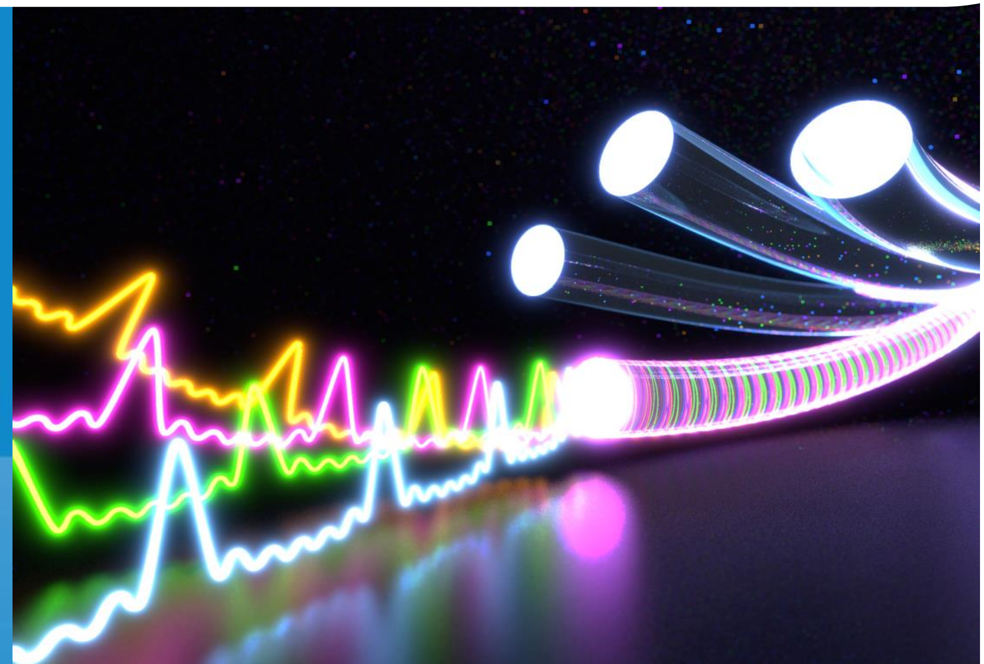
Lecture 5
Dielectric Waveguides & Optical Fibers II

ECE 325

OPTOELECTRONICS

Menoufia University



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Kasap–2.4, 2.5, 2.6, 2.8 and 2.9

Dispersion = Spread of Information

- **Intermode (Intermodal) Dispersion:** **Multimode fibers only**
- **Material Dispersion**

  Group velocity depends on N_g and hence on λ

- **Waveguide Dispersion**

  Group velocity depends on waveguide structure

- **Chromatic Dispersion**

  Material dispersion + Waveguide Dispersion

- **Profile Dispersion**

  Like material and waveguide dispersion.

  Add all 3 Material + Waveguide + Profile

- **Polarization Dispersion**

Group Velocity & Group Delay

- The **group velocity** is given by:

$$V_g = \frac{d\omega}{d\beta}$$

- The **group delay** is given by:

$$\tau_g = \frac{L}{V_g} = L\frac{d\beta}{d\omega}$$

- It is important to note that all above quantities depend both on **frequency** & the **propagation mode**.

Group Velocity and Group Delay

Consider a single mode fiber with core and cladding indices of 1.4480 and 1.4400, core radius of 3 μm, operating at 1.5 μm. ***What are the group velocity and group delay at this wavelength*****?**

$$b \approx \left(1.1428 - \frac{0.996}{V}\right)^2 \qquad 1.5 < V < 2.5$$

$$b = \frac{(\beta/k) - n_2}{n_1 - n_2} \Longrightarrow \beta = n_2 k[1 + b\Delta]$$

$k = 2\pi/\lambda = 4{,}188{,}790\ \text{m}^{-1}$ and $\omega = 2\pi c/\lambda = 1.255757 \times 10^{15}\ \text{rad s}^{-1}$

$V = (2\pi a/\lambda)(n_1^2 - n_2^2)^{1/2} = 1.910088$

$b = 0.3860859$, and $\beta = 6.044796 \times 10^{6}\ \text{m}^{-1}$.

Group Velocity and Group Delay

Increase wavelength by 0.1% and recalculate. Values in the table

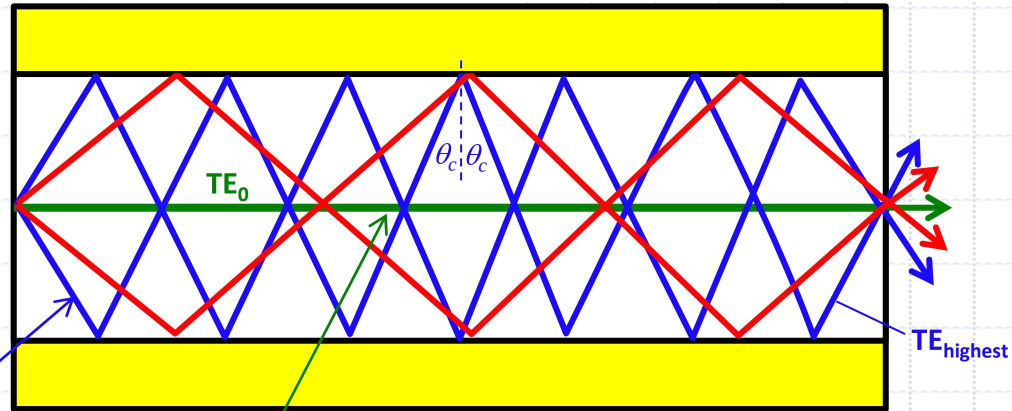
$$\lambda' = 1.5(1+0.001)\ \mu\text{m} = 1.50150\ \mu\text{m}$$

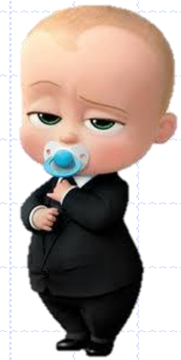
Calculation →	V	k (m^{-1})	ω (rad s^{-1})	b	β (m^{-1})
λ = 1.500000 μm	1.910088	4188790	1.255757×10^{15}	0.3860859	6.044818×10^{6}
λ' = 1.50150 μm	1.908180	4184606	1.254503×10^{15}	0.3854382	6.038757×10^{6}

$$v_g = \frac{d\omega}{d\beta} = \frac{\omega' - \omega}{\beta' - \beta} = \frac{(1.254503 - 1.255757)\times10^{15}}{(6.038757 - 6.044818)\times10^{6}} \approx 2.07\times10^{8}\ \text{m s}^{-1}$$

The group delay τ_g over 1 km is $\tau_g = \frac{L}{V_g} = 4.83$ μs

Intermode Dispersion (MMF)





$$v_{g\min} \approx \frac{c}{n_1}\sin\theta_c = \frac{c}{n_1}\left(\frac{n_2}{n_1}\right)$$

$$v_{g\max} \approx \frac{c}{n_1}$$

$$\Delta\tau = \frac{L}{v_{g\min}} - \frac{L}{v_{g\max}}$$

$$\frac{\Delta\tau}{L} = \frac{(n_1 - n_2)}{c}\left(\frac{n_1}{n_2}\right)$$

$$\frac{\Delta\tau}{L} \approx \frac{n_1 - n_2}{c}$$

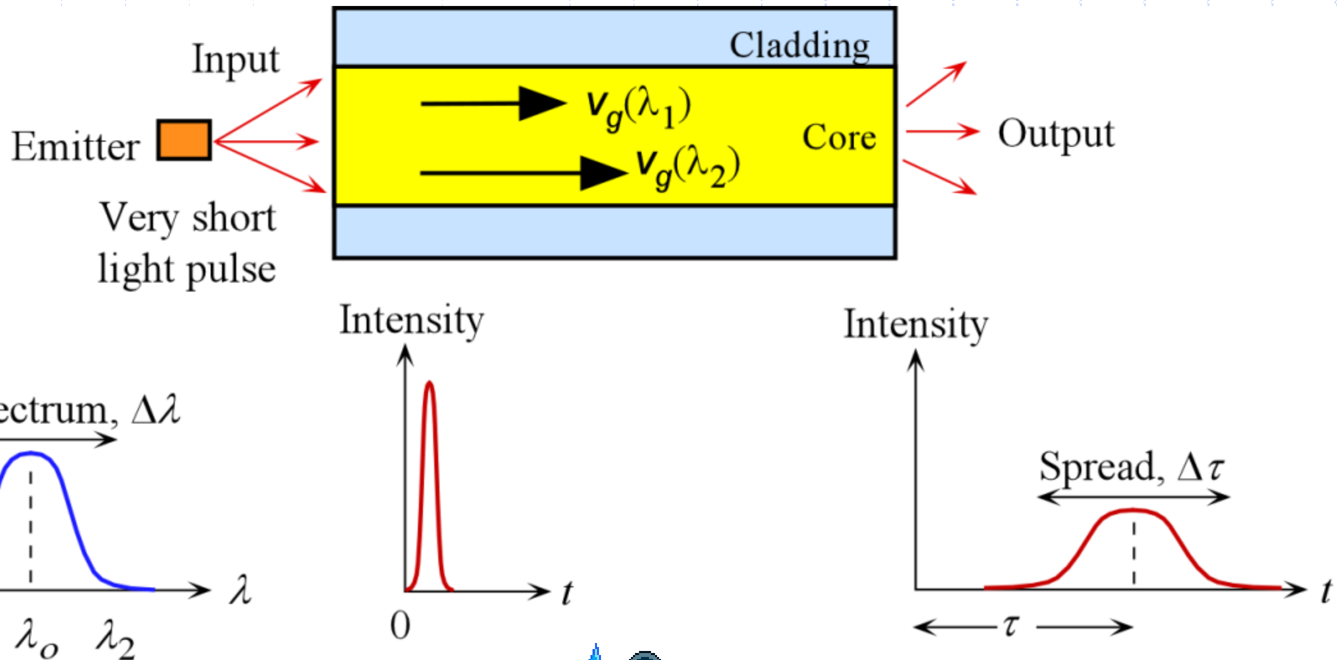
(Since $n_1/n_2 \approx 1$)

$\Delta\tau/L \approx 10 - 50$ ns / km

Depends on length!

Intramode Dispersion (SMF)

Dispersion in the fundamental mode



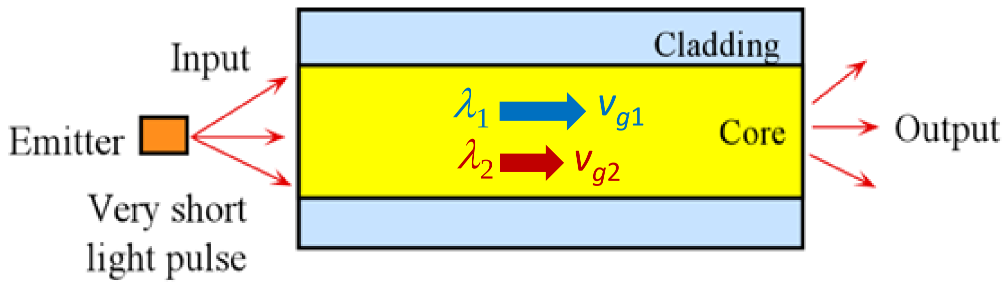
Group Delay $\tau = L / v_g$

Group velocity v_g depends on

Refractive index = $n(\lambda)$	**Material Dispersion**
V-number = $V(\lambda)$	**Waveguide Dispersion**
$\Delta = (n_1 - n_2)/n_1 = \Delta(\lambda)$	**Profile Dispersion**

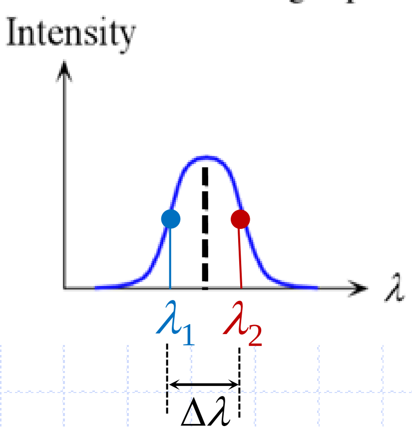
Intramode Dispersion (SMF)

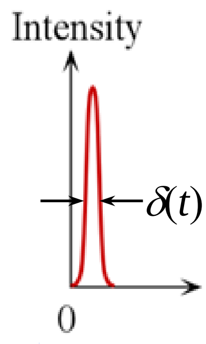
Chromatic dispersion in the fundamental mode

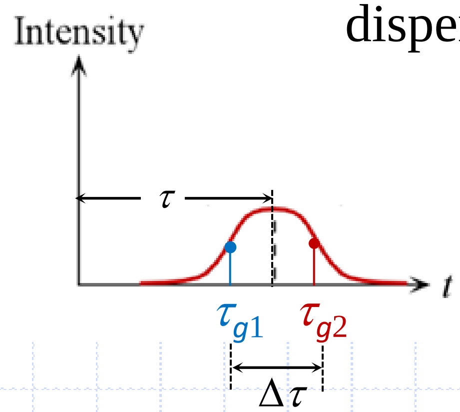


$$\Delta\tau = DL\Delta\lambda$$

Output pulse dispersed







$$\Delta\lambda = \lambda_2 - \lambda_1$$

Chromatic spread

$$D = \frac{\Delta\tau}{L\Delta\lambda}$$

$$\Delta\tau = \tau_{g1} - \tau_{g2}$$

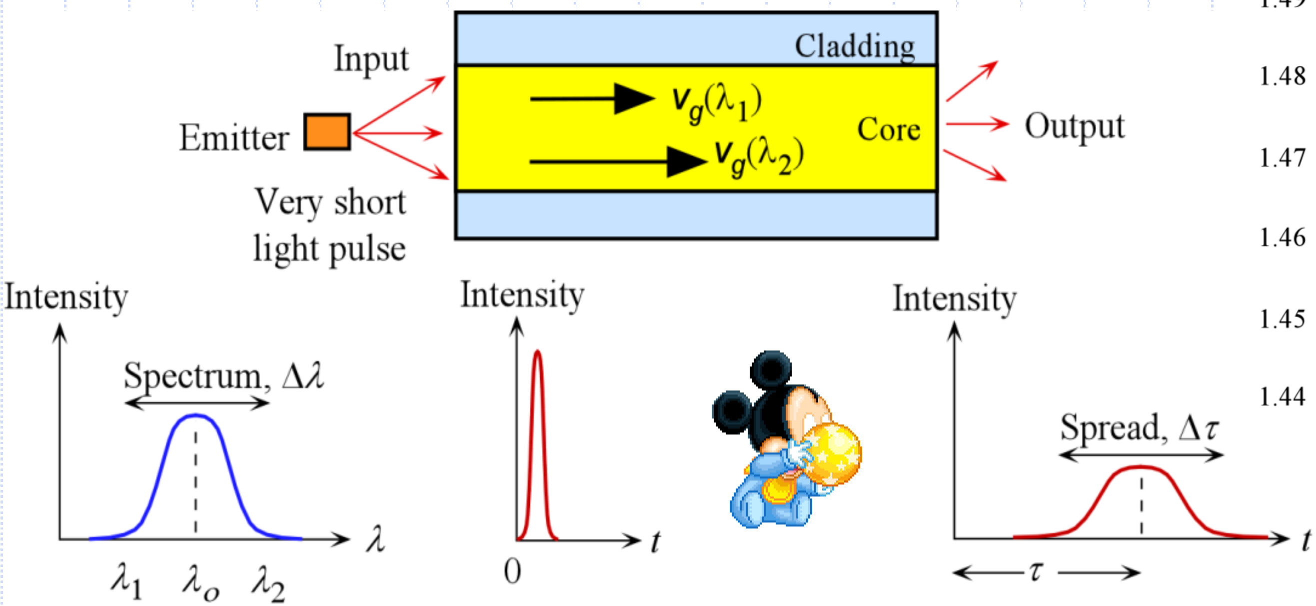
Dispersion

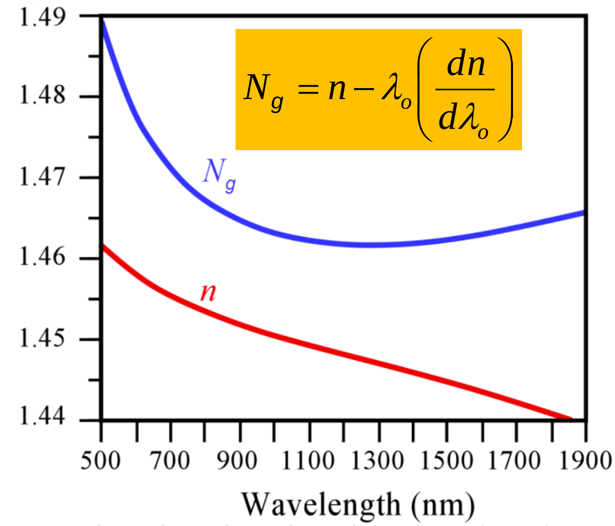
OR

$$D = \frac{d\tau}{Ld\lambda}$$

Definition of Dispersion Coefficient

Material Dispersion





Emitter emits a spectrum $\Delta\lambda$ of wavelengths.

Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

$$v_g = c / N_g$$

Group velocity

Depends on the wavelength

$$D_m \approx -\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right)$$

$$\frac{\Delta\tau}{L} = D_m\Delta\lambda$$

D_m = Material dispersion coefficient, ps nm^{-1} km^{-1}

Waveguide Dispersion

b hence β depend on V and hence on λ

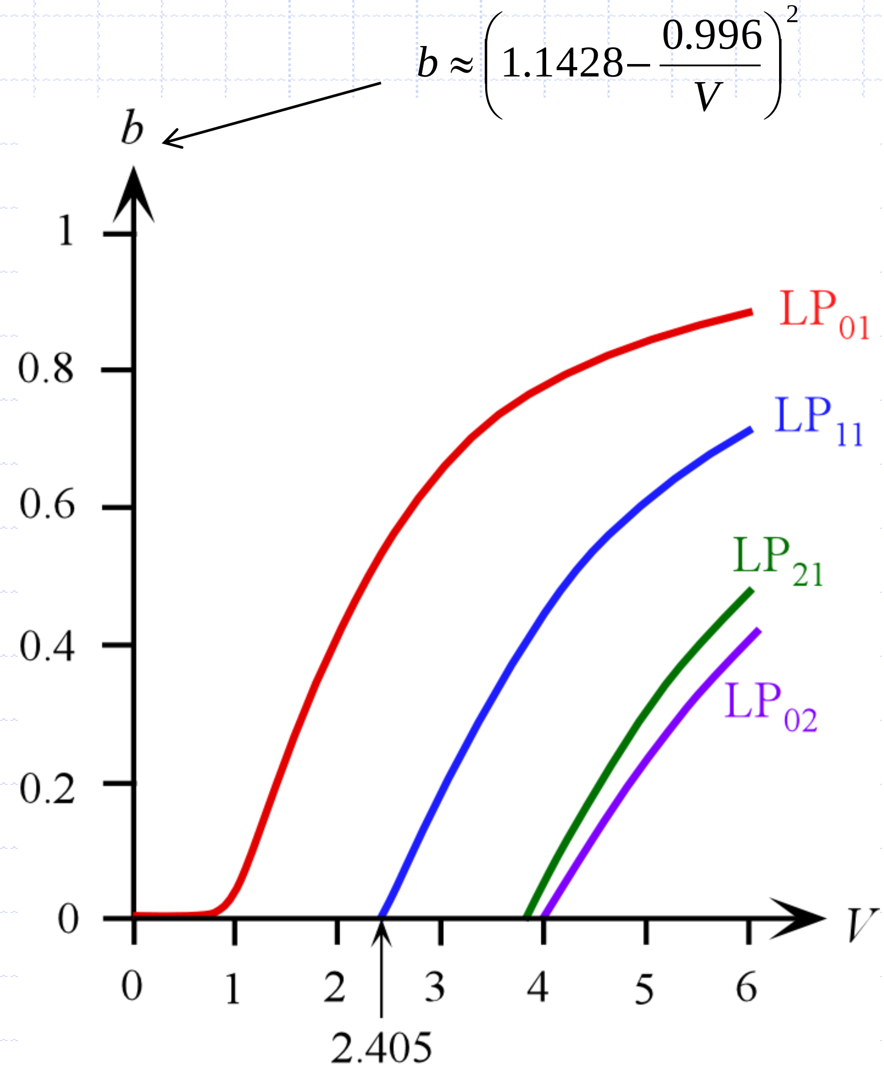
$$V = \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2}$$

Normalized propagation constant

$$b = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2}$$

$$k = 2\pi/\lambda$$

$$\beta \approx n_2 k(1 + b\Delta)$$

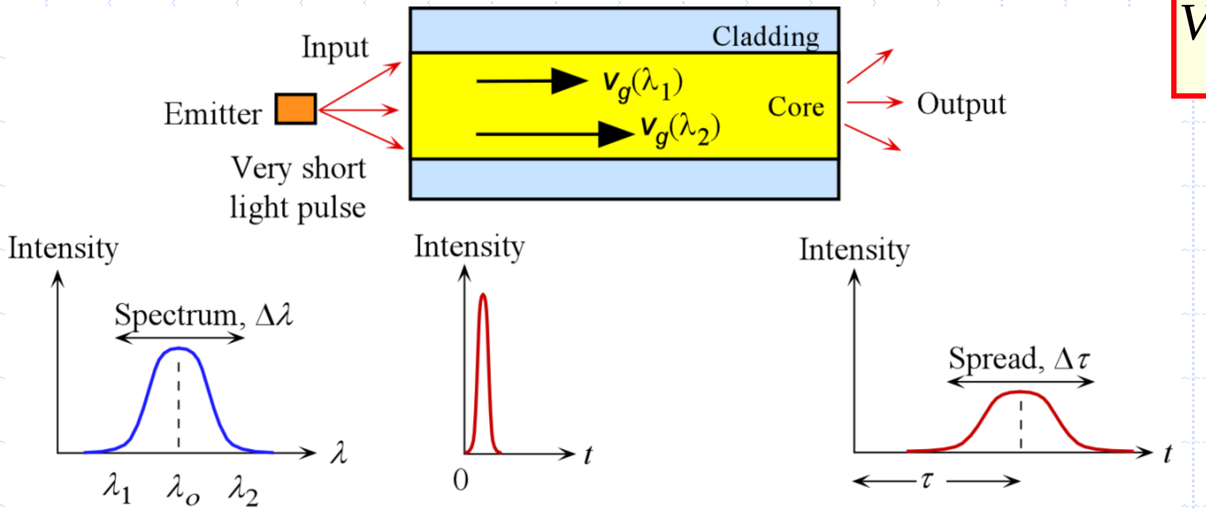


Using V number:

$$V \approx k a n_2 \sqrt{2\Delta}$$

Waveguide Dispersion

$$V = \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2}$$



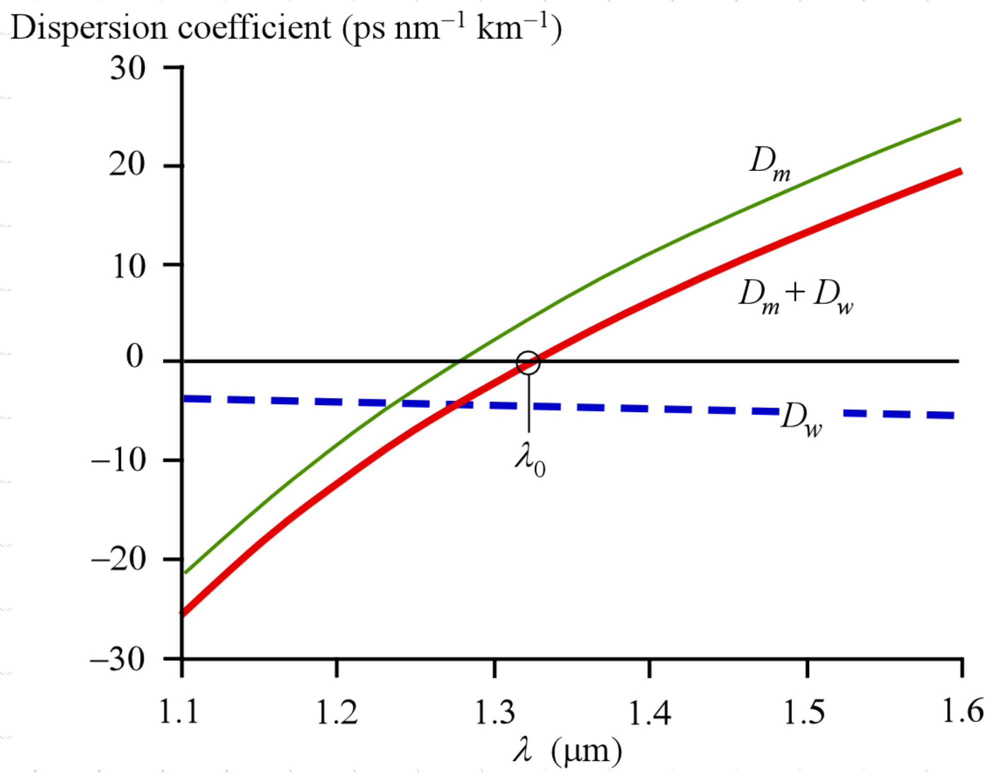
Waveguide dispersion: The group velocity $v_g(01)$ of the fundamental mode depends on the V-number, which itself depends on the source wavelength λ, even if n_1 and n_2 were constant. Even if n_1 and n_2 were **wavelength independent** (no material dispersion), we will still have waveguide dispersion by virtue of $v_g(01)$ depending on V and V depending **inversely** on λ. Waveguide dispersion arises as a result of the guiding properties of the waveguide which imposes a **nonlinear ω vs. β_{lm} relationship**.

$$\frac{\Delta\tau}{L} = D_w \Delta\lambda$$

D_w = waveguide dispersion coefficient

D_w depends on the waveguide structure, ps nm^{-1} km^{-1}

Chromatic Dispersion



Material dispersion coefficient (D_m) for the core material (taken as SiO_2), waveguide dispersion coefficient (D_w) (a = 4.2 µm) and the total or chromatic dispersion coefficient D_{ch} (= $D_m + D_w$) as a function of free space wavelength, λ

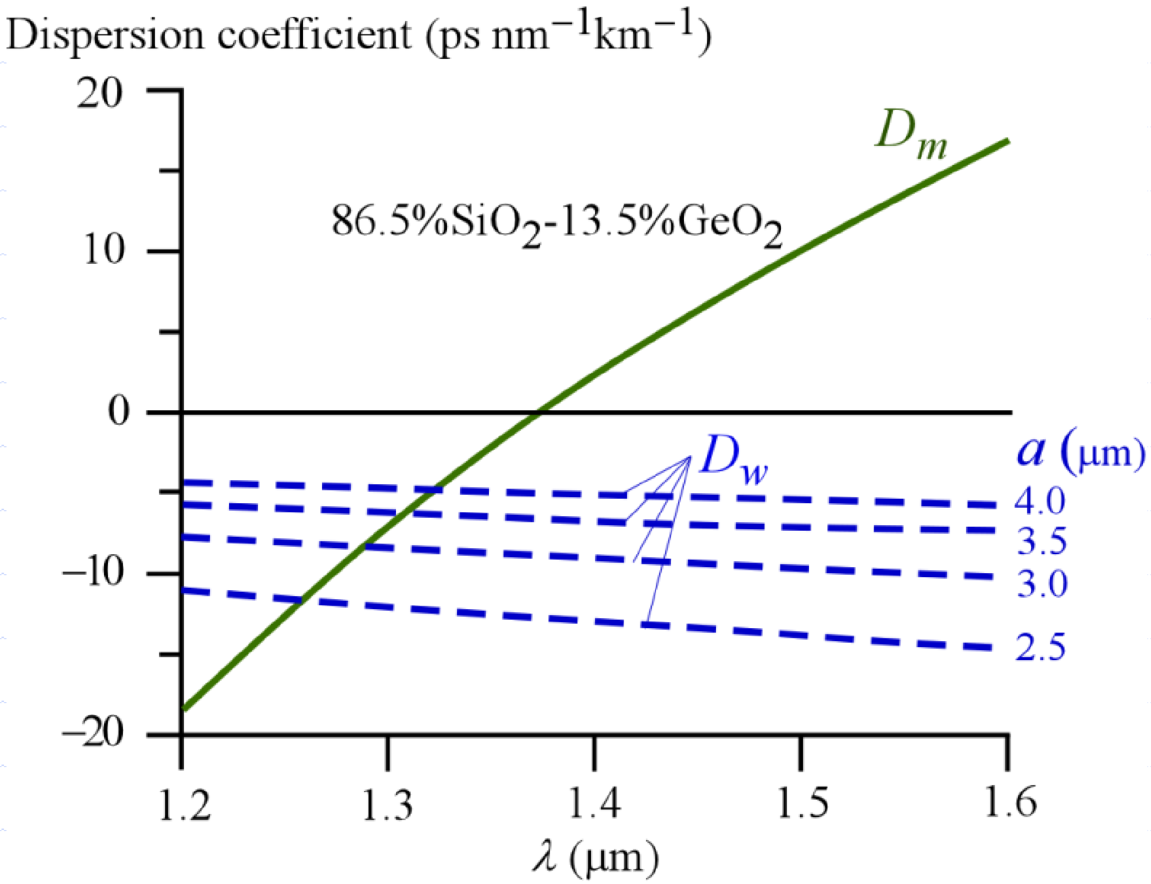
Chromatic = Material + Waveguide

$$\frac{\Delta\tau}{L} = (D_m + D_w)\Delta\lambda$$

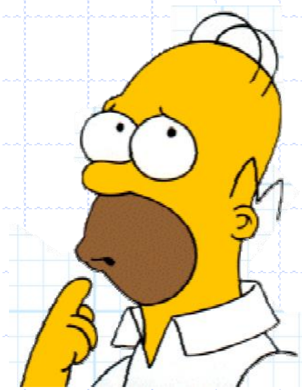
Chromatic dispersion coefficient

$$D_{ch} = D_m + D_w$$

Waveguide Dimension & Chromatic Dispersion



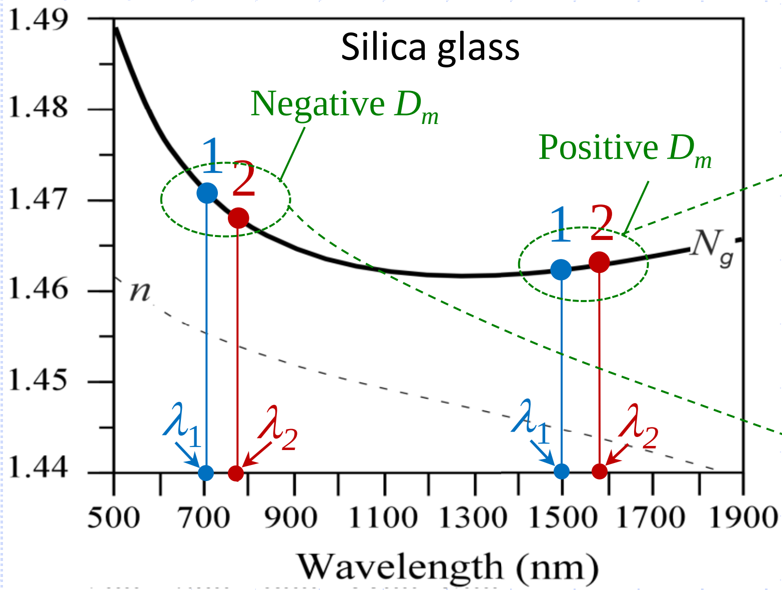
$$D_w \approx -\frac{0.025\lambda}{a^2 c n_2}$$

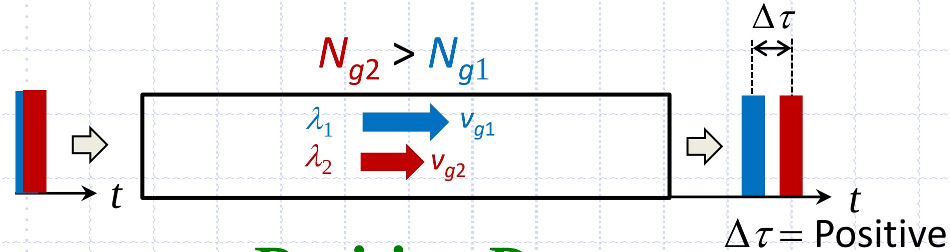


$$D_w(\text{ps nm}^{-1}\,\text{km}^{-1}) \approx -\frac{83.76\,\lambda(\mu\text{m})}{[a(\mu\text{m})]^2\, n_2}$$

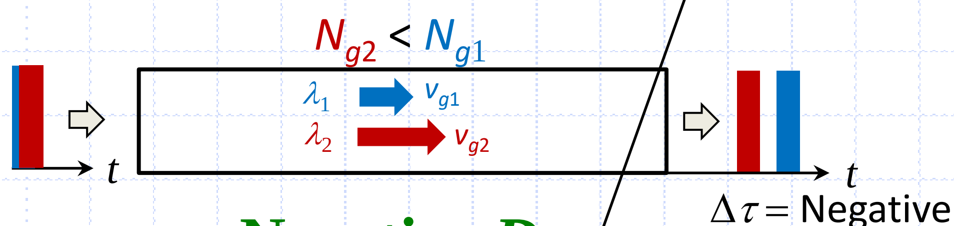
Waveguide dispersion depends on the guide properties

What do Negative and Positive D_m mean?

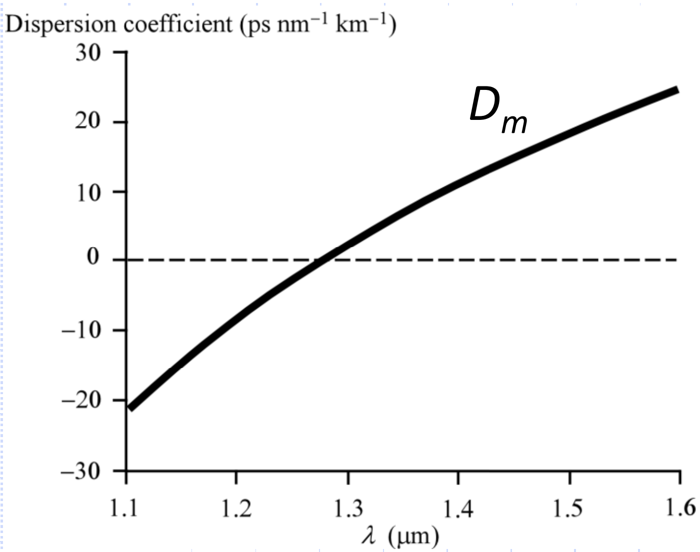




Positive D_m



Negative D_m



$$D_m = \frac{\Delta\tau}{L\Delta\lambda}$$

$\Delta\lambda = \lambda_2 - \lambda_1$

Profile Dispersion

Group velocity $v_g(01)$ of the fundamental mode depends on Δ, refractive index difference.

Δ may not be constant over a range of wavelengths: $\Delta = \Delta(\lambda)$

$$\beta \approx n_2 k(1 + b\Delta)$$

$$\frac{\Delta\tau}{L} = D_p \Delta\lambda$$

$D_p = \textit{Profile dispersion coefficient}$

$D_p <$ 0.1 ps nm^{-1} km^{-1}

Can generally be ignored

Chromatic Dispersion

Total intramode (chromatic) dispersion coefficient D_{ch}

$$D_{ch} = D_m + D_w + D_p$$

where D_m, D_w, D_p are material, waveguide and profile dispersion coefficients respectively

$$\frac{\Delta\tau}{L} = D_{ch}\Delta\lambda$$

S_0 = Chromatic dispersion slope at λ_0

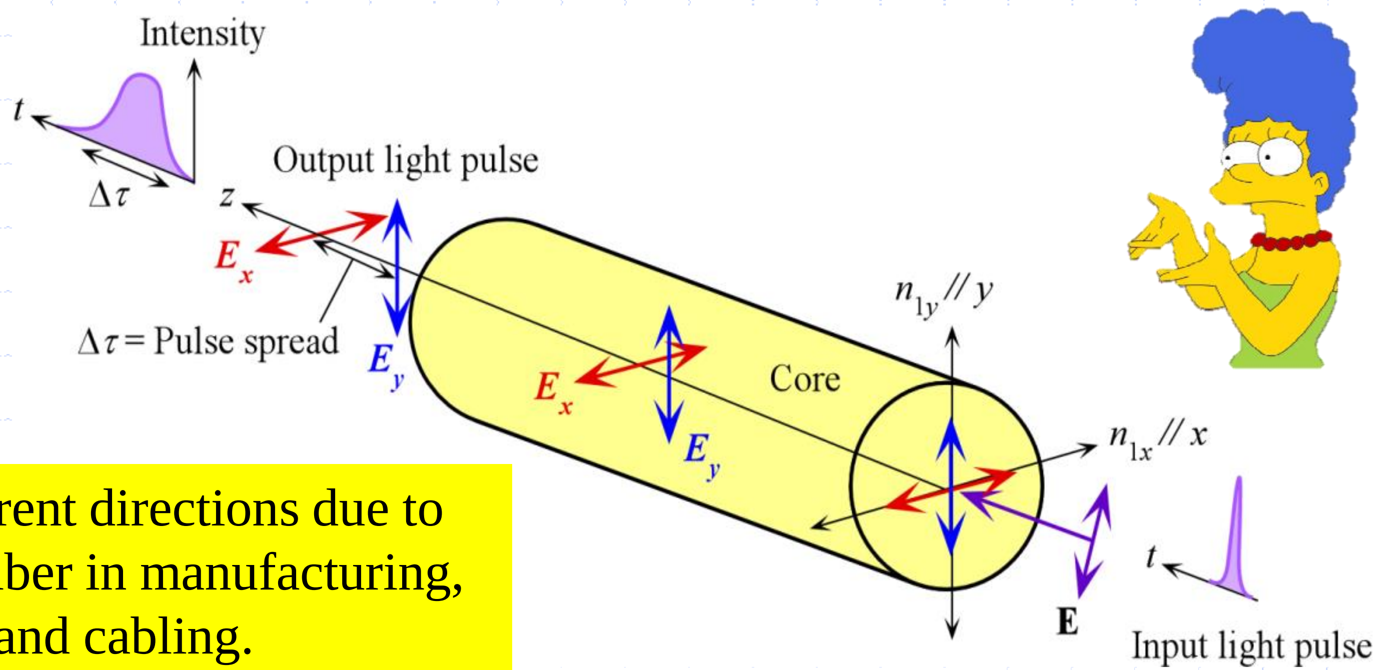
Chromatic dispersion is zero at $\lambda = \lambda_0$

$$D_{ch} = \frac{S_0\lambda}{4}\left[1-\left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

Polarization Dispersion

Polarization mode dispersion (PMD): is due to slightly different velocity for each polarization mode because of the **lack of perfectly symmetric & anisotropicity** of the fiber. If the group velocities of two orthogonal polarization modes are $\boldsymbol{v_{gx}}$ and $\boldsymbol{v_{gy}}$, then the differential time delay $\Delta\tau$ between these two polarization over a distance L is

$$\Delta\tau = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right|$$



n different in different directions due to induced strains in fiber in manufacturing, handling and cabling.

$$\Delta\tau \approx D_{\text{PMD}}\sqrt{L}$$

D_{PMD} = Polarization dispersion coefficient

Typically $D_{\text{PMD}} = 0.1 – 0.5$ ps nm^{-1} km$^{-1/2}$

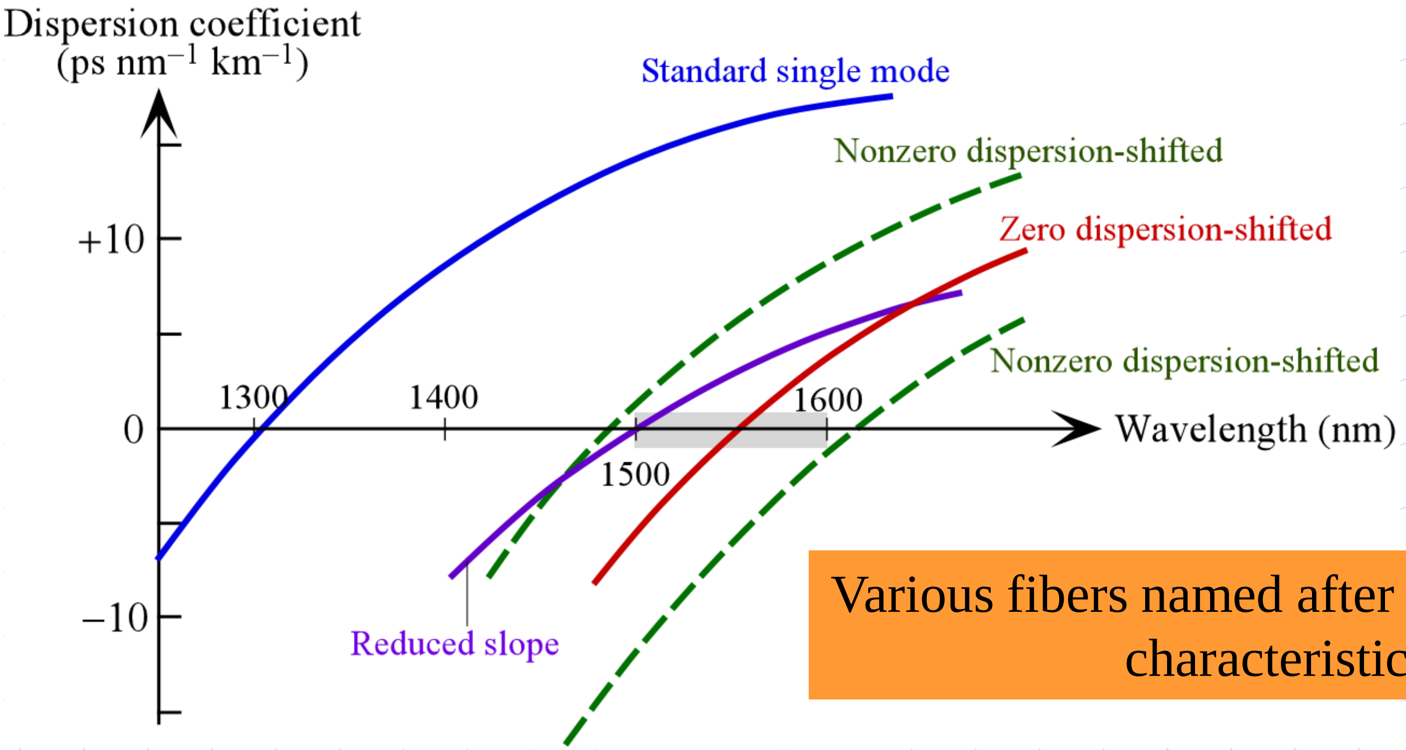
Nonzero Dispersion Shifted Fiber

For Wavelength Division Multiplexing (WDM) avoid 4 wave mixing: cross talk.

We need dispersion not zero but very small in Er-amplifer band (1525-1620 nm)

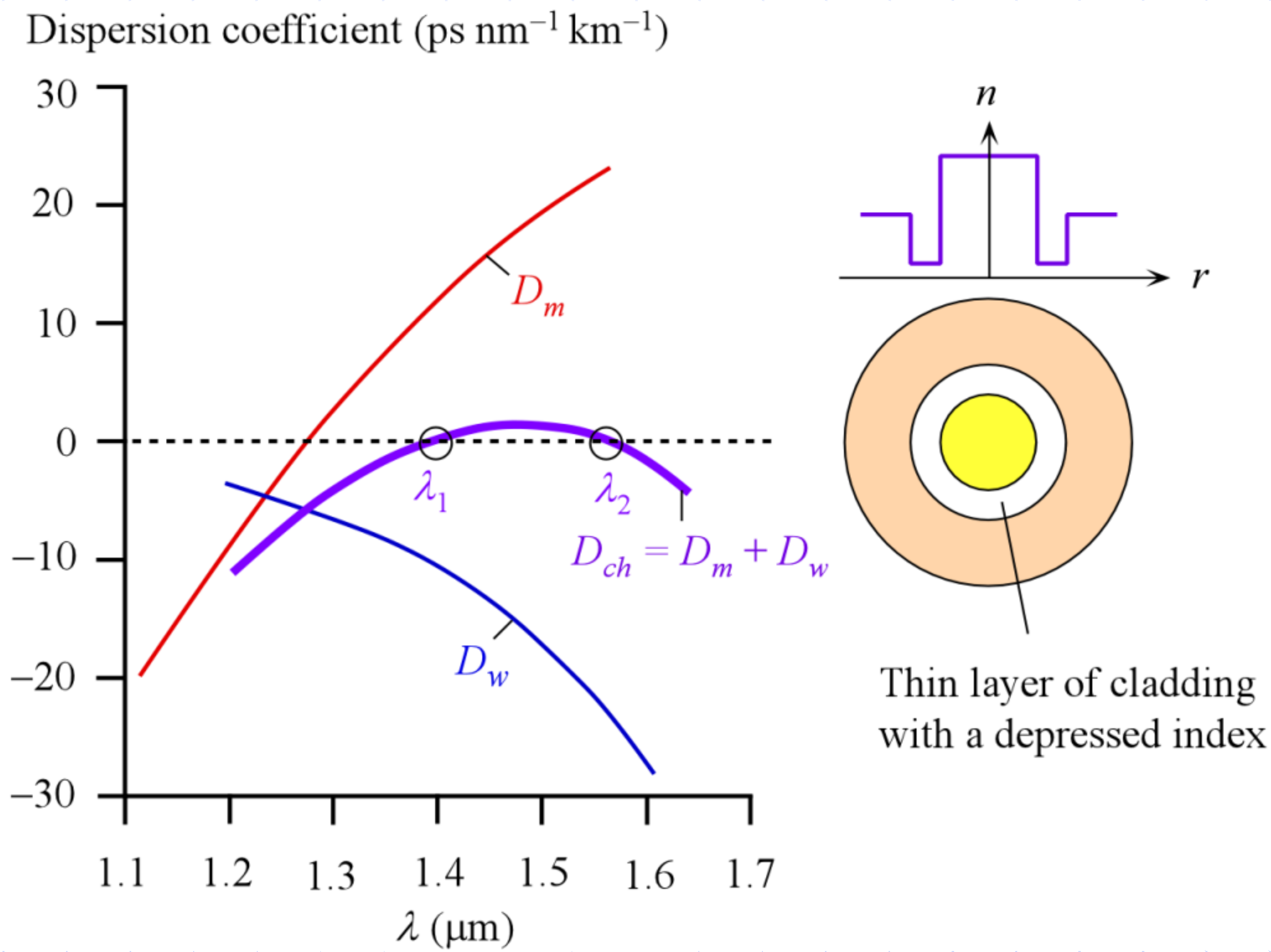
D_{ch} = 0.1 - 6 ps nm^{-1} km^{-1}.

Nonzero dispersion shifted fibers



Various fibers named after their dispersion characteristics.

Dispersion Flattened Fiber



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.

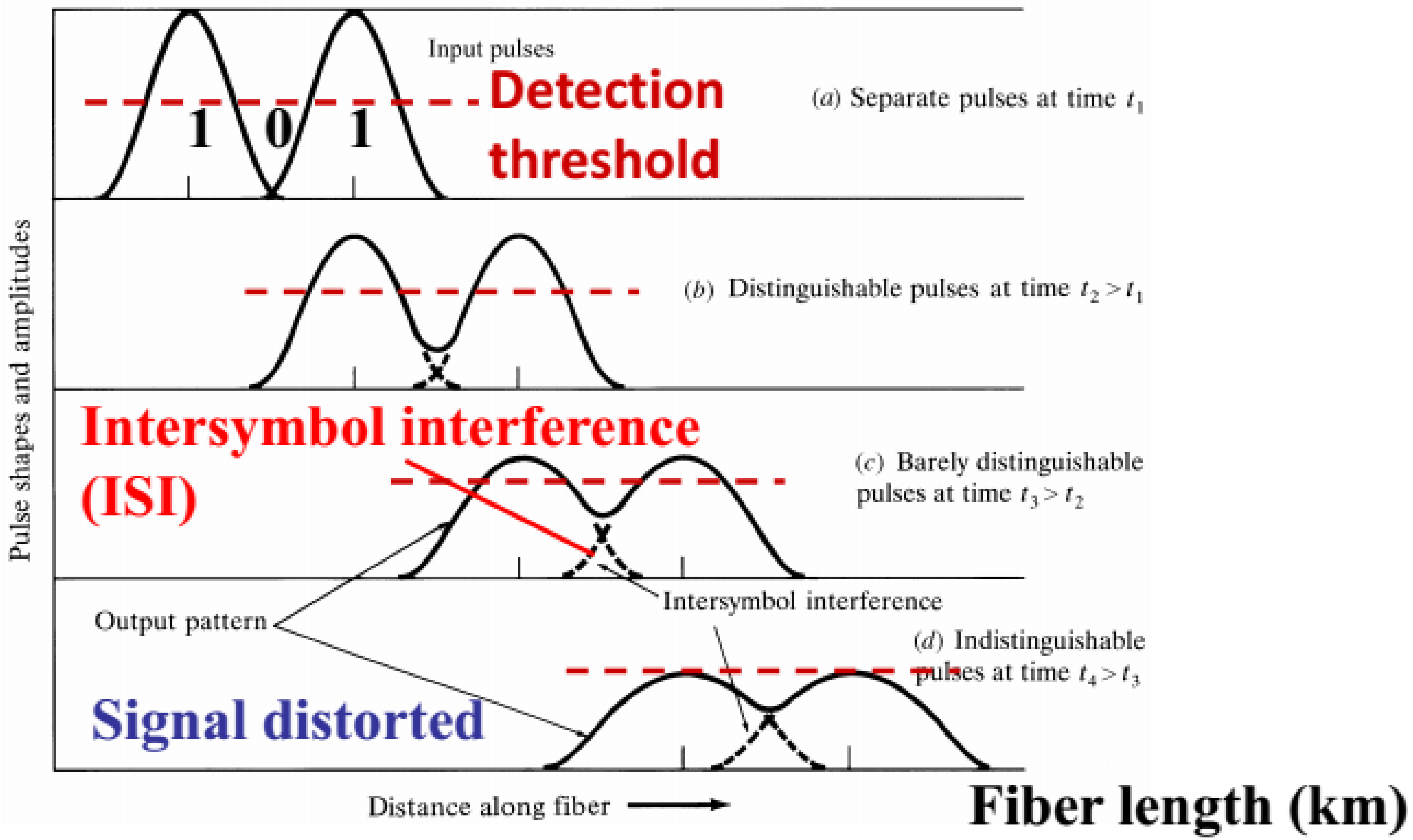
Commercial Fibers for Optical Communications

TABLE 2.3 Selected single-mode fibers

Fiber	D_{ch}(ps nm^{-1} km^{-1})	S_0(ps nm^{-2} km^{-1})	D_{PMD}(ps km$^{-1/2}$)	Some attributes
Standard single mode, ITU-T G.652	17 (1550 nm)	≤0.093	<0.5 (cabled)	$D_{ch} = 0$ at $\lambda_0 \approx 1312$ nm. MFD = 8.6–9.5 μm at 1310 nm. $\lambda_c \leq 1260$ nm.
Nonzero dispersion-shifted fiber, ITU-T G.655	0.1–6 (1530 nm)	<0.05 at 1550 nm	<0.5 (cabled)	For 1500–1600 nm range. WDM application. MFD = 8–11 μm.
Nonzero dispersion-shifted fiber, ITU-T G.656	2–14	<0.045 at 1550 nm	<0.20 (cabled)	For 1460–1625 nm range. DWDM application. MFD = 7–11 μm (at 1550 nm). Positive D_{ch}. $\lambda_c < 1310$ nm
Corning SMF28e$^+$ (Standard SMF)	18 (1550 nm)	0.088	<0.1	Satisfies G.652. $\lambda_0 \approx 1317$ nm, MFD = 9.2 μm (at 1310 nm), 10.4 μm (at 1550 nm); $\lambda_c \leq 1260$ nm.
OFS TrueWave RS Fiber	2.6–8.9	0.045	0.02	Satisfies G.655. Optimized for 1530–1625 nm. MFD = 8.4 μm (at 1550 nm); $\lambda_c \leq 1260$ nm.
OFS REACH Fiber	5.5–8.9	0.045	0.02	Higher performance than G.655 specification. Satisfies G.656. For DWDM from 1460 to 1625 nm. $\lambda_0 \leq 1405$ nm. MFD = 8.6 μm (at 1550 nm)

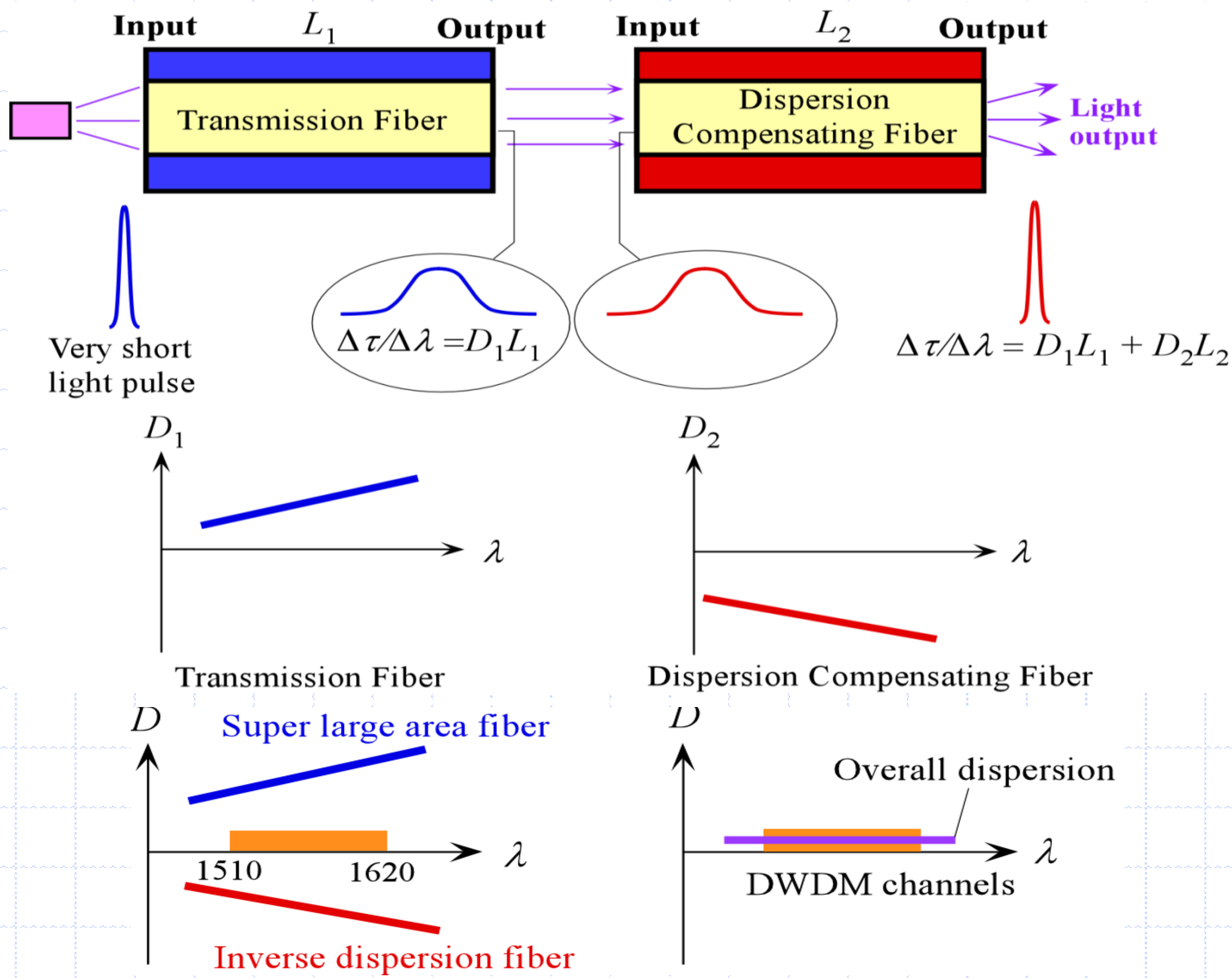
Note: ITU-T is the International Telecommunications Union with the suffix T representing the Telecommunication Standardization Sector in ITU. G.652, G.655, and G.656 are their standards for three single-mode fibers: a standard SMF, nonzero dispersion-shifted fibers for WDM (wavelength division multiplexing), and DWDM (dense WDM) applications, respectively. A few selected commercial SMF properties are also given. λ_0 is the wavelength at which $D_{ch} = 0$.

Inter-Symbol Interference (ISI)



- Most commercial transmission systems rely on **sampling and threshold-based detection**.
- ISI leads to high bit error rate (BER).

Dispersion Compensation



Total dispersion $= D_tL_t + D_cL_c = (10\text{ ps nm}^{-1}\text{ km}^{-1})(1000\text{ km}) + (-100\text{ ps nm}^{-1}\text{ km}^{-1})(80\text{ km})$

$= 2000\text{ ps/nm for }1080\text{ km}$

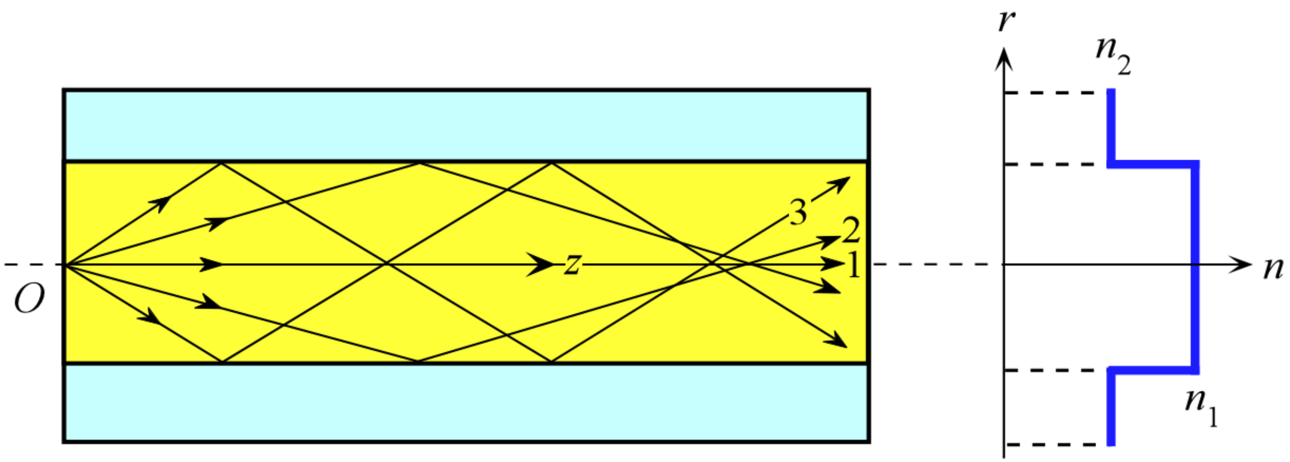
$D_{\text{effective}} = 1.9\text{ ps nm}^{-1}\text{ km}^{-1}$

Dispersion Compensation and Management

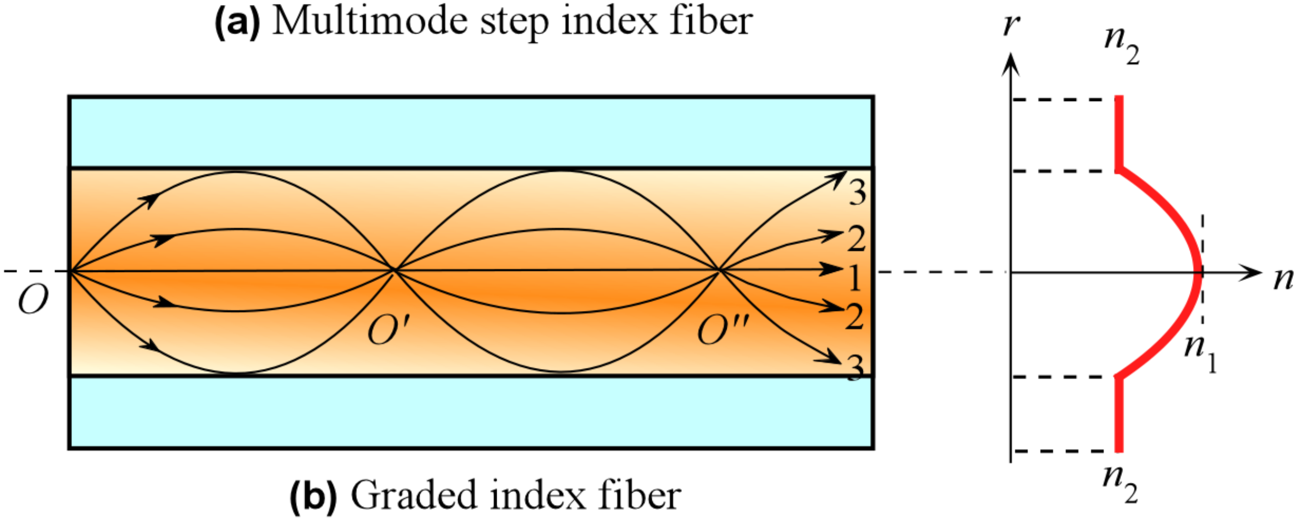
- Compensating fiber has higher attenuation.
  Doped core. Need shorter length
- More susceptible to nonlinear effects.
  Use at the receiver end.
- Different cross sections. Splicing/coupling losses.
- Compensation depends on the temperature.
- Manufacturers provide transmission fiber spliced to inverse dispersion fiber for a well defined *D* vs. λ

- DCM (Dispersion Compensation Module):
  - compensates 40 km per Module,
  - adds 5.5 dB loss (loss can be compensated with EDFAs)

Graded Index (GRIN) Fiber



(a) Multimode step index fiber

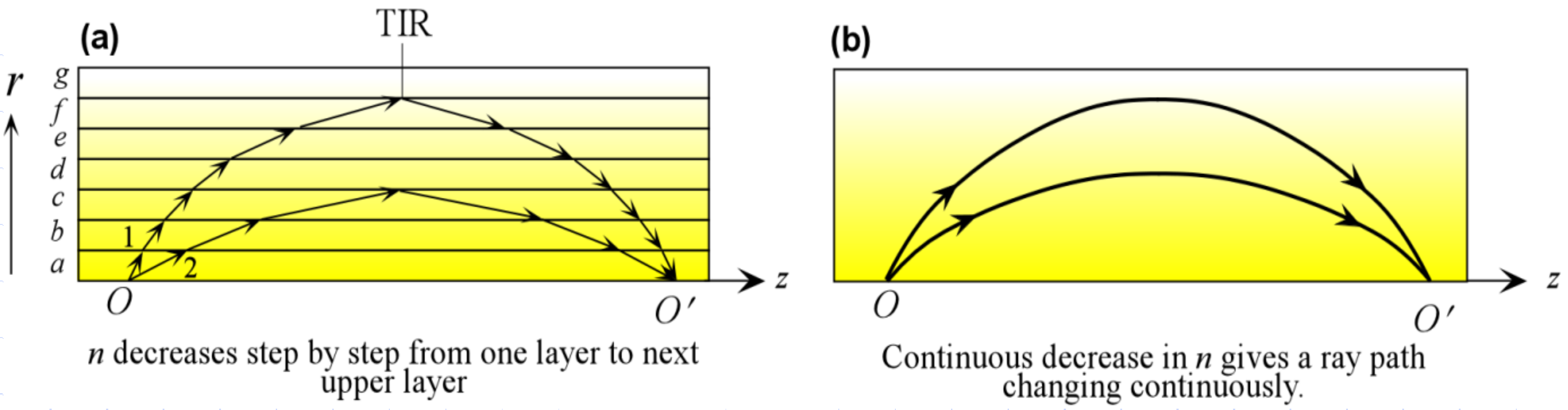


(b) Graded index fiber

(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.

(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.

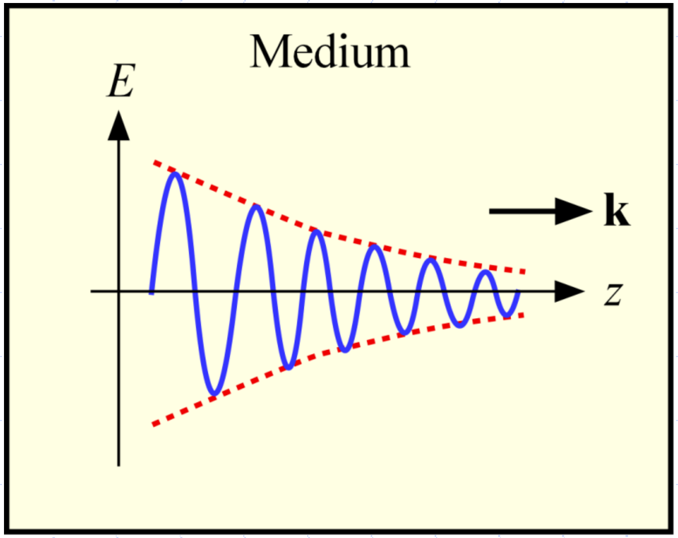
Graded Index (GRIN) Fiber



(a) A ray in thinly stratifed medium becomes refracted as it passes from one layer to the next upper layer with lower n and eventually its angle satisfies TIR.

(b) In a medium where n decreases continuously, the path of the ray bends continuously.

Attenuation



The attenuation of light in a medium

Z=0

P_{in} mW

Z= L

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

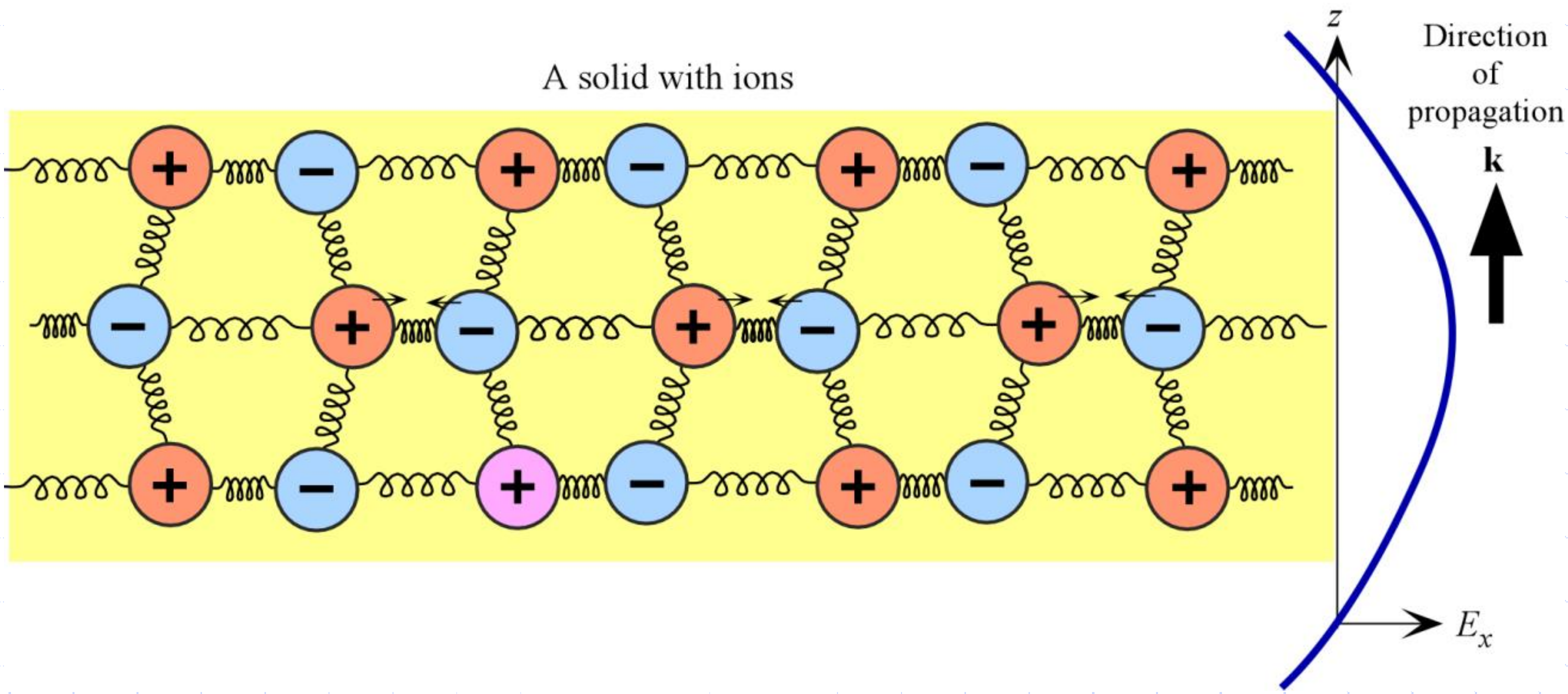
Attenuation = Absorption + Scattering

Attenuation coefficient α is defined as the *fractional decrease in the optical power per unit distance*. α is in m^{-1}.

$$P_{out} = P_{in}\exp(-\alpha L)$$

$$\alpha_{dB} = \frac{1}{L} 10\log\left(\frac{P_{in}}{P_{out}}\right) \qquad \alpha_{dB} = \frac{10}{\ln(10)}\alpha = 4.34\alpha$$

Lattice (intrinsic) Absorption



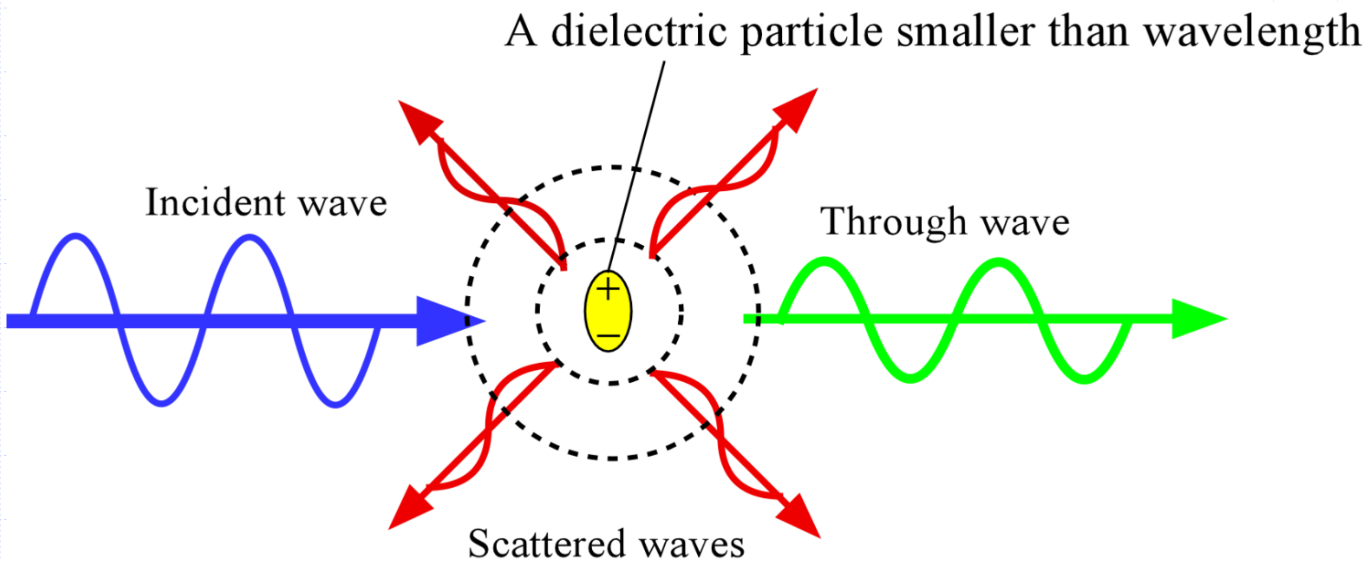
EM Wave oscillations are coupled to lattice vibrations (phonons), vibrations of the ions in the lattice. Energy is transferred from the EM wave to these lattice vibrations.

This corresponds to "Fundamental Infrared Absorption" in glasses

$$\alpha_{\mathrm{FIR}} = A\exp(-B/\lambda)$$

$A = 7.81\times10^{11}\ \mathrm{dB\ km}^{-1}$ $B = 48.5\ \mu\mathrm{m}$

Rayleigh Scattering



Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength. The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

$$\alpha_R = \frac{A_R}{\lambda^4}$$

A_R in dB km^{-1} μm^4

λ in μm

α_R in dB km^{-1}

$$A_R \approx 0.90\ \text{dB km}^{-1}\mu\text{m}^4$$

Rayleigh Scattering Coefficient, A_R

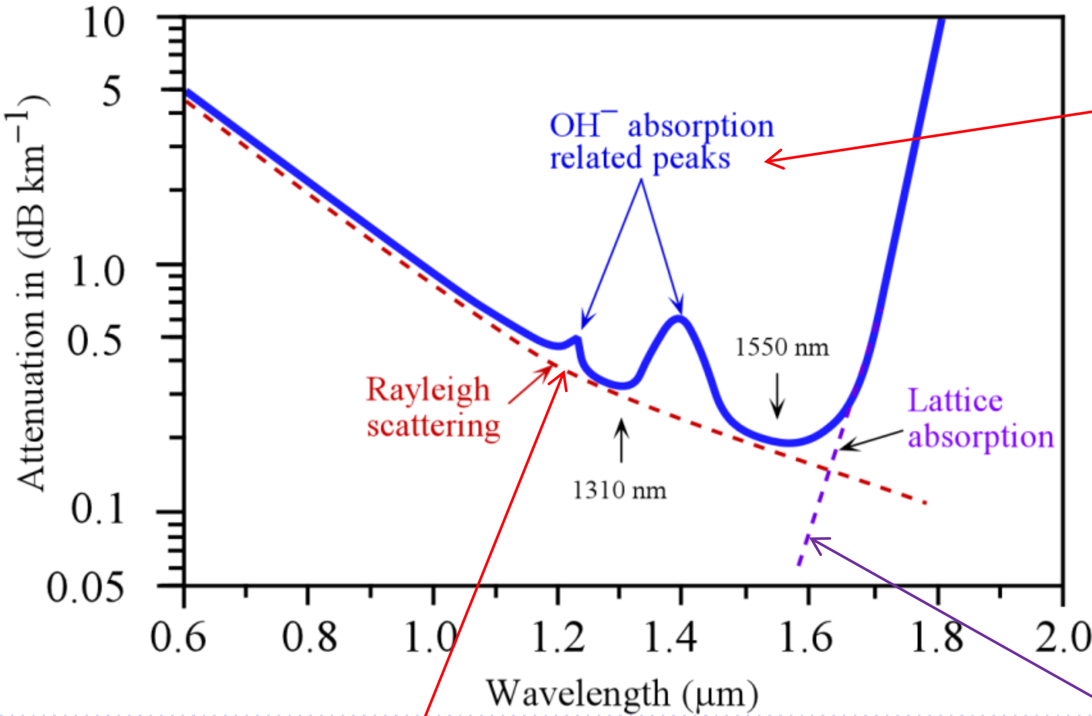
TABLE 2.6 Approximate attenuation coefficients for silica-based fibers for use in Eqs. (2.9.7) and (2.9.8)

Glass	A_R (dB km^{-1})	Comment
Silica fiber	0.90	"Rule of thumb"
SiO_2-GeO_2 core step-index fiber	$0.63 + 2.06 \times NA$	NA depends on $(n_1^2 - n_2^2)^{1/2}$ and hence on the doping difference.
SiO_2-GeO_2 core graded index fiber	$0.63 + 1.75 \times NA$	
Silica, SiO_2	0.63	Measured on preforms. Depends on annealing. A_R(Silica) $= 0.59$ dB km^{-1} for annealed.
65%$SiO_2$35%GeO_2	0.75	On a preform. A_R/A_R(silica) $= 1.19$
$(SiO_2)_{1-x}(GeO_2)_x$	A_R(silica) $\times (1 + 0.62x)$	$x = [GeO_2]$ = Concentration as a fraction (10% GeO_2, $x = 0.1$). For preform.

(*Source:* Data mainly from K. Tsujikawa *et al.*, *Electron. Letts.*, *30*, 351, 1994; *Opt. Fib. Technol.*, *11*, 319, 2005; H. Hughes, *Telecommunications Cables*, John Wiley & Sons, 1999, and references therein.)

Note: Square brackets represent concentration as a fraction. NA = numerical aperture. $A_R = 0.59$ used as reference for pure silica, and represents A_R(silica).

Attenuation in Optical Fibers



Extrinsic absorption

Attenuation vs. wavelength for a standard silica based fiber.

$$\alpha_R = \frac{A_R}{\lambda^4}$$

A_R in dB km^{-1} µm^4

α_R in dB km^{-1}

λ in µm

$$\alpha_{\mathrm{FIR}} = A\exp(-B/\lambda)$$

$$A = 7.81\times 10^{11}\ \mathrm{dB\ km}^{-1}$$

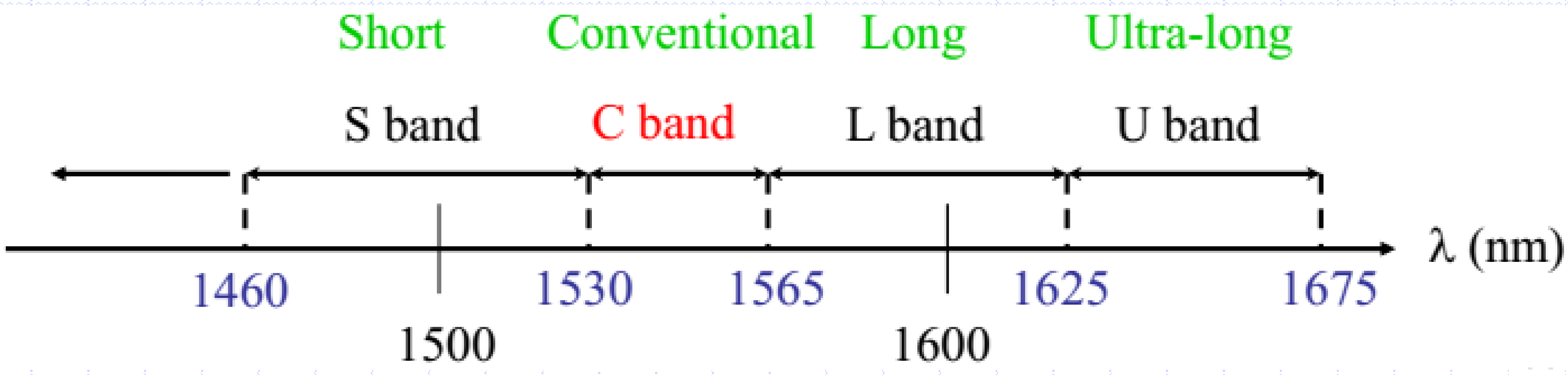
$$B = 48.5\ \mu\mathrm{m}$$

$$A_R \approx 0.90\ \mathrm{dB\ km}^{-1}\mu\mathrm{m}^4$$

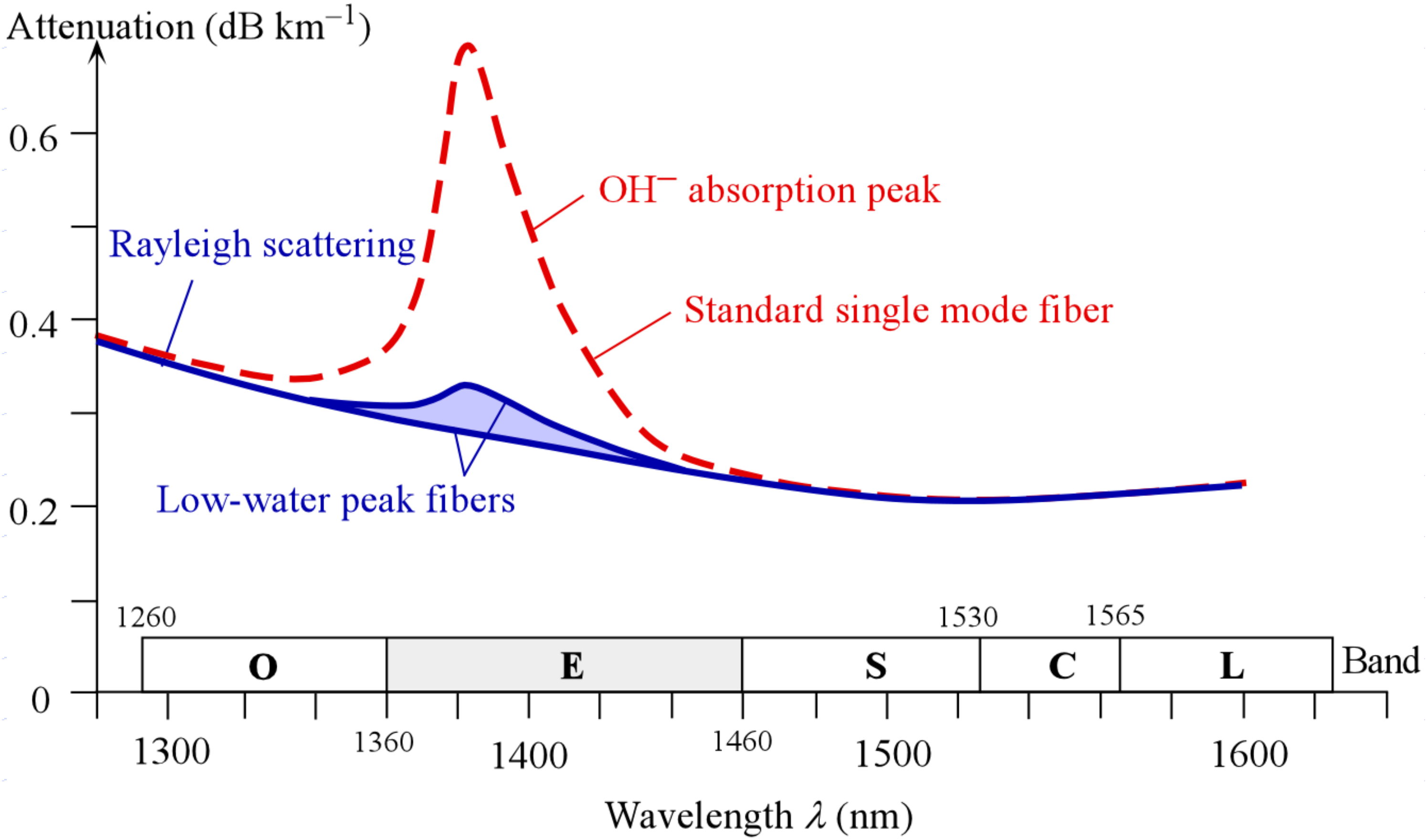
Three major spectral windows where fiber attenuation is low

- 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.



Low-water-peak fiber has no OH^- peak



E-band is available for communications with this fiber

Rayleigh Scattering

Example: Consider a single mode step index fiber, which has a numerical aperture of 0.14. Predict the expected attenuation at 1.55 mm, and compare your calculation with the reported (measured) value of 0.19 - 0.20 dB km^{-1} for this fiber. Repeat the calculations at 1.31 μm, and compare your values with the reported 0.33 - 0.35 dB km^{-1} values.

Solution

First, we should check the fundamental infrared absorption at 1550 nm.

$$\alpha_{\mathrm{FIR}} = A\exp\left(-B/\lambda\right) = 7.8\times10^{11}\exp[-(48.5)/(1.55)]$$

$= 0.020$ dB km^{-1}, very small

Rayleigh scattering at 1550 nm, the simplest equation with $A_R = 0.9$ dB km^{-1} μm^4, gives

$$\boldsymbol{\alpha_R = A_R/\lambda^4 = (0.90\ \mathrm{dB\ km^{-1}\ \mu m^4})/(1.55\ \mu\mathrm{m})^4 = 0.178\ \mathrm{dB\ km^{-1}}}$$

This equation is basically a rule of thumb. The total attenuation is then

$\alpha_{\mathrm{R}} + \alpha_{\mathrm{FIR}} = 0.178 + 0.02 =$ **0.198 dB km^{-1}**.

Rayleigh Scattering

Solution

The current fiber has NA = 0.14.

$\therefore \quad A_R = 0.63 + 2.06\times\text{NA} = 0.63 + 2.06\times0.14 = 0.918 \text{ dB km}^{-1}\ \mu\text{m}^4$

i.e. $\quad \alpha_R = A_R/\lambda^4 = (0.918 \text{ dB km}^{-1}\ \mu\text{m}^4)/(1.55\ \mu\text{m})^4 = 0.159 \text{ dB km}^{-1}$,

which gives a total attenuation of 0.159 + 0.020 or **0.179 dB km^{-1}**.

We can repeat the above calculations at $\lambda = 1.31\ \mu$m. However, **we do not need** to add α_{FIR}.

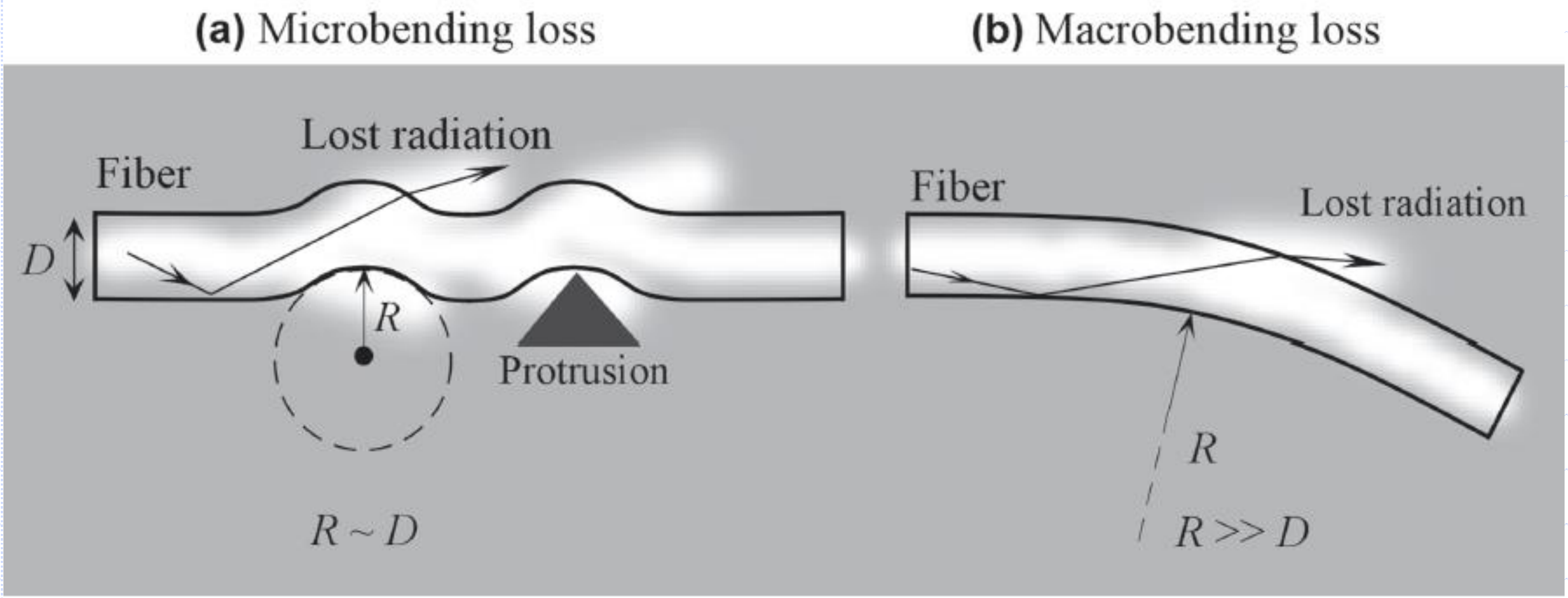
$\alpha_R = A_R/\lambda^4 = (0.90 \text{ dB km}^{-1}\ \mu\text{m}^4)/(1.31\ \mu\text{m})^4 =$ **0.306 dB km^{-1}**

and using the NA based for A_R,

$\alpha_R = A_R/\lambda^4 = (0.918 \text{ dB km}^{-1}\ \mu\text{m}^4)/(1.31\ \mu\text{m})^4 =$ **0.312 dB km^{-1}**.

Both close to the measured value.

Bending Loss



Definitions of (a) microbending and (b) macrobending loss and the definition of the radius of curvature, *R*. (A schematic illustration only.) The propagating mode in the fiber is shown as white painted area. Some radiation is lost in the region where the fiber is bent. *D* is the fiber diameter, including the cladding.

Bending Loss

Microbending loss

the radius of curvature *R* of the bend is sharp
bend radius is comparable to the diameter of the fiber

Typically microbending losses are significant when the radius of curvature of the bend is less than 0.1 - 1 mm.

They can arise from careless or poor cabling of the fiber or even in flaws in manufacturing that result in variations in the fiber geometry over small distances.

Bending Loss

Macrobending losses

Losses that arise when the bend is much larger than the fiber size

Typically much grater than 1 mm

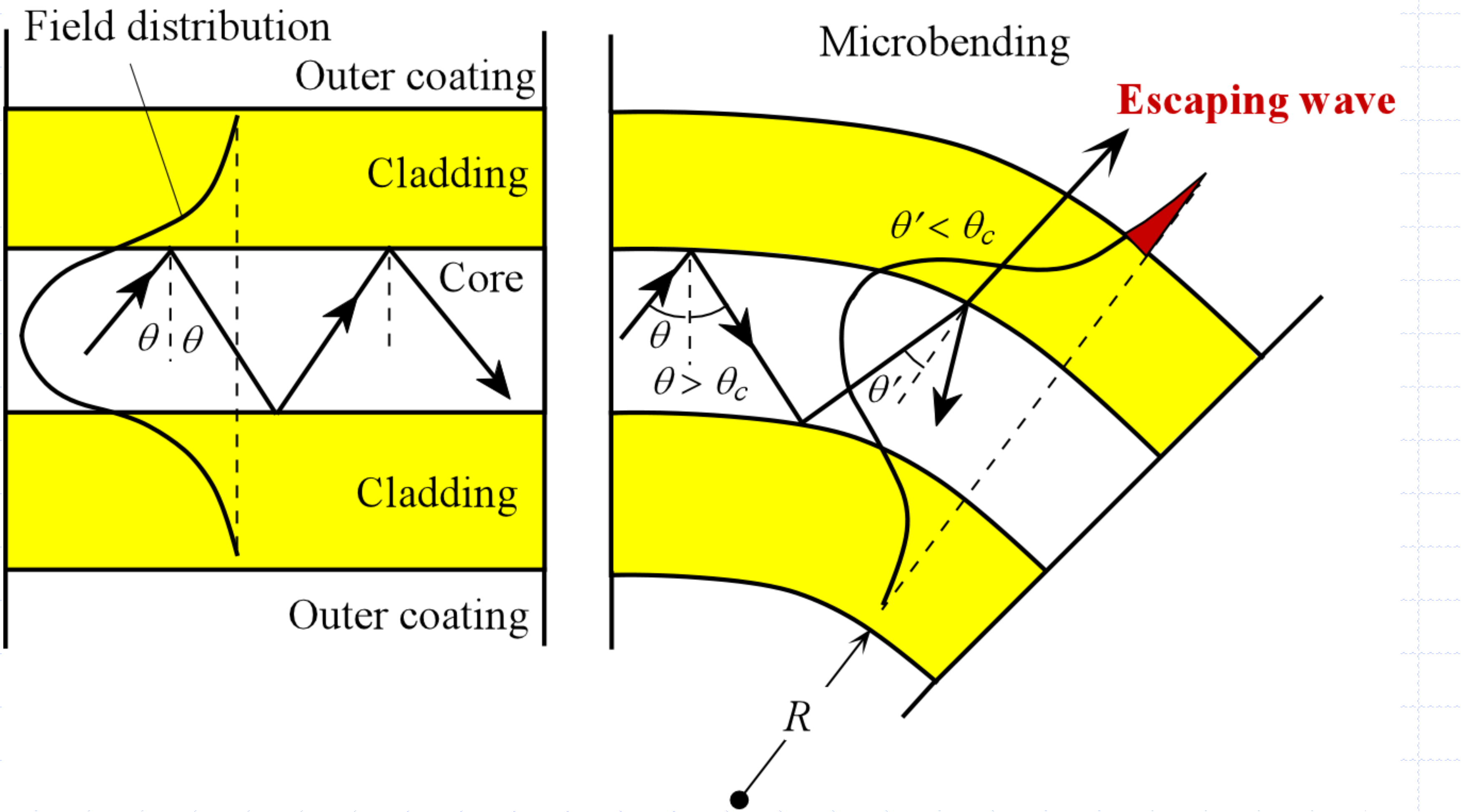
Typically occur when the fiber is bent during the installation of a fiber optic link such as turning the fiber around a corner.

There is no simple precise and sharp boundary line between microbending and macrobending loss definitions.

Both losses essentially result from changes in the waveguide geometry and properties as the fiber is subjected to external forces that bend the fiber.

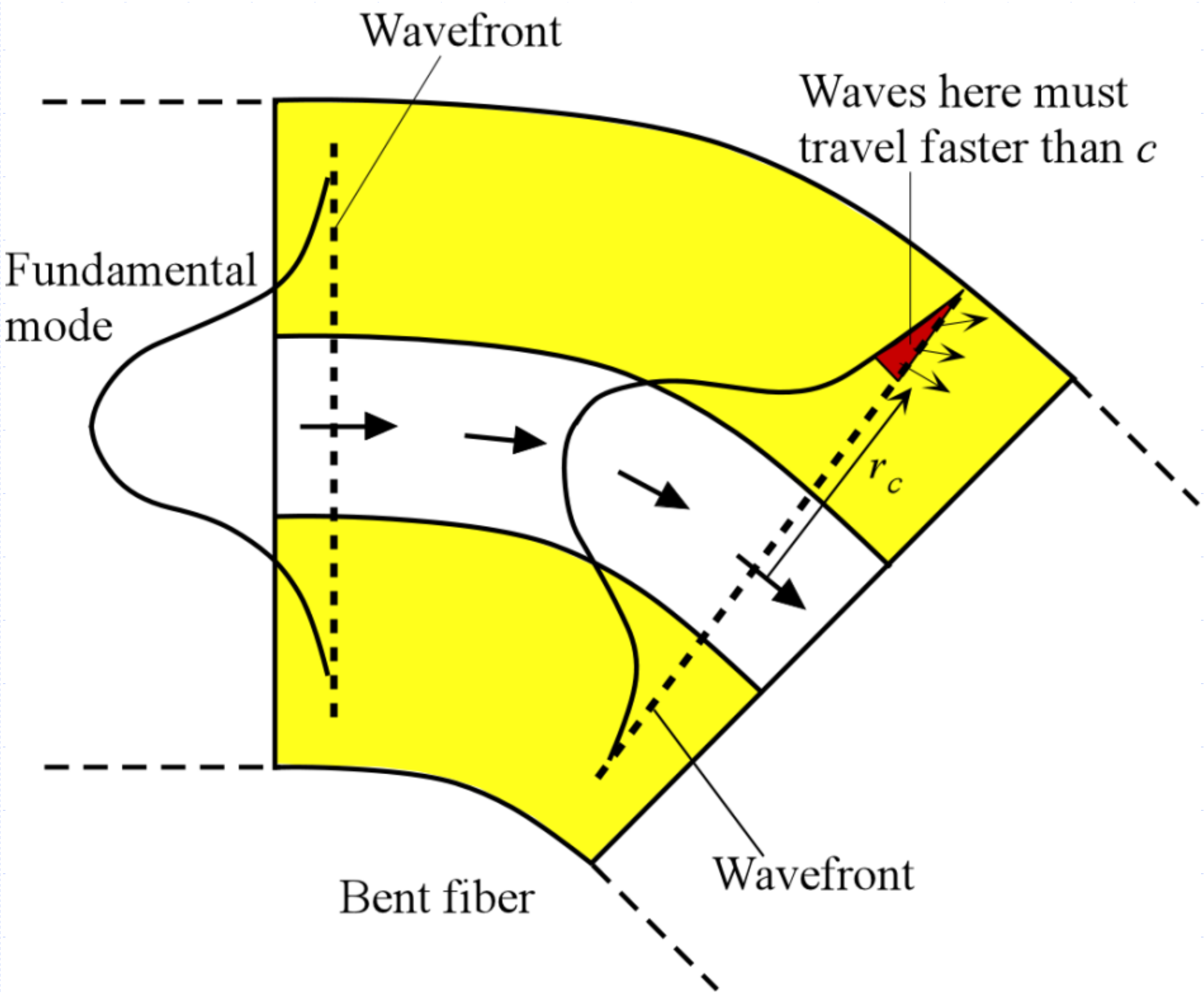
Typically, macrobending loss crosses over into microbending loss when the radius of curvature becomes less than a few millimeters.

Bending Loss



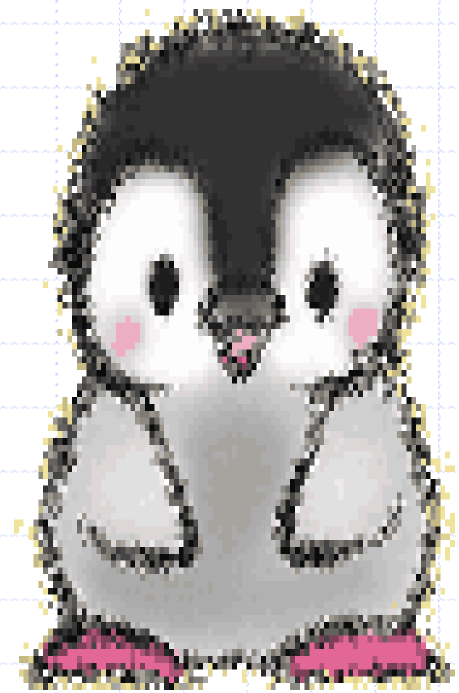
Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle smaller than θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy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

Bending Loss



When a fiber is bent sharply, the propagating wavefront along the straight fiber cannot bend around and continue as a wavefront because a portion of it (black shaded) beyond the critical radial distance r_c must travel faster than the speed of light in vacuum. This portion is lost in the cladding- radiated away.

Thank you



Have a nice day.

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