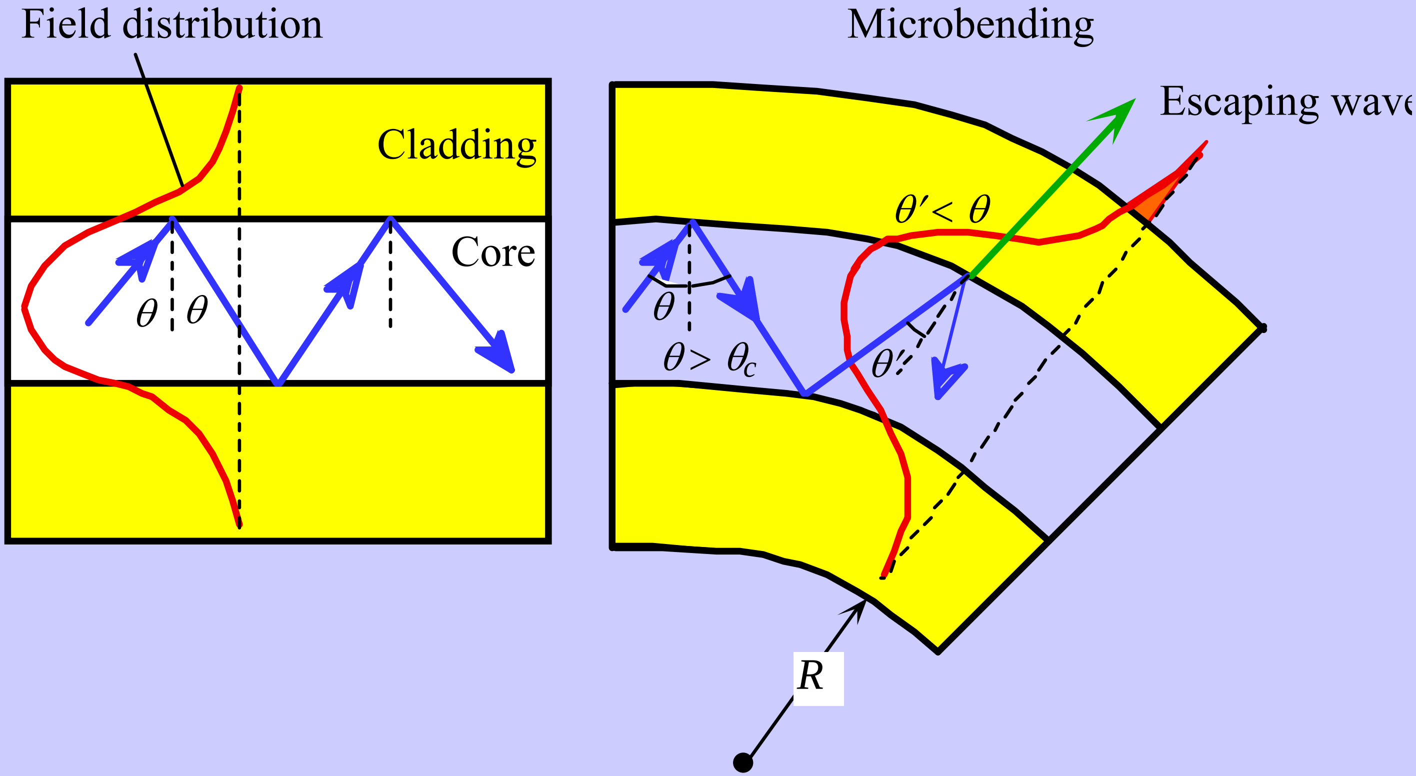
The main optical parameters of an optical fiber are:

- numerical aperture, NA = $(n_{core}^2 - n_{clad}^2)^{1/2}$
- optical loss
- dispersion

The fiber loss may be: (1) *intrinsic* (absorption and scattering); (2) *extrinsic* (absorption by impurities like OH^- and transition metal ions such as Fe^{2+}, Fe^{3+}, Cu^{2+}, …; scattering by bubbles and microcrystals; microbending losses).

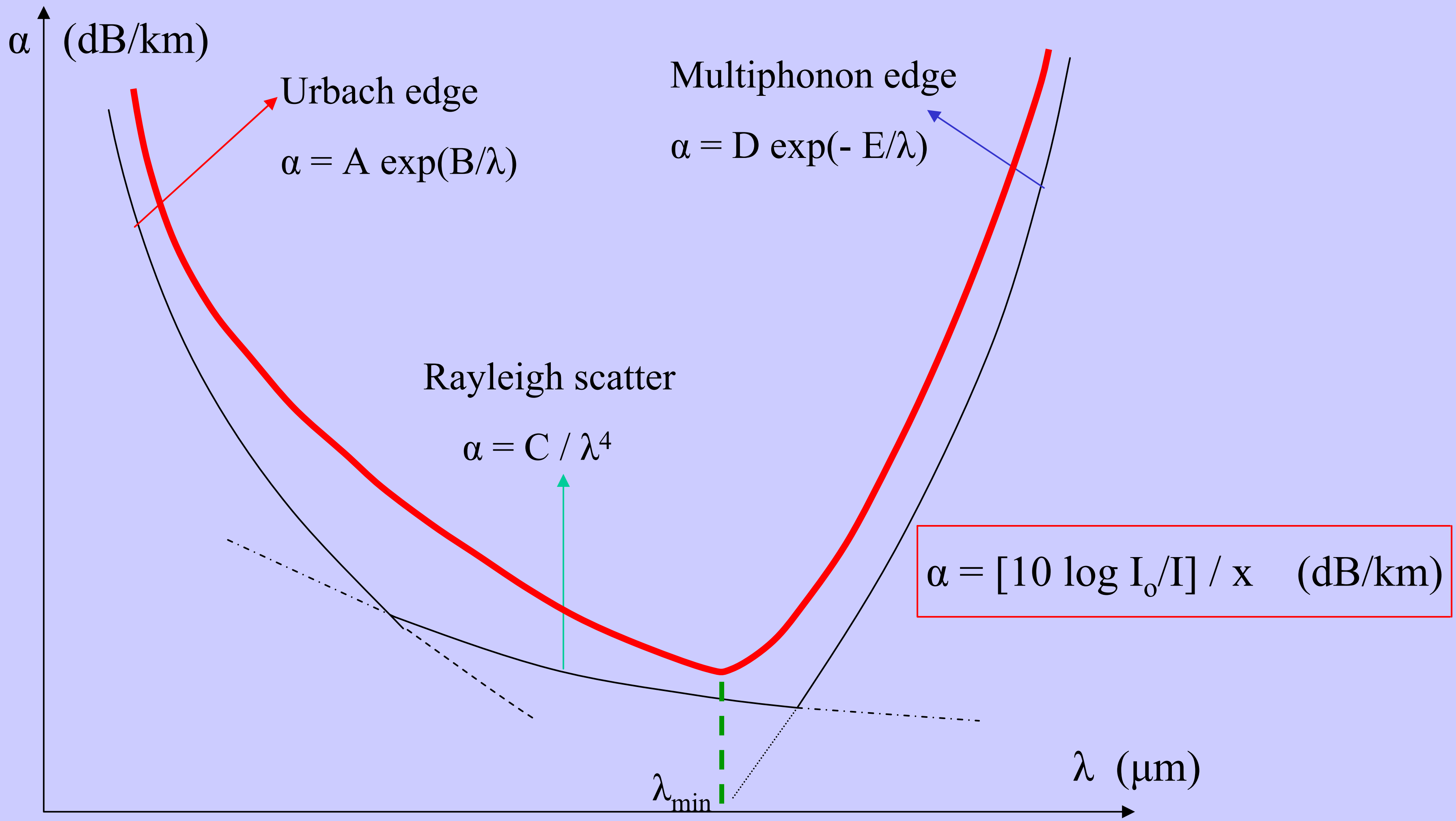
Intrinsic absorption is due to: (1) electronic (UV-visible) absorption at the Urbach edge; (2) vibrational (IR) absorption at the "multiphonon" edge.

Intrinsic scattering is due to: (1) elastic Rayleigh scattering, due to atomic scale density and compositional fluctuations which cause refractive index fluctuations, which is a function of the glass refractive index and T_g; (2) inelastic Raman / Brillouin scattering (only ~ 0.1% of the Rayleigh scattering contribution).



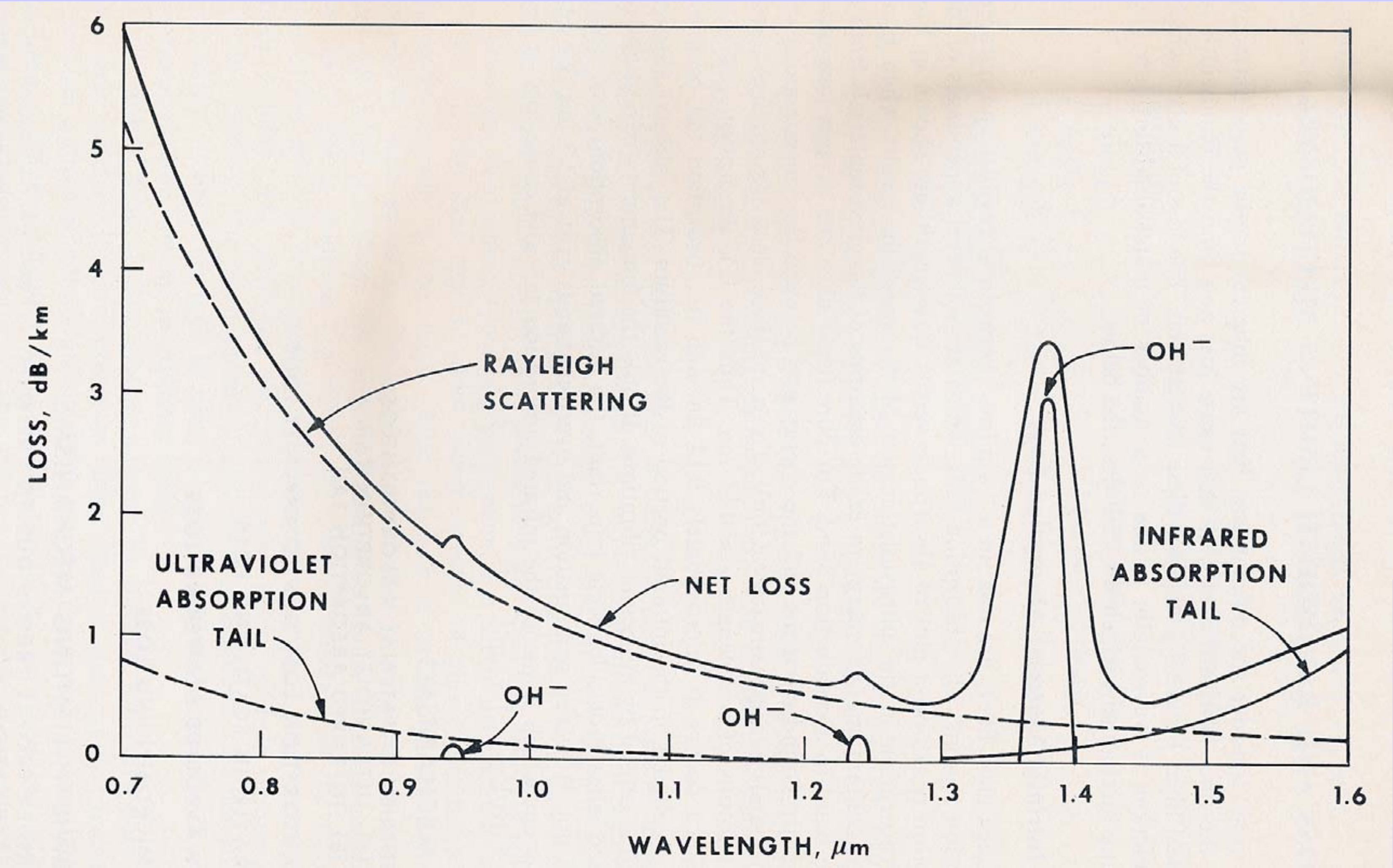
Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.

Intrinsic **optical losses** are generally the result of the intersection of the electronic absorption, Rayleigh scattering and multiphonon absorption curves, corresponding to a typically **V-shaped curve** :



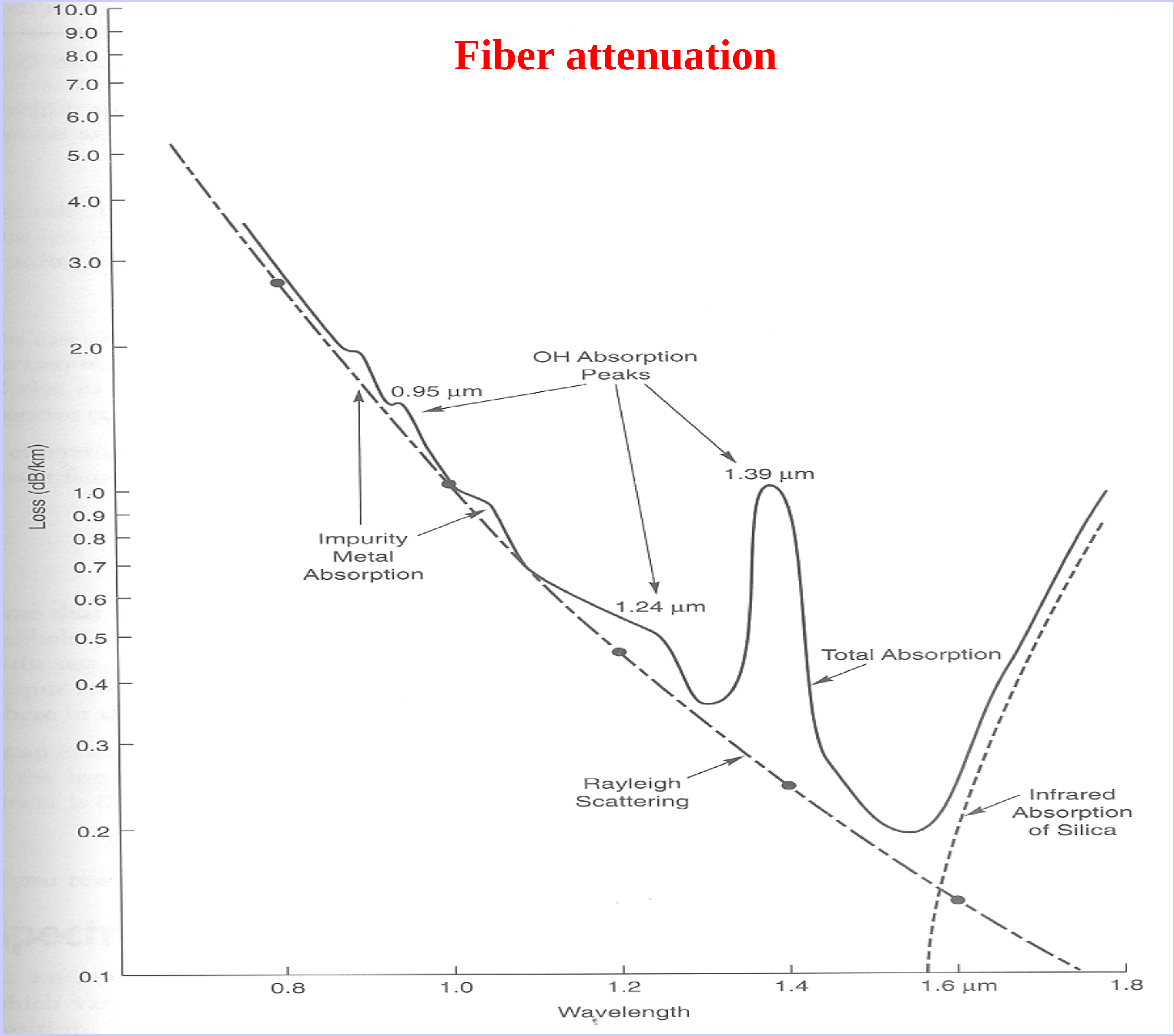
The wavelength of minimum loss, λ_{min}, is usually located near the intersection of the Rayleigh scattering and multiphonon absorption curves.

Optical fiber loss



(Adapted from: *An introduction to optical fibers*, A.H. Cherin, McGraw-Hill, 1983)

Fiber attenuation



(Adapted from: *Understanding Fiber Optics*, Jeff Hecht, Prentice-Hall, 1999)

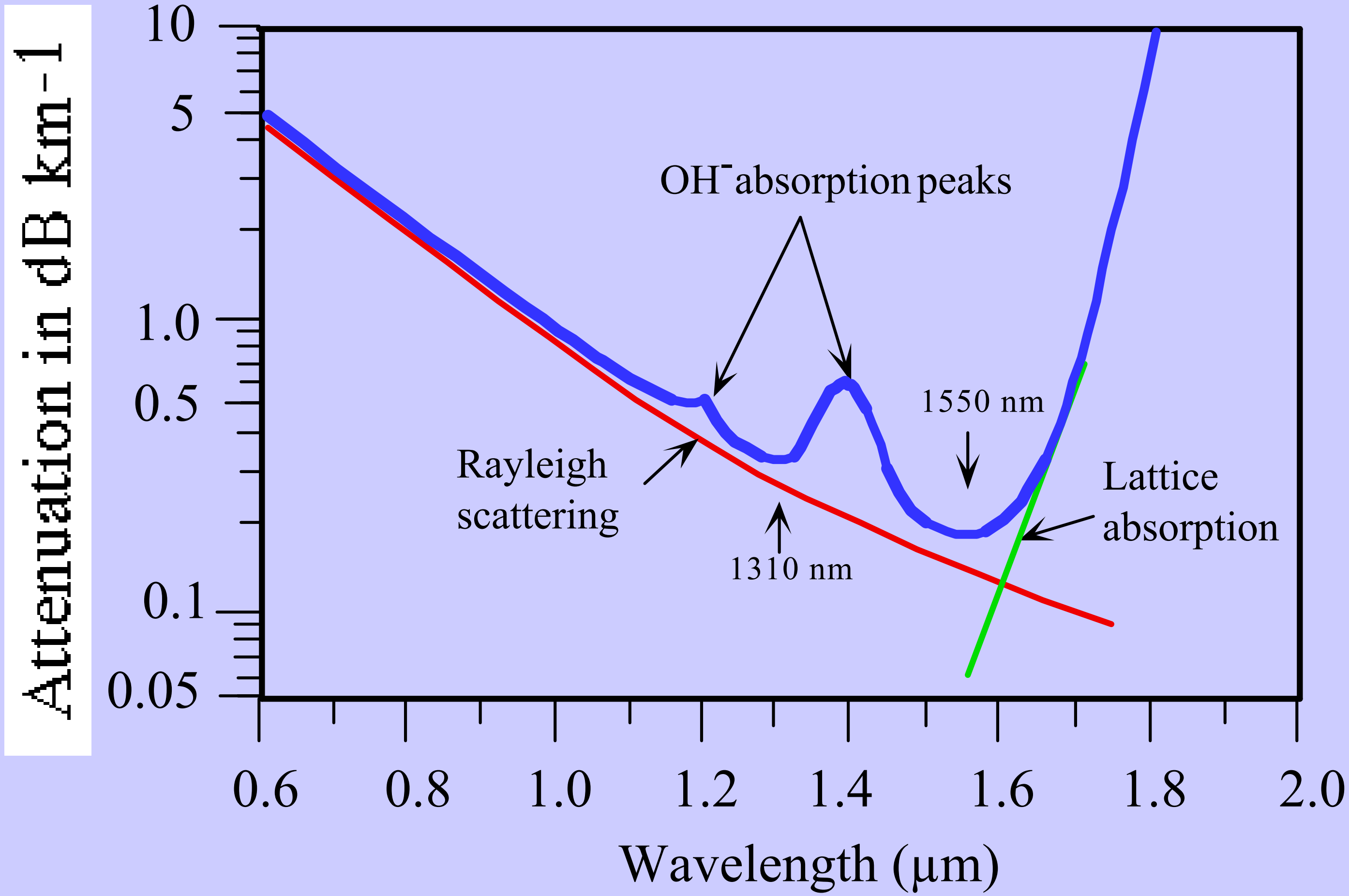
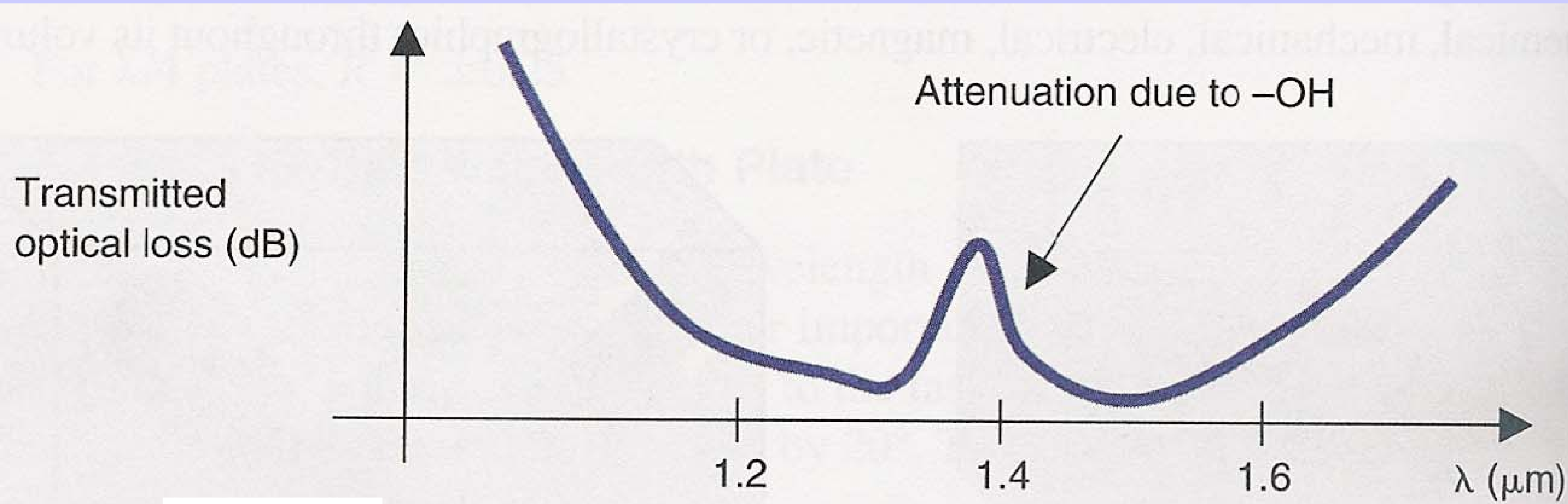


Illustration of a typical attenuation vs. wavelength characteristics of a silica based optical fiber. There are two communications channels at 1310 nm and 1550 nm.

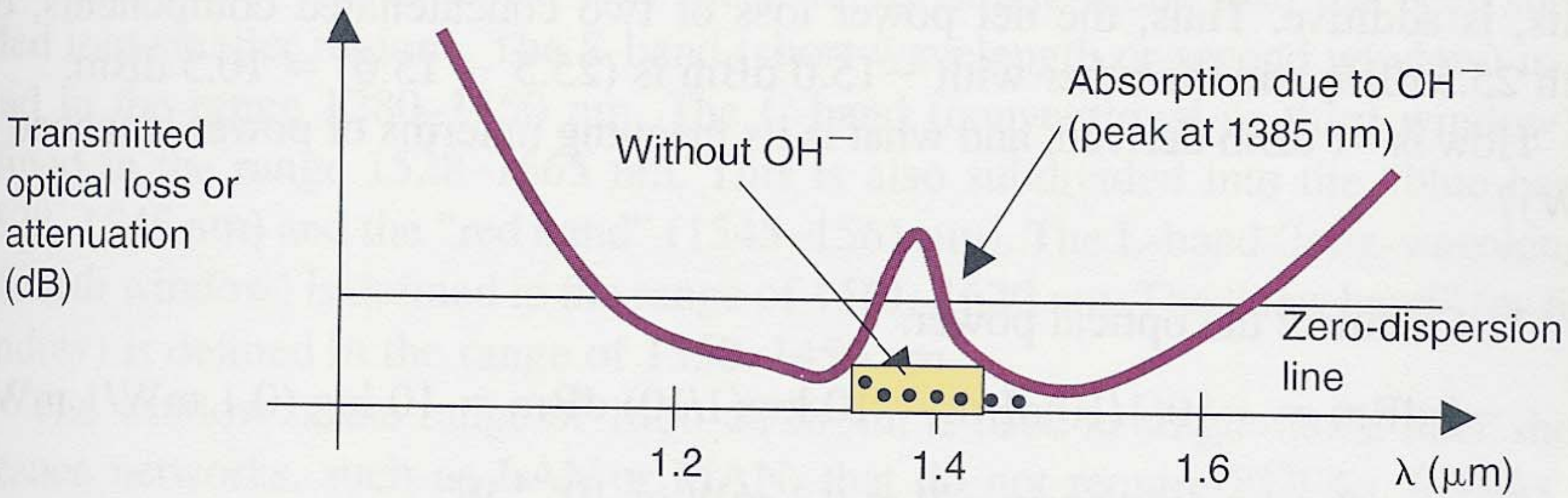
Optical fiber loss: OH effect



Optical loss (or attenuation) by impurities in transparent matter.

(Adaptyed from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

Optical fiber loss due to OH groups



Typical single-mode fiber attenuation graph (a zero-dispersion level is included for reference). The Lucent Technologies AllWave™ fiber has eliminated the losses due to OH^- (dotted line).

(Adapted from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

Optical fiber dispersion

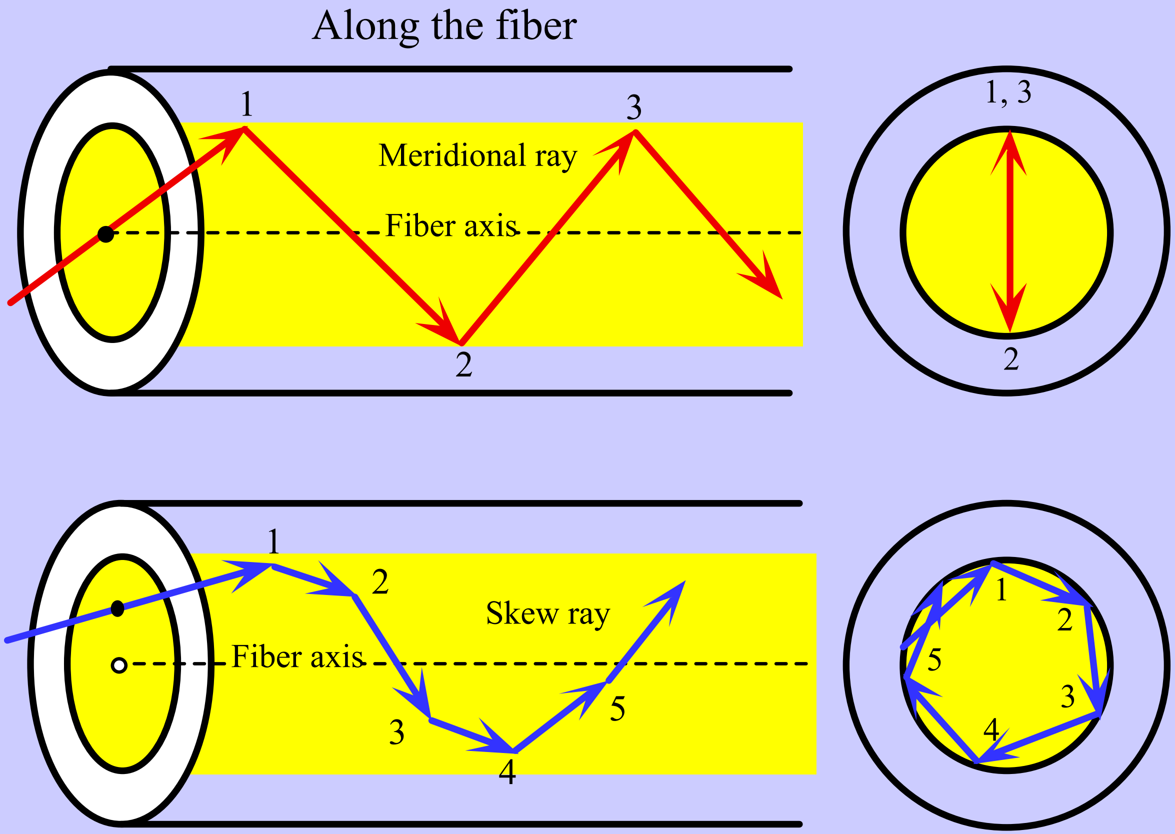
Dispersion here refers to the spreading of the light pulses which carry information along a fiberoptic link. These pulses may be broadened, with consequent distortion and loss of information, due to three main causes:

- modal dispersion
- material dispersion
- waveguide dispersion

Modal dispersion refers to the spreading of light pulses in step-index multimode fibers, as a result of the different light paths traveled by the lowest order propagating modes (with the axial ray traveling the shortest distance along the fiber) and the highest order modes, whose light rays will be reflected an increasing number of times at the core/clad interface (called *meridional* when they cross the fiber axis, or *skew*, when they do not).

This type of dispersion is basically eliminated in multimode graded index and especially in monomode fibers, although not completely. In terms of time lag between the first and last modes to arrive at the end of a fiber of length L, modal dispersion is approximately given by:

$$\Delta t_{modal} = (n_1 - n_2)\, L / c_o \qquad (n_1=1.51 \text{ and } n_2=1.48 \Rightarrow \Delta t = 100 \text{ ns/km})$$



(a) A meridiona
ray always
crosses the fibe
axis.

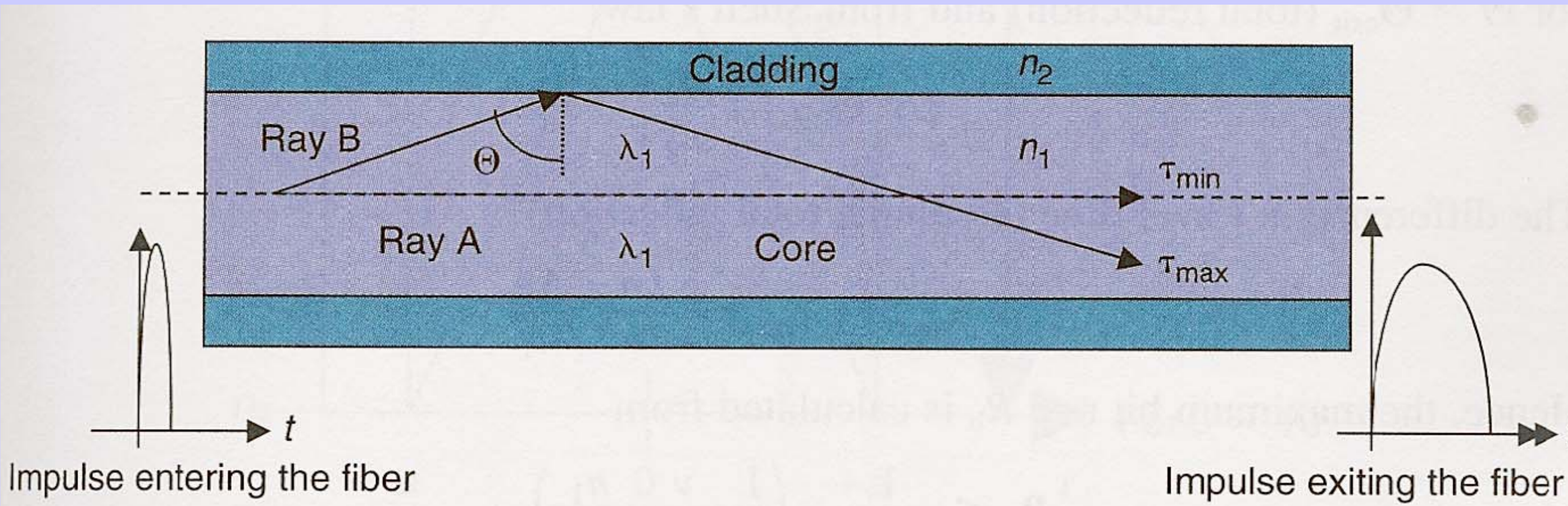
(b) A skew ray
does not have
to cross the
fiber axis. It
zigzags around
the fiber axis.

Ray path along the fiber

Ray path projected
on to a plane normal
to fiber axis

Illustration of the difference between a meridional ray and a skew ray.
Numbers represent reflections of the ray.

Modal dispersion

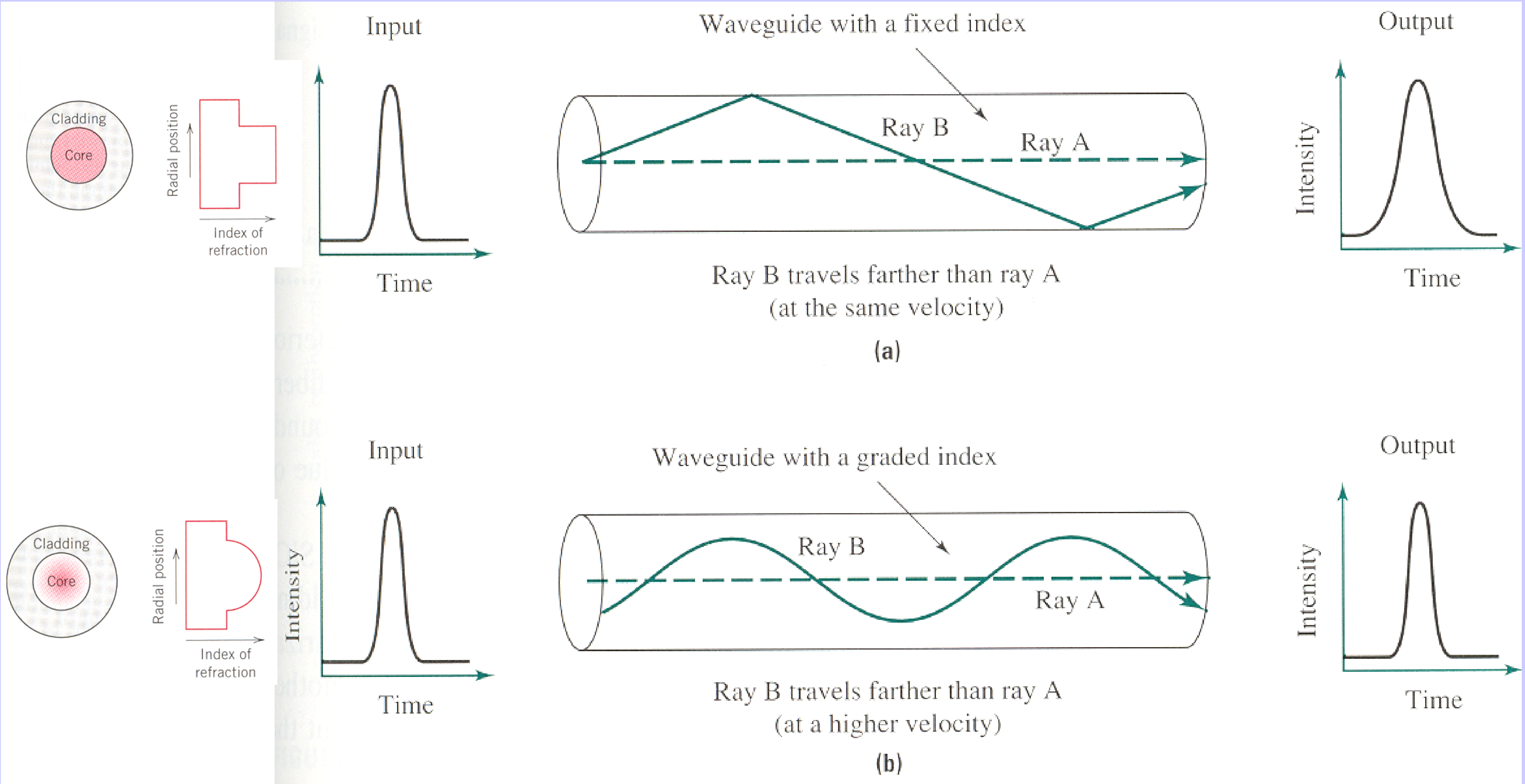


Initial narrow pulse spreads out because of modal dispersion.

(Adapted from: *Introduction to DWDM Technology*, S.V. Karatalopoulos, IEEE Press, 2000)

Mode-induced pulse stretching in multimode fibers with *step (fixed)* and *graded* refractive indices

(modal dispersion)

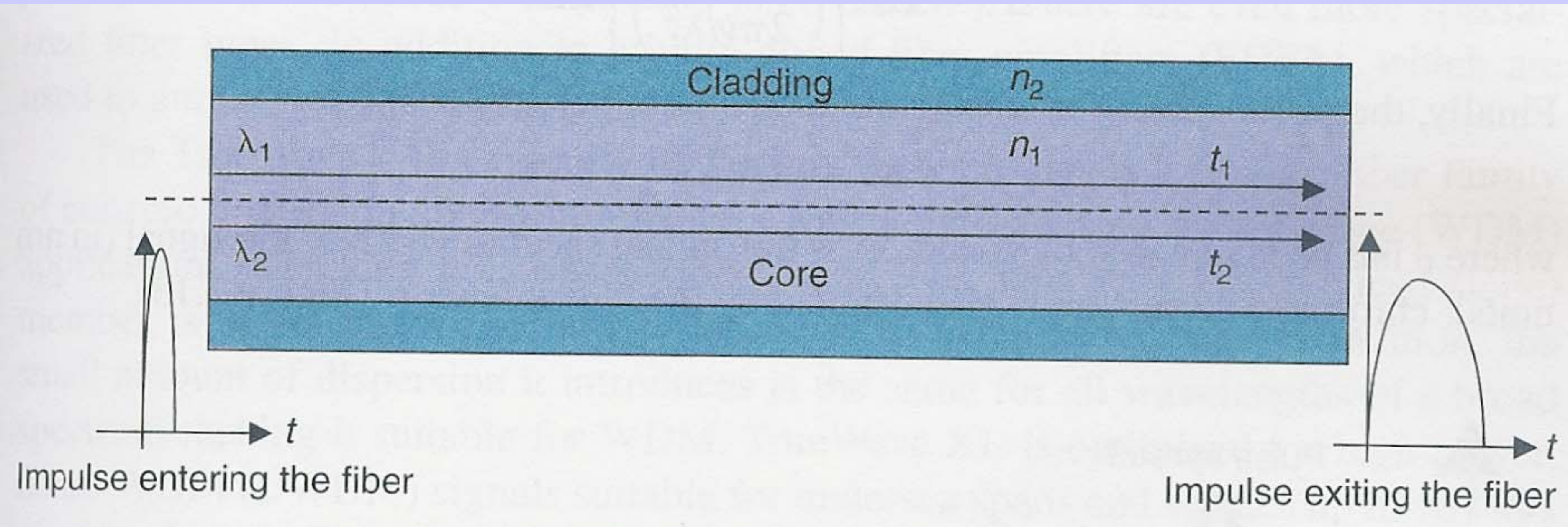


(Adapted from: *The science and design of engineering materials*, J.P. Schaffer et al., McGraw-Hill, 1999)

Material dispersion

Material dispersion is due to the fact that even laser light sources have a finite spectral width (e.g. ~ 10 nm) and are therefore not perfectly monochromatic, causing each of its constituent wavelengths to travel along the fiber at slightly different velocities, $c(\lambda) = c_o / n_1(\lambda)$. This occurs even in single mode fibers. It can be shown that:

$$\Delta t_{mater} \sim - (d^2n/d\lambda^2)\, \lambda_{ctr}\, \Delta\lambda\, L / c_o \qquad \text{(ps/km)}$$



(Adapted from: *Introduction to DWDM Technology*, S.V. Kartalopoulos, IEEE Press, 2000)

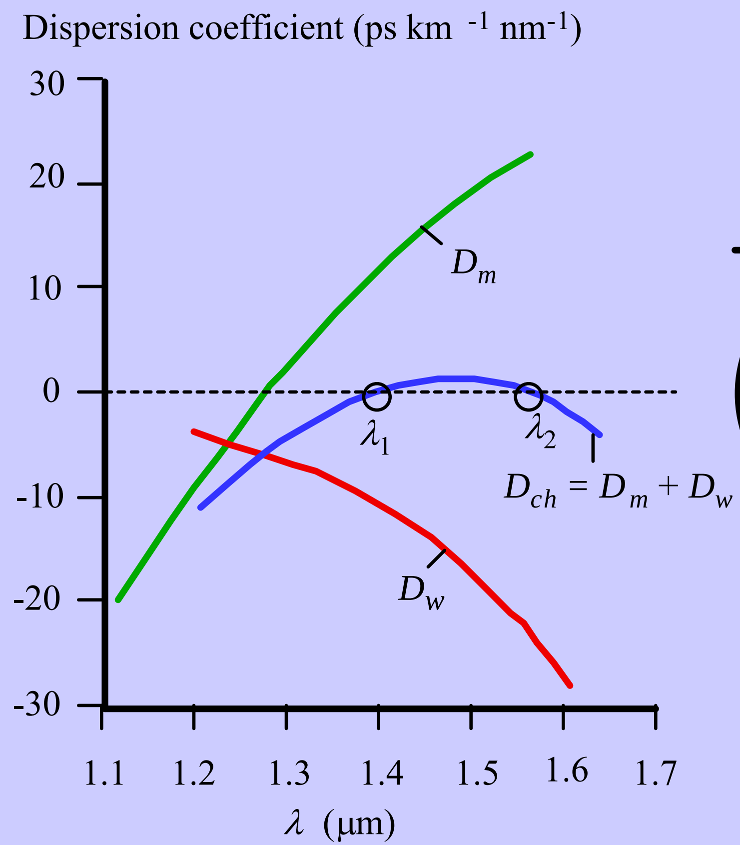
Waveguide dispersion

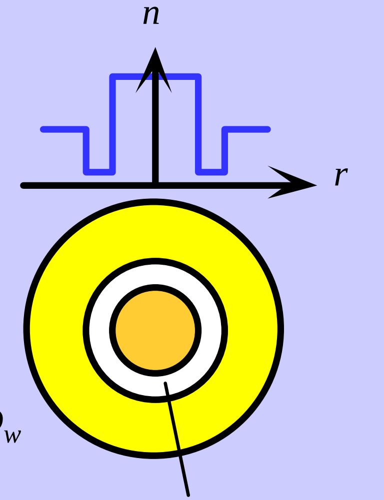
Monomode fibers, which have a core so thin (e.g. ~ 5 - 8 μm in diameter, compared to a diameter of 125 μm for the cladding) that only one electromagnetic mode (or light ray) propagates along its axis, still have two major sources of dispersion:

- material dispersion
- waveguide dispersion

Material dispersion was just discussed. *Waveguide dispersion* is a result of the fact that the optical fiber needs a cladding of lower index to function, where the *evanescent* (exponentially decaying) electric *field* of the only propagating mode will propagate at a speed slightly higher than that in the core, accelerating and distorting the tails of the originally gaussian mode profile. The sum of the material and waveguide dispersion is called *chromatic* dispersion.

The evanescent field penetrates more deeply into the cladding as the wavelength increases, or, in multimode fibers, for increasingly higher order modes.





Dispersion flattened fiber example. The material dispersion coefficient (D_m) for the core material and waveguide dispersion coefficient (D_w) for the doubly clad fiber result in a flattened small chromatic dispersion between λ_1 and λ_2.