Incab

Fiber Optics 101

Tim Buffkin
National Sales Manager – Broadband

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PURPOSE AND LEARNING OBJECTIVES

This course will teach you the basics of optical fiber and how it functions

After this class, you will be able to:

1. Explain **what an optical fiber is** and the purpose of each of its three components: core, cladding, and coating.
2. Explain the meaning and importance **"total internal reflection."**
3. State the advantages of using **fiber optics versus** using **copper cables**.
4. Explain the meaning and importance of these **concepts** as they apply to optical fiber: Snell's Law, index of refraction, and angle of incidence.
5. Explain the meaning and importance of **wavelength and frequency** as they apply to optical fiber and know those most used.
6. Explain what **attenuation** is, what its two sources are, and what its typical limits are.
7. Explain what **dispersion** is and what three types of it there are.
8. Name two **newer, advanced fiber types** and why they are used.

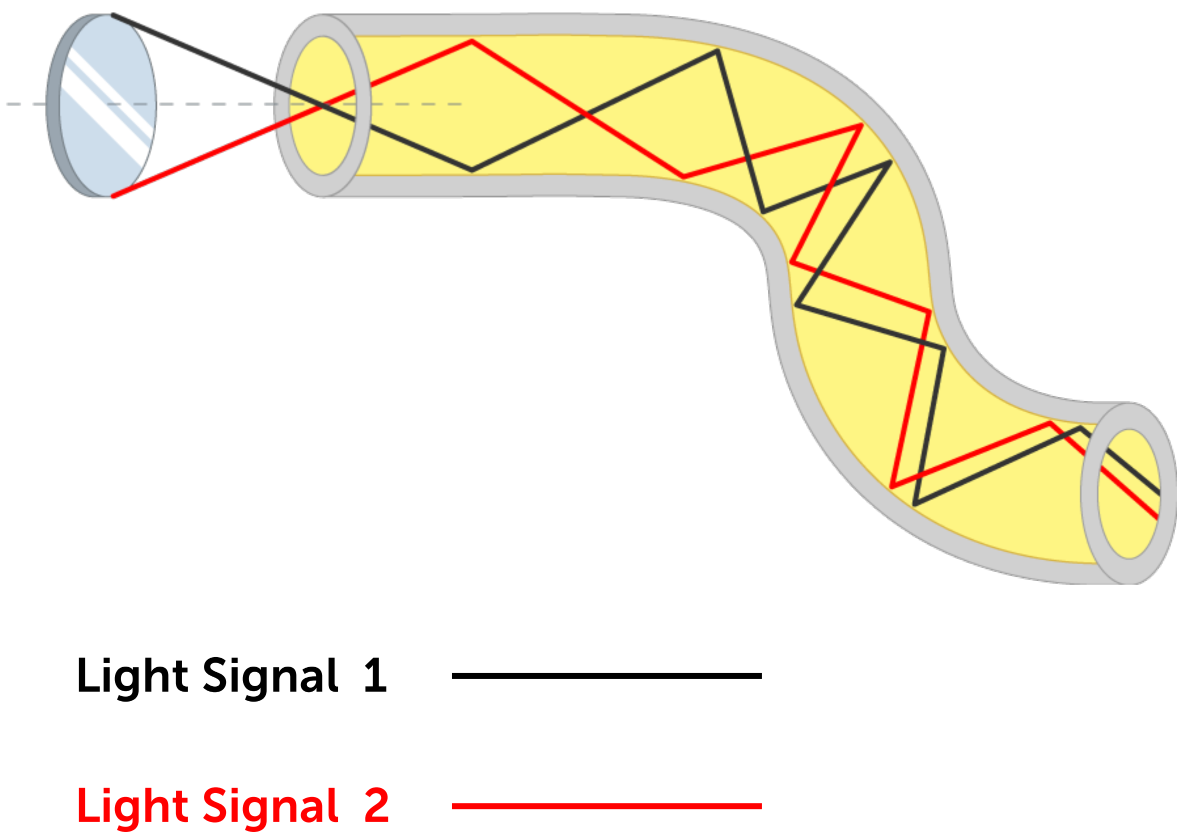
Incab University "School of Excellence in Fiber Optics"
Agenda

- Introduction
- Learning Objectives
- Presentation
- Q&A (Technical questions only)
- Let's start!

Fiber Optics

- The technology used to transmit information as pulses of light through thin strands of glass or plastic fibers over long distances

- Light constantly bounces from the cladding back into the core as it travels down the fiber



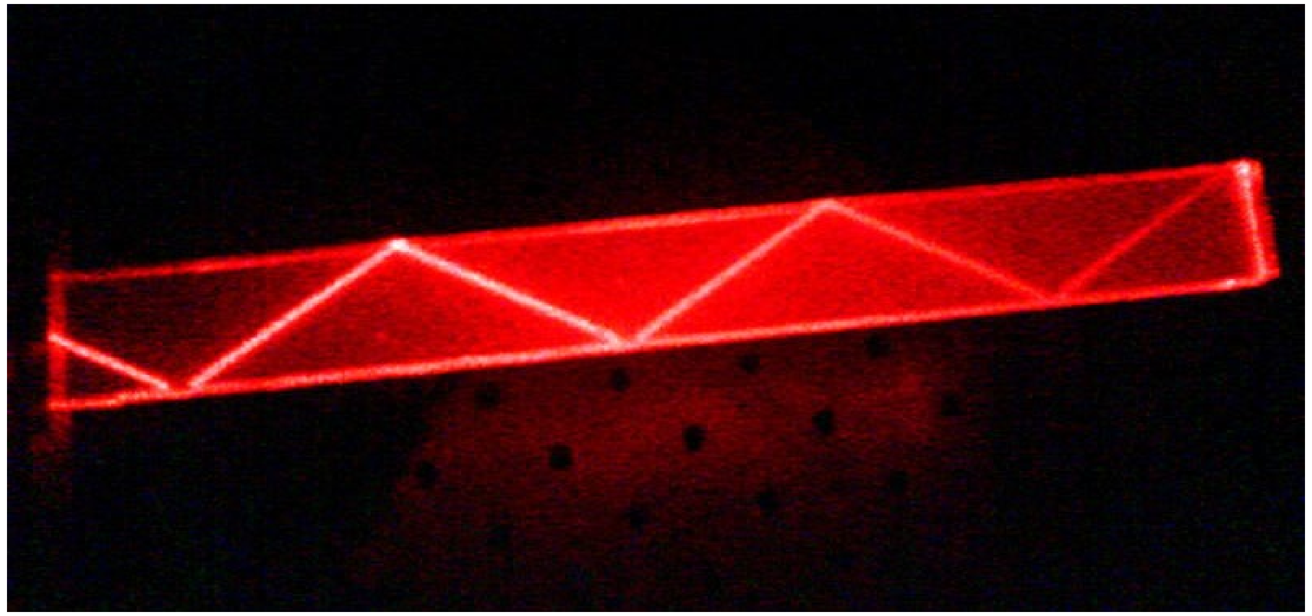
Total Internal Reflection (TIR)

- **TIR** occurs in nature with light, electromagnetic wave, sound, and even water waves.

- With light, TIR occurs when the light reaches the boundary of two mediums and:

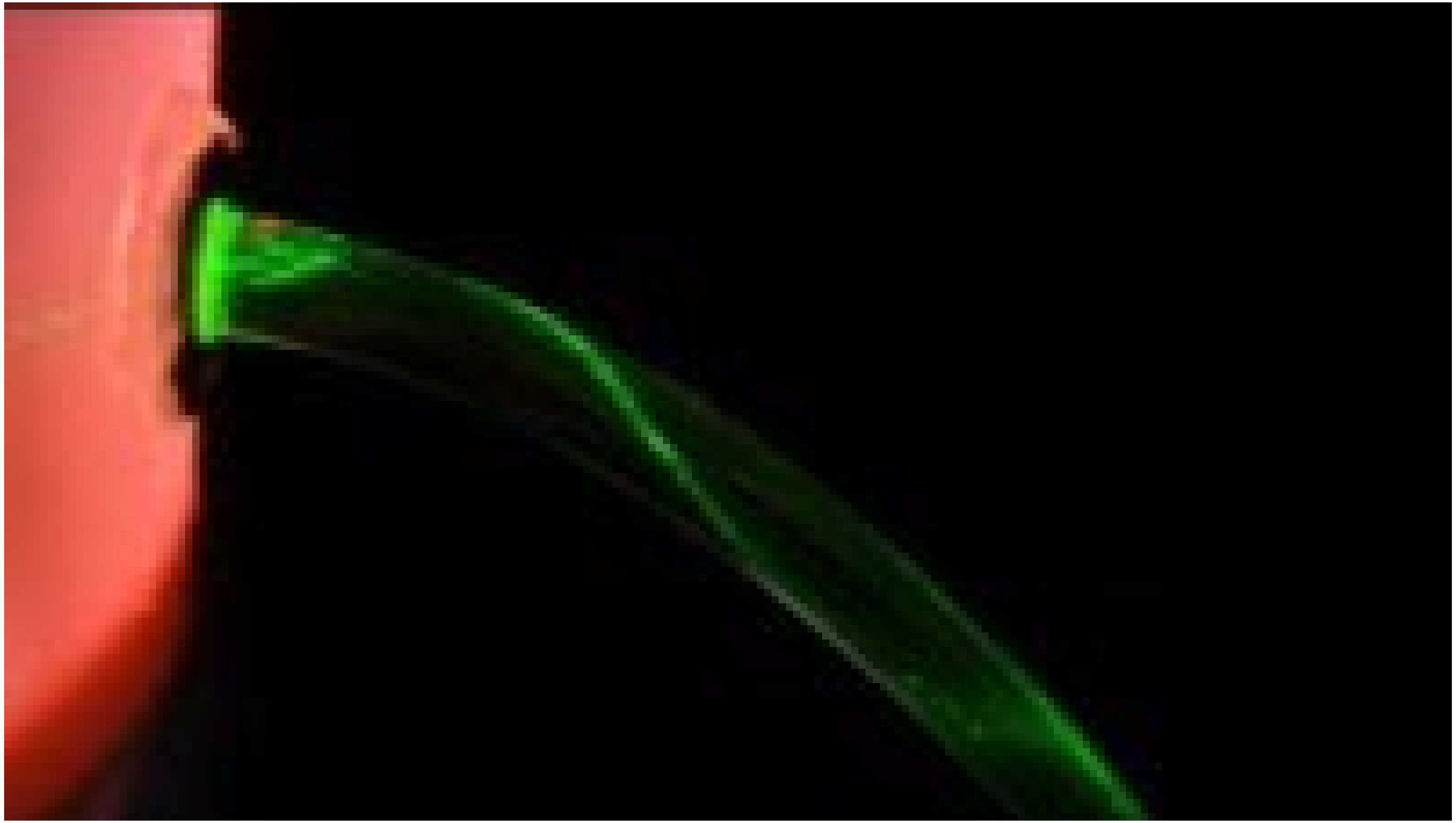
  - The angle it hits at (“angle of incidence”) is greater than the “critical angle”
  - The light is going from a dense medium to a less-dense one (example: water to air)

TIR in everyday life



TIR in an acrylic rod

How it works

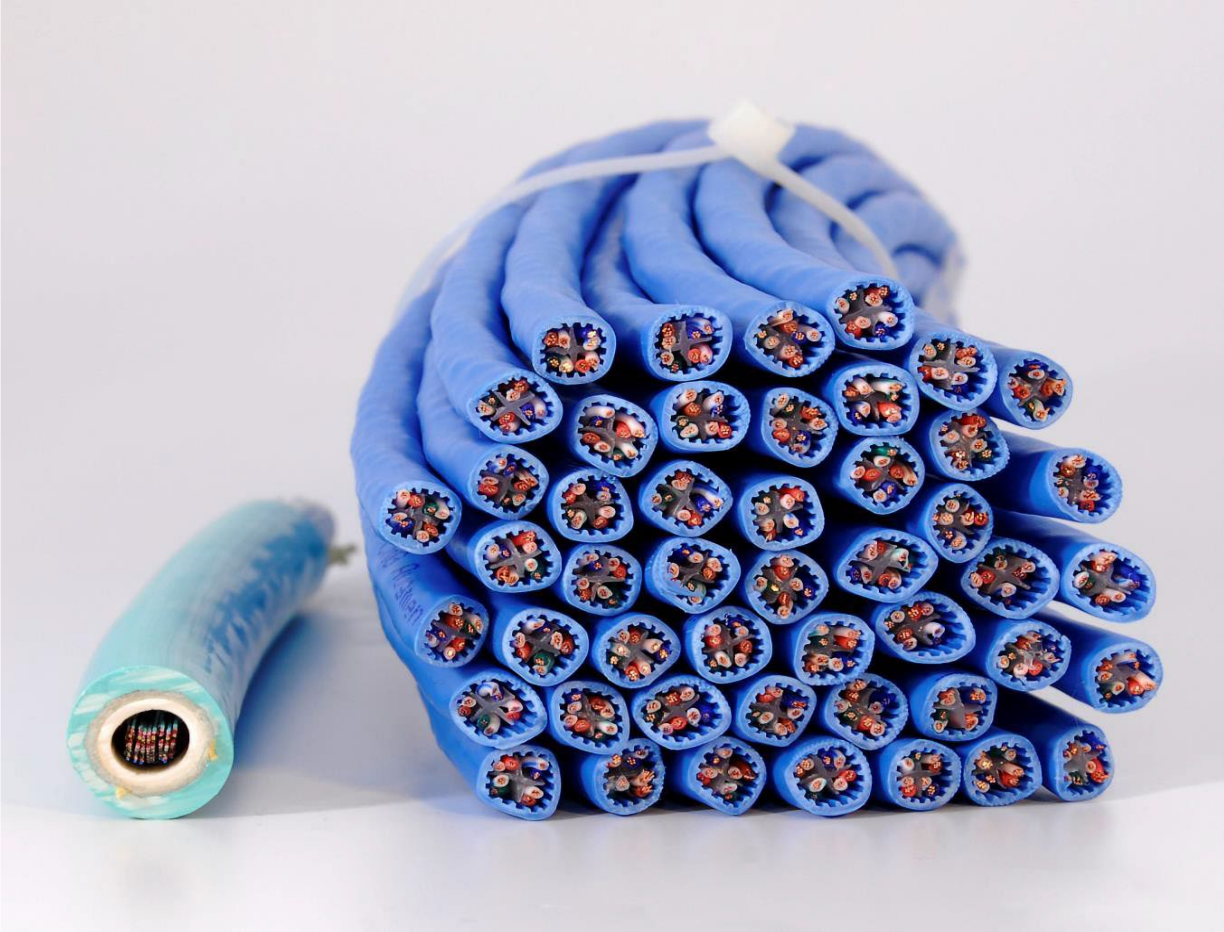


Credits to @engineerguy on YouTube

Why use Fiber Optic Cable?

Reason 1 — requires much less space

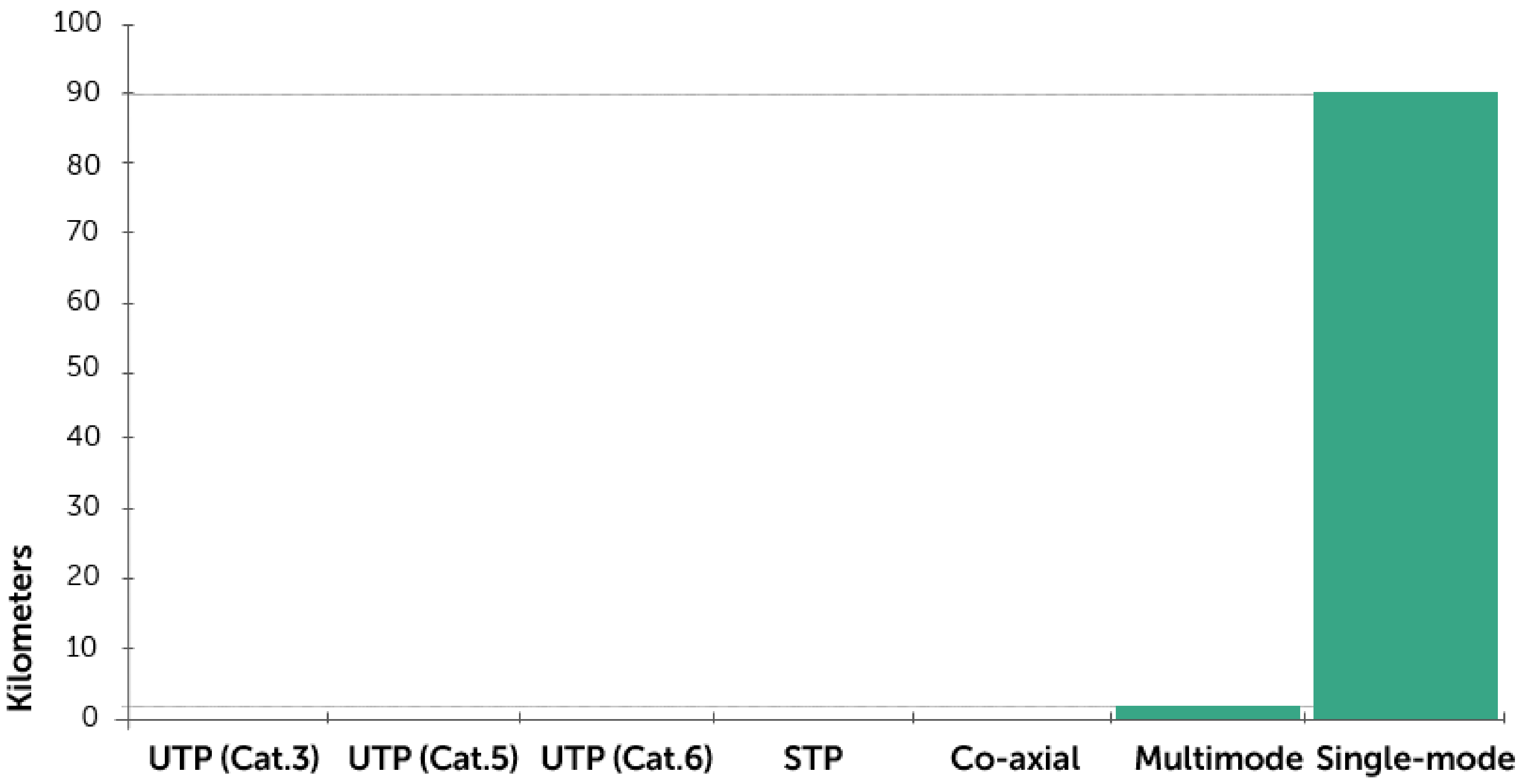
- A fiber optic cable with the same bandwidth capacity as a comparable copper cable is less than 1% of both the size and weight



Fiber optic cable vs CAT6 copper cable

Why use Fiber Optic Cable?

Reason 2 – can go much farther than copper cables for a given "bandwidth" (amount of information transmitted)



* Typical distance for 1 Gbps system capability

Why use Fiber Optic Cable?

Other Reasons:

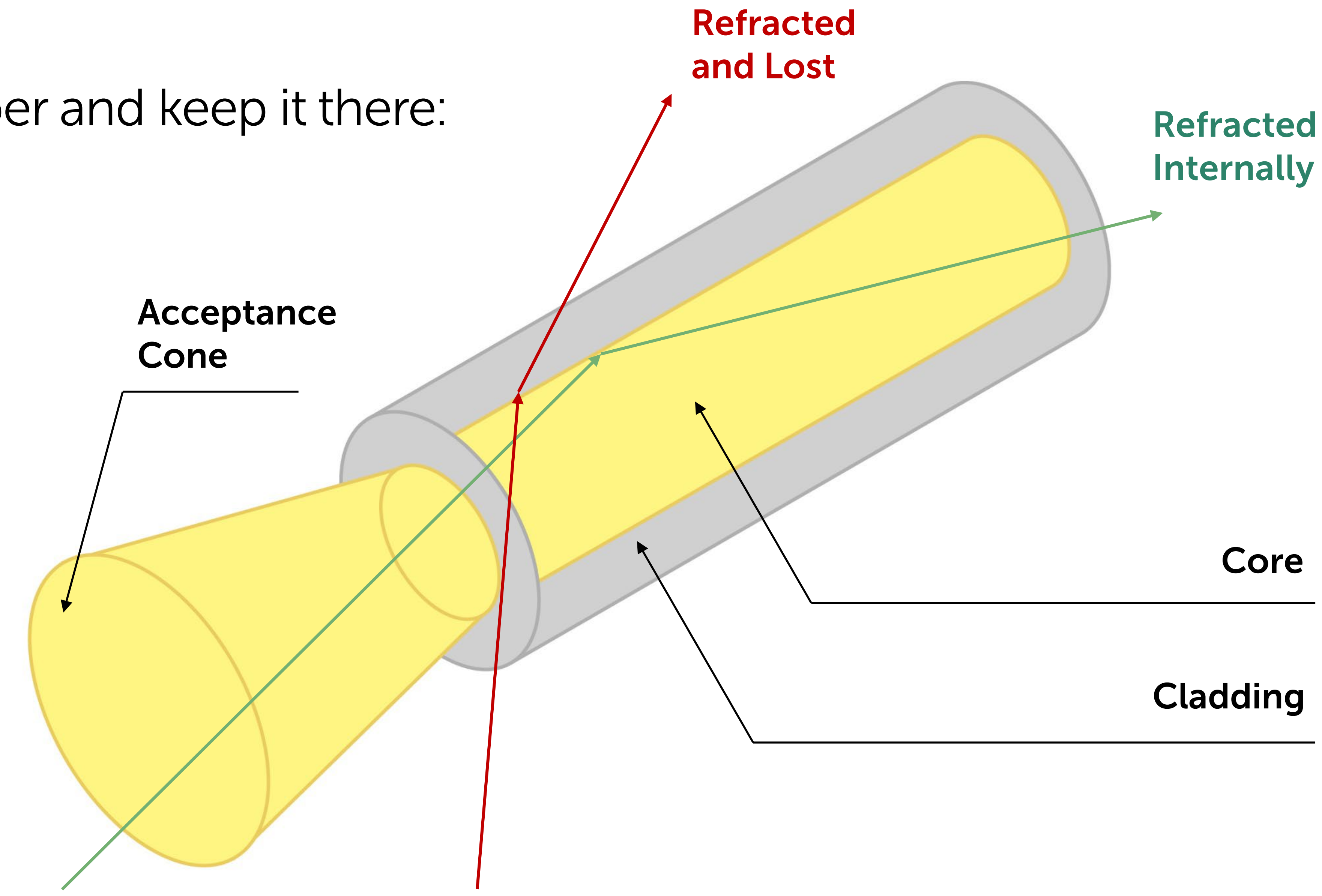
- No Interference -Immune to electromagnetic interference (EMI) and radio frequency interference (RFI) so there’s no “crosstalk” as with copper cables

- More Secure - Difficult to tap

How Does it Work?

"Refracted" = fancy word meaning "bent"

How to couple the light into the fiber and keep it there:



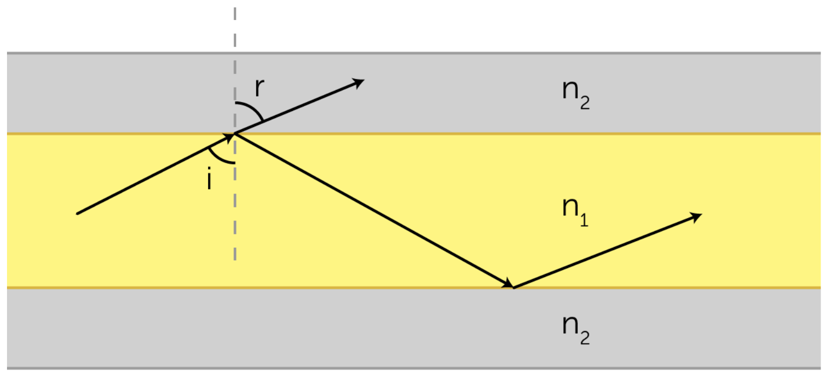
Remember:
Total Internal Reflection

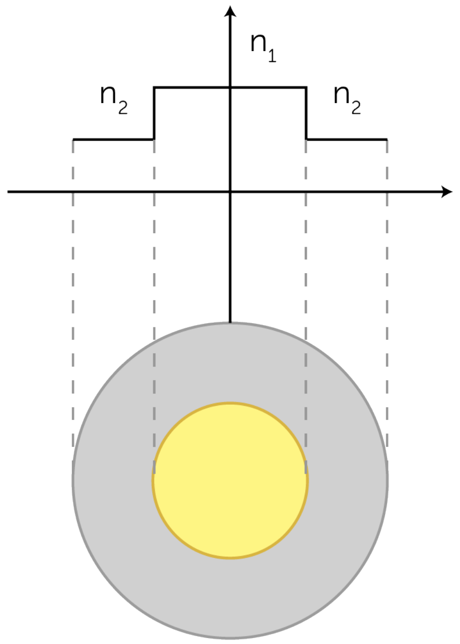
Physics Behind Fiber Optics

- An optical fiber is composed of two concentric layers with different indices of refraction:
  - **Core – refractive index = n_1**
  - **Cladding – refractive index = n_2**

- The index of refraction is a way of measuring the speed of light in a material.

- Light travels fastest in a vacuum.





Refractive index of the medium = [Speed of light in a vacuum / Speed of light in the medium]

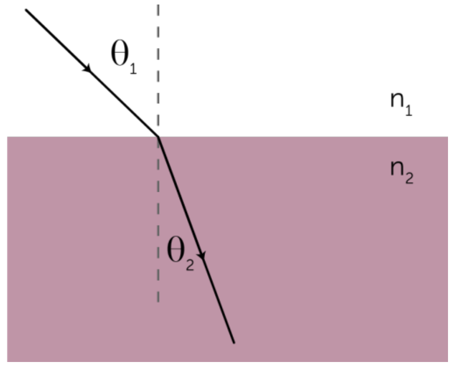
Physics Behind Fiber Optics

Snell's Law

Discovered by Willebrord Snell in 1621.

A relationship relating the index of refraction in a given a medium and incident light angle to the index of refraction in the new medium and the refracted light angle.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

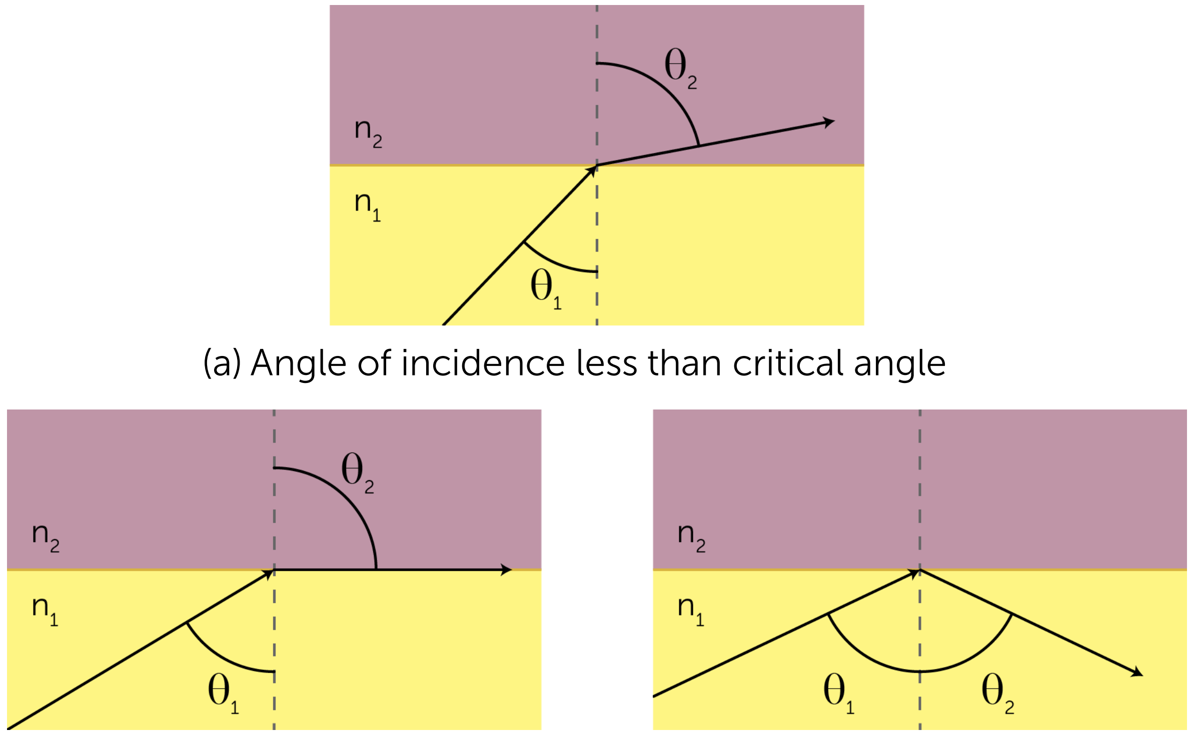


n_1: index of refraction of medium 1
n_2: index of refraction of medium 2

θ_1: the angle of light in medium 1
θ_2: the angle of light in medium 2

Light bends towards the normal when going from a medium with a smaller index of refraction to a larger index of refraction. (Light will have the smaller angle in the medium with the greater index of refraction).

Refraction & Total Internal Reflection



(a) Angle of incidence less than critical angle

(b) Angle of incidence equal to critical angle

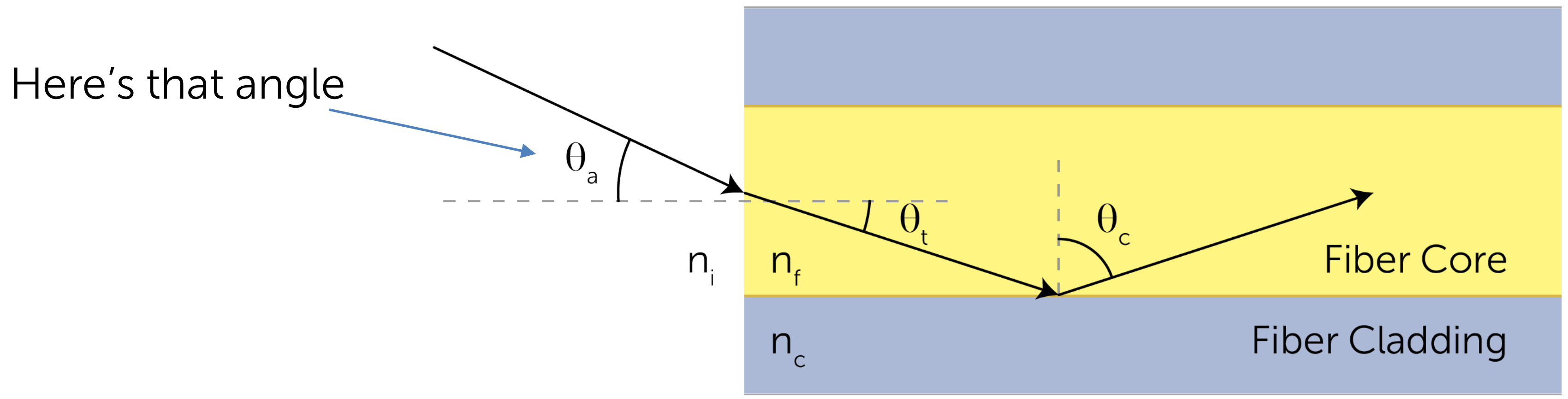
(c) Angle of incidence greater than critical angle

Physics Behind Fiber Optics

Using Snell's Law, we can determine an angle that's really important:

- If light enters the fiber core at or below this angle, then it will be reflected down the core
- And, the light will continue to be reflected down the core

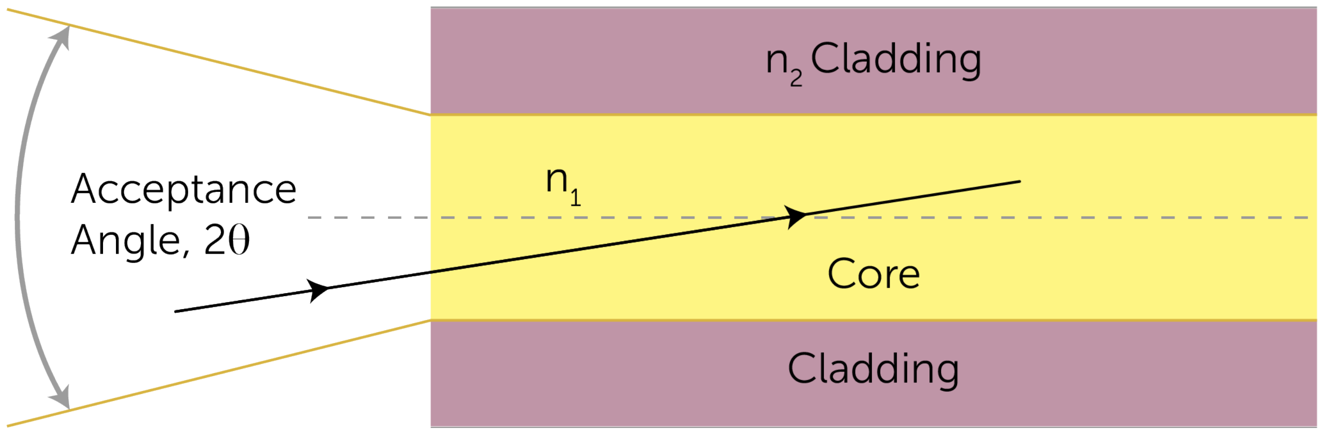
➔ That is, there will be "total internal reflection"



Physics Behind Fiber Optics

We call that "really important angle" the "Acceptance Angle"

- **Acceptance angle** = The maximum angle at which a ray of light will enter the core and propagate through it in a zigzag pattern



Physics Behind Fiber Optics

- There are two more important concepts of how optical fiber work that we need to understand

  1. Numerical aperture

  2. Mode field diameter

Let’s look at each…

Physics Behind Fiber Optics

Numerical Aperture

- Recall "acceptance angle" – You understood that concept immediately, didn't you?
  - Consider that a laser needs to inject light into a fiber within that angle
    - Consequently, you might expect that the laser and fiber manufacturers would both find this angle very useful and refer to it routinely
      - ➔ You'd be wrong
- Instead, they use "numerical aperture" (NA)

Physics Behind Fiber Optics

Numerical Aperture, continued

NA is similar to **acceptance angle** in concept

Working definition: A dimensionless number that characterizes the light gathering capability of an optical fiber

- Higher NA → larger acceptance angle → increased ability to gather (or emit) light

Physics Behind Fiber Optics

Numerical Aperture, conclusion

Why use NA and not acceptance angle? Two reasons:

1. Because in single-mode fibers you cannot calculate the acceptance angle using just the indices of refraction for the core and cladding
    - What?! Why? Because the light does not stay in the core alone
        - Instead, it penetrates just a little into the cladding
        - Consequently, the energy of the light is spread out over an area greater than just that of the core
            - We will call this area the “Mode Field” and discuss it real soon

2. Because NA is what fiber manufacturers use (See next slide)

Physics Behind Fiber Optics

Numerical Aperture, illustrated

Extract from Corning's datasheet for its SMF-28® Ultra fiber:

Performance Characterizations

Characterized parameters are typical values.

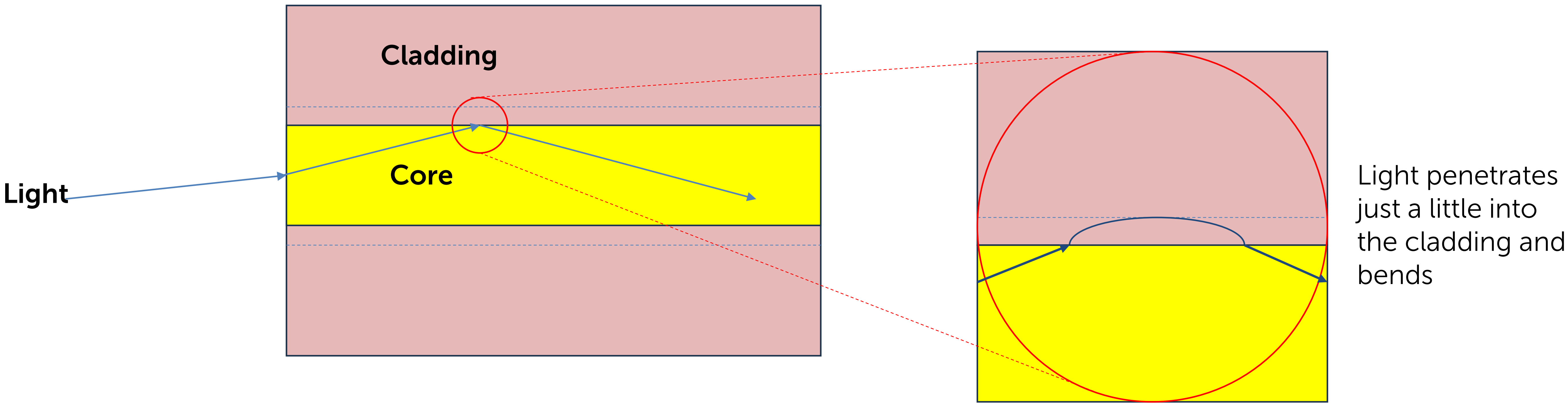
Core Diameter	8.2 µm
Numerical Aperture	0.14 NA is measured at the one percent power level of a one-dimensional far-field scan at 1310 nm.
Effective Group Index of Refraction (n_{eff})	1310 nm: 1.4676 1550 nm: 1.4682

- You won't find "acceptance angle" on the datasheet
- Value of 0.14 is typical for standard single-mode fiber

Physics Behind Fiber Optics

Mode Field

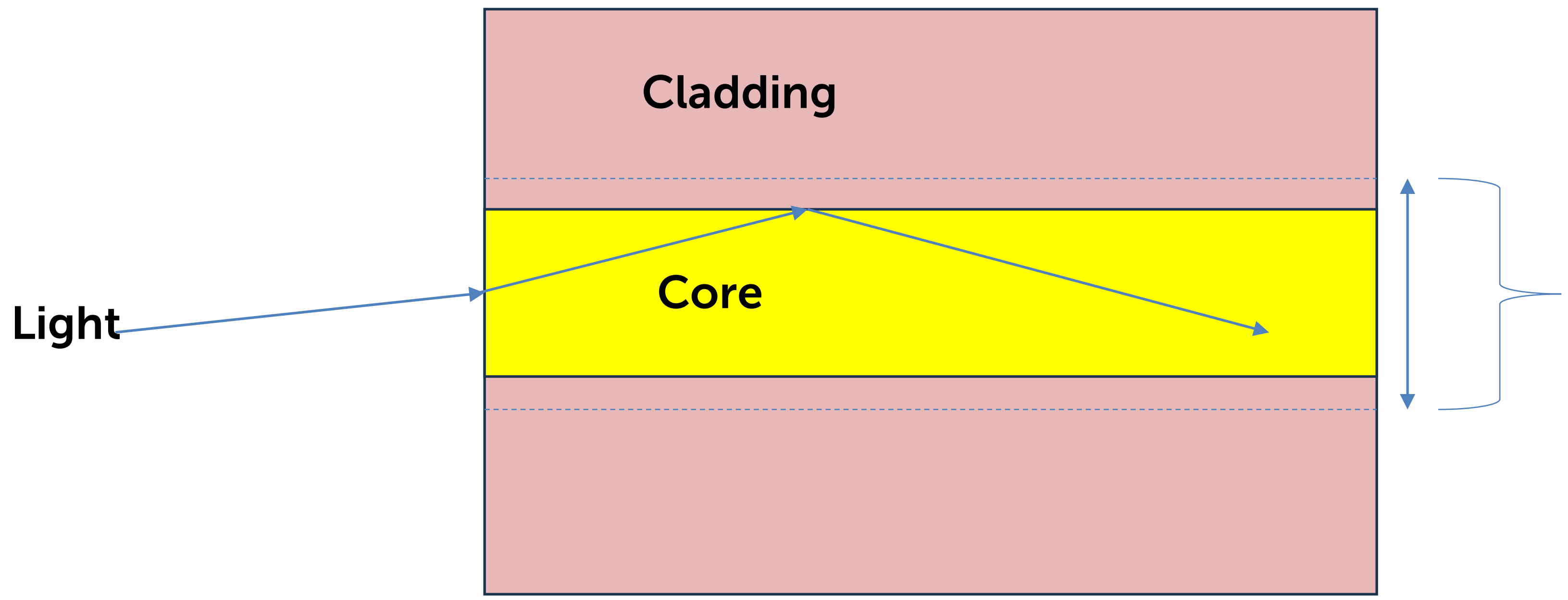
Recall that the light goes outside the core into the cladding… Up close, this looks like…



Physics Behind Fiber Optics

Mode Field Diameter

Recall that the light goes outside the core into the cladding… Up close, this looks like…



Mode Field Diameter is the width of the full area over which the light’s energy is distributed

- Unit is micron (μm)

Physics Behind Fiber Optics

Mode Field Diameter, illustrated

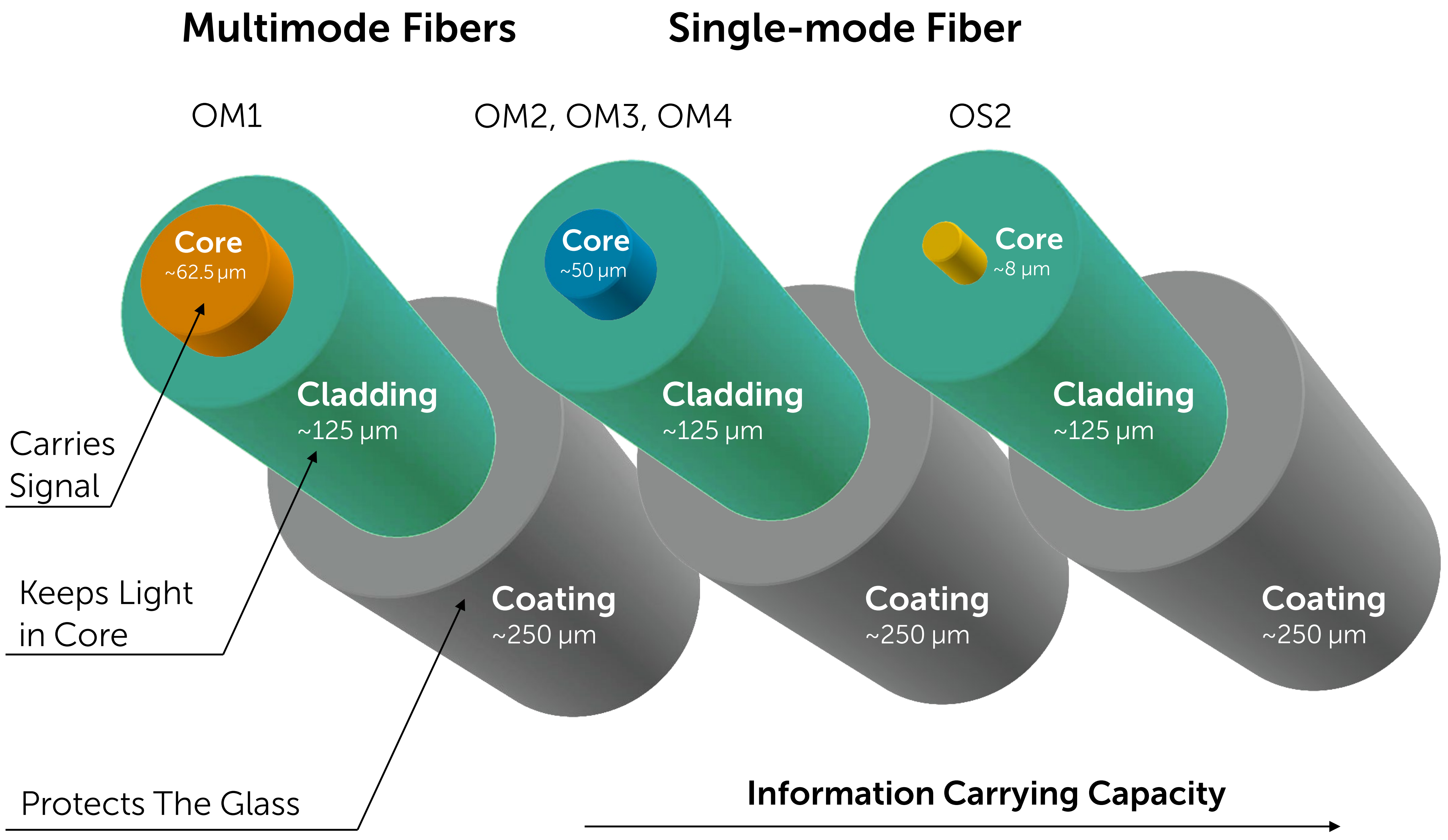
Back to Corning's datasheet for its SMF-28® Ultra fiber:

Mode Field Diameter

Wavelength (nm)	Mode Field Diameter (µm)
1310	9.2 ± 0.4
1550	10.4 ± 0.5

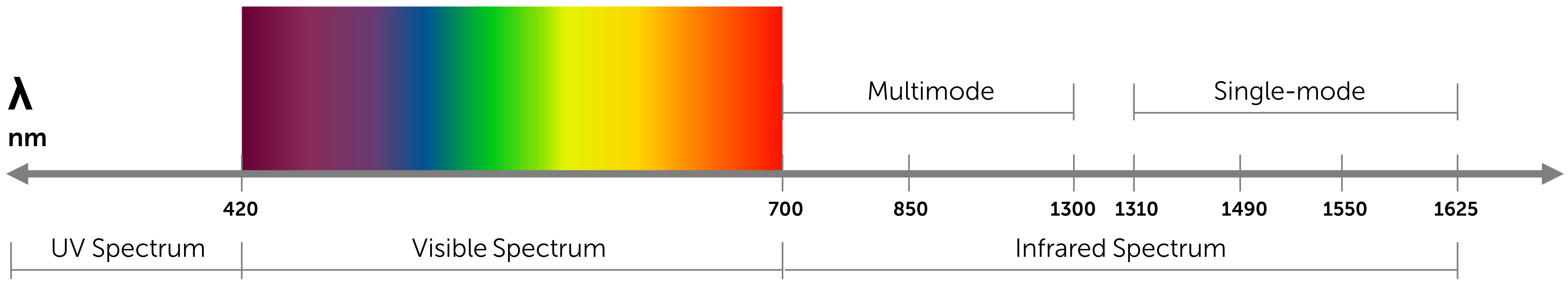
- Notice that MFD varies by wavelength

Basic Types of Fiber



Electromagnetic Spectrum

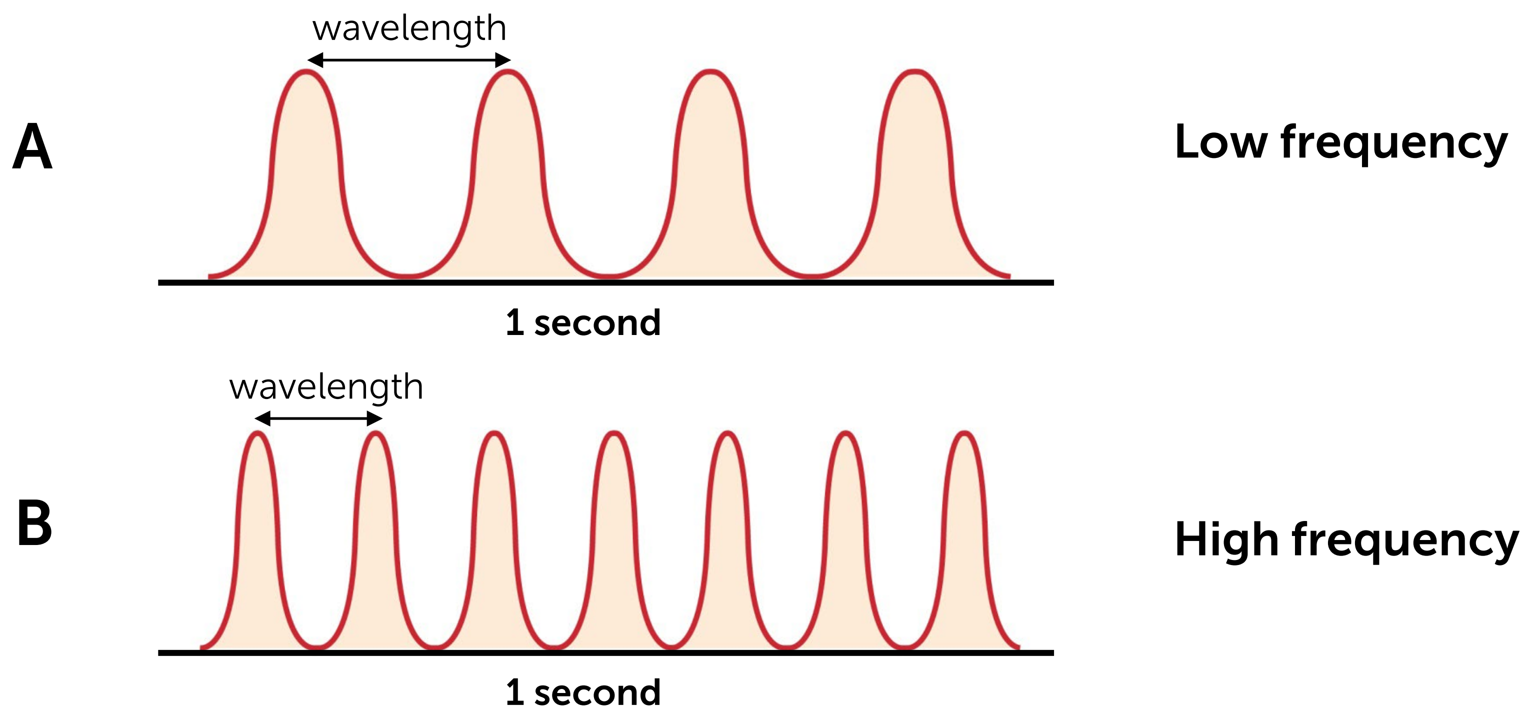
- **Wavelength**



Operating Wavelengths:
850 nm = Short Wave Multimode
1300 nm = Long-Wave Multimode
1310 nm = Traditional Standard Single-mode
1490 nm = FTTx (Downstream Data/Voice)
1550 nm = Long-Wave Single-mode
1625 nm = Extra Long-Wave Single-mode (WDM)

Properties of Electromagnetic Signals

- **Wavelength**
  - The distance between identical points on a wave (typically expressed in nanometers or “nm”)



“B” represents a shorter wavelength than “A”

Fiber Performance Factors

The two key optical fiber performance factors are:

- **Attenuation — loss of signal strength**
  - Expressed in decibels of power lost (dB)
  - Intrinsic Attenuation
  - Extrinsic Attenuation
  - Impacts ability to reach the receiver with sufficient power
  - A 3dB loss in power equates to a 50% loss from what you started with

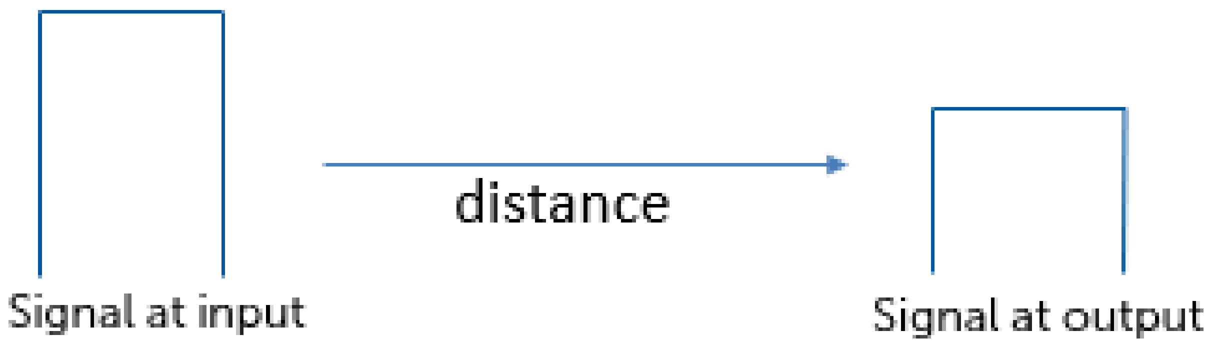
- **Dispersion — spreading of signal pulses**
  - Modal Dispersion
  - Chromatic Dispersion
  - Polarization Mode Dispersion
  - Impacts the ability to distinguish discreet signal pulses

Fiber Performance

Attenuation = Loss of signal strength

- The single most important fiber performance specification for the user
- Loss of power per unit distance

Attenuation: The loss of power over distance (dB/km)



Maximum Attenuation

Wavelength (nm)	Maximum Value* (dB/km)
1310	≤ 0.32
1383**	≤ 0.32
1490	≤ 0.21
1550	≤ 0.18
1625	≤ 0.20

Fiber Performance

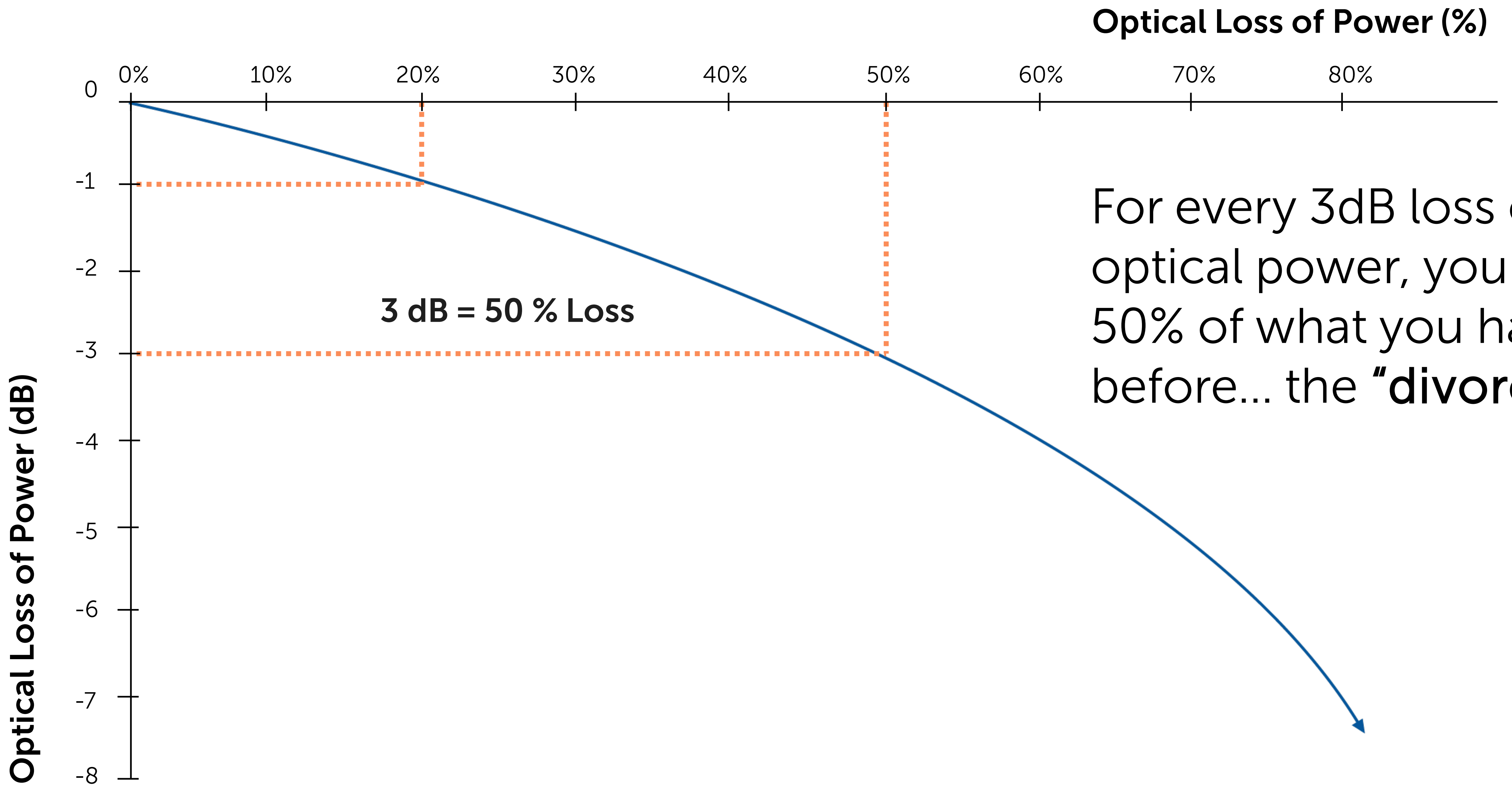
Splicing/Connectors/Splitters

- Each splice point or connector down line will create a db loss
- Fusion splicing is the most efficient with a db loss of .05 or lower
- Mechanical connectors are convenient because they can be disconnected and reconnected as needed, but can cause a db loss between .2 – 1
- Optical splitters used for a fiber to the home build also causes large losses of light

Splitter Ratio	1:2	1:4	1:8	1:16	1:32	1:64	1:128
Loss (dB)	4	7	11	15	18	21	24

Fiber Performance

Impact of dB Loss

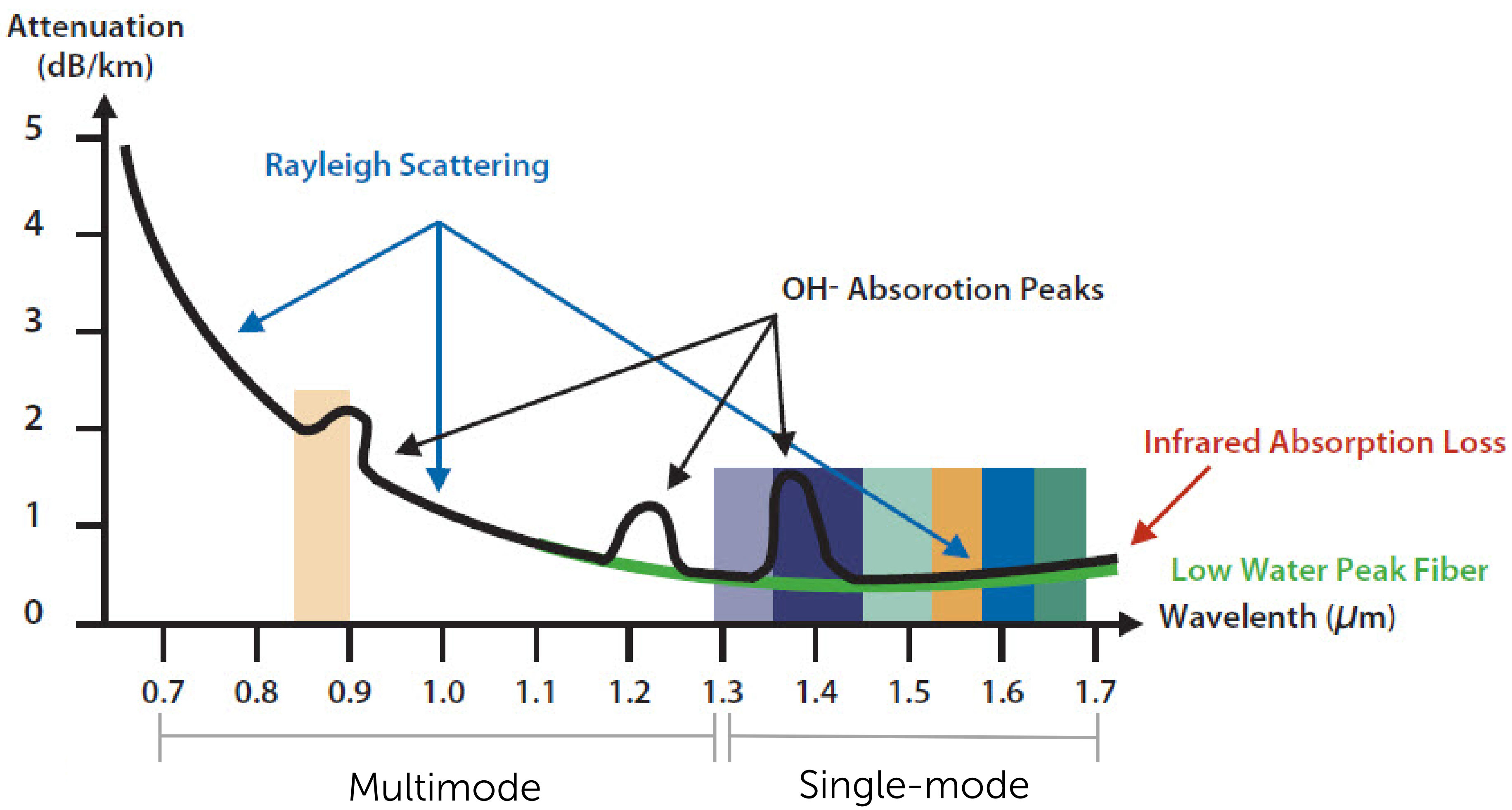


For every 3dB loss of optical power, you lose 50% of what you had before... the **"divorce law"**

Fiber Performance

Intrinsic Attenuation – loss of signal strength

1. Caused by substances within the optical fiber
2. Expressed in decibels of power lost (dB)
3. Impacts ability to reach the receiver with sufficient power
4. A 3dB loss in power equates to a 50% loss from what you started with

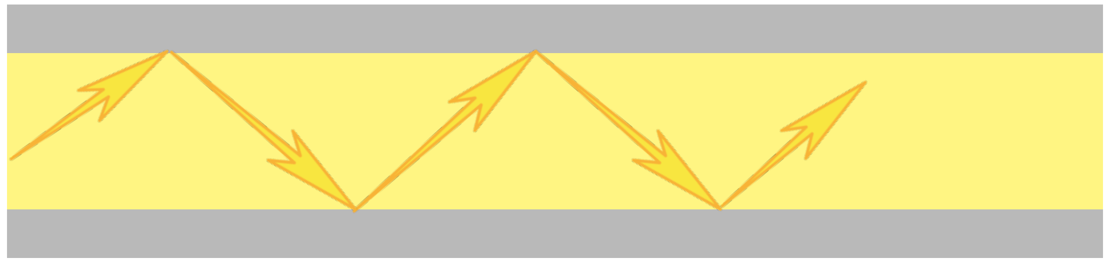


Fiber attenuation as a function of wavelength

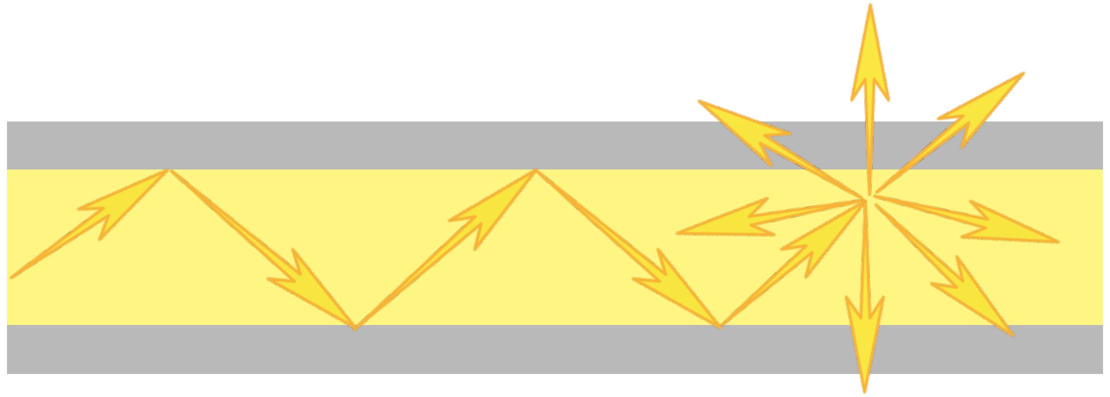
Fiber Performance

- **Intrinsic Attenuation**
  - Internal — Can’t be affected by outside influences

- **Absorption**
  - A photon will give up kinetic energy when it interacts with an electron and excites it to a higher energy level.



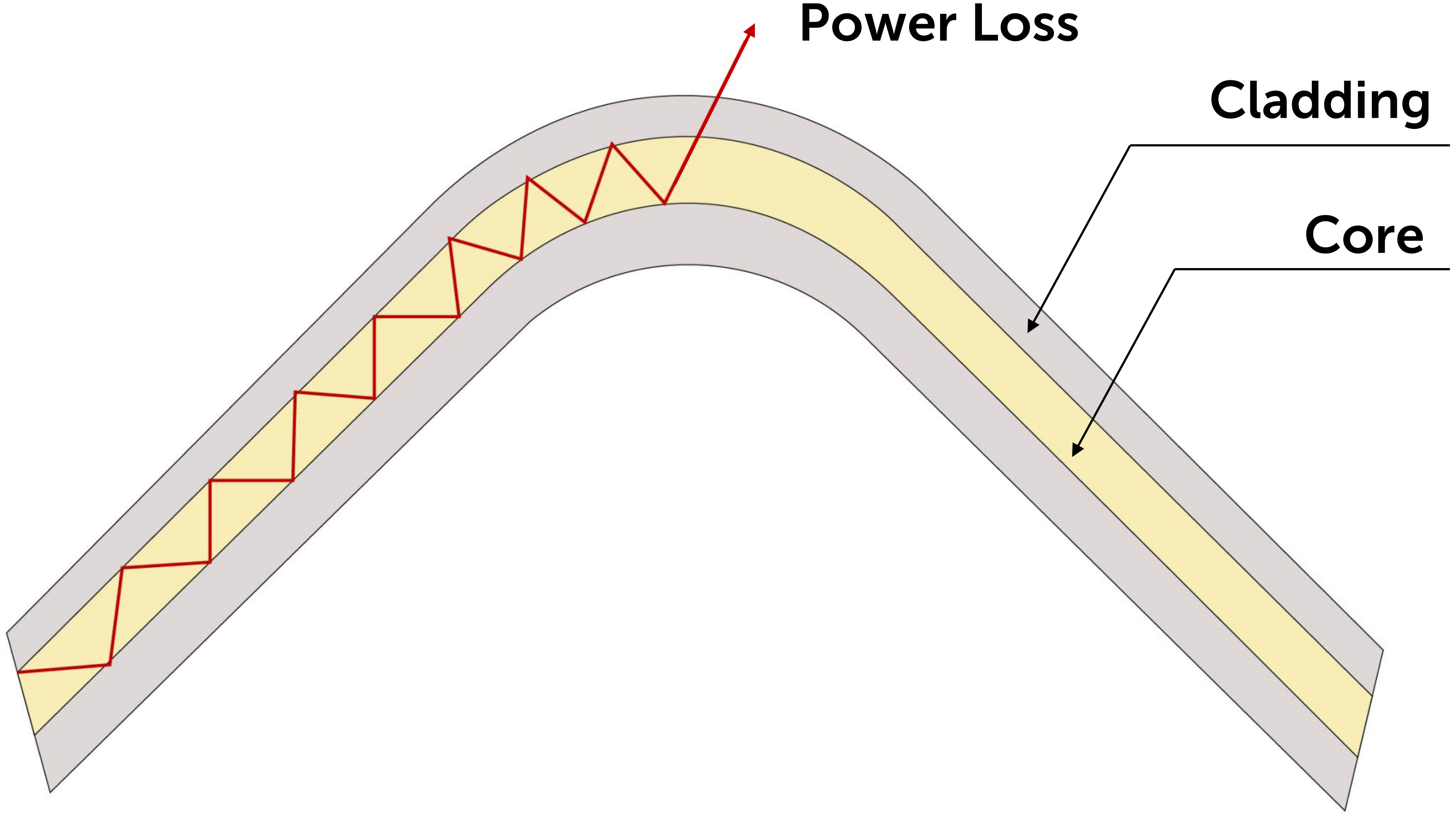
- **Rayleigh Scattering**
  - Light is scattered as the result of inhomogeneities and defects in the glass. These imperfections are microscopic and happen during production.



Fiber Performance

Extrinsic attenuation

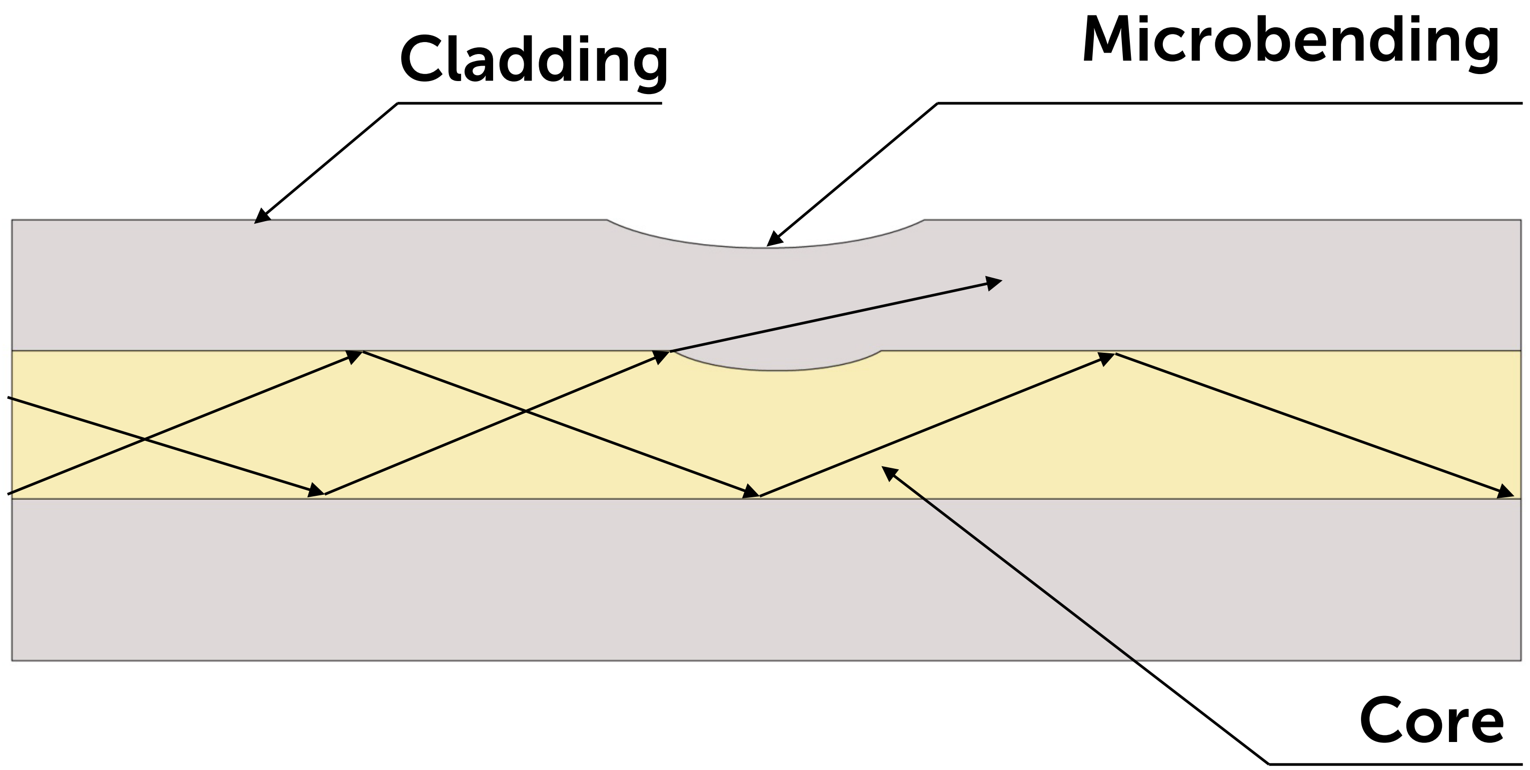
- **Macrobend**
  - Caused by a large-scale bend of the fiber which is visible and less than the safe minimum bending radius.
  - The loss is generally reversible once the bend is removed.



Fiber Performance

Extrinsic attenuation

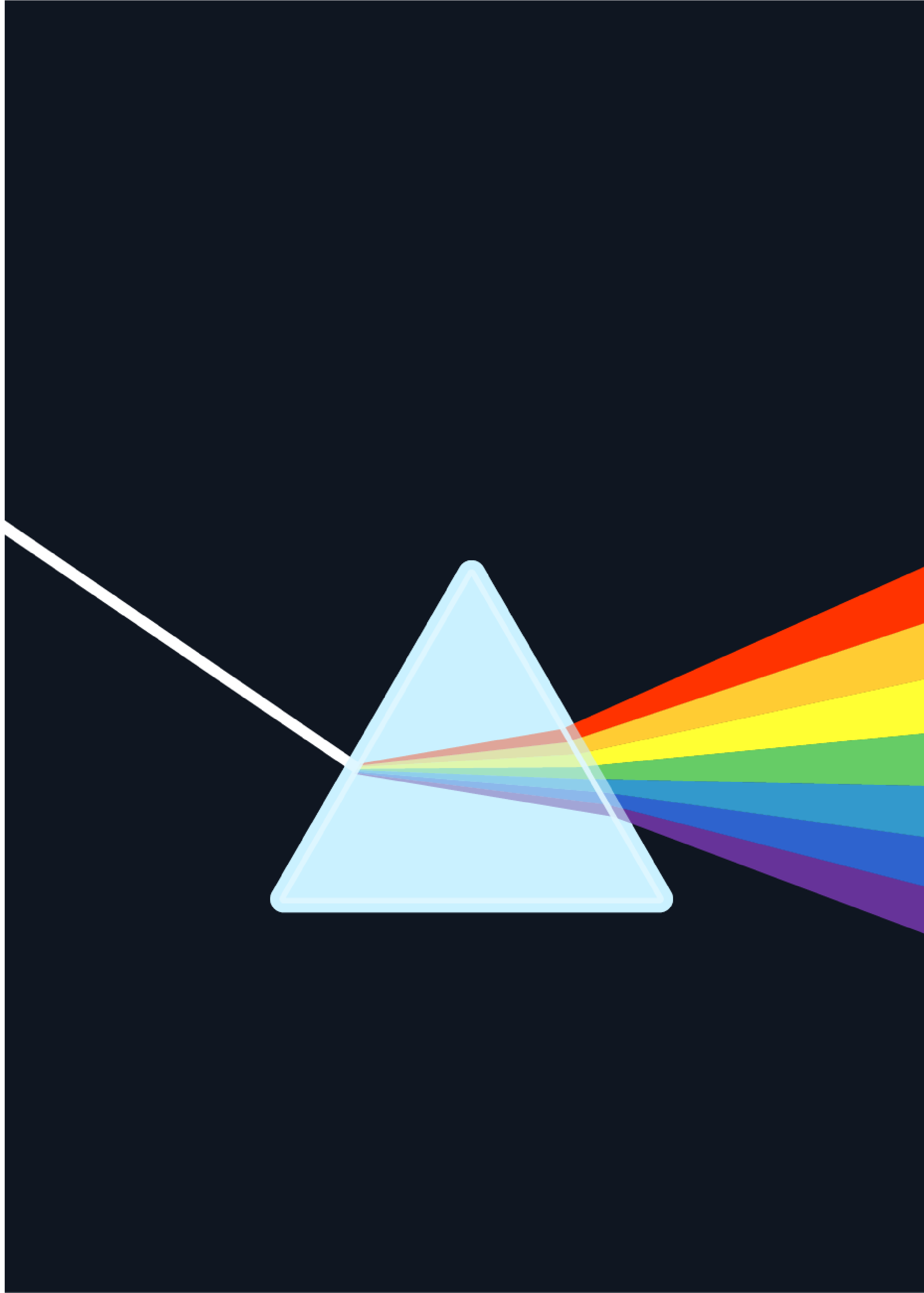
- **Microbend**
  - Small-scale distortions in the geometry of the fiber core
  - Can be caused during the manufacturing process, or by “cross-overs” in a tube
  - Can be reversible, unless the core has been permanently deformed



Dispersion

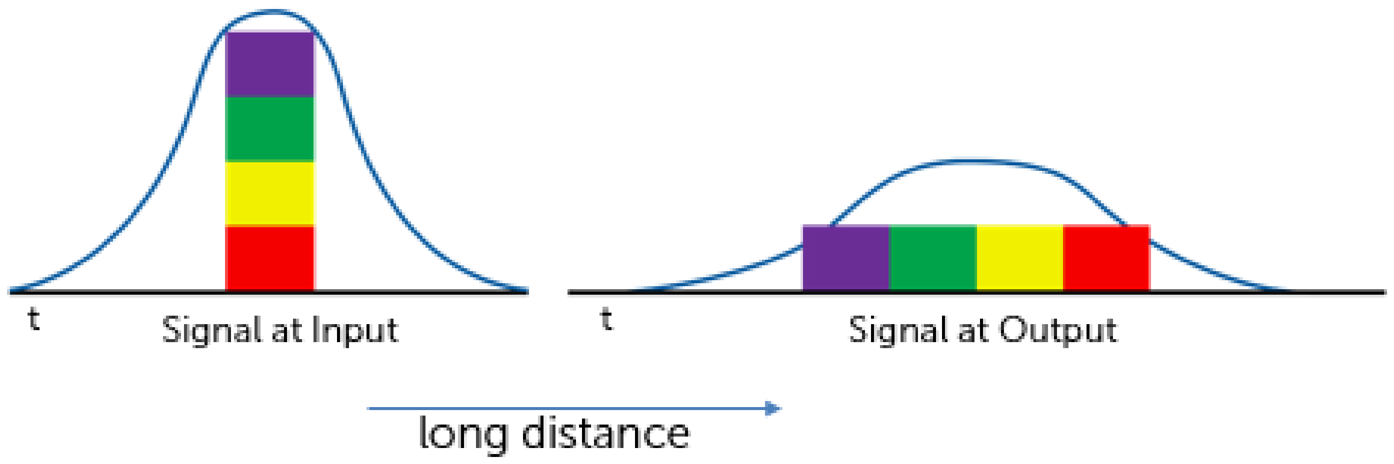
- Dispersion is the spreading out of a light pulse as it travels through the fiber

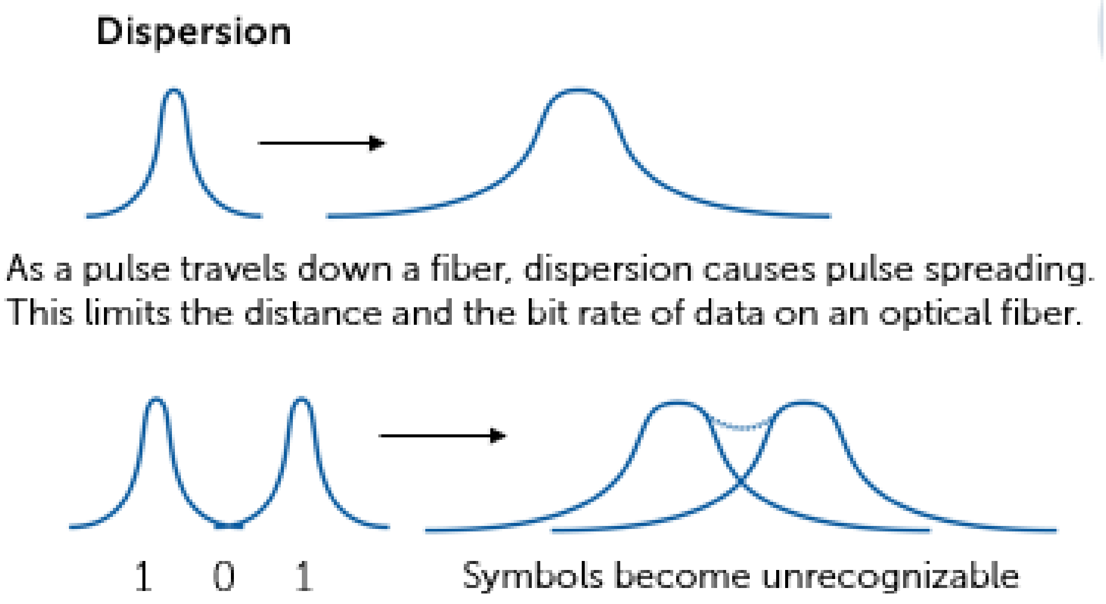
- **Three types of dispersion:**
  1. Chromatic Dispersion
  2. Modal Dispersion
  3. Polarization Mode Dispersion (PMD)



Dispersion

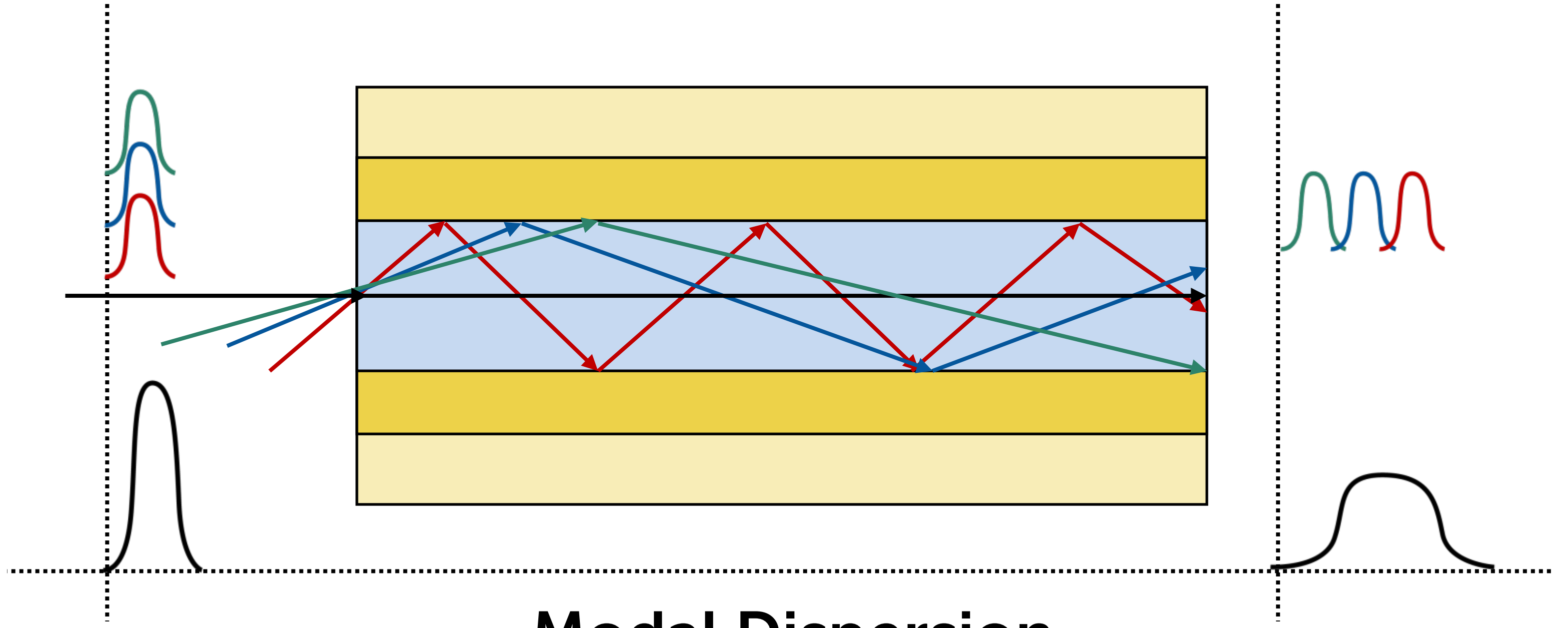
- **Chromatic Dispersion**
  - The phenomenon of pulse spreading due to the different colors of light (wavelengths) travelling at slightly different speeds through the fiber.





Dispersion

- **Modal (a.k.a. Intermodal) Dispersion in Multimode (MM) Fiber**
  - Spreading of signal pulses as they travel down the fiber (May cause pulses to overlap as they arrive at the receiver, and cause bit errors)

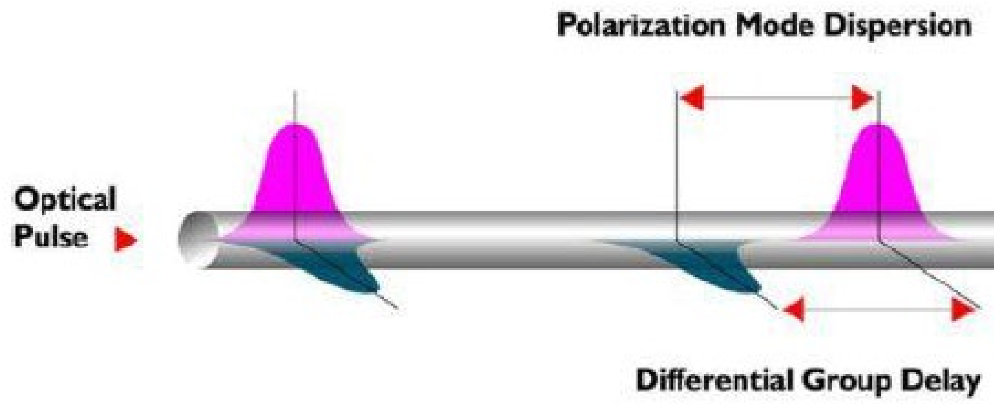


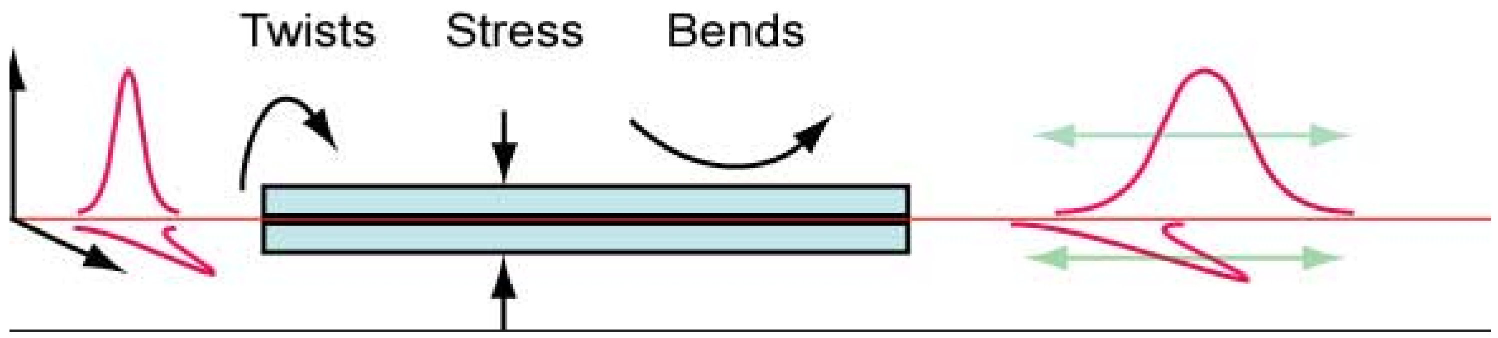
Modal Dispersion

Dispersion

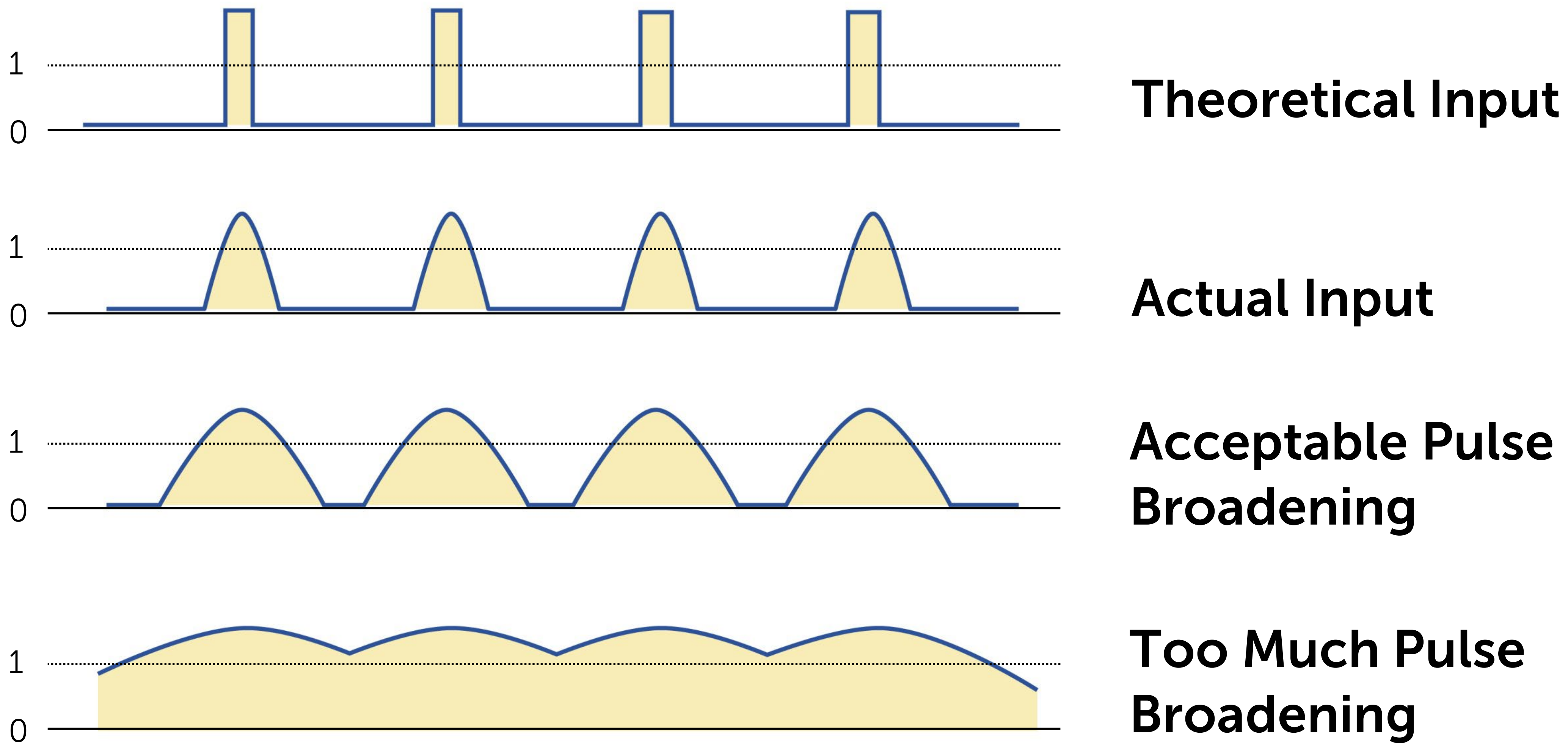
- **Polarization Mode Dispersion (PMD)**
  - Single-Mode optical fiber consists of one propagation mode, which in turn, is comprised of two orthogonal polarization modes.
  - Asymmetrical differences in the fiber introduce small refractive index variations between the two modes. This is known as birefringence.

- **Caused by ovality of core due to:**
  - Manufacturing Process
  - Internal Stress (Cabling)
  - External Stress
  - Not Discovered until the 1990's
  - Becomes critical as transmission speeds increase





Dispersion Leads to Bit Error



Applying Performance Factors

- **Attenuation – recall: loss of signal strength**
  - Very much affected by cable manufacturing processes
  - Can’t get better (lower), only worse (higher)
- Typical **maximum**, **individual**, **final** (“cabled”) values for single-mode fiber:
  - At 1310 and 1550 nm = 0.35 and 0.25
  - Best practice = 0.34 and 0.20 (and 0.22 at 1625 nm)
- Typical maximum, individual, final values for multimode fiber:
  - At 850 and 1300 nm = 3.5 and 1.5
  - Best practice = ? and ?

Applying Performance Factors

- **Dispersion – recall: spreading of signal pulses**
  - Overwhelmingly from the fiber manufacturing process
  - Specified by the fiber supplier
  - Therefore, typically not affected by the cable design or manufacturing processes
  - "It is what it is" in a finished cable (unless a cable is very poorly made?)
  - Finished cable limits not used

Advanced Fiber Types

Increases in bandwidth demand and transmission distances have led to two special types of single-mode (SM) fiber:

1. **Non-Zero Dispersion Shifted (NZDS) SM Fiber**

   Recall "Chromatic Dispersion"

   - You can correct for dispersion much like eyeglasses do

   The two best known NZDS SM fibers are Corning® LEAF® and OFS TrueWave® RS

   - Standard is ITU-T G.655

   Designed for use with Dense Wavelength Division Multiplexing (DWDM) to boost bandwidth

   Compare:

   - Standard SM fiber: Commonly 10Gbit/s, as much as 40 Gbit/s
   - NZDS SM fiber: 100 Gbit/s and more!

   Or, to enable transmission over longer distances

   Compare:

   - Standard SM fiber: 60 – 90 miles
   - NZDS SM fiber: up to 250 miles

Advanced Fiber Types

2. Cut-Off Shifted SM Fiber or "G654" SM Fiber

An "ultra-low-loss" type fiber

Originally, used for transoceanic submarine cables

Current G.654.E fiber allows even higher data rates: 400 Gbit/s up to 1 Tbit/s

Longer distances too: Up to 900 km (560 miles)

Optimized for use between 1550 – 1625 nm

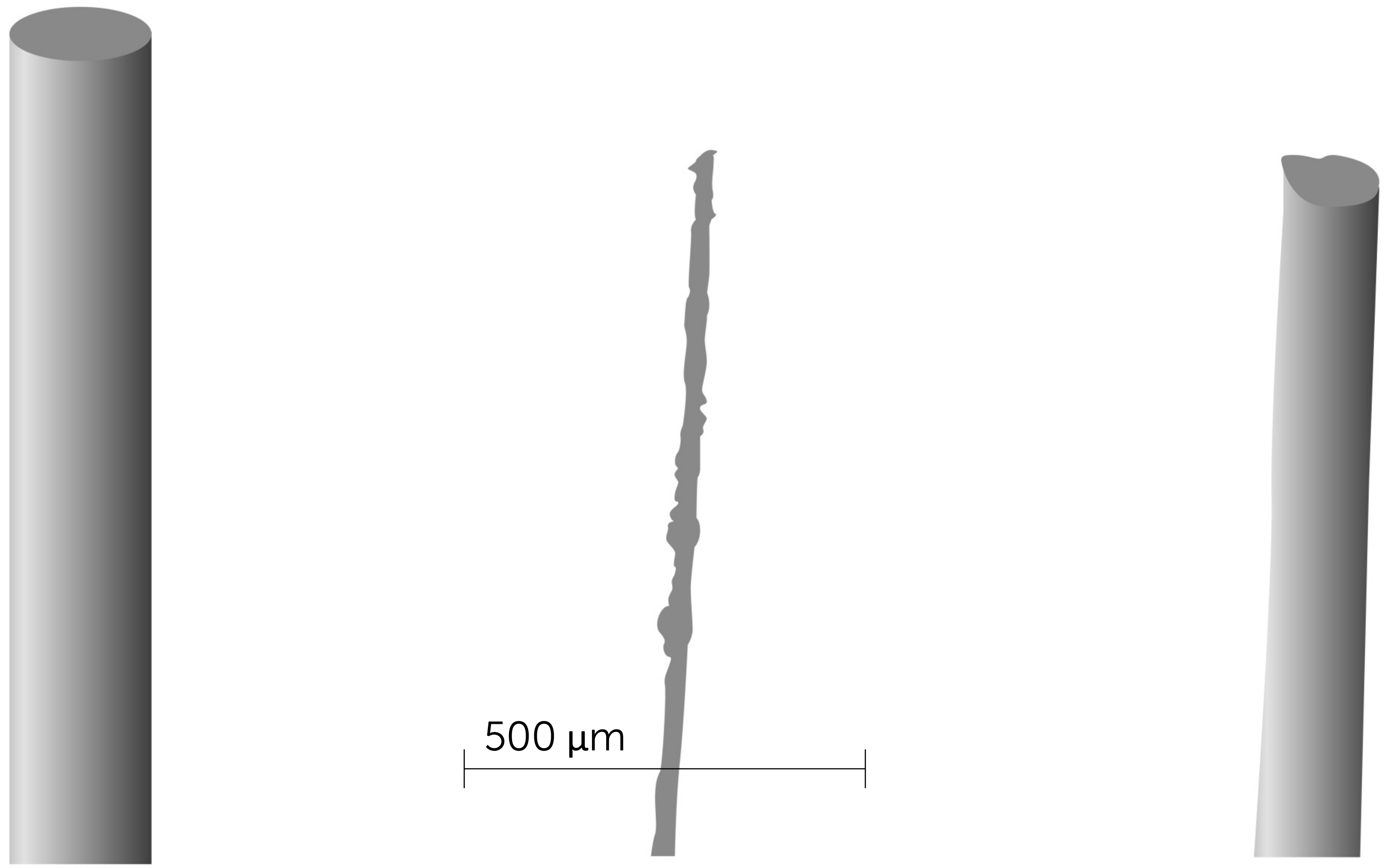
Typical attenuation limits:

- 1550nm $\leq$ 0.17dB/km
- 1625nm $\leq$ 0.19dB/km

An example of this fiber type is Corning® TXF™

In closing, just for fun!

Relative size of optical fiber



Optical fiber
(glass only)

Fiberglass from ceiling tile

Human hair

Incab

Thank you!

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