VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Basics of Fiber Propagation

Fiber 1

Module Prerequisites

- Introduction to Fiber-Optic Communications I & II

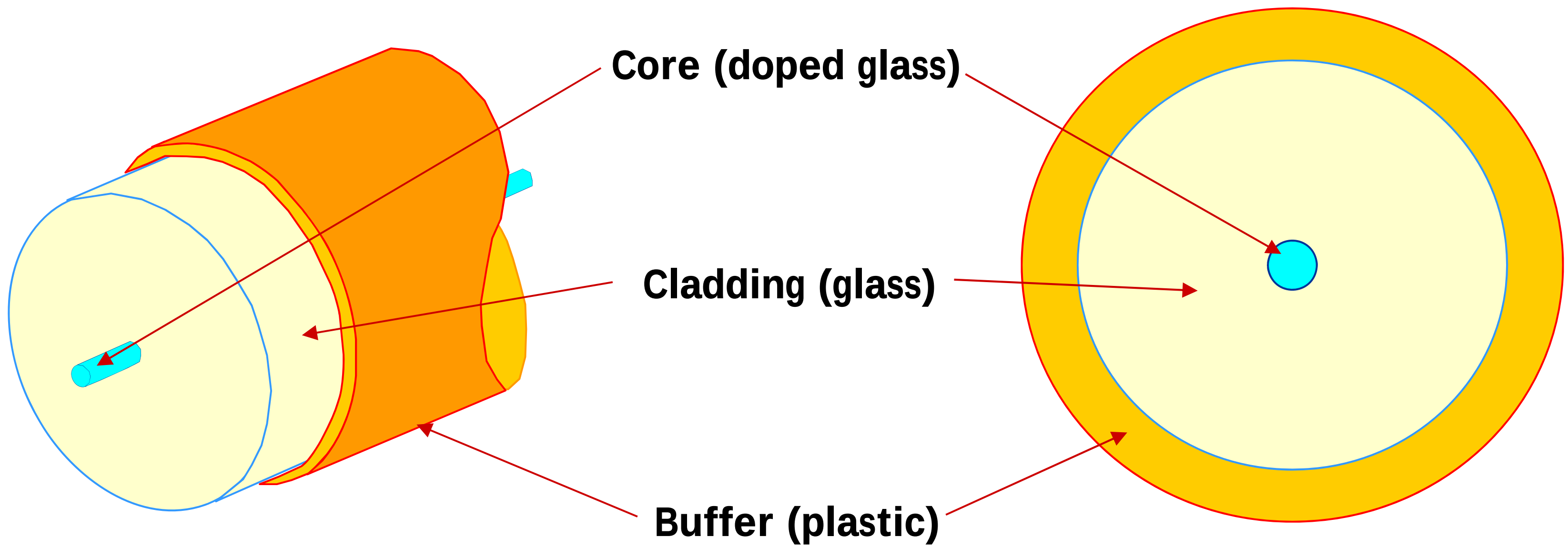
Module Objectives

- Structure of optical fibers
- Ray representation of fiber optic transmission
  - Snell's Law, Total internal reflection
- Wave representation of fiber optic transmission
  - Modes, multimode and single mode fibers
- Attenuation in optical fibers
- Dispersion in optical fibers

The Structure of an Optical Fiber

An optical fiber is made up of:

- Doped core: refractive index $n_1 \cong 1.5$
- Cladding: refractive index $n_1 > n_2$
- Buffer (or primary coating): protects fiber from damage

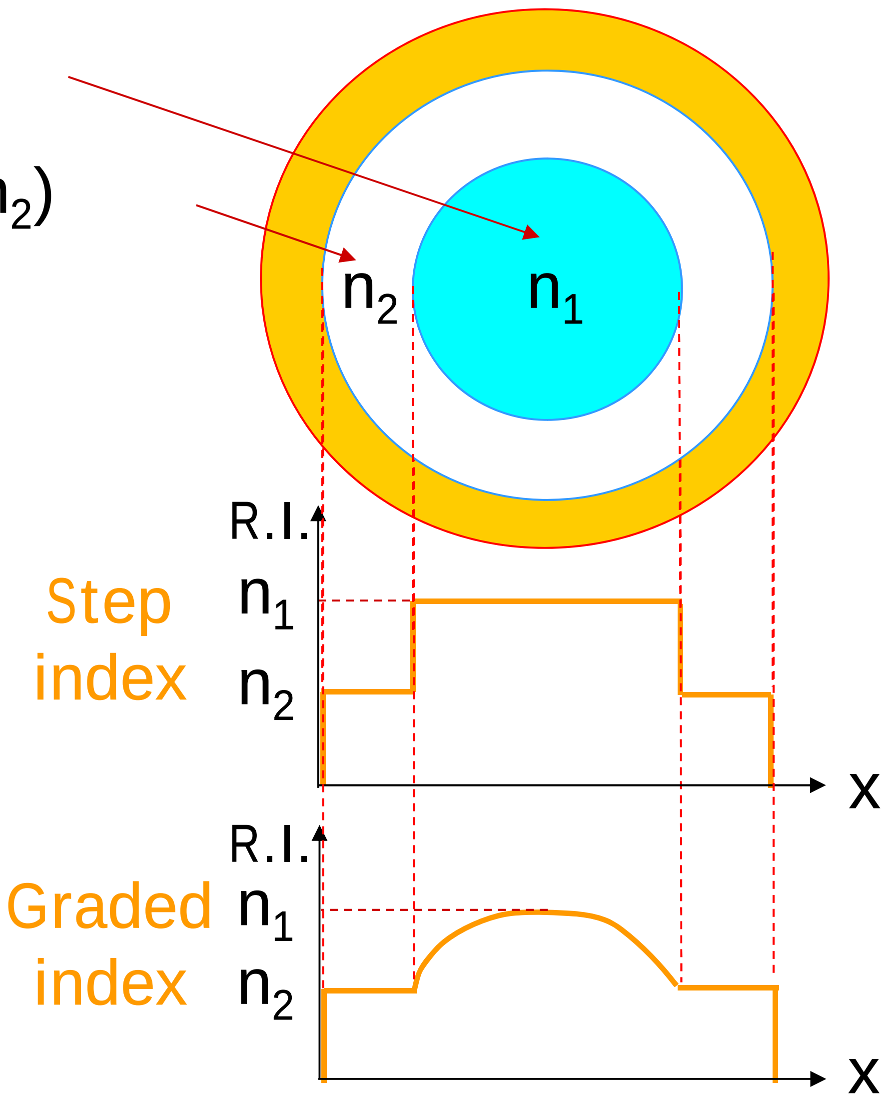


perspective view

transverse section

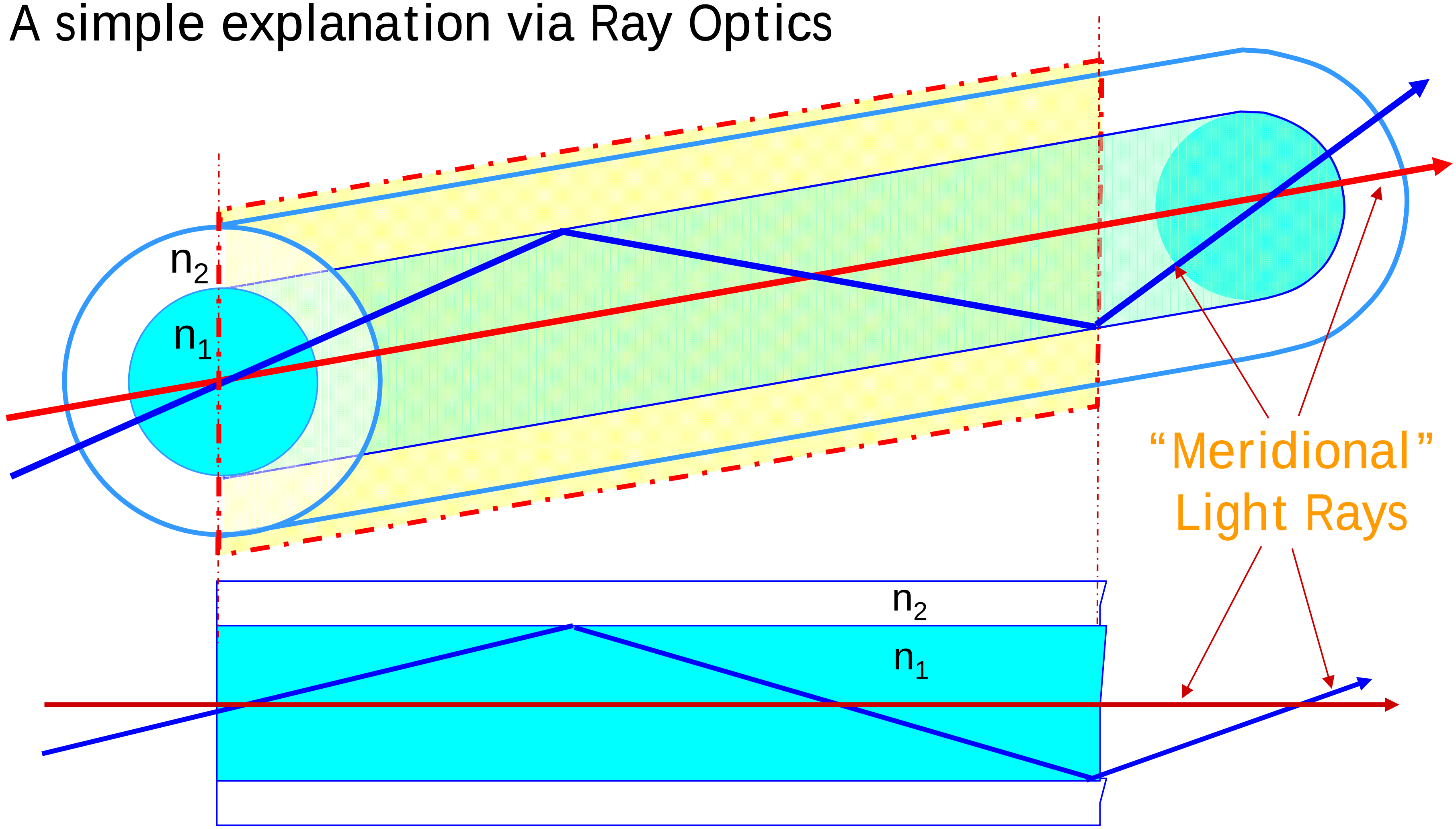
Fiber Refractive Index Profile

- Core Refractive Index (n_1)
- Cladding Refractive Index (n_2)
- Step Index Profile
- Graded Index Profile
- $n_1 - n_2 << 1$
- Why different profiles?



How do Fibers Transmit Light?

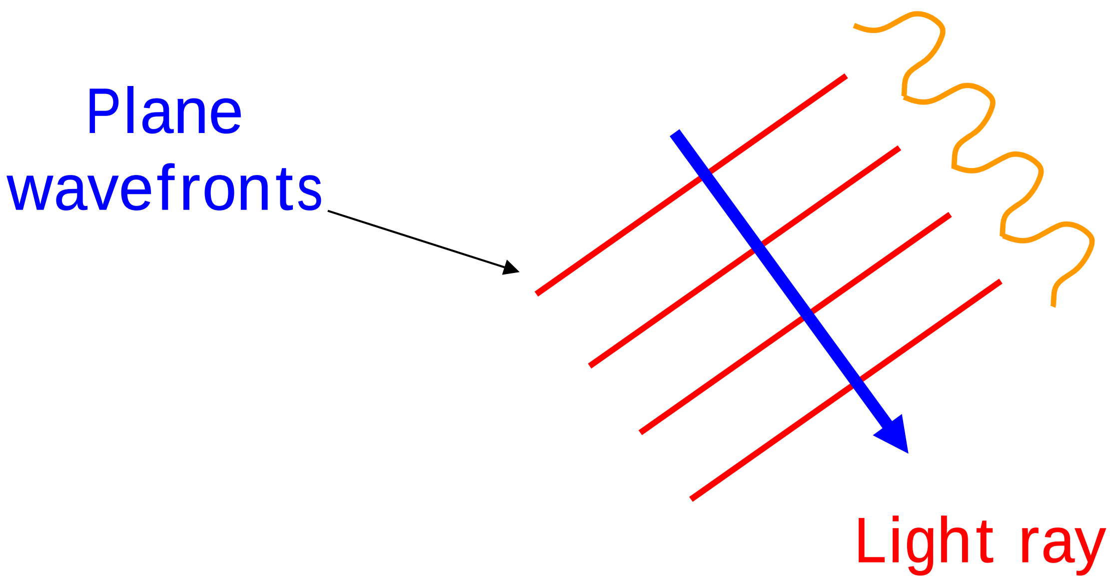
A simple explanation via Ray Optics



Longitudinal Section

What is a Ray?

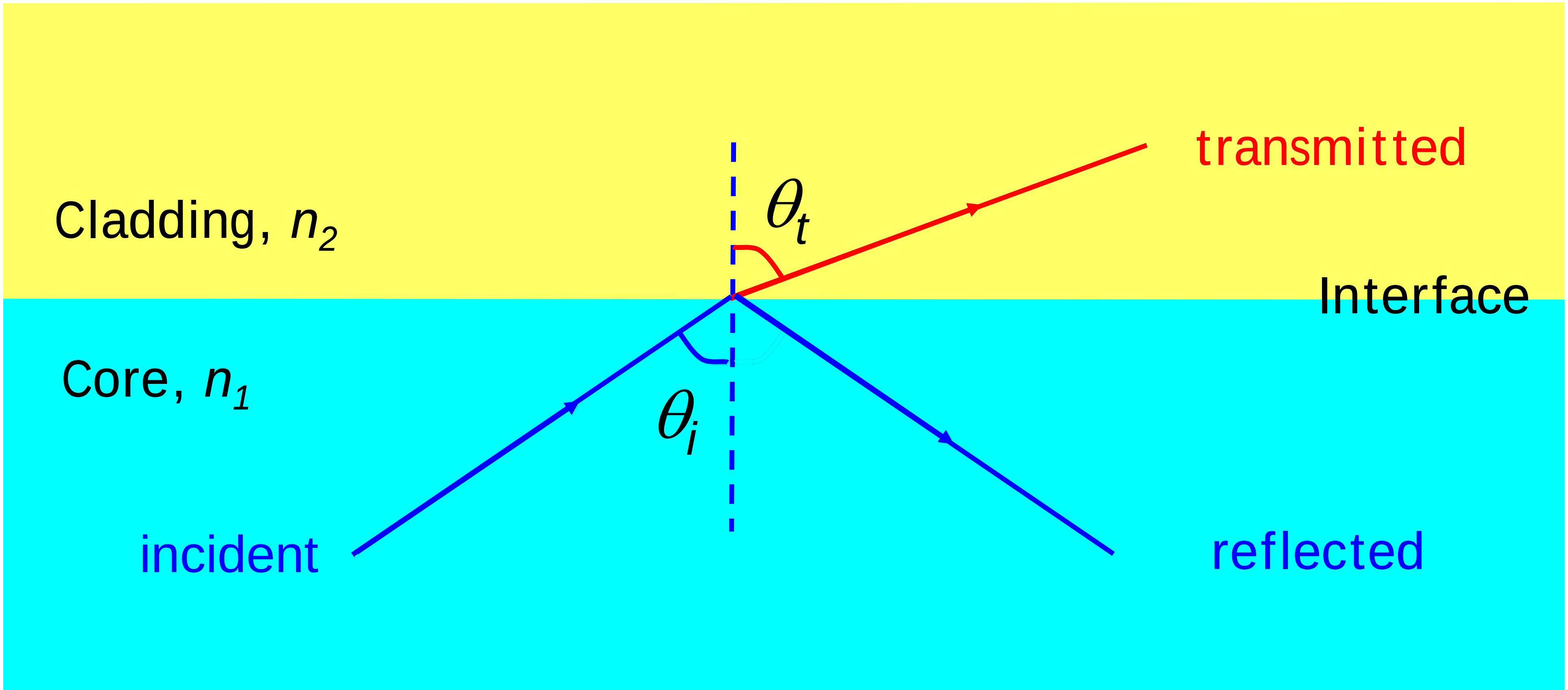
- Light is an electromagnetic field
- Propagates as a wave $E(z, t) = E \cos(\omega t - \beta z)$
- Ray = vector of the direction of wave propagation



Law of Reflection and Snell's Law

Angle of Incidence θ_i = Angle of Reflection θ_r

Snell's Law: $n_1 \sin\theta_i = n_2 \sin\theta_t$

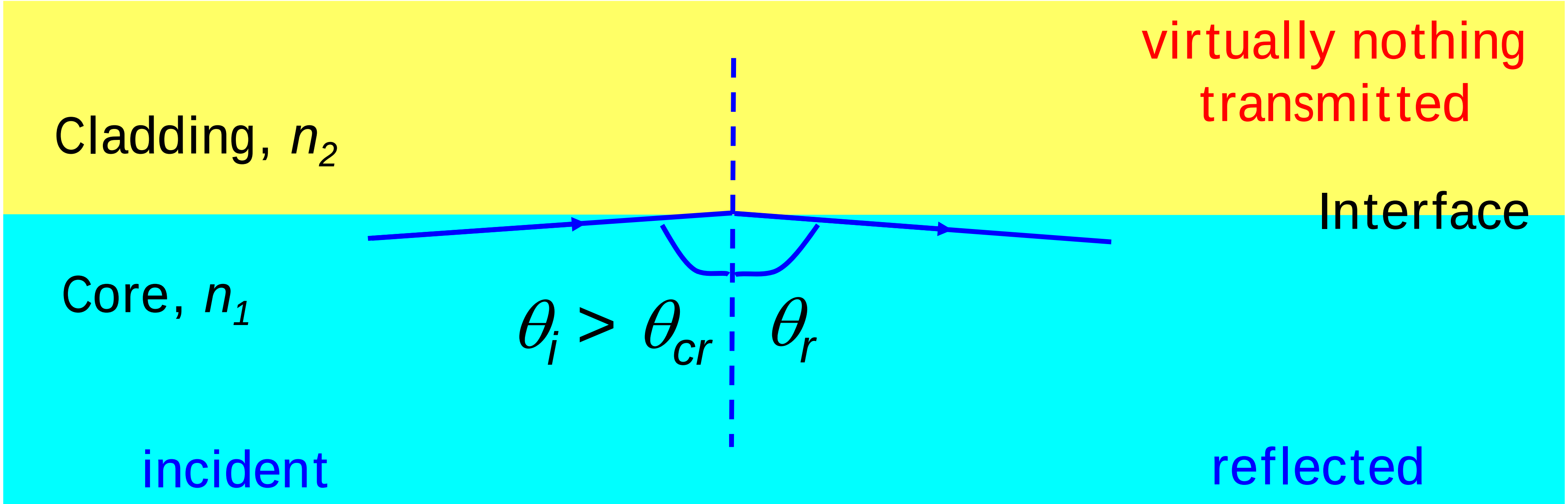


Total Internal Reflection

As θ_i *increases…* θ_t increases… until $\theta_t = 90^o$

Value of θ_i (where $\theta_t = 90^o$) = “Critical Angle” = θ_{cr}

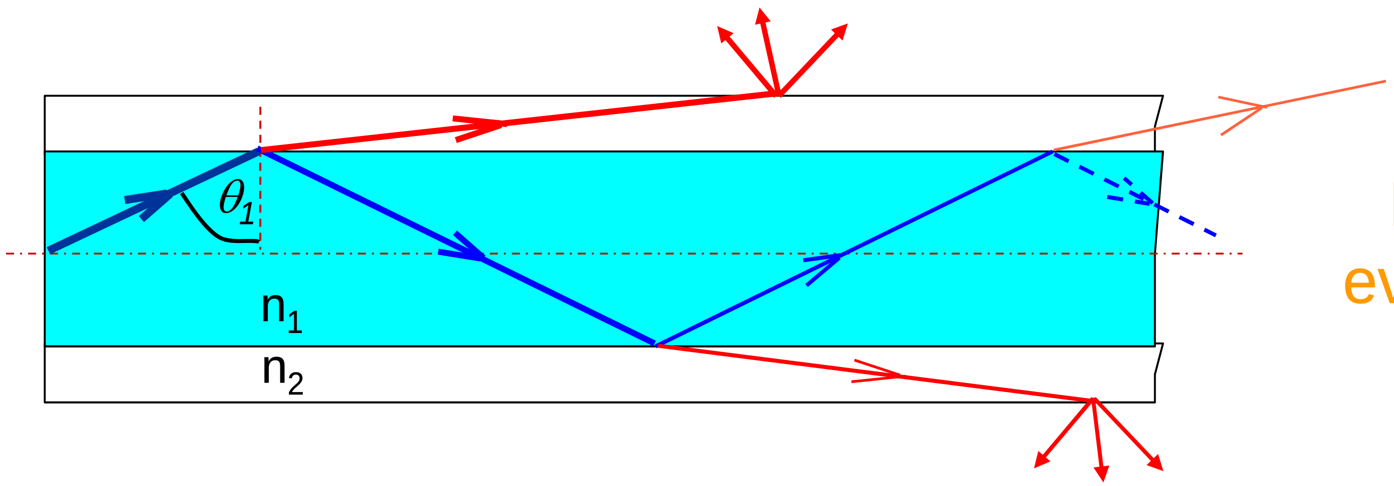
For $\theta_i > \theta_{cr}$, the ray is totally reflected



Total Internal Reflection

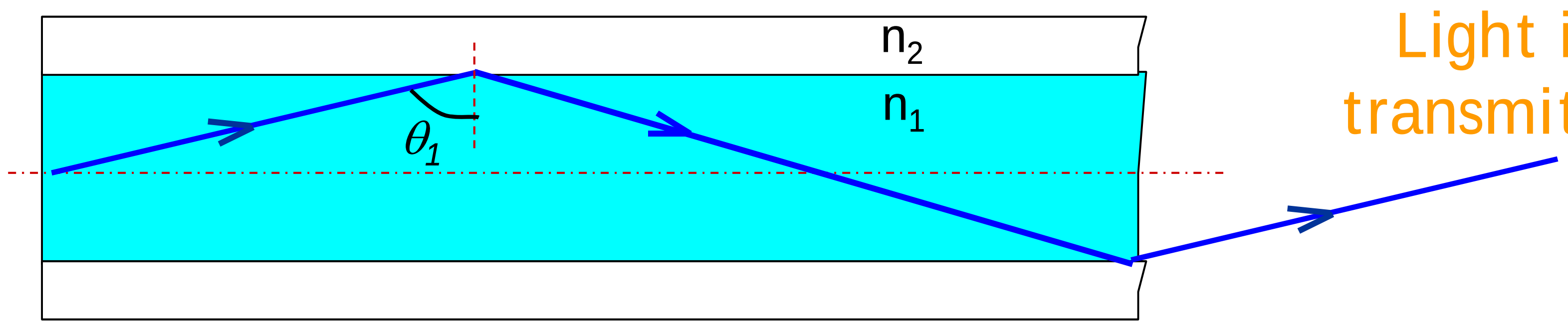
How do Fibers Transmit Light?

if θ_1 < critical angle θ_{cr} , ray refracted and reflected



Light is eventually lost

if θ_1 > critical angle θ_{cr} , ray totally reflected



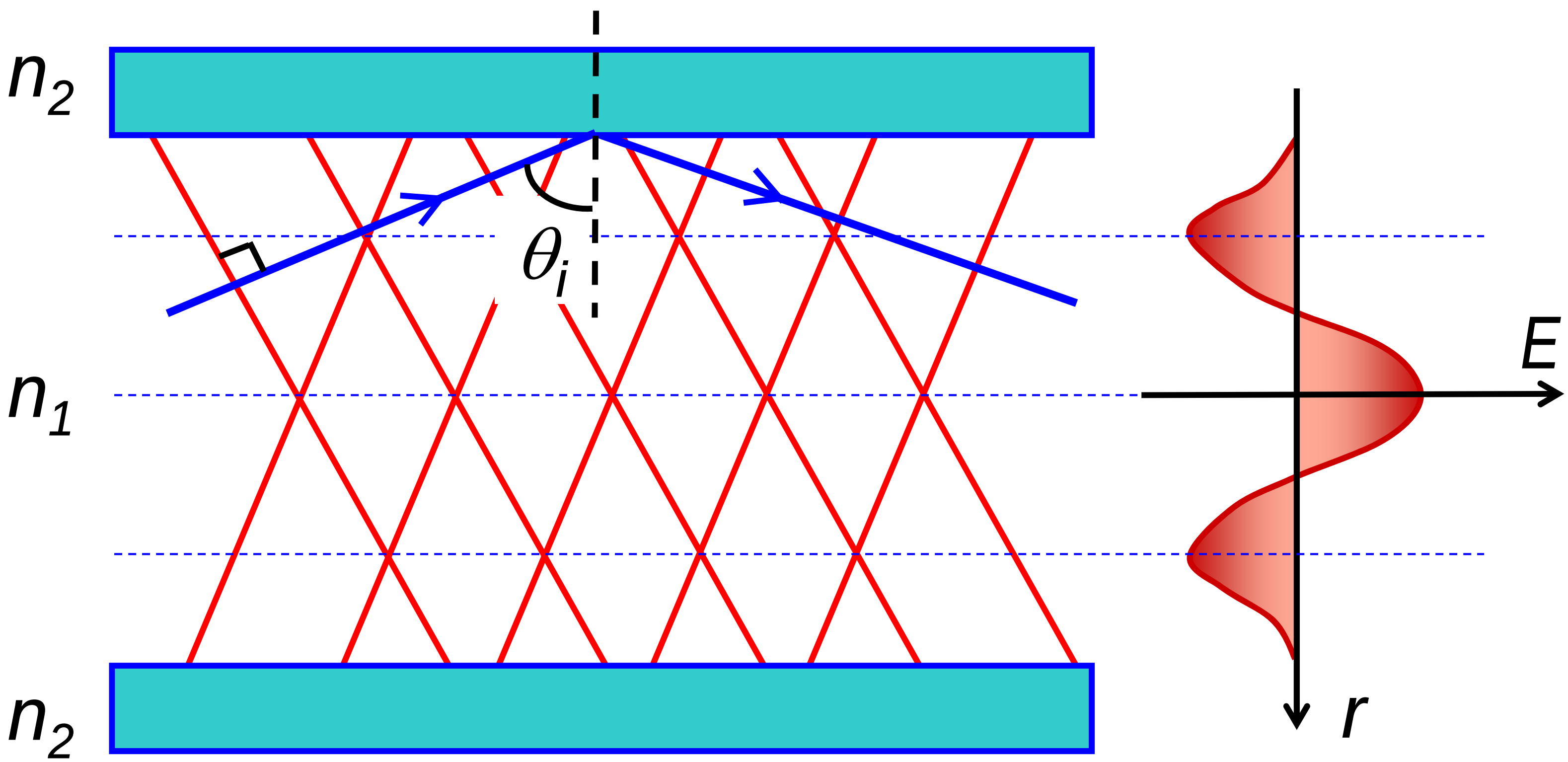
Light is transmitted

Rays, Wavefronts and Modes

Waves reflecting inside fiber interfere

Only rays yielding a standing wave allowed

Each allowed ray is a “mode” of the fiber

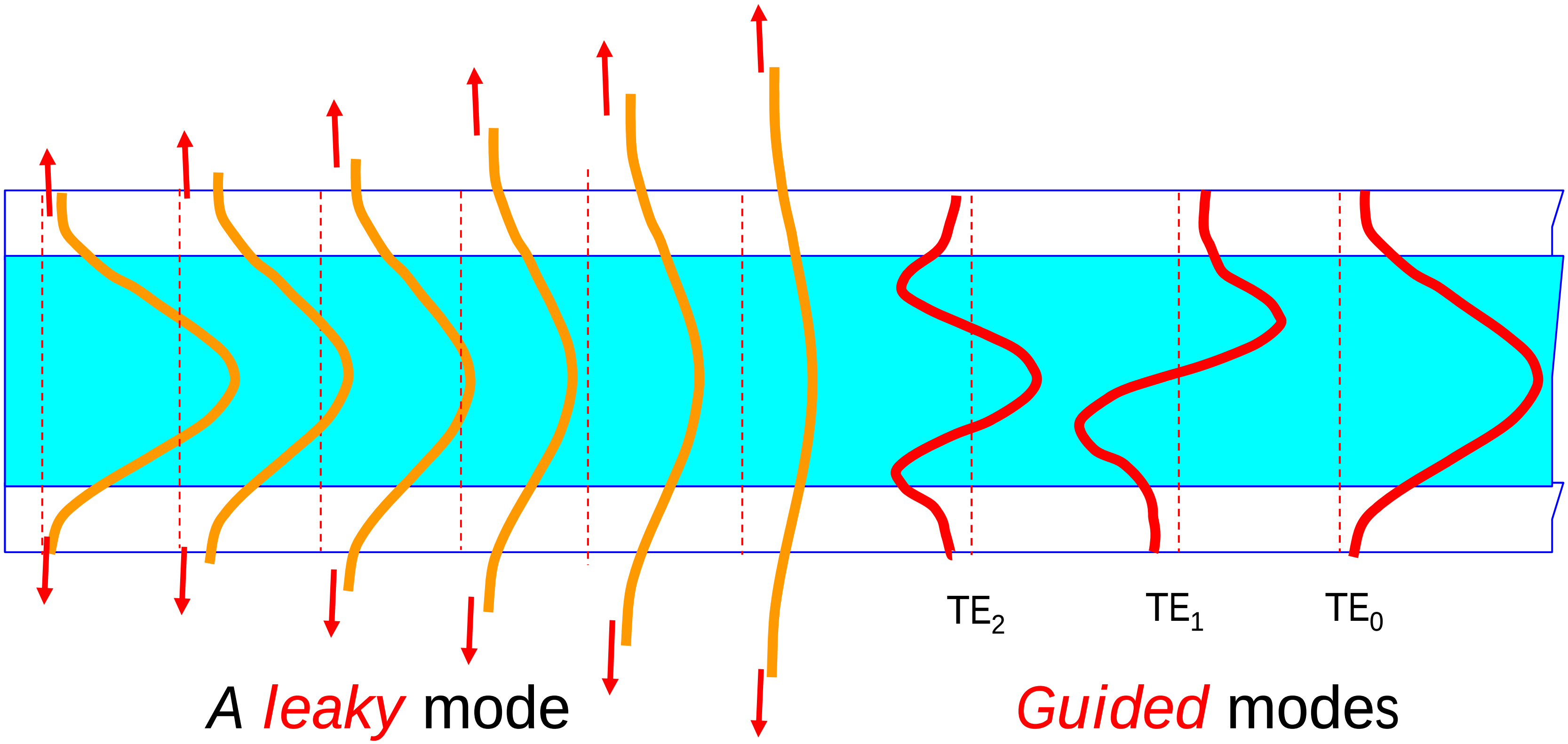


Wave Representation of Modes

Solve Maxwell's equations

A finite number of *guided* modes

An infinite number of *radiation (leaky)* modes

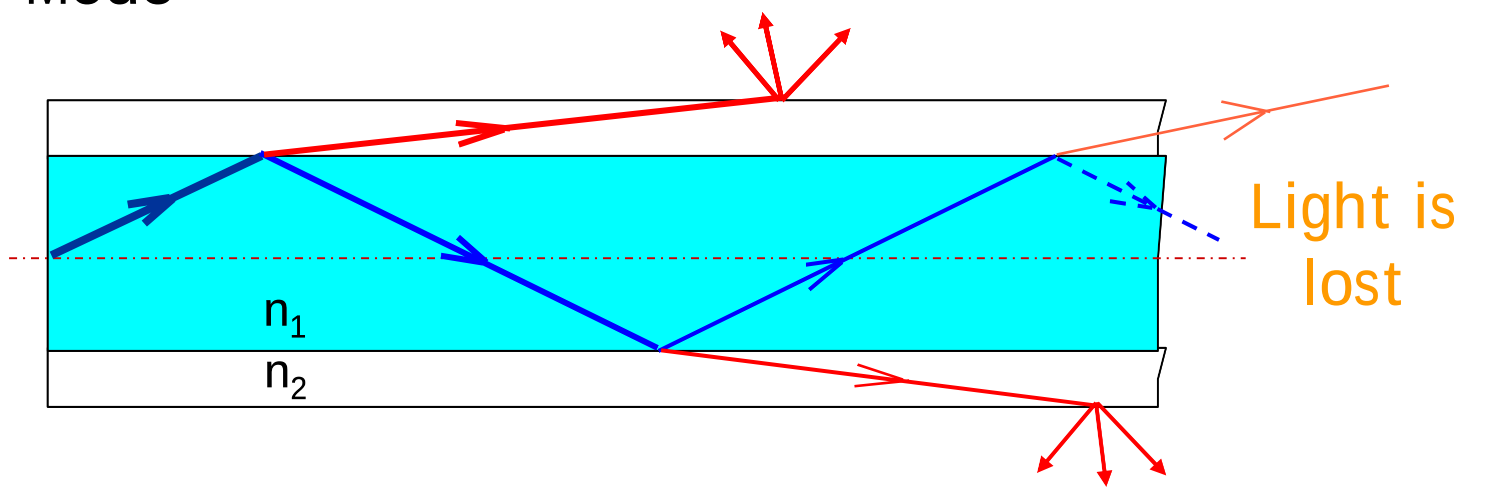


A leaky mode

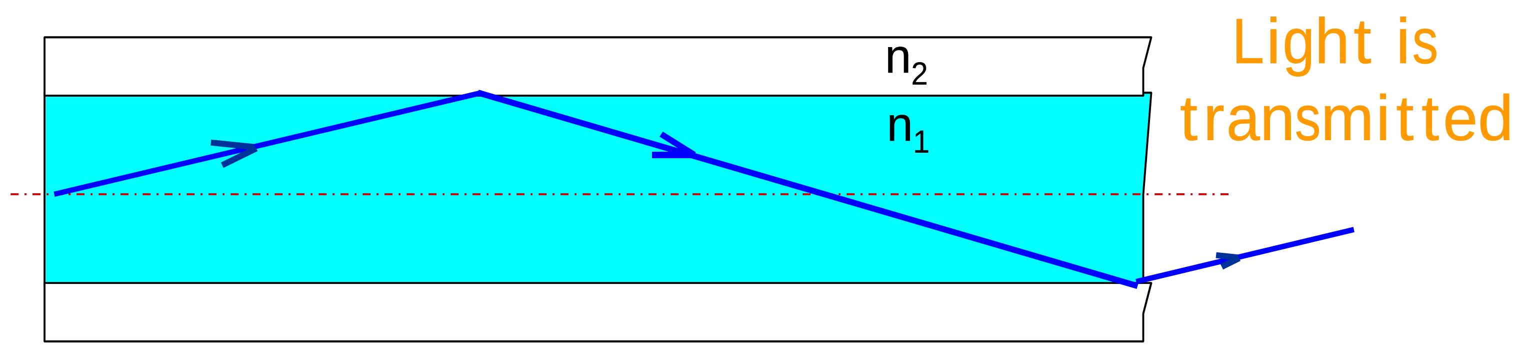
Guided modes

Mode Picture of Light Transmission

Leaky Mode



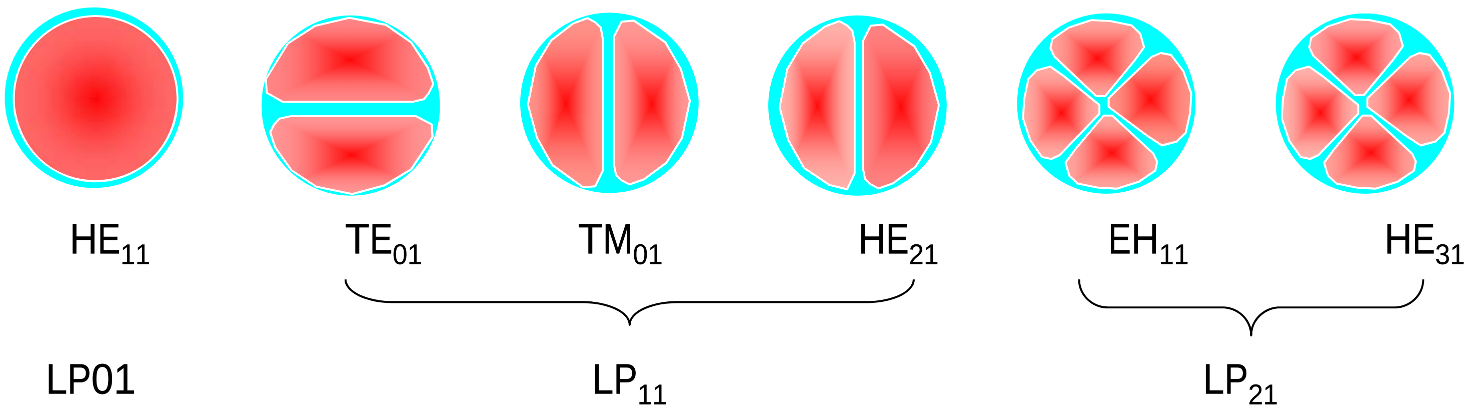
Guided Mode



Guided Modes in an Optical Fiber

In any waveguide, many modes can form at once

Below are some guided modes of an optical fiber



Cross-sectional view of fiber core the intensity distribution

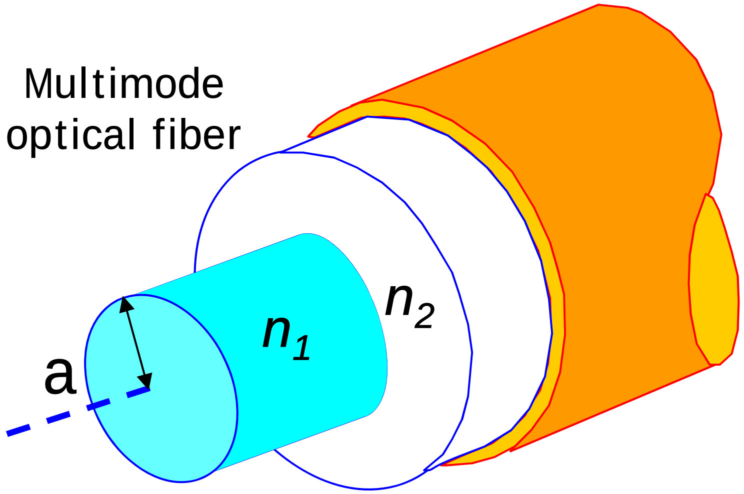
Different modes can propagate simultaneously

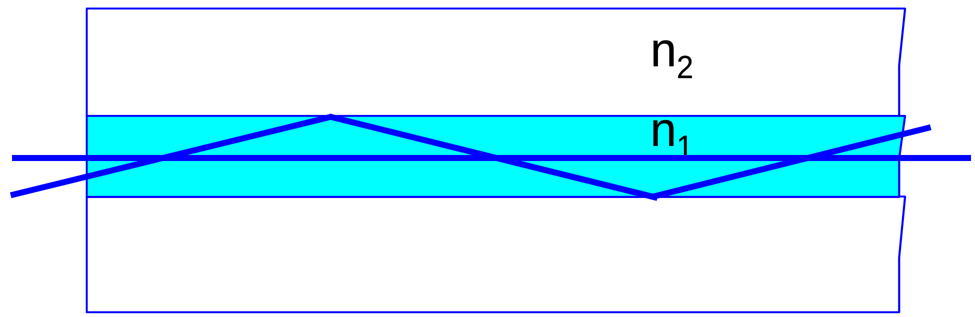
A multimode fiber. Also single mode fiber.

Single mode & Multimode optical fiber

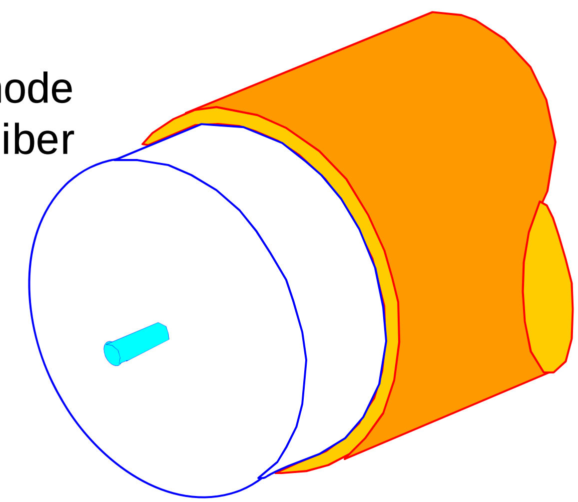
What makes a fiber single mode or multimode?

Multimode optical fiber





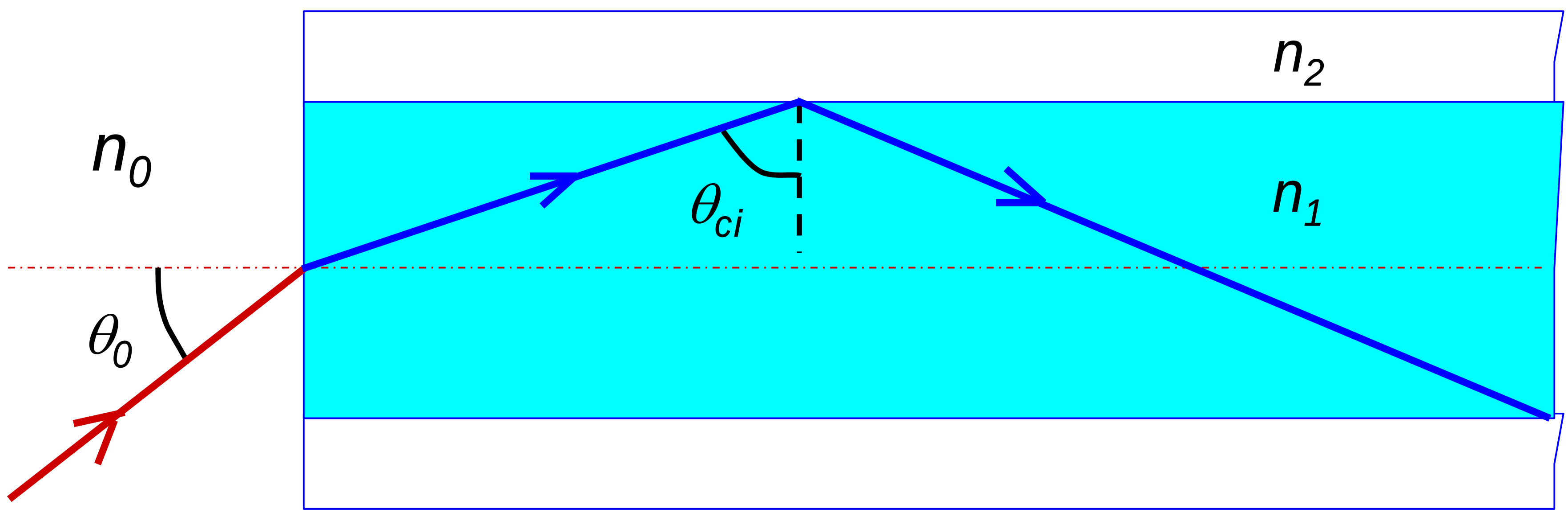
Single mode optical fiber



- dimension of core
- n_1 and n_2
- wavelength

Numerical Aperture (NA)

NA measures light gathering ability of a fiber

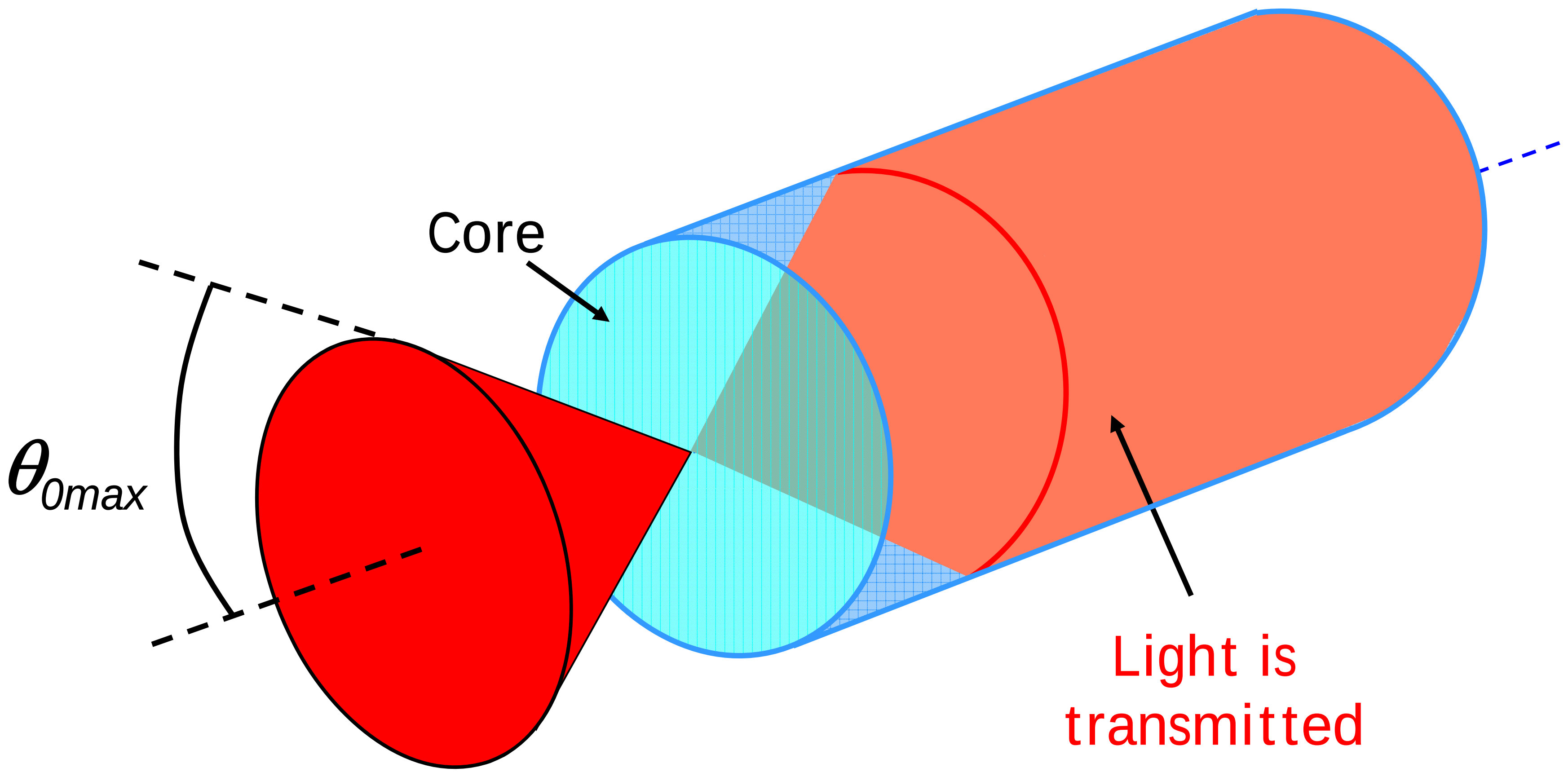


$$NA = n_0 \sin\theta_{0max} = n_1 \cos\theta_{ci} = (n_1^2 - n_2^2)^{0.5}$$

Acceptance Angle

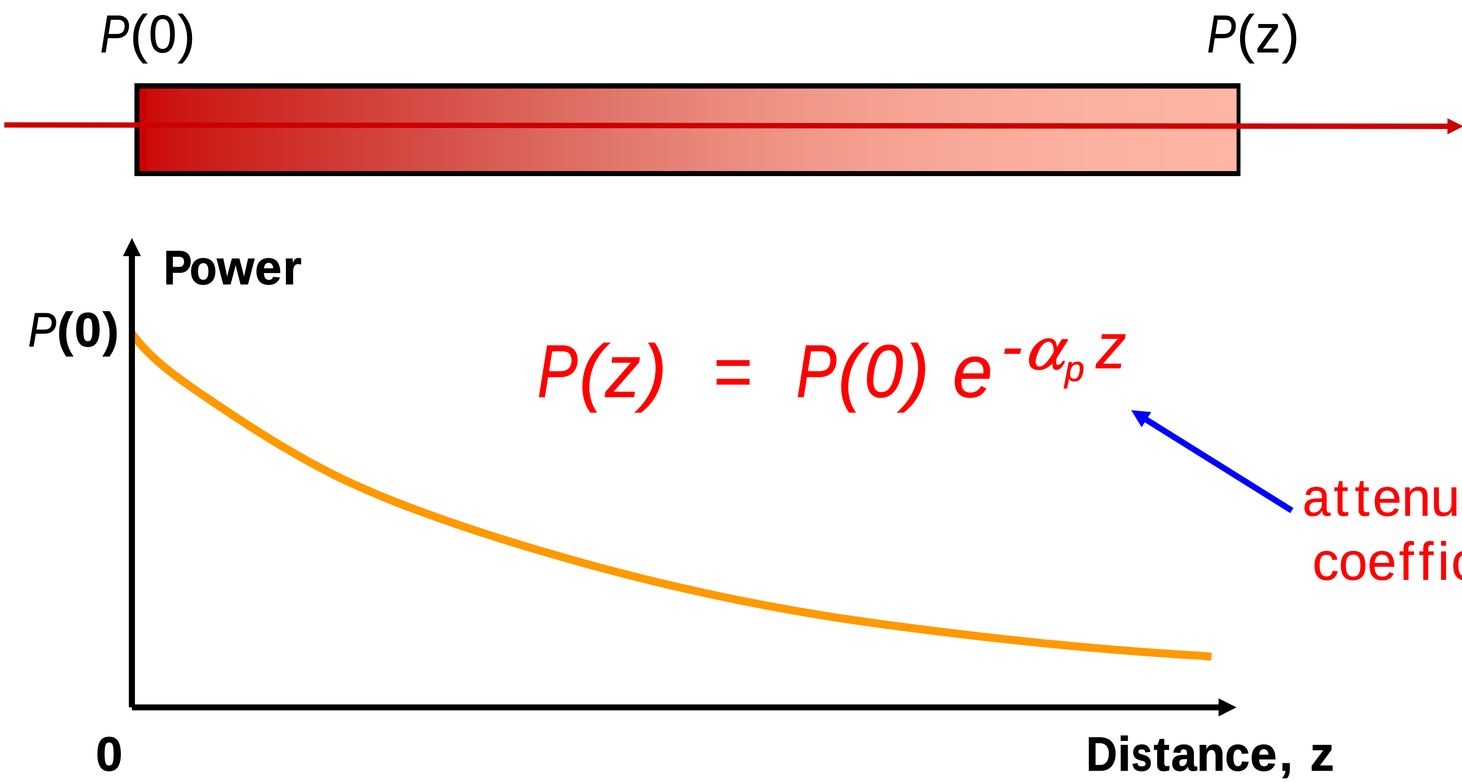
How much light can be captured by the fiber core?

Within the angle θ_{0max}, such that light is transmitted



Fiber Attenuation

As light travels along a fiber, its power decreases exponentially with distance

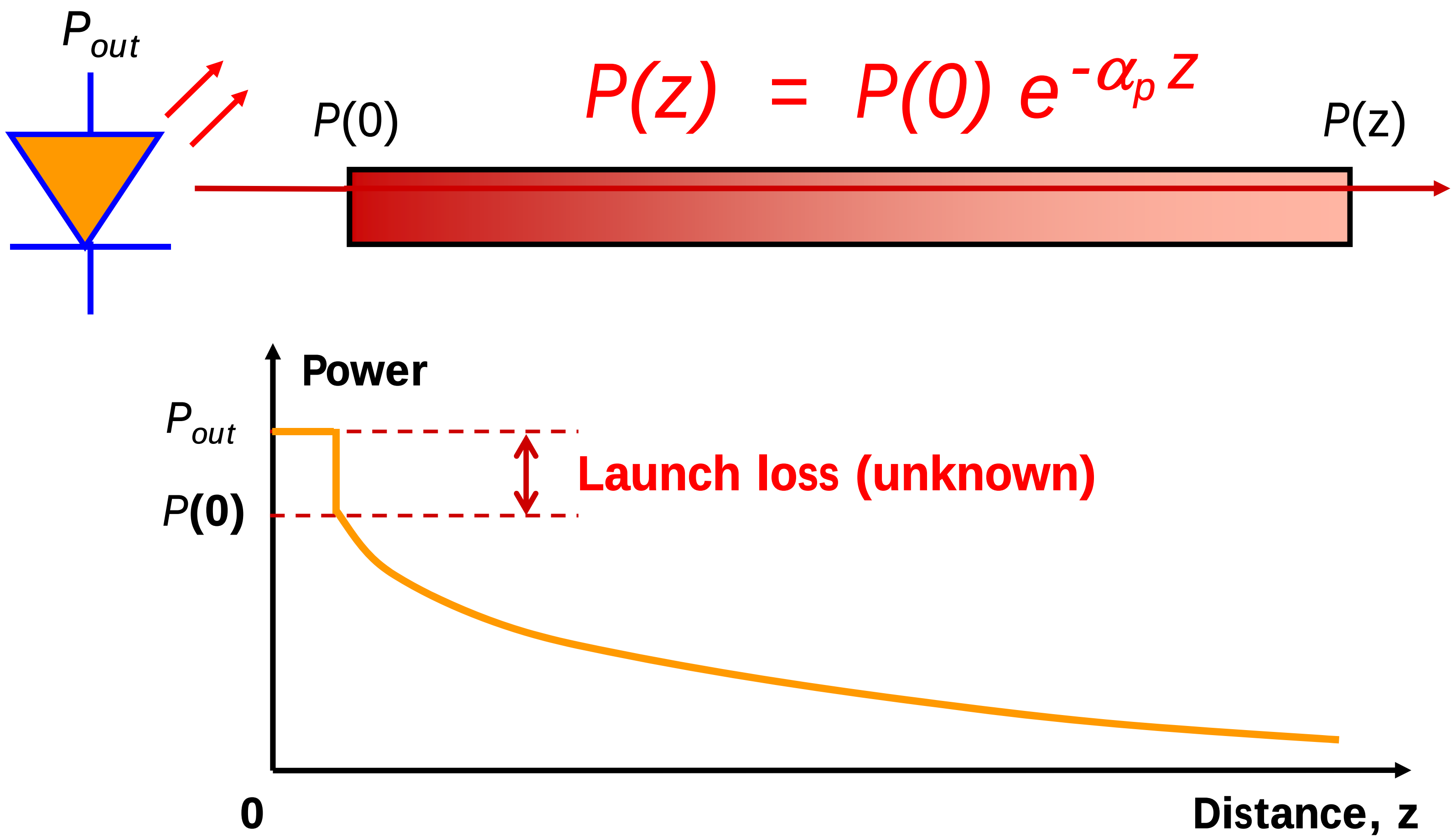


$$P(z) = P(0)\, e^{-\alpha_p z}$$

attenuation coefficient

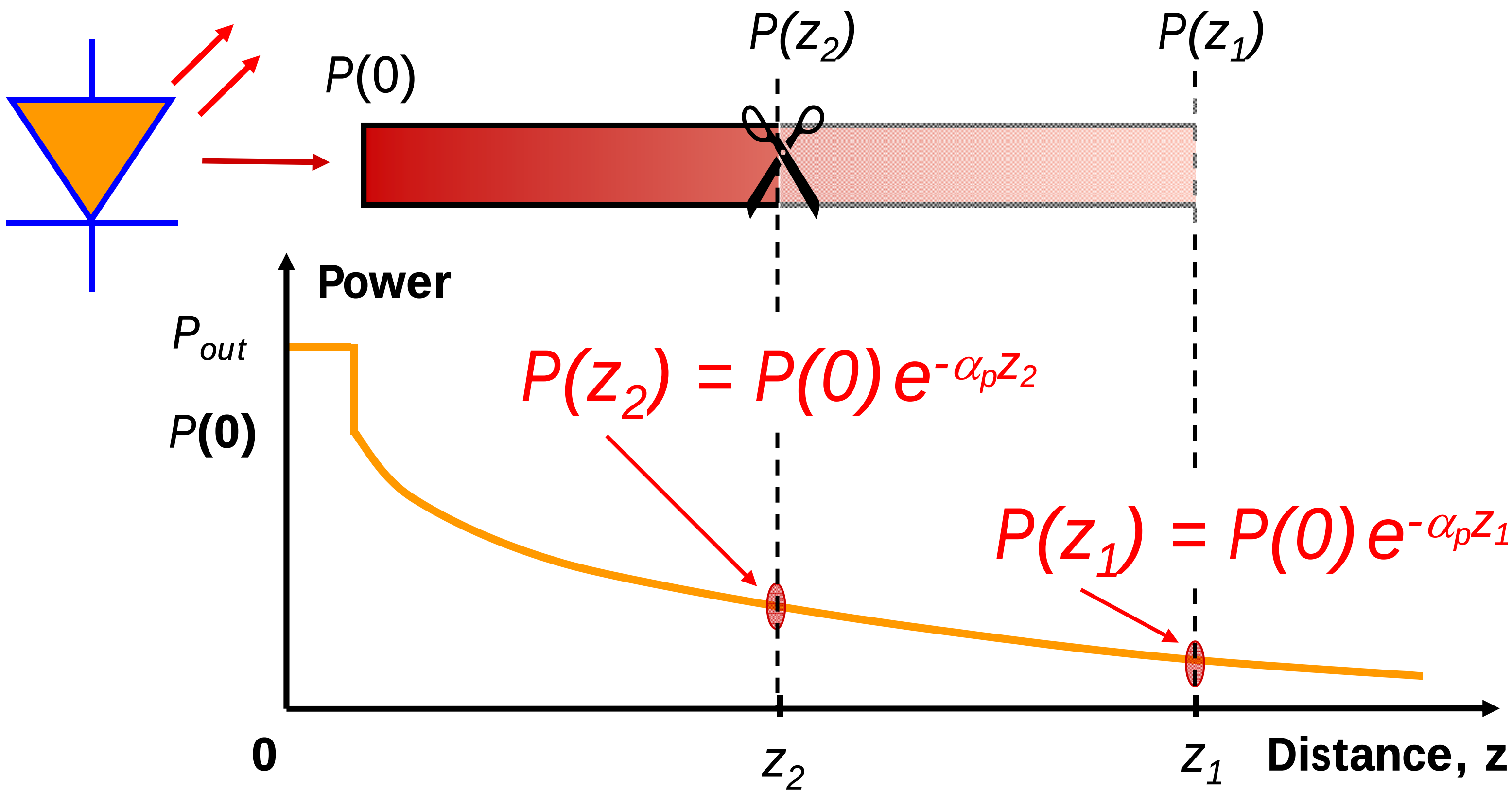
Fiber Attenuation

How to determine the attenuation coefficient α_p?



Fiber Attenuation

The “cut-back” method



Fiber Attenuation

$$\alpha_p = \frac{-1}{(z_1 - z_2)} \, ln \left[\frac{P(z_1)}{P(z_2)} \right]$$

Note that α_p is not in decibel units

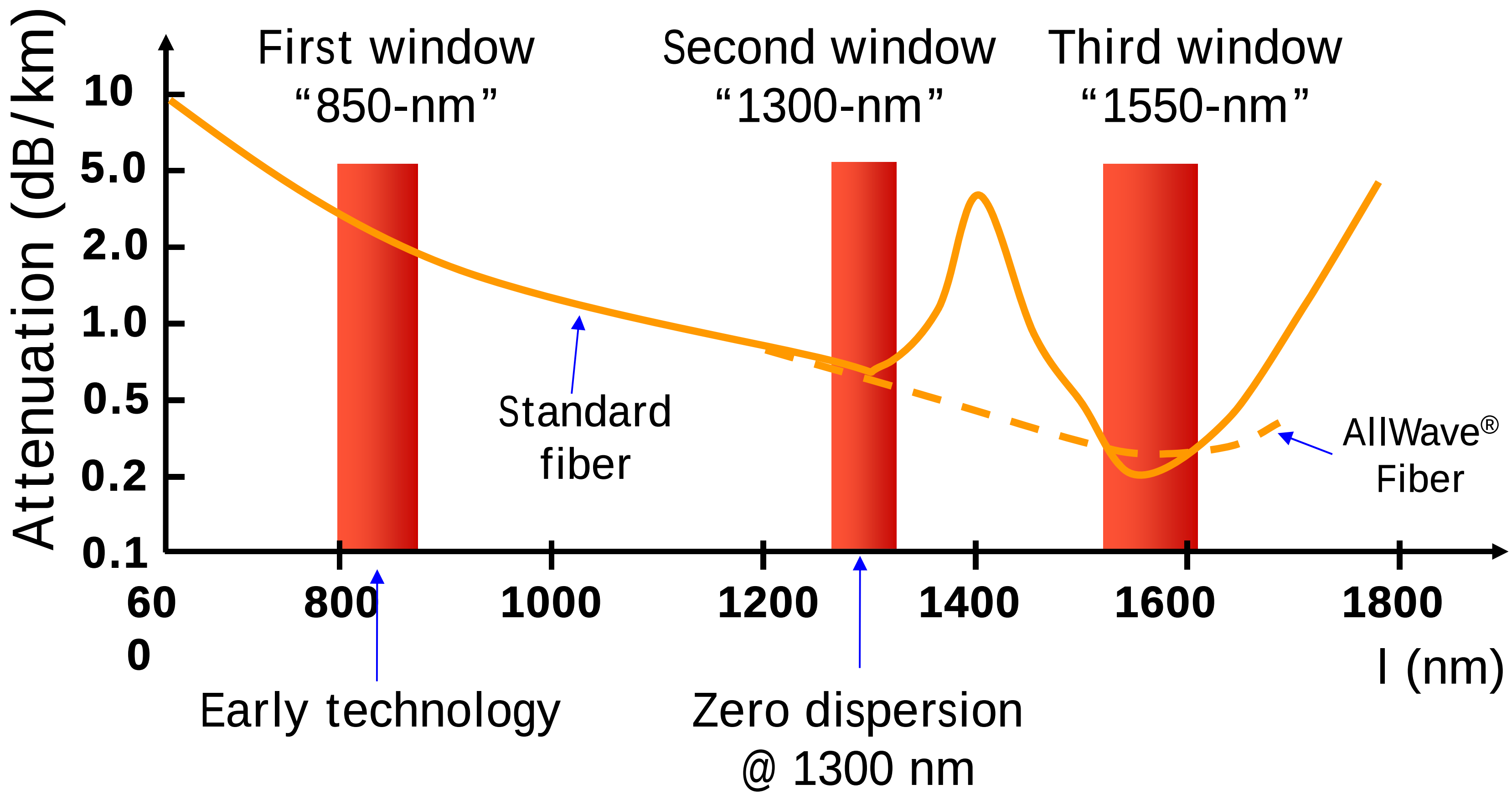
Prefer attenuation coefficient in decibel units

$$a \text{ (dB/km)} = \frac{P_2\text{(dBm)} - P_1\text{(dBm)}}{\left| L_2\text{(km)} - L_1\text{(km)} \right|} \text{ (dB/km)}$$

a (dB/km) is referred to as the fiber attenuation

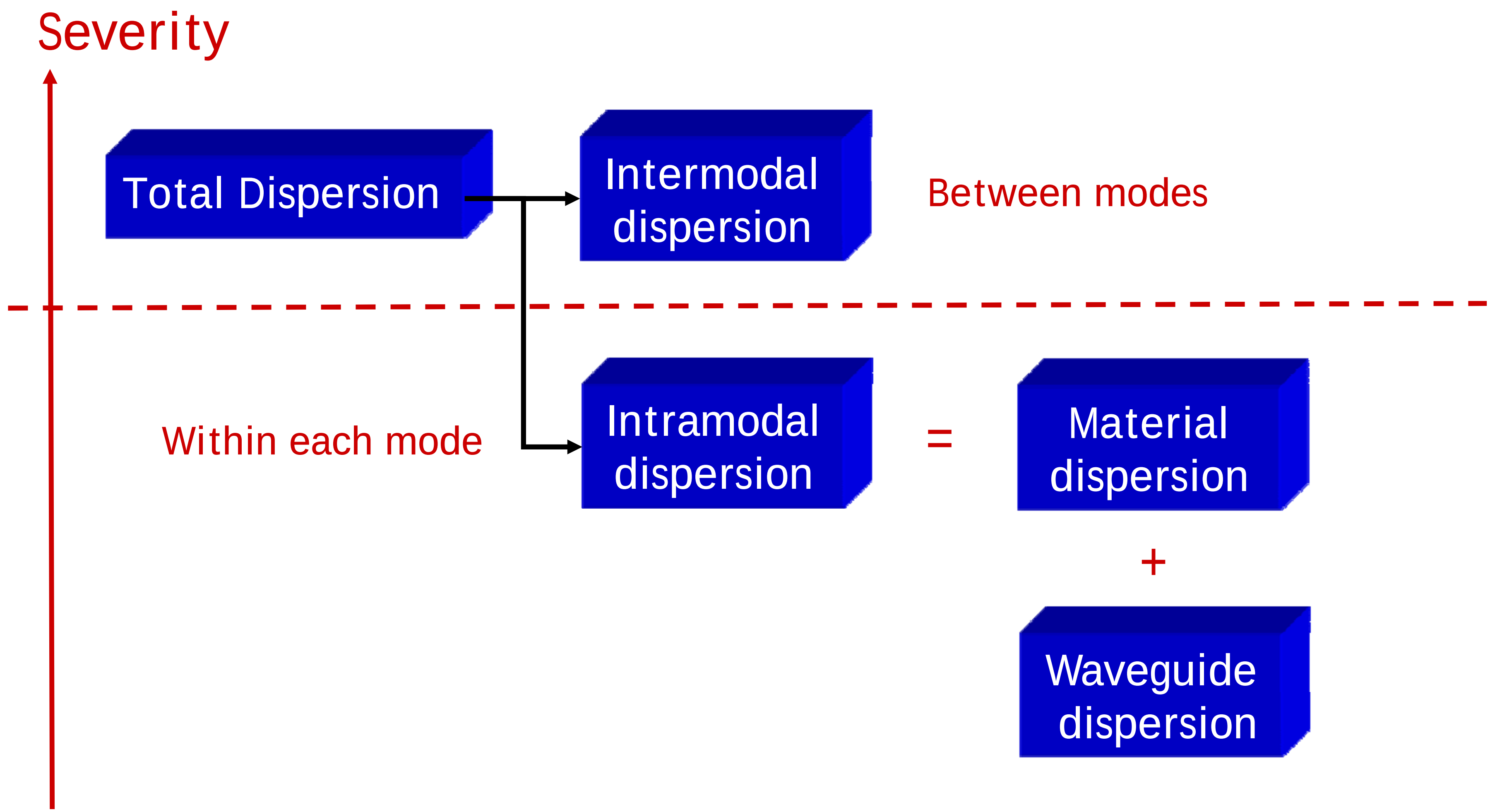
Fiber Attenuation

Fiber attenuation is a function of the wavelength



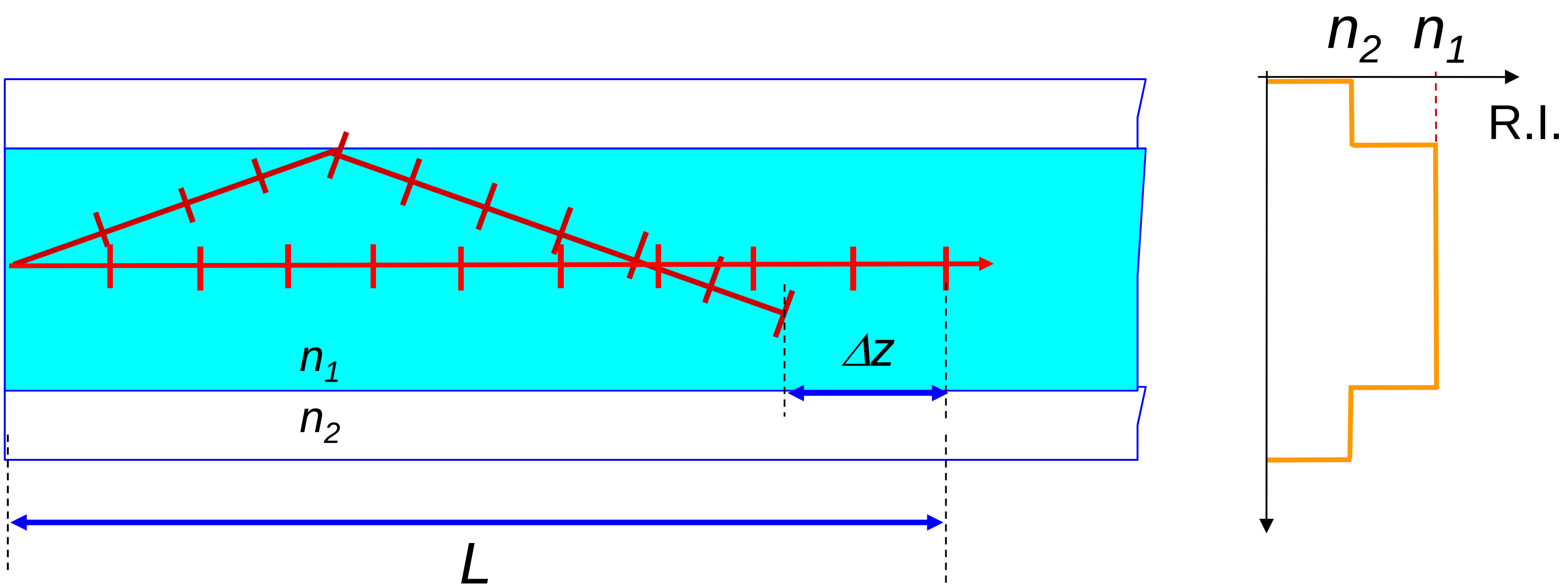
Fiber Dispersion

Fiber dispersion is made up of several components



Intermodal Dispersion

Each mode experiences different group velocity



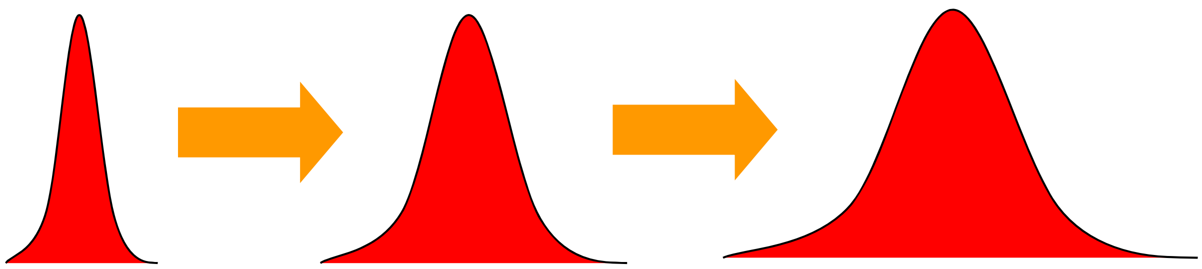
Minimum transit time $t_{min} = (L/c)\cdot n_1$

Maximum transit time $t_{max} = (L/c)\cdot(n_1^2/n_2)$

Intermodal Dispersion

The delay difference or pulse spread in time:

$$\delta t_{mod} = t_{max} - t_{min} = (L/c)n_1(n_1/n_2-1) \cong (L/c)(NA^2/2n_1)$$

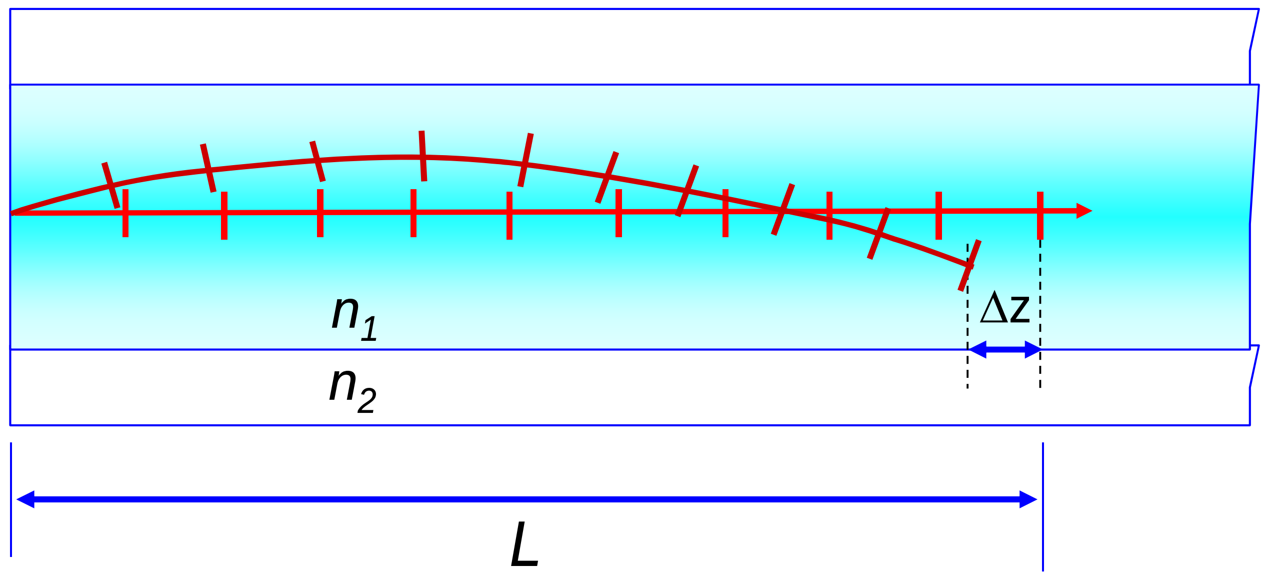


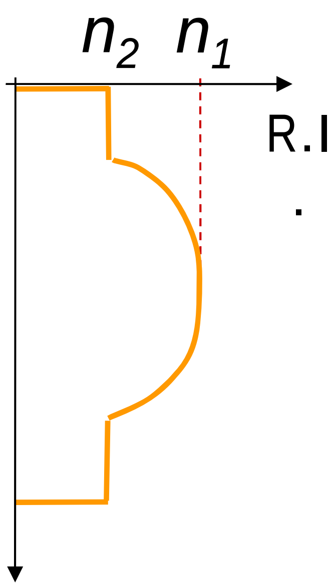
The rms pulse broadening per unit length due to intermodal dispersion (for a step index fiber):

$$\sigma_{mod} \cong \frac{(NA)^2}{4\sqrt{2}n_1 c} \quad \text{ns/km}$$

Intermodal Dispersion

Can be reduced by using a graded index profile



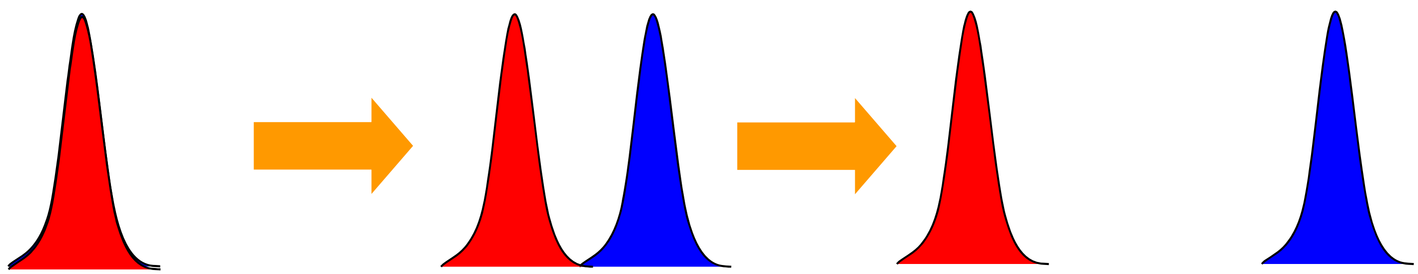


Minimized using a nearly parabolic index profile

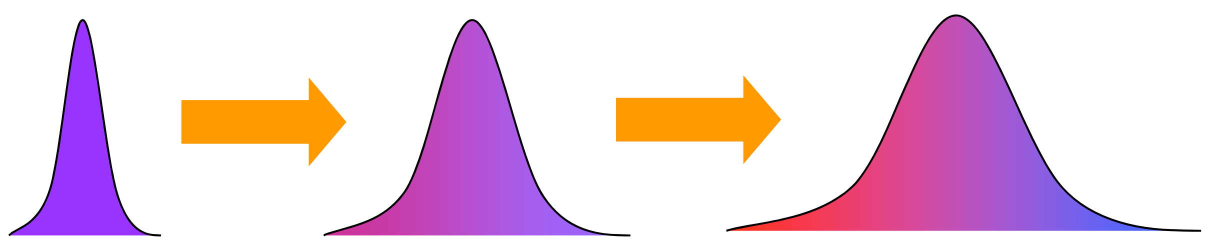
Intramodal Dispersion: GVD

Group Velocity Dispersion (GVD)

Discrete spectral components of a pulse travel at different speeds (e.g. in a multi-frequency laser)

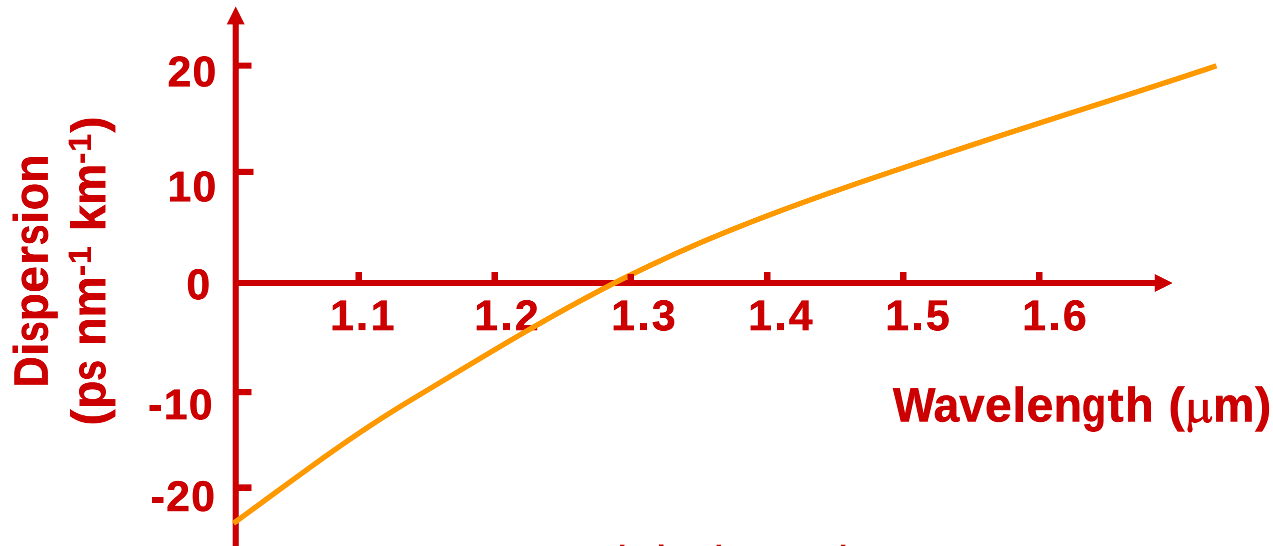


Pulse spreads out (its width increases) in time (e.g. in a modulated single frequency laser)



Intramodal Dispersion: Material Dispersion

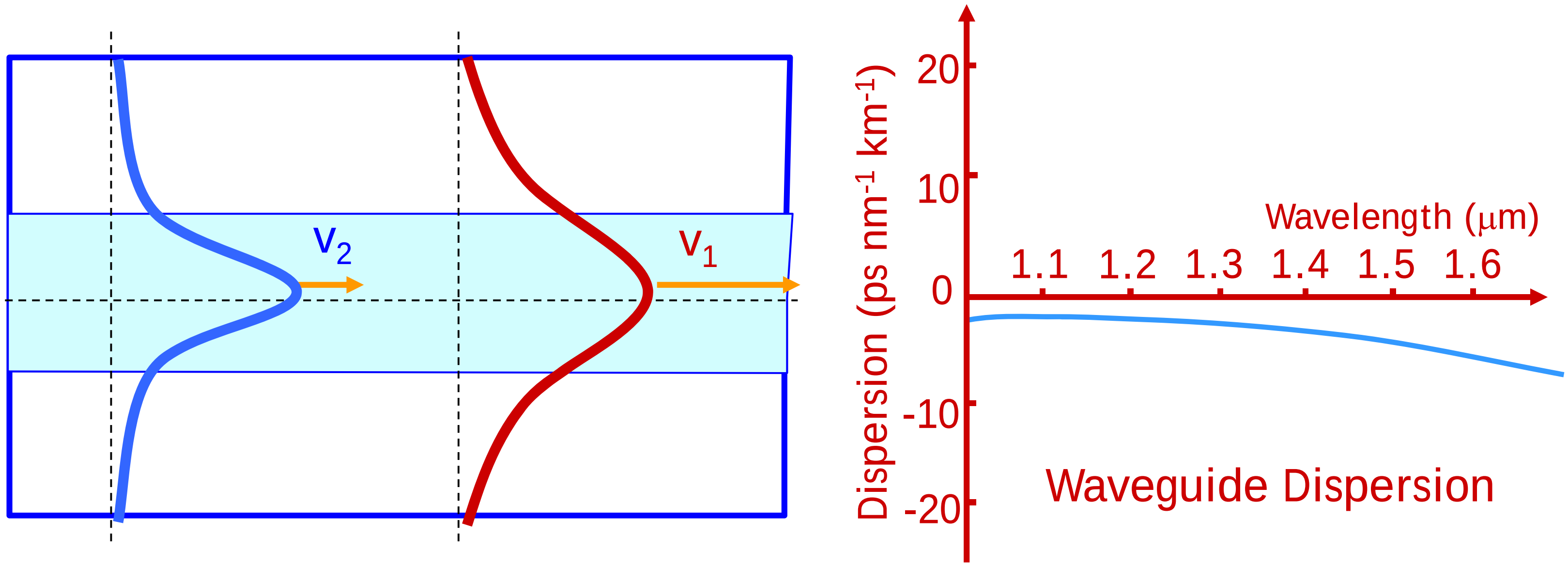
Refractive index varies with wavelength.



Material Dispersion

Intramodal Dispersion: Waveguide Dispersion

- An SMF confines ~ 80 % of optical power to the core
- Velocity depends on the proportion of power in the core



- At longer wavelengths, the wave is less tightly confined
- Therefore, on average, it sees a lower refractive index

Total Dispersion: Multimode Fibers

- Includes Intramodal σ_c and Intermodal σ_n dispersion
- The total fiber dispersion per unit length:

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{1/2} \quad \text{ns/km}$$

- Pulse width will increase by s_T after 1 km

Total Dispersion: Single Mode Fibers

- GVD measured by a single Dispersion Parameter *D*

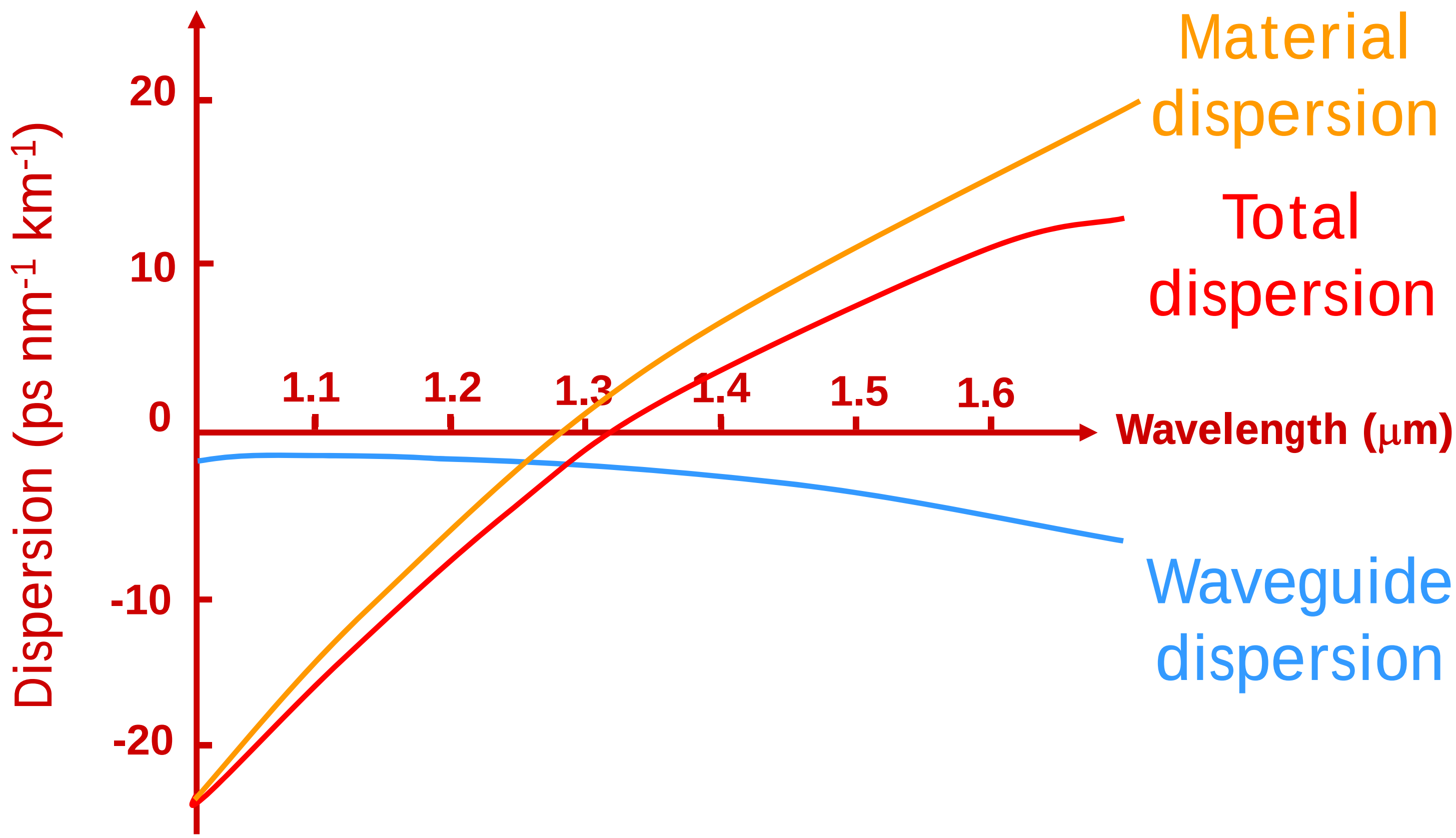
$$D = -\frac{2\pi}{c\lambda^2} \cdot \frac{d^2\beta}{dk^2} \qquad \text{ps nm}^{-1}\text{km}^{-1}$$

- *D* is not normally calculated, but is measured and quoted as a characteristic of the fiber

- A pulse will spread out by *D* ps for every nm of spectral width and every km of distance traveled

Total Dispersion: Single Mode Fibers

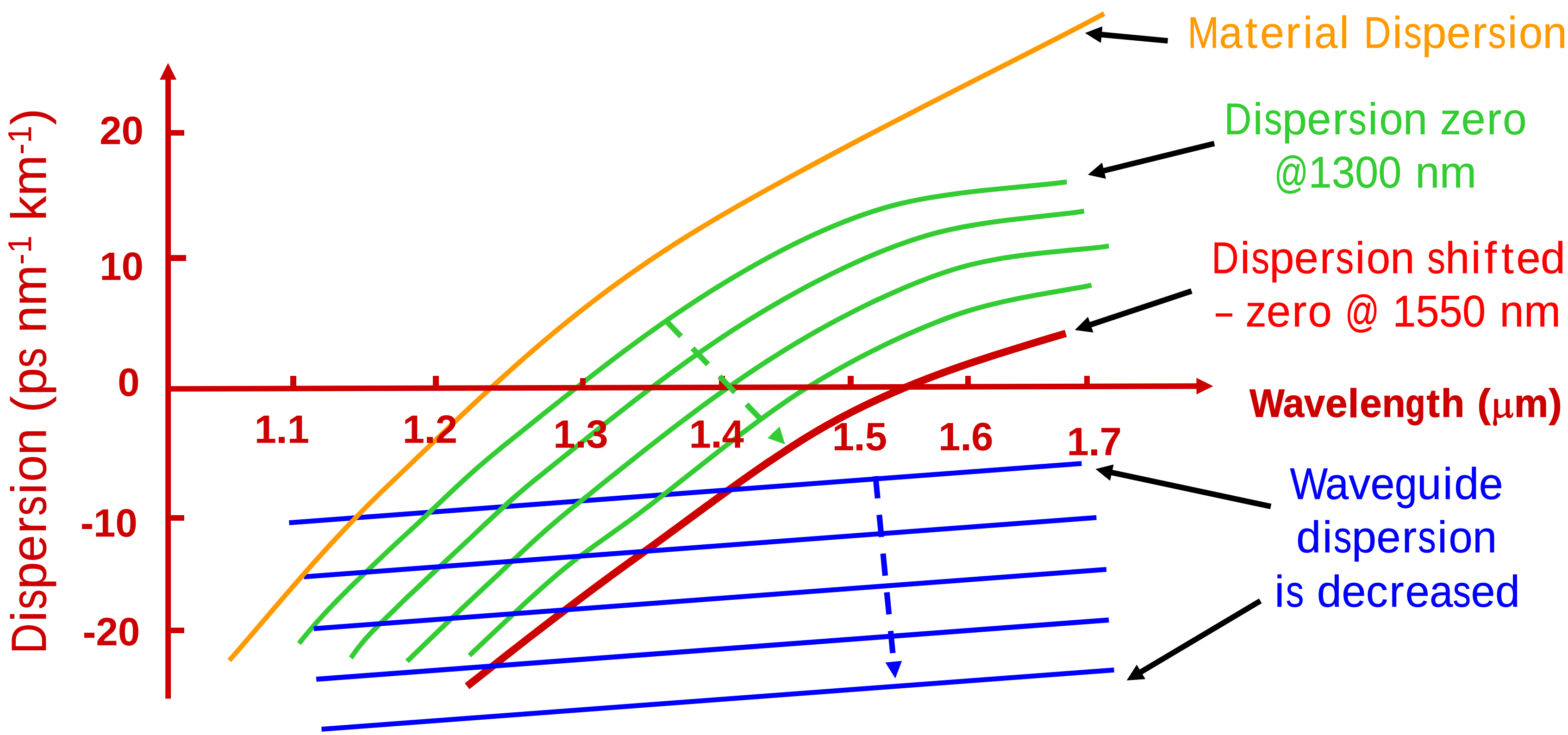
Combination of material and waveguide dispersion



Dispersion Modified Single Mode Fibers

Dispersion shifted fiber:

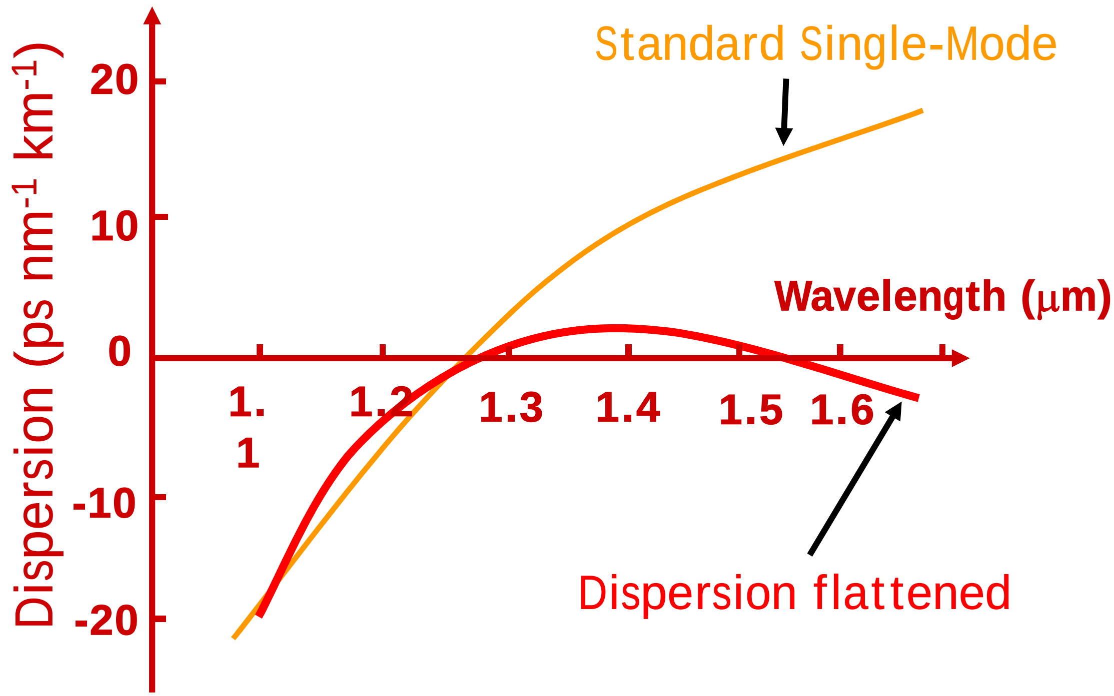
- By controlling the core radius and refractive index, it is possible to change the wavelength of the dispersion zero

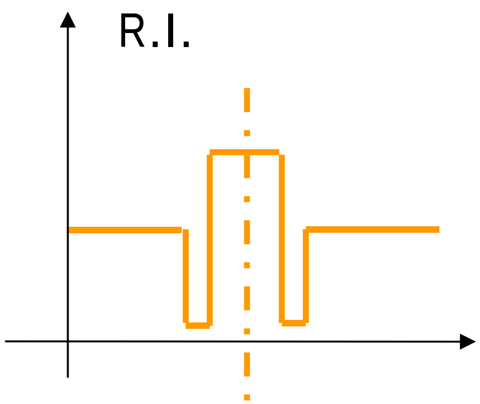


Dispersion Modified Single Mode Fibers

Dispersion flattened fibers:

- The typical fiber with 'W' core structure





Refractive index profile of "W" fiber

Summary

- Structure of fiber
- Ray representation in optical fiber
- Wave representation in optical fiber
- Attenuation in fiber
- Dispersion in fiber
- Total dispersion of multimode fiber
- Total dispersion of signal mode fiber
- Dispersion modified single mode fibers

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