

# Everything You Always Wanted to Know About Optical Networking – But Were Afraid to Ask

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# Purpose of This Tutorial

- Why give a talk about optical networking?
  - The Internet as an industry is largely based around fiber.
  - Yet many router jockeys don't get enough exposure to it.
  - This leads to a wide variety of confusion, misconceptions, and errors when working with fiber optic networks.
- Will this presentation make me an optical engineer?
  - Probably not.
  - The purpose of this tutorial is to touch on a little of every topic, from the mundane to the unusual.
  - But it helps to have a basic understanding of these topics, even if you aren't designing fiber networks.

# **The Basics of Fiber Optic Transmission**

# What is Fiber, and Why Do We Use It?

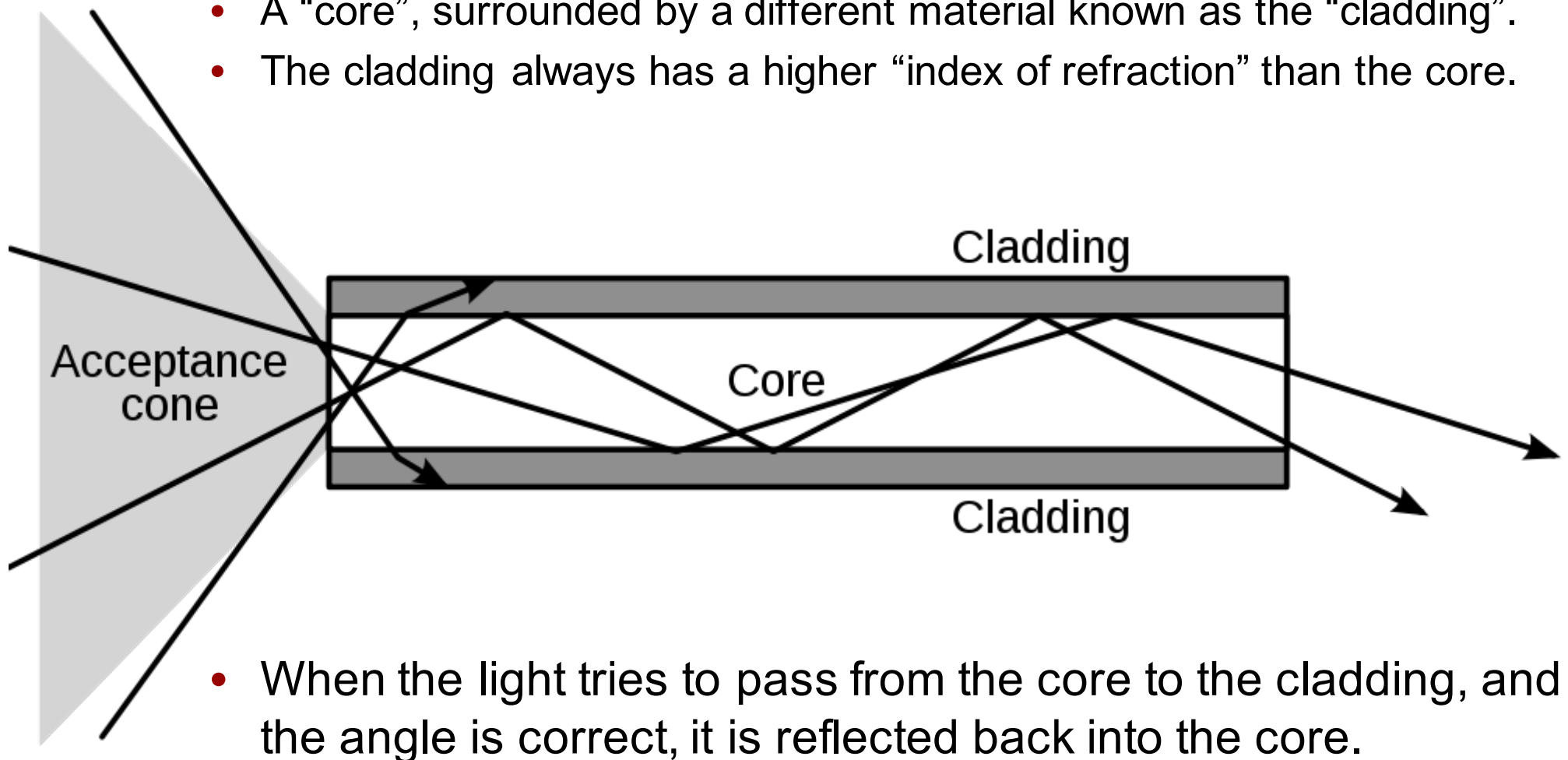
- Fiber is essentially a “waveguide” for light.
  - AKA “light that goes in one end, comes out the other end”.
  - Most commonly made of glass/silica, but can also be plastic.
- Why do we use fiber for communications systems?
  - Fiber is a low-cost and extremely light medium to carry signals.
  - A tremendous amount of information can be encoded into light.
  - Many different signals can be encoded onto the same strand of fiber, using different “forms” and “frequencies” of light.
  - These signals can be carried for very long distances without losing the signal and needing to be regenerated.
  - Technology continues to radically improve what we can do with our existing fiber infrastructure, without digging or disruption.

# Hold it Down Like I'm Giving Lessons in Physics

- A quick recap from Physics class:
  - Light propagating through a vacuum is (theoretically) the maximum speed at which anything in the universe can travel.
    - That speed is 299,792,458 meters per second, otherwise known as “ $c$ ”.
    - For doing shorthand math, you can round this up to 300,000 km/s.
  - But when light passes through materials that **aren't** a perfect vacuum, it actually propagates much slower than this.
    - The speed for a particular material is expressed as a ratio relative to “ $c$ ”, known as that material's “refractive index”.
    - E.g. Water has a refractive index of “1.33”, or 1.33x slower than “ $c$ ”.
  - And when light tries to pass from one medium to another with a different index of refraction, a reflection can occur instead.
    - This is why you see a reflection when you look up from under water.

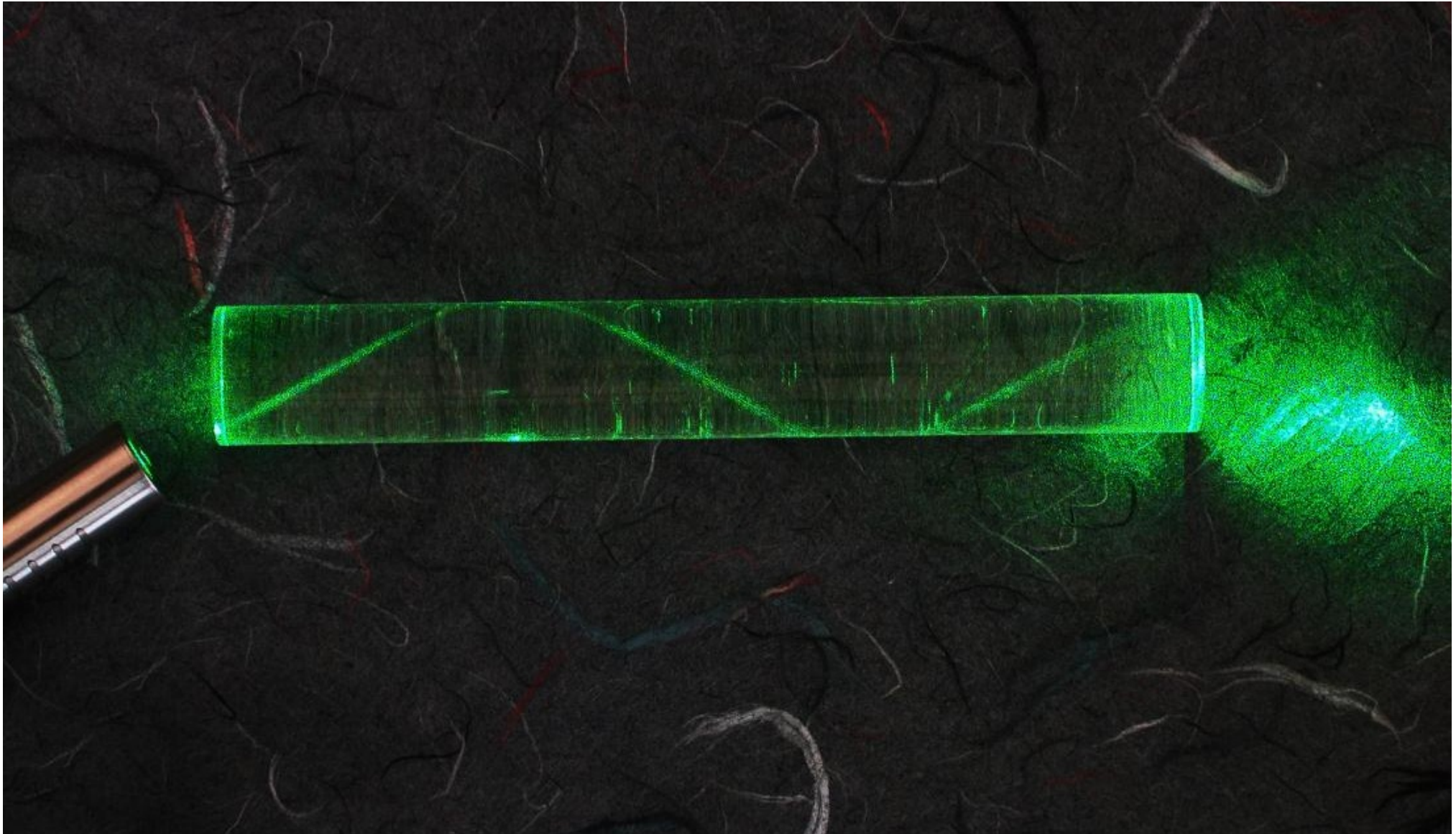
# Fiber Works by “Total Internal Reflection”

- Fiber optic cables are internally composed of two layers.
  - A “core”, surrounded by a different material known as the “cladding”.
  - The cladding always has a higher “index of refraction” than the core.

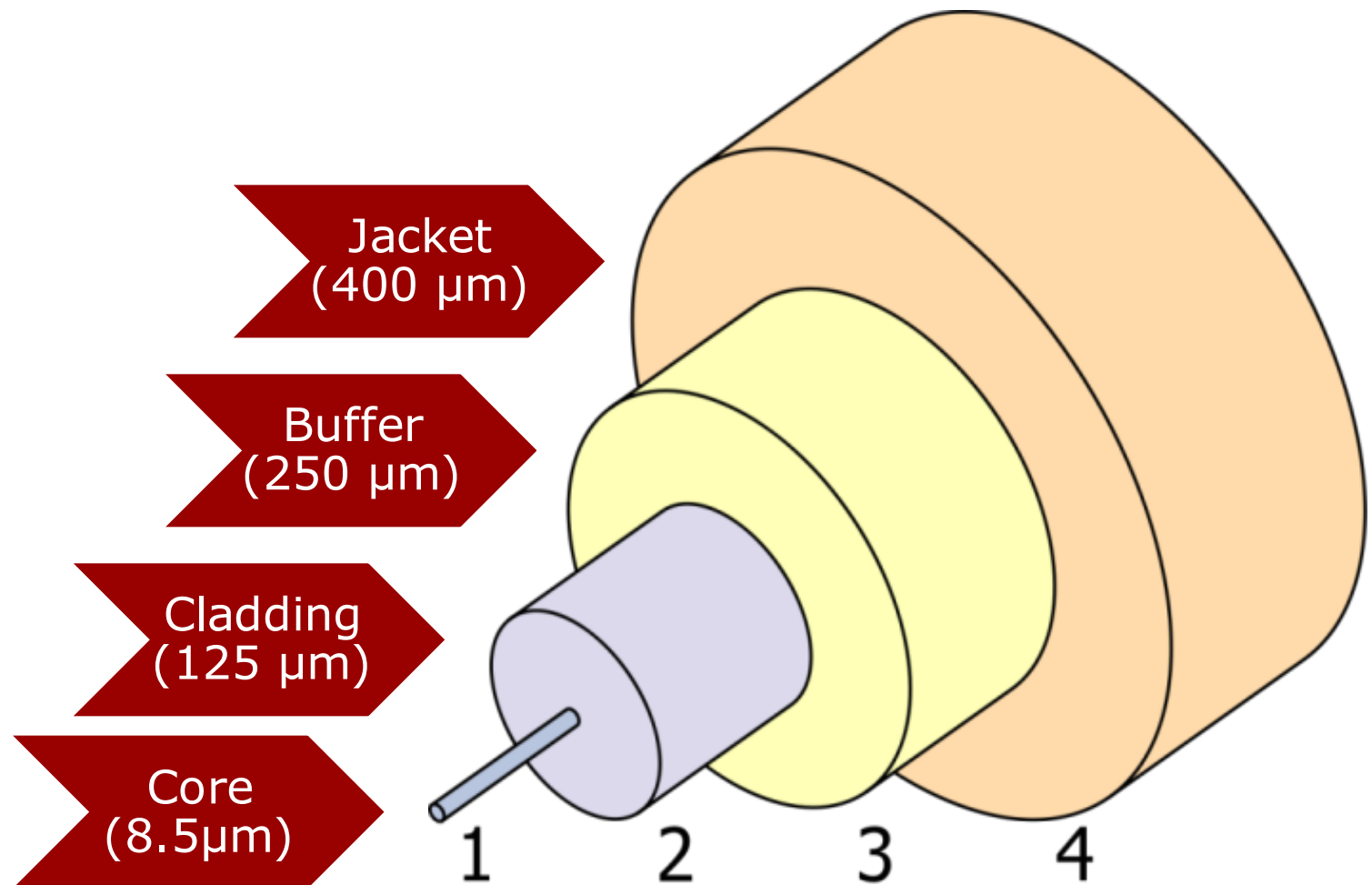


- When the light tries to pass from the core to the cladding, and the angle is correct, it is reflected back into the core.

# Demonstration Using a Laser Pointer



# The Inside of a Common Fiber Cable





# What Do We Actually Transmit Over Fiber?

- Most basic systems operate in “duplex” (as a pair of fibers)
  - One fiber used to transmit a signal, the other to receive one.
  - Using this technique, no advanced optical components are required.
  - But more advanced systems can “multiplex” both transmit and receive onto a single strand, doubling capacity.
- The digital signals must be encoded into analog pulses of light
  - Historically “Intensity Modulation with Direct Detection” (IMDD)
    - The most common method of which is “Non-Return to Zero” (NRZ).
    - Which is really just a fancy way of saying “bright for a 1, dim for a 0”.
    - These are then modulated many tens of thousands of times per second.
    - This technique was used for essentially all optical signals up to 40Gbps.
  - The receiving side “sees” these pulses of light, and translates them back into electrical digital signals.

# **Multi-Mode vs Single Mode Fiber**

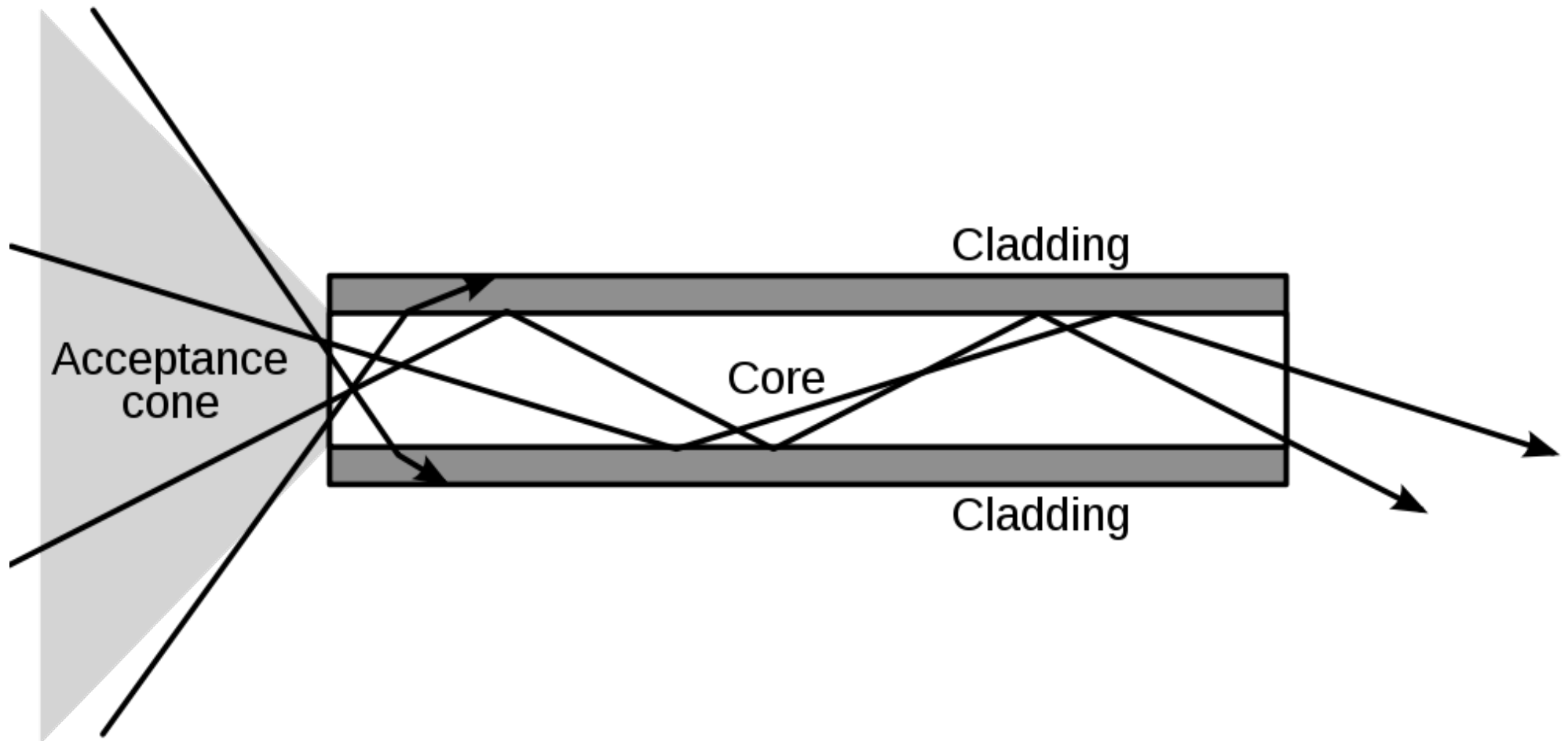
# Multi-Mode Fiber

- Multi-Mode Fiber
  - Usually found as orange fiber jackets inside the datacenter.
  - Two common core sizes, 62.5 microns ( $\mu\text{m}$ ) and 50 $\mu\text{m}$ .
  - Typically carries signals at 850nm, but sometimes 1310nm.
- Specifically designed for use with “cheaper” light sources.
  - The “wide” core lets you use cheaper, less precisely focused, aimed, and/or calibrated light sources on each end.
- But this comes at the expense of long-distance reach.
  - “Modal distortions” significantly limit the maximum distances.
  - Typically limited to between “tens to hundreds” of meters.
- Recently augmented with OM3 and OM4 “laser optimized” standards for achieving similar distances for 10/40/100G.

# Single Mode Fiber

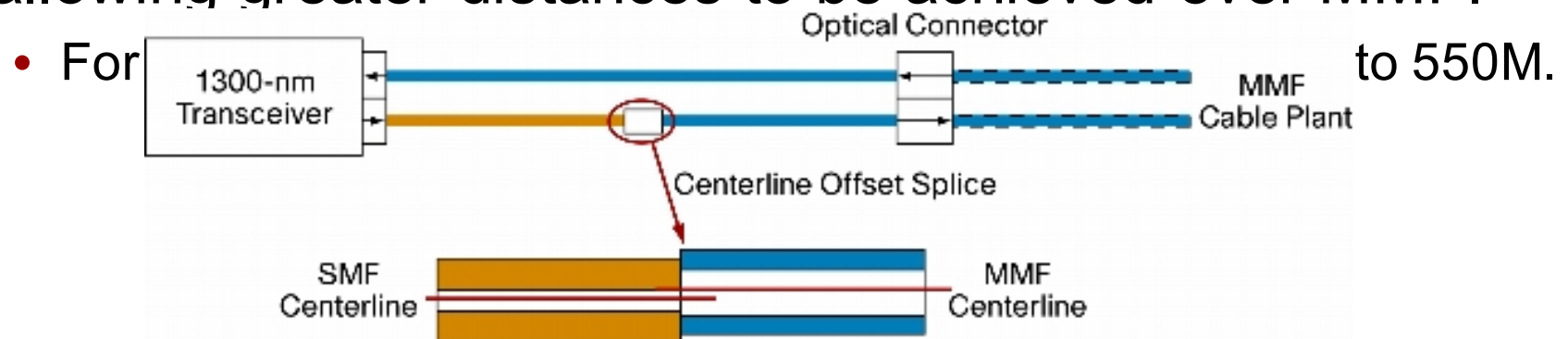
- Single Mode Fiber (SMF)
  - Has a core size of between 8-10 microns ( $\mu\text{m}$ )
  - No inherent distance limitations caused by modal distortions
    - Can easily support distances of several thousand kilometers, with appropriate amplification and dispersion compensation.
  - But requires more expensive laser light sources.
    - Typically in the 1270nm – 1625nm range.
  - “Classic” Single-Mode Fiber is frequently called SMF-28
    - Which is actually a Corning product name.
    - But a wide variety of specialty fibers have been developed as well.
    - Low Water Peak Fiber (LWPF), Dispersion Shifted Fiber (DSF), Non-Zero Dispersion Shifted Fiber (NZDSF), etc, etc, etc.

# Modal Distortion in Multimode Fiber



# Mode Conditioning Cables

- What happens to a “narrow” laser inside “wide” MMF?
  - It gets bounced around, causing modal distortions.
- This can be improved with a Mode Conditioning Cable
  - A manufactured splice between the SMF and MMF cables, precisely setting the angle of the light sent into the MMF.
  - By controlling the angle, modal distortions can be reduced, allowing greater distances to be achieved over MMF.



# What Happens When You...?

Transmit Optic Type	Multimode Fiber	Single-mode Fiber
LED Source (traditional 850nm/SX Gigabit optics, FDDI, etc)	Limited by modal distortion, achieves a few hundred meters depending on the exact signal and type of fiber.	Limited by attenuation, diffuse signal doesn't fit into the narrow fiber core, you may achieve a few meters at best.
Laser Source (LX/LR, ER, ZX/ZR, etc)	Limited by modal distortion, but should perform as well or better than an LED source. Not recommended, but it will "work" with a dB hit if you pass a long-reach signal through a short stretch of MMF (patch cable, etc).	Achieves maximum distance determined by signal attenuation and other criteria (10km, 40km, 80km, etc).

# Optical Networking Terms and Concepts



# Optical Power

- What is optical power?
  - Quite simply, the brightness (or “intensity”) of light.
  - As light travels through fiber, some energy is lost.
    - Absorbed by glass particles and converted into heat;
    - Or scattered by microscopic imperfections in the fiber.
  - This loss of intensity is called “attenuation”.
- We typically measure optical power in “Decibels”
  - A decibel (dB, 1/10<sup>th</sup> of a Bel) is a logarithmic-scale unit expressing the relationship between two values.
  - The decibel is a “dimensionless-unit”, meaning it does not express an actual physical measurement on its own.

# Optical Power and the Decibel

- A decibel is simply a ratio between two values
  - 0 dB is no change, +3 dB is double, -3 dB is half, etc.
  - To express an absolute value (i.e. an actual light level), it must be compared to a known reference value.
- In optical networking, this is typically the “dBm”.
  - That is, a decibel relative to 1 milliwatt (mW) of power.
  - 0 dBm is 1 mW, 3 dBm is 2 mW, -3 dBm is 0.5mW, etc.
  - So what does this make 0mW? Negative Infinity dBm.
  - Confusion between dB and dBm is one of the most common mistakes when working with optical networks!

# Optical Power and the Decibel

- Why do we measure light with the Decibel?
  - Light, like sound, follows the inverse square law.
    - The signal is inversely proportional to the distance squared.
      - A signal travels distance  $X$  and loses half of its intensity.
      - The signal travels another distance  $X$  and loses another half.
      - After  $2X$  only 25% remains, after  $3X$  only 12.5% remains.
  - Using a logarithmic scale simplifies the calculations.
    - A 3dB change is approximately half/double the original signal.
    - In the example above, there is a 3dB loss per distance  $X$ .
    - At distance  $2X$  there is 6dB of loss, at distance  $3X$  it is 9dB.
    - This allows us to use simple addition/subtraction when measuring gains/losses.

# Decibel to Power Conversion Table

**Table 1** - Decibel to Power Conversion

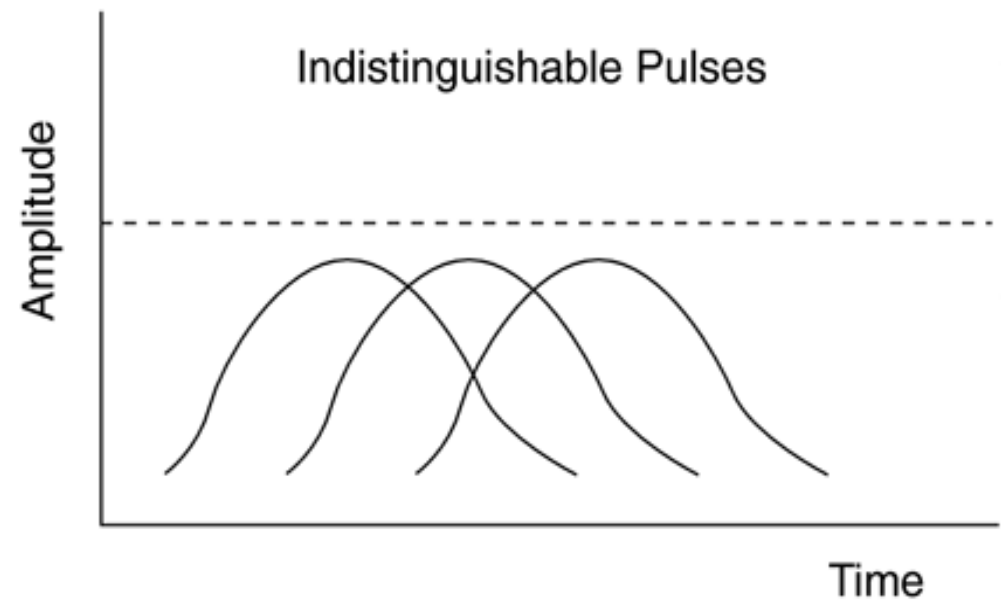
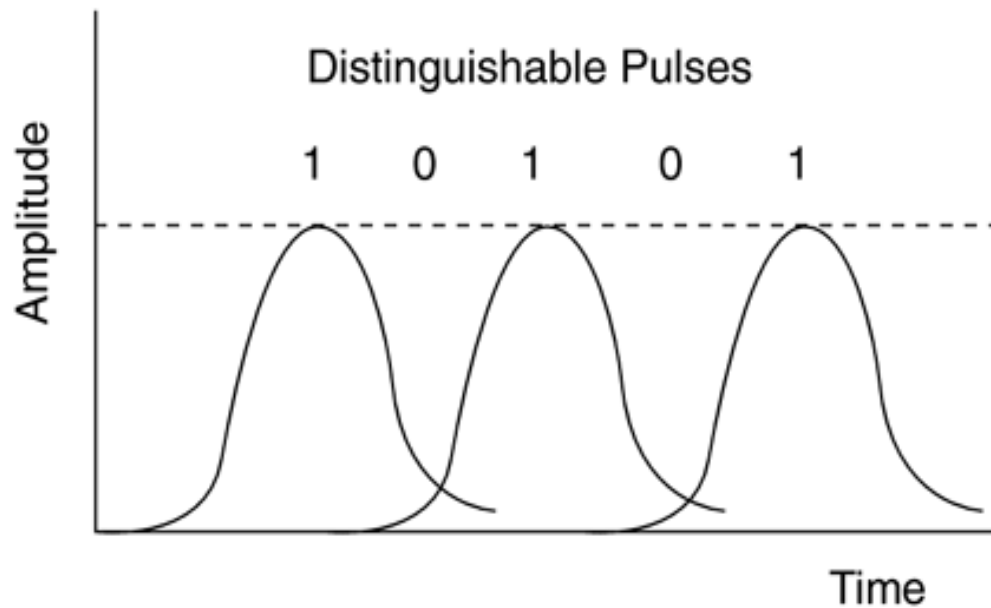
dB (loss)	Power Out as a % of Power In	% of Power Lost	Remarks
1	79%	21%	---
2	63%	37%	---
3	50%	50%	1/2 the power
4	40%	60%	---
5	32%	68%	---
6	25%	75%	1/4 the power
7	20%	80%	1/5 the power
8	16%	84%	1/6 the power
9	12%	88%	1/8 the power
10	10%	90%	1/10 the power
11	8%	92%	1/12 the power
12	6.3%	93.7%	1/16 the power
13	5%	95%	1/20 the power
14	4%	96%	1/25 the power
15	3.2%	96.8%	1/30 the power
16	2.5%	97.5%	1/40 the power
17	2%	98%	1/50 the power
18	1.6%	98.4%	1/60 the power
19	1.3%	98.7%	1/80 the power
20	1%	99%	1/100 the power
25	0.3%	99.7%	1/300 the power
30	0.1%	99.9%	1/1000 the power
40	0.01%	99.99%	1/10,000 the power
50	0.001%	99.999%	1/100,000 the power

# Dispersion

- Dispersion simply means “to spread out”.
  - In optical networking, this results in signal degradation.
- There are two main types of dispersion to deal with
  - Chromatic Dispersion
    - Different frequencies of light propagate through a non-vacuum at slightly different speeds. This is why optical prisms work.
    - But if one part of an optical signal travels faster than the other part, the signal will eventually “smear out” over long distances.
  - Polarization Mode Dispersion
    - Caused by imperfection in shape of the fiber (not perfectly round).
    - One polarization of light propagates faster than the other.
    - Older fiber is particularly affected, may get worse with age.

# The Effects of Dispersion

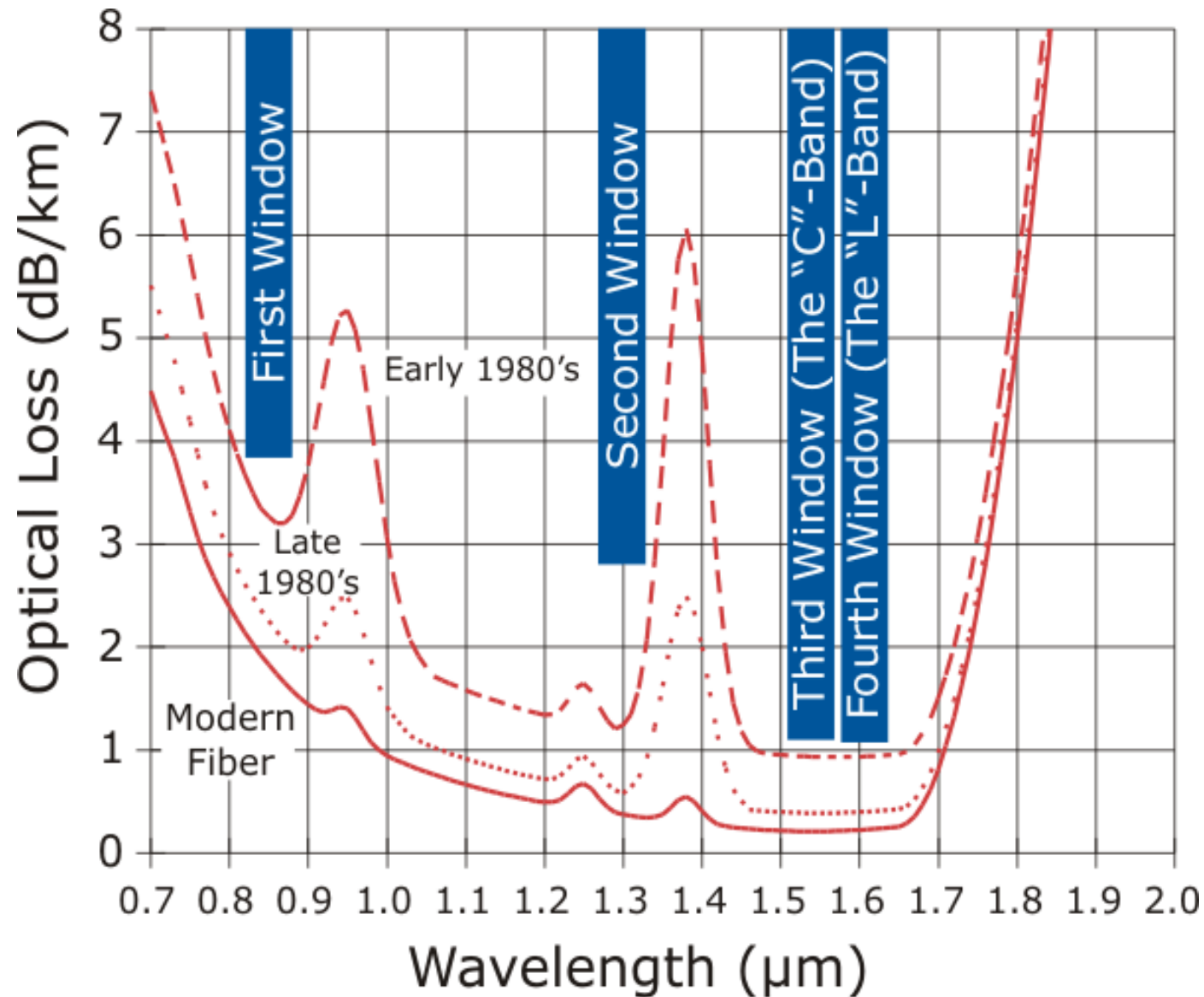
- As the signal is dispersed, it is no longer distinguishable as individual pulses at the receiver.



# Fiber Optic Transmission Bands

- There are several frequency “windows” available
  - 850nm – The First Window
    - Highest attenuation, only used for short reach applications today.
  - 1310nm – The Second Window (O-band)
    - The point of zero dispersion on classic SMF, but high attenuation.
    - Primarily used for medium-reach applications (up to 10km) today.
  - 1550nm – Third Window (C-band)
    - Stands for “conventional band”, covers 1525nm – 1565nm.
    - Has the lowest rate of attenuation over SMF.
    - Used for almost all long-reach and DWDM applications today.
  - Forth Window (L-band)
    - Stands for “long band”, covers 1570nm – 1610nm.

# Fiber Optic Transmission Bands

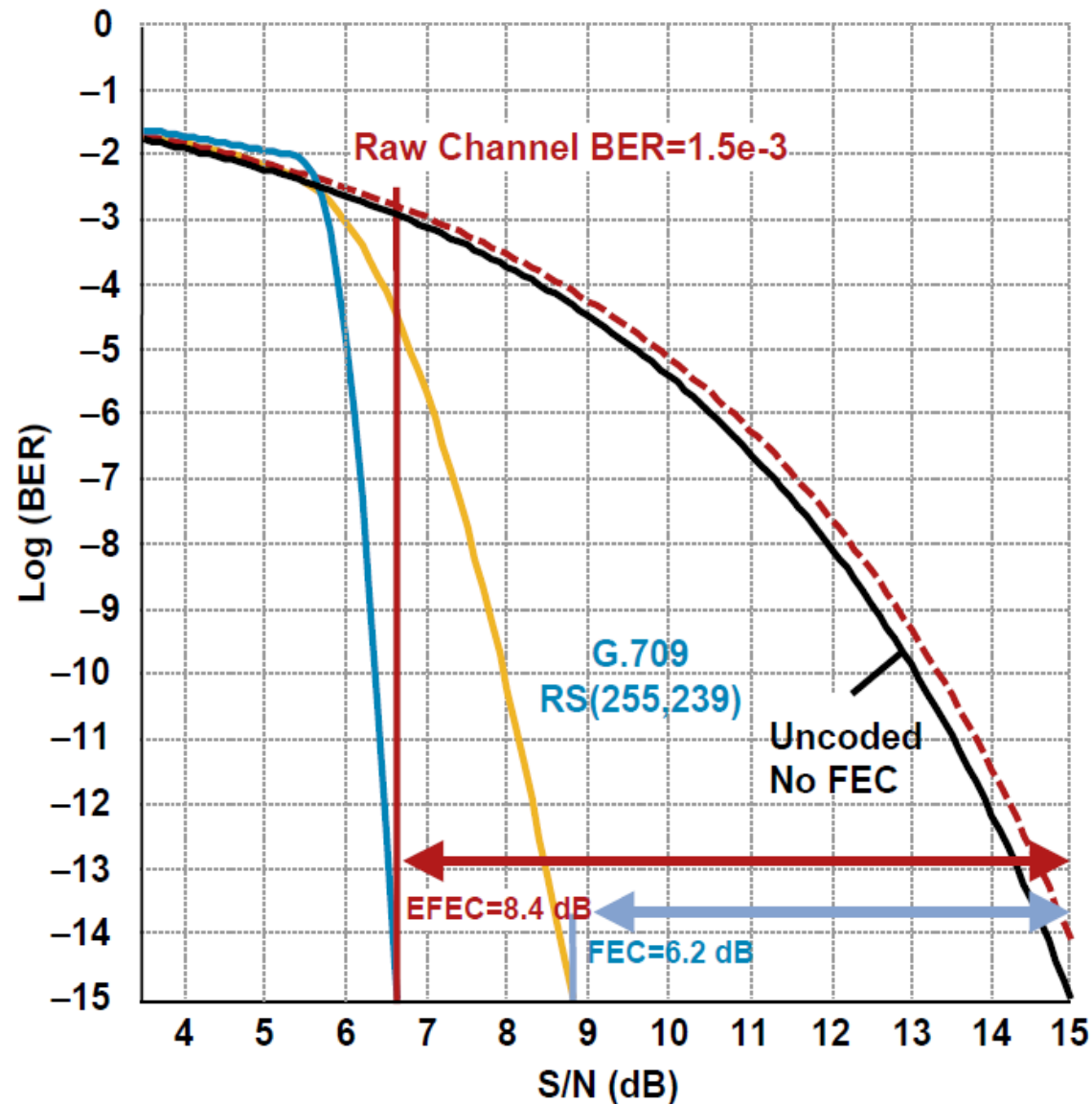




# Forward Error Correction

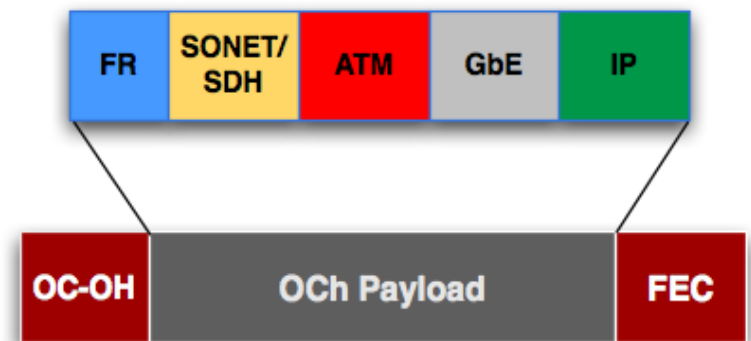
- Forward Error Correction
  - Adds extra/redundant information to a transmission so that a receiver can “recover” from small errors.
  - Think of it like RAID5 for your wavelengths. Even if you lose some bits, you can still recover them computationally.
  - FEC works by extending the receiver sensitivity to levels which would normally have too many bit errors to use.
  - Using clever math, padding a 10.325Gbps signal to 11Gbps (7% overhead) can extend a 80km wavelength to 120km or beyond, at the same or better bit error rate.
  - Typically implemented as a digital “wrapper” (G.709) on an existing signal.

# The Benefits of Forward Error Correction



# OTN Digital Wrapper Technology (G.709)

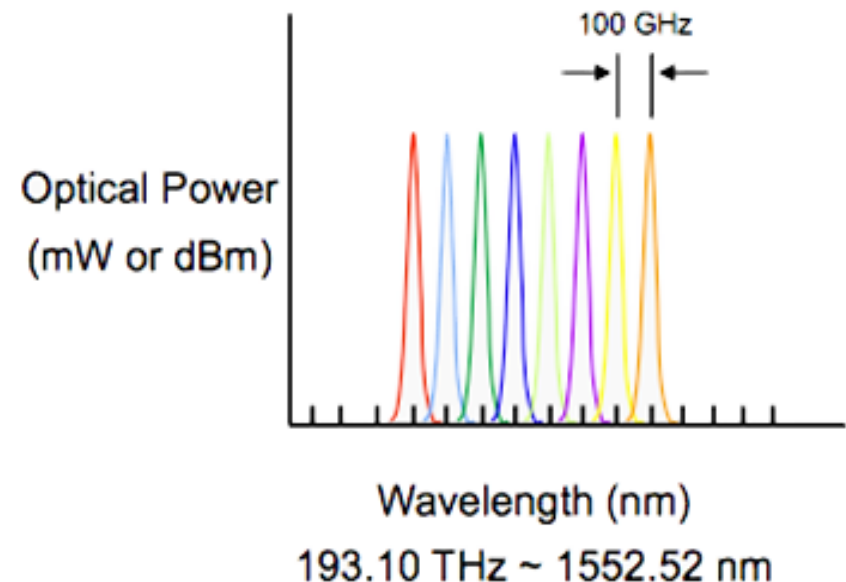
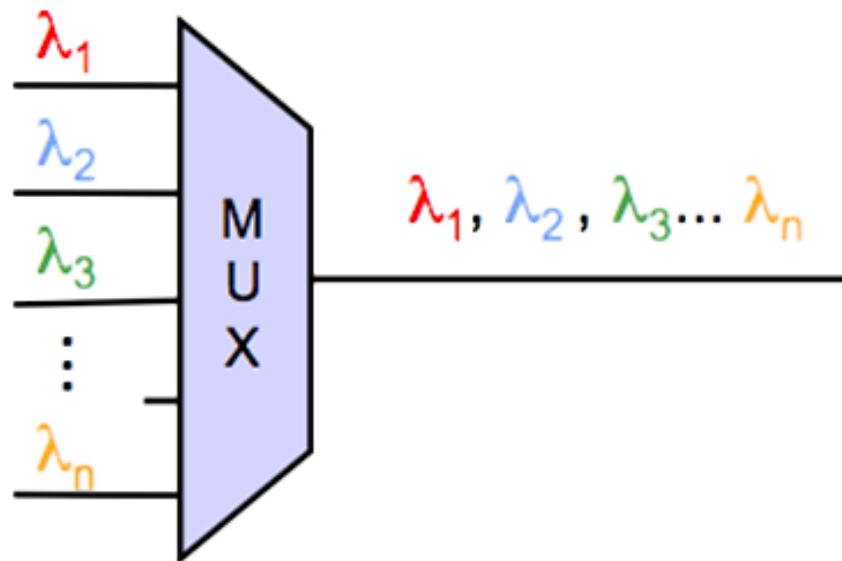
- OTN stands for Optical Transport Network
  - A set of standards which allow interoperability and the generic transport of any protocol across an optical network.
  - Implemented as a “wrapper” around another protocol.
  - Why is this needed?
    - So the optical network can be completely transparent.
    - Also, some protocols don't have the same level of troubleshooting capabilities as other protocols.
      - For example, Ethernet is not as good as SONET, because Ethernet wasn't originally designed for the WAN.
    - An OTN wrapper allows the optical troubleshoot with OTN instead.



# Wave Division Multiplexing

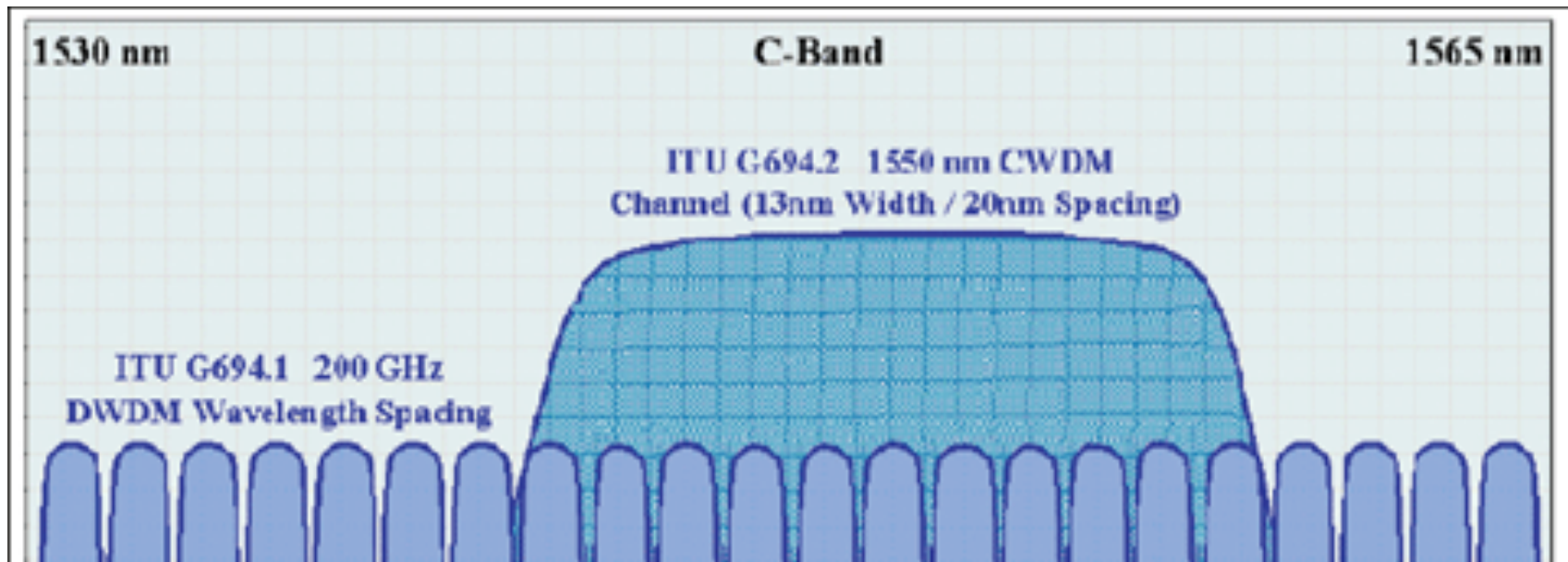
# Wave Division Multiplexing (WDM)

- What is Wave Division Multiplexing (WDM)?
  - We know that light comes in many different colors.
  - These different colors can be combined on the same fiber.
  - The goal is to put multiple signals on the same fiber without interference (“ships in the night”), thus increasing capacity.



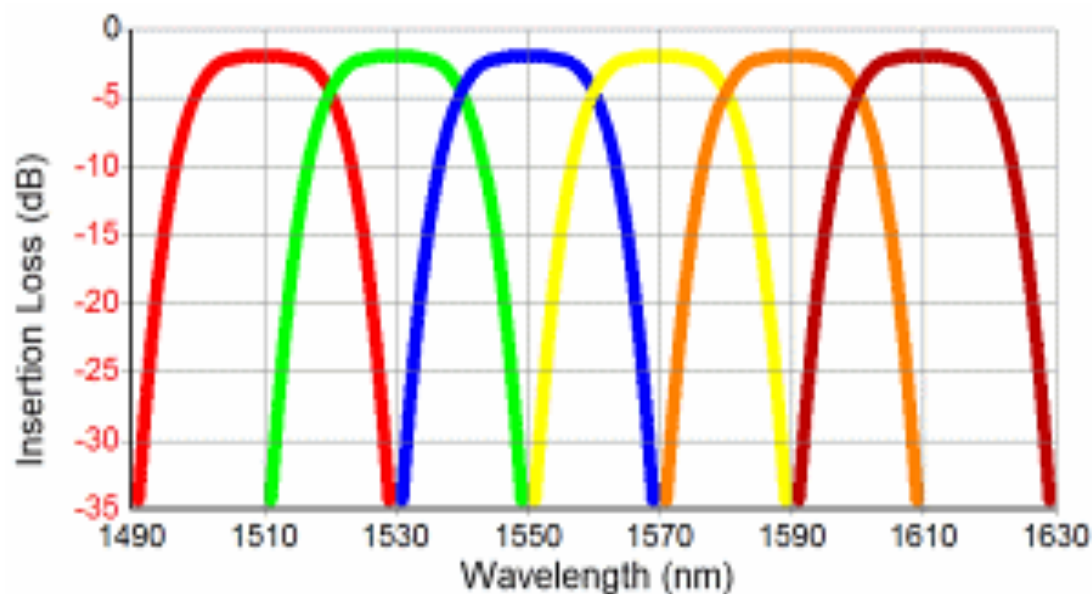
# Different Types of WDM

- There are several different types of WDM
  - The most common terms are Dense and Coarse.
  - Essentially they both do the same thing in the same way.
  - The only difference is the channel spacing.
    - And sometimes the range of the optical spectrum they cover.



# Coarse Wavelength-Division Multiplexing

- CWDM is loosely used to mean “anything not DWDM”
  - One “popular” meaning is 8 channels with 20nm spacing.
    - Centered on 1470 / 1490 / 1510 / 1530 / 1550 / 1570 / 1590 / 1610



- With Low Water Peak fiber, another 10 channels are possible
  - Centered on 1270/1290/1310/1330/1350/1370/1390/1410/1430/1450.
- Can also be used to refer to a simple 1310/1550nm mux.

# Dense Wavelength-Division Multiplexing

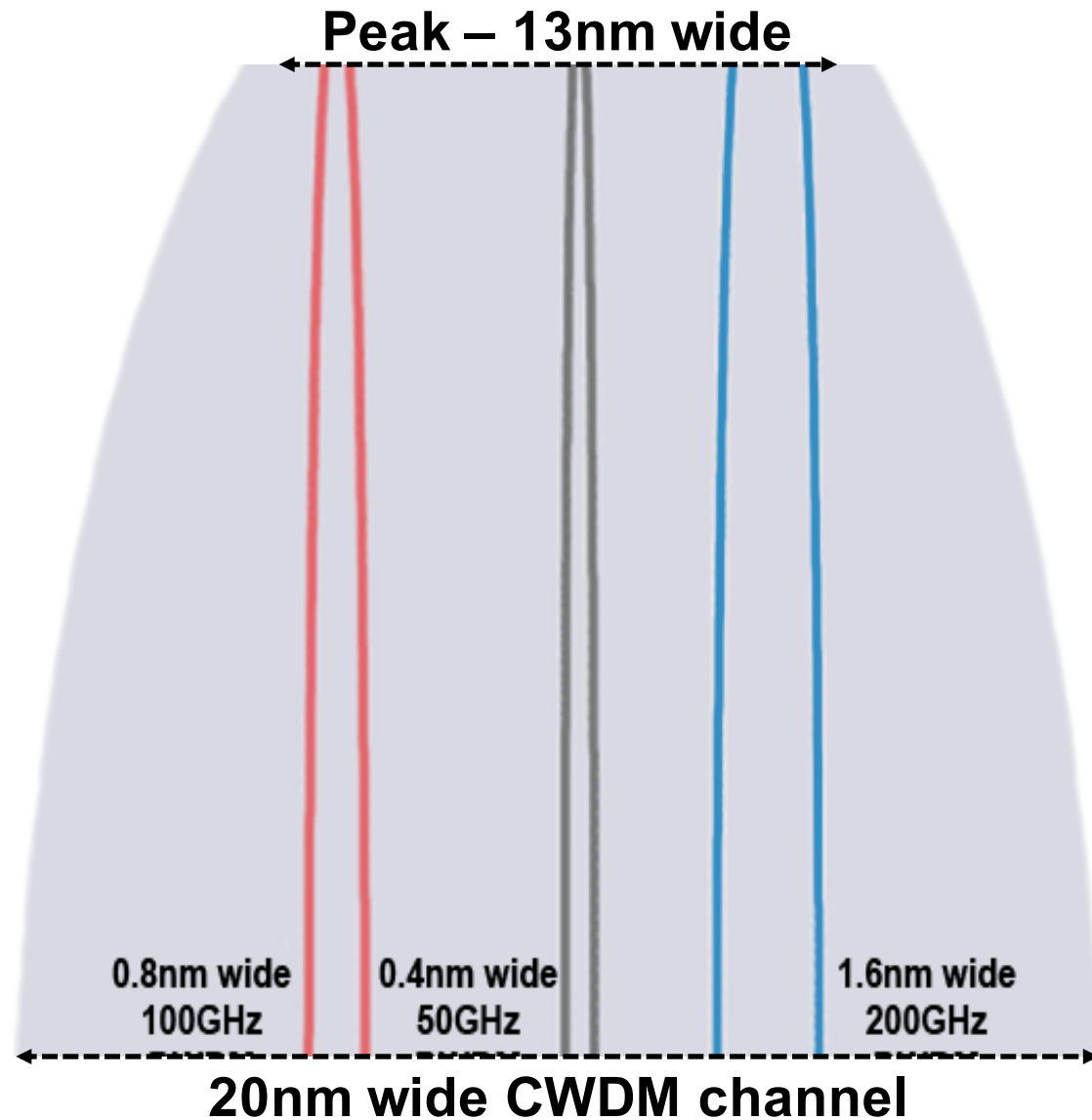
- So what does that make Dense WDM (DWDM)?
  - A much more tightly packed WDM system.
  - Defined by the ITU-T G.694.1 as a “grid” of specific channels.
  - Within C-band, these channel spacings are common:
    - 200GHz – 1.6nm spacing, 20 channels
    - 100GHz – 0.8nm spacing, 40 channels
    - 50GHz – 0.4nm spacing, 80 channels
    - 25GHz – 0.2nm spacing, 160 channels
  - A rough guideline:
    - 200GHz is “2000-era” old tech, rarely seen in production any more.
    - 100GHz is still quite common for metro DWDM tuned pluggables.
    - 50GHz is common for commercial, long-haul, and 100G systems.
    - 25GHz was used for high-density 10G systems, before the move to more modern 100G systems at 50GHz spacings.



# What Are The Advantages?

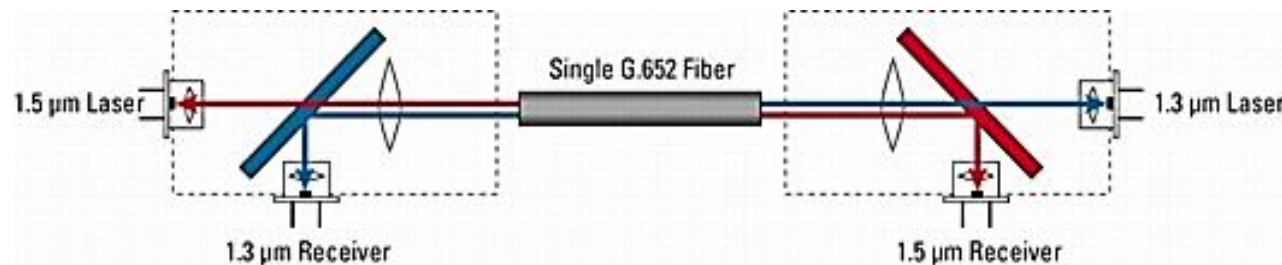
- CWDM
  - Cheaper, less precise lasers can be used.
    - The actual signal in a CWDM system isn't really any wider.
    - But the wide channel allows for large temperature variations.
    - Cheaper, uncooled lasers can more easily stay within the window.
- DWDM
  - Far more channels are possible within the same fiber.
    - 160 channels (at 25GHz) in 32nm of spectrum, vs. 8ch in 160nm.
  - Can stay completely within the C-band
    - Where attenuation and dispersion are far lower than other bands.
    - Where Erbium Doped Amplifiers (EDFAs) work.

# CWDM vs. DWDM Relative Channel Sizes



# Other Uses of WDM

- WDM is also used in other channel combinations
  - 10GBASE-LX4 optics, 10GbE over 4x3.2G WDM lanes
    - Uses non-standard 1275 / 1300 / 1325 / 1350nm channels.
    - Used to achieve longer distances over older grade MMF.
    - 40GE and 100GE will likely offer similar integrated WDM optics.
  - 1310/1550 muxes
    - Simple combination of two popular windows onto a single strand.
  - 1GBASE-BX optics for use on single-strand fibers
    - 1310 / 1490nm mux integrated into a pluggable transceiver.



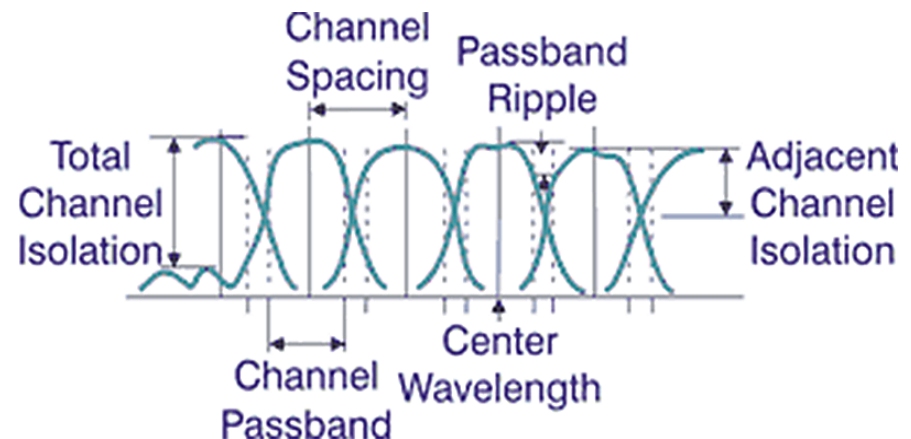
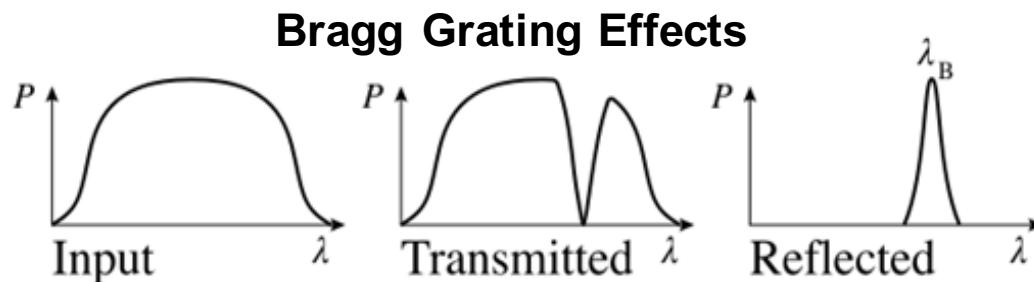
# WDM Networking Components

# WDM Mux/Demux

- The Mux/Demux
  - Short for “multiplexer”, sometimes called a “filter” or “prism”.
    - The term “filter” is how it actually works, by filtering specific colors.
    - But most people understand a “prism” splits light into the spectrum.
  - A simple device which combines or splits multiple colors of light into a single fiber (called the “common” fiber).
  - Muxes are entirely passive devices, requiring no power.
  - A complete system requires a mux+demux for TX and RX.
  - Most modern devices function the same in both directions, as a mux or demux, so the actual device is the same.
  - Many vendors combine the mux+demux into a single unit for simplicity, but it is really 2 distinct components.

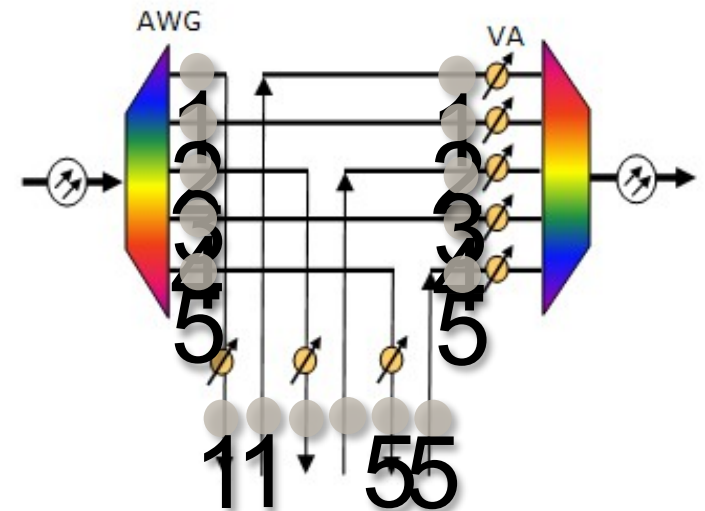
# How a Mux Works

- Muxes are actually optical bandpass filters
  - Typically based on Bragg Grating or Dichroic filters.
    - Some frequencies are reflected, the rest are passed through.
  - The channels actually overlap slightly, but have enough isolation to prevent cross-talk interference.



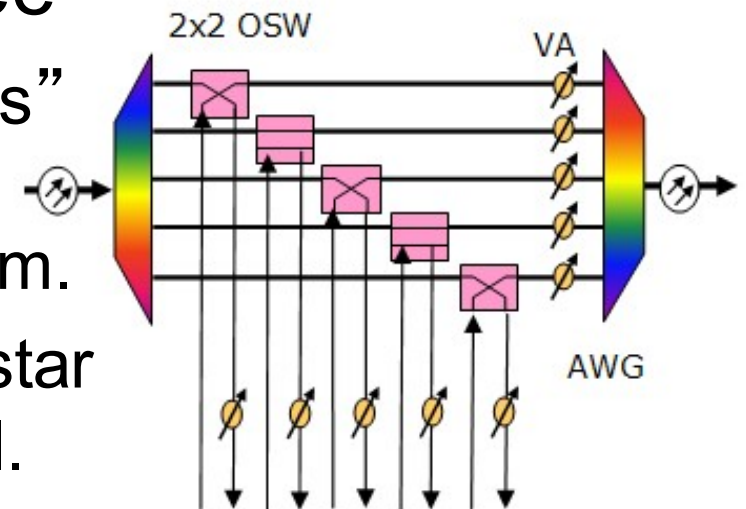
# The Optical Add/Drop Multiplexer (OADM)

- The Optical Add/Drop Multiplexer (OADM)
  - Selectively Adds and Drops certain WDM channels, while passing other channels through without disruption.
  - Where a mux is used at the end-point of a WDM network to split all of the component wavelengths, an OADM is used at a mid-point, often in a ring.
  - With a well-constructed OADM ring any node can reach any other node in the ring, potentially reusing the same wavelength multiple times across different portions of the ring



# The ROADM

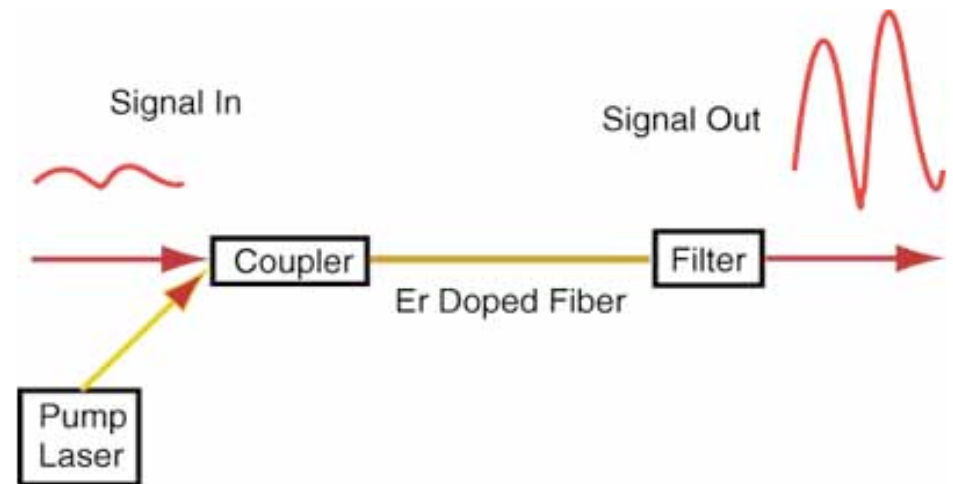
- A somewhat recent addition to optical networking.
  - The “Reconfigurable Optical Add/Drop Multiplexer”.
  - Essentially a “tunable OADM”, usually in software.
  - Allows you to control which channels are dropped and which are passed through, increasing channel flexibility.
- Some ROADMs are multi-degree
  - Instead of only being able to “pass” or “drop”, there are more than 2 directions of “pass” to choose from.
  - This allows you to build complex star topologies at a purely optical level.





# Optical Amplifiers

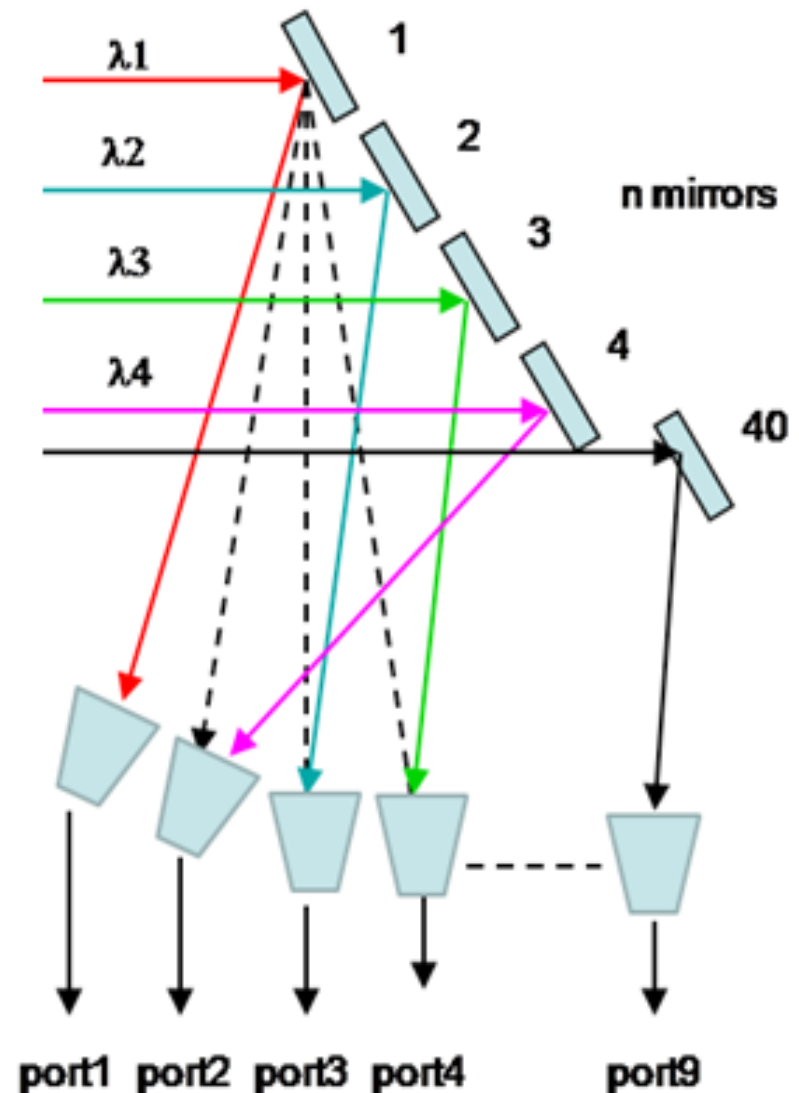
- Optical amplifiers increase the intensity of a signal
  - There are different types, for different spectrums of light.
  - The most common is the Erbium Doped Fiber Amplifier.
    - Another method is Raman Amplification, typically for ultra long-haul.
  - In an EDFA, a piece of fiber is “doped” with Erbium ions.
  - Additional laser power at 980nm and/or 1480nm is pumped in via a coupler.
  - The interaction between the Erbium and the pump laser causes the emission of light in the C-band spectrum, amplifying the signal.



# Optical Switches

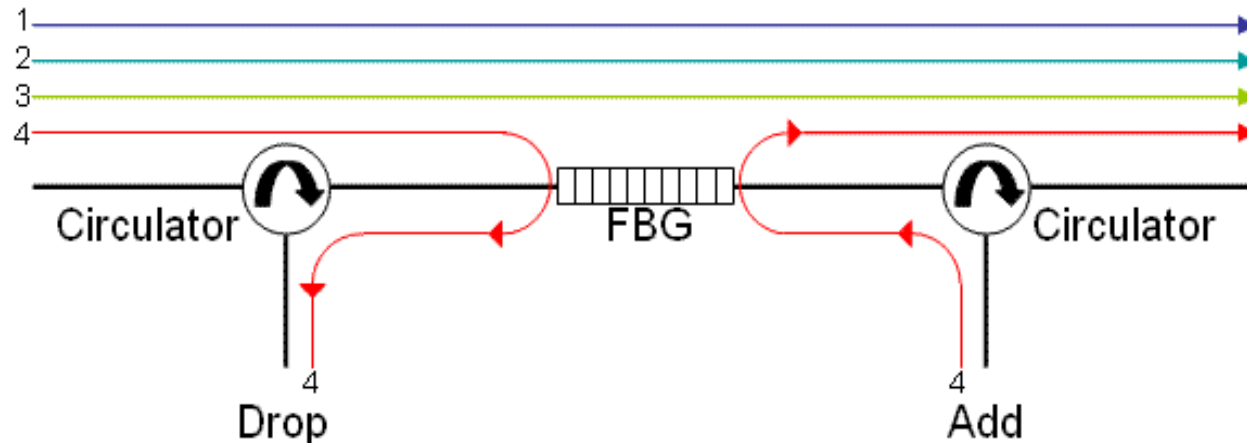
- Optical Switches

- Let you direct light between ports, without doing O-E-O conversion.
- Built with an array of tiny mirrors, which can be moved electrically.
- Allows you to connect two fibers together optically in software.
- Becoming popular in optical cross-connect and fiber protection roles.
- Also used inside of complex multi-degree ROADMs, called a WSS (wavelength selectable switch).



# Circulator

- A component typically not seen by the end user
  - But used to implement various other common components.
    - Such as muxes, OADMs, and dispersion compensators.
- A circulator has 3 fiber ports.
  - Light coming in port 1 goes out port 2.
  - Light coming in port 2 goes out port 3.



# Splitters and Optical Taps

- Optical Splitters
  - Do exactly what they sound like they do, split a signal.
- Common examples are:
  - A 50/50 Splitter
    - Often used for simple “optical protection”.
    - Split your signal in half and send down two different fiber paths.
    - Use an optical switch with power monitoring capabilities on the receiver, have it automatically pick from the strongest signal.
    - If the signal on one fiber drops, it switches to the other fiber.
  - A 99/1 Splitter
    - Often used for “Optical Performance Monitoring”.
    - Tap 1% of the signal and run it to a spectrum analyzer.

# Types of Single Mode Optical Fiber

# Types of Single-Mode Fiber

- We've already discussed how single-mode fiber is used for essentially all long-reach fiber applications.
- But there are also several different types of SMF.
- The most common types are:
  - “Standard” SMF (ITU-T G.652) A.K.A. SMF-28
  - Low Water Peak Fiber (ITU-T G.652.C/D)
  - Dispersion Shifted Fiber (ITU-T G.653)
  - Low-Loss Fiber (ITU-T G.654)
  - Non-Zero Dispersion Shifted Fiber (ITU-T G.655)
  - Bend Insensitive Fiber (ITU-T G.657)

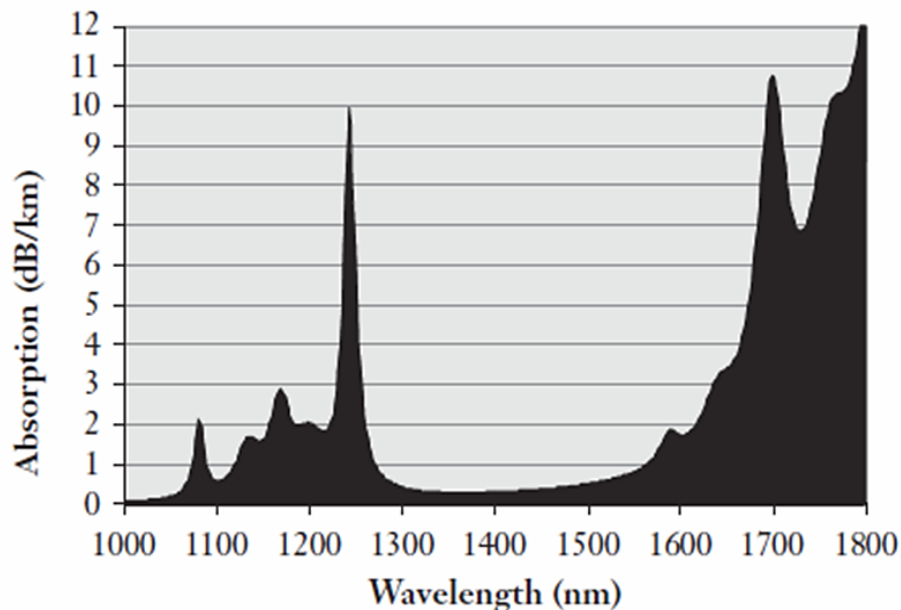
# “Standard” Single-Mode Fiber (G.652)

- One of the original fiber cables.
  - Deployed widely throughout the 1980s.
- Frequently called “SMF-28”, or simply “classic” SMF.
  - SMF-28 is actually a product name from Corning.
  - Also called NDSF (Non-Dispersion Shifted Fiber).
- Optimized for use by the 1310nm band.
  - Has the lowest rate of dispersion here.
  - Originally deployed before the adoption of WDM.

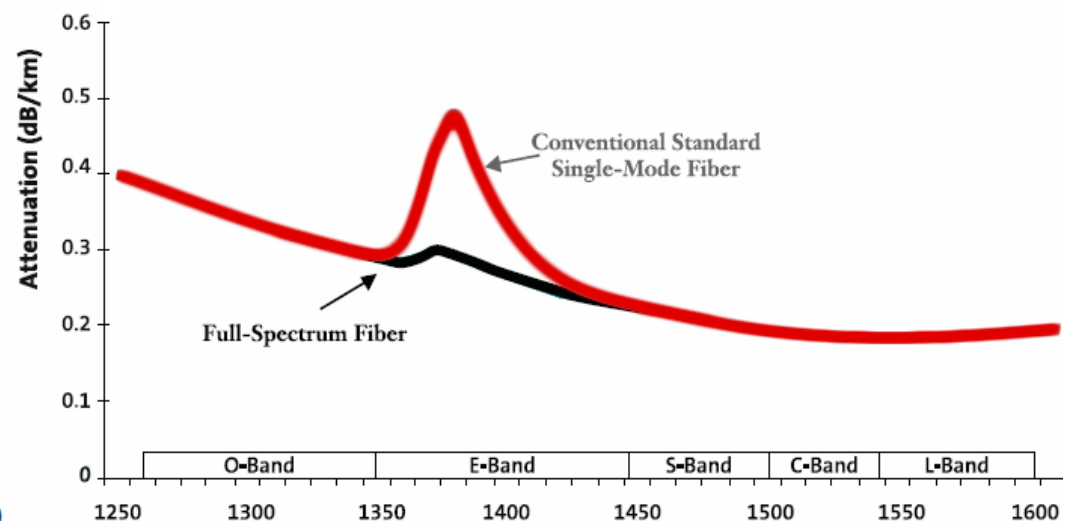
# Low Water Peak Fiber (G.652.C/D)

- Modified G.652, designed to reduce water peak.
  - Water peak is a high rate of attenuation at certain frequencies due to OH- hydroxyl molecule within the glass.
  - This high attenuation makes certain bands “unusable”.

Absorption of Light by Hydrogen at Various Wavelengths



Attenuation of Standard vs. Low Water Peak Fiber





# Dispersion Shifted Fiber (ITU-T G.653)

- An attempt to improve dispersion at 1550nm.
  - The rate at which chromatic dispersion occurs will change across different frequencies of light.
    - The point of lowest dispersion in G.652 occurs at 1300nm.
    - But this is not the point of lowest attenuation, which is around 1550nm.
  - DSF shifts the point of lowest dispersion to 1550nm too.
- But this turned out to cause big problems.
  - Running DWDM over DSF causes non-linear interactions.
  - One notable example is called Four Wave Mixing
    - 3 equally spaced wavelengths interact to produce a 4<sup>th</sup> wavelength.
  - As a result, this fiber is rarely used today.

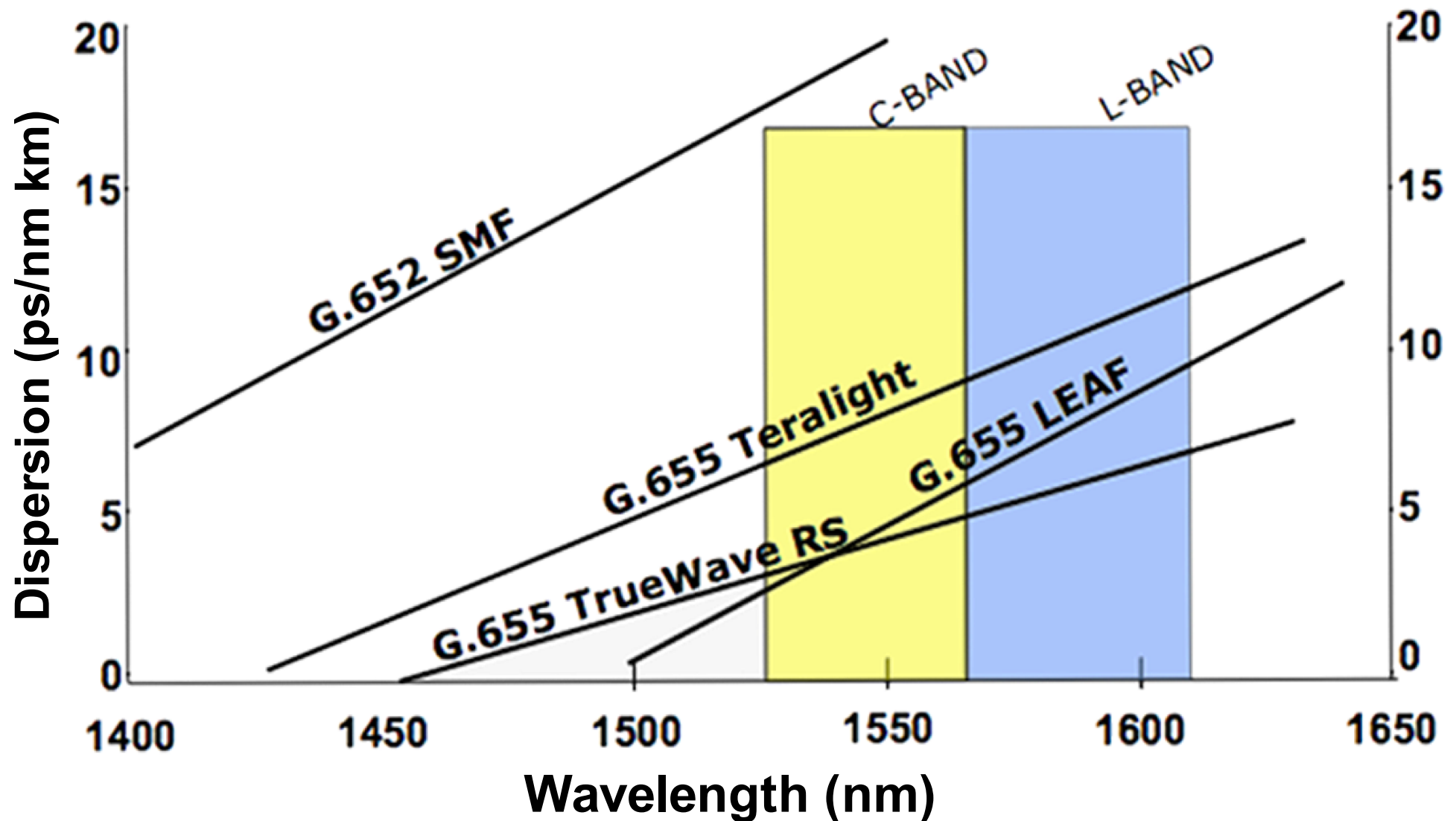
# Non-Zero Dispersion Shifted Fiber (G.655)

- Similar concept to Dispersion Shifted Fiber
  - But the zero point is moved outside of the 1550nm band.
  - This leaves a small amount of dispersion, but avoids the non-linear cross-channel interactions cause by DSF.
- To manage dispersion, NZDSF comes in 2 types
  - NZD+ and NZD-, with opposite dispersion “slopes”.
    - One spreads the 1550nm band out.
    - The other compresses it in the opposite direction.
  - By switching between the two slopes, the original signal can be maintained even over extremely long distances.

# Other Single-Mode Fiber Types

- G.654
  - Low-attenuation fiber, at the expense of dispersion.
  - Designed for high-power systems like undersea cables.
- G.657
  - Bend Insensitive fiber (reduced sensitivity at any rate).
  - Uses a higher refractive index cladding than normal fiber.
  - Designed for premise use where the high bend radius of a well designed datacenter may not be practical.
- Modern fibers are usually better than the spec.
  - But much of what's actually in the ground is old fiber.

# Dispersion Rates of Commercial Fibers



# Engineering an Optical Network

# Insertion Loss

- Even the best connectors and splices aren't perfect.
  - Every time you connect two fibers together, you get loss.
  - The typical budgetary figure is 0.5dB per connector.
    - Actual loss depends on your fiber connector and mating conditions.
- Insertion loss is also used to describe loss from muxes.
  - Since it is the “penalty you pay just for inserting the fiber”.
  - Some real-life examples:
    - 8-channel CWDM 20nm Mux/Demux: 3.5dB
    - 16-channel DWDM 100GHz Mux/Demux: 7.5dB
    - 32-channel DWDM 100GHz Mux/Demux: 9.5dB

Mismatched Cores



Misaligned Cores

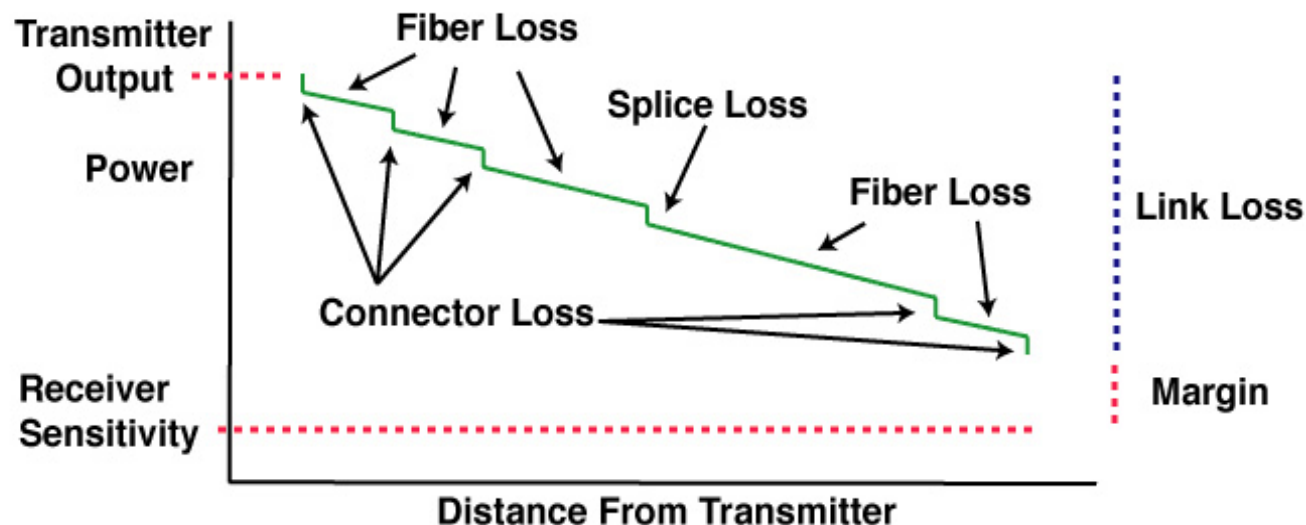


Air Gap Between Fibers



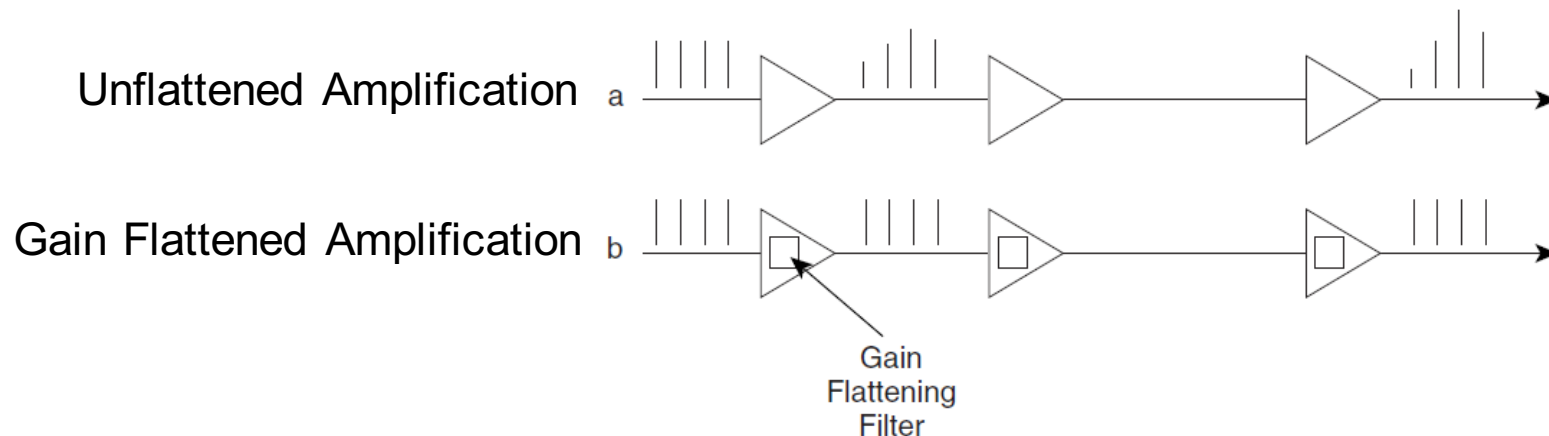
# Balling On An Optical Budget

- To plan your optical network, you need a budget.
  - When an optic says “40km”, this is only a guideline.
  - Actual distances can be significantly better or worse.
  - It’s also smart to leave some margin in your designs.
    - Patch cables get bent and moved around, optic transmitters will cool with age, a fiber cut fix will add more splices, etc.



# Amplifiers and Power Balance

- Amplifiers introduce their own unique issues.
  - Amplifier gain is not consistent across all wavelengths.
  - The gain must be equalized, or after several amplification stages the power of some channels will be far higher.
  - Mismatched channel powers causes SNR issues.
  - Care must also be taken when using OADM's, to balance power on passed-thru vs. newly added channels.





# Amplifiers and Total System Power

- Amplifiers also have limits on their total system power
  - Both what they can output, and what they can take as input.
  - But the total input power changes as you add channels
    - A single DWDM channel at 10dBm is 0.1mW of input power.
    - 40 DWDM channels at 10dBm is 4mW of power (or 6dBm).
    - If your amplifier's maximum input power is -6dBm, and you run 40 DWDM channels through it, each channel must be below -22dBm.
    - Failing to plan for this can cause problems as you add channels.
  - The total input power also changes as you lose channels.
    - Imagine power fails to a POP, and many channels are knocked offline.
    - Suddenly the total system power has changed.
    - A good EDFA needs to monitor system power levels and apply dynamic gain adjustments to maintain a working system.

# Dealing with Dispersion

- Dispersion Compensation Unit
  - Essentially just big a spool of fiber in a box.
    - Designed to cause dispersion in the opposite direction (with the opposite “slope”) as the transmission fiber used.
    - Passing the signal through this spool reverses the effects of dispersion caused by transmission through the normal fiber.
    - But it also adds extra distance to the normal fiber path, causing additional attenuation, requiring more amplification
    - Dispersion Compensation spools are typically positioned at optical amplification points for this reason.
    - Circulators can be used to reduce the total amount of fiber needed.



# Dealing with Dispersion

- Electronic Dispersion Compensation
  - Dispersion which used to completely ruin a signal can now be compensated for electronically at the receiver.
  - Modern long-haul DWDM systems can handle 4500km of dispersion compensation entirely electronically.
    - Through sophisticated Digital Signal Processors (DSPs) which compensate for the signal distortion computationally.
  - EDC is being integrated into pluggable optics too.
    - Largely responsible for the 300 meter ranges which can now be achieved over MMF with modern optical standards like 10GBASE-LRM.
  - Technology is getting better all the time too.

# Re-amplifying, Reshaping, and Retiming

- Signal Regeneration (Repeaters)

- Different types are described by the “R” s” that they perform.

- 1R – Re-amplifying

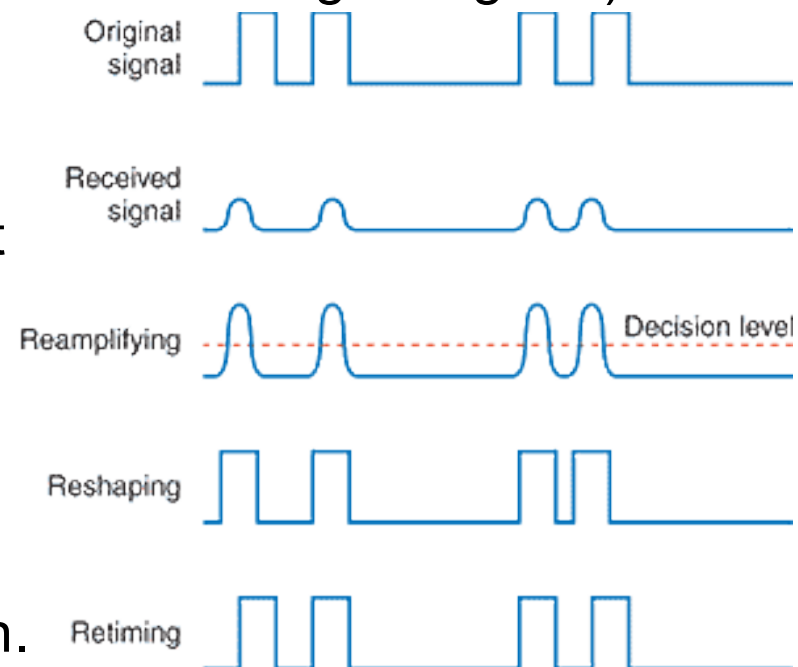
- Makes the analog signal stronger (i.e. makes the light brighter)
- Typically performed by an amplifier.

- 2R – Reshaping

- Restores the original pulse shape that is used to distinguish 1’ s and 0’ s.

- 3R – Retiming

- Restores the original timing between the pulses.
- Usually involves an O-E-O conversion.



# Bit Error Rates

- As optical impairments (noise, distortion, dispersion, loss of signal, etc) increase...
- The link typically doesn't just outright “die”.
  - It starts taking bit errors, at progressively higher rates.
  - The target maximum Bit Error Rate (BER) is generally  $10^{-12}$ .
    - You can get by with another dBm less signal at  $10^{-11}$  BER.
    - And another dBm less signal after that at  $10^{-10}$  BER.
    - But with exponential progression, the errors gets very bad quickly.

# Coherent Optical Technologies

# Coherent Optical Technologies

- What exactly are “coherent” optics?
  - A group of advancements in optical technology, which combine to deliver significantly increased optical performance.
  - Specifically, coherent technologies consist of:
    - High-order phase modulation.
    - Polarization multiplexing.
    - Improved signal detection using a local laser as a reference oscillator.
    - Advanced Digital Signal Processors (DSPs) which are necessary to tie all of these together, recombine the signals, and compensate for impairments.
  - These technologies combine to deliver:
    - Significantly improved spectrum efficiency (from 1.6Tbps to 9.6Tbps+)
    - True 100G and beyond optical signals, not just Nx10G signals.
    - High-bandwidth optical signals which are usable over long distances.
    - No need for physical Dispersion Compensation Units.

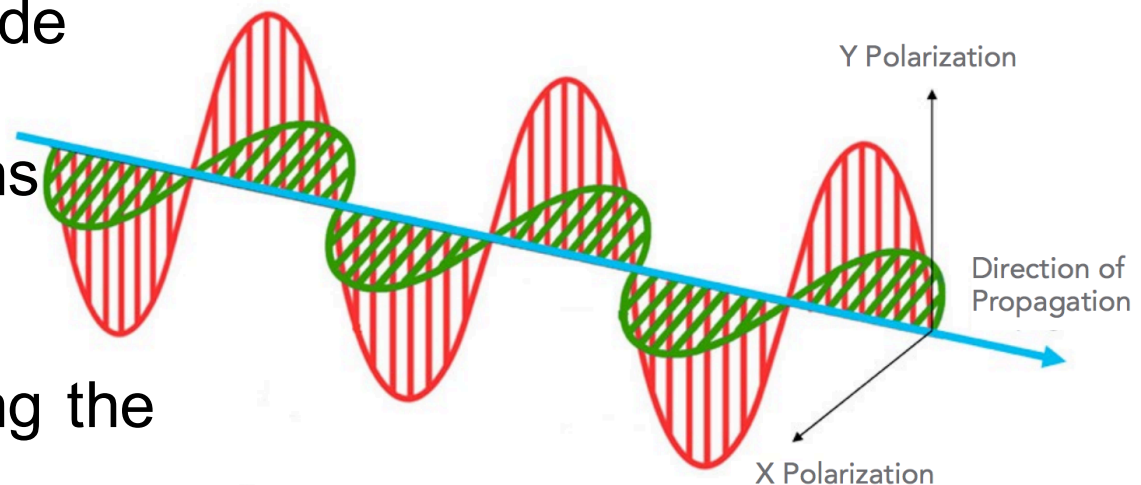
# Improved Modulation Techniques

- Historically optical systems used “IM-DD” modulation.
  - Simplistic “bright for a 1, dim for a 0” type modulation.
  - This yields only 1 data bit per “symbol”, or modulation change.
  - 10GE meant modulating the light 10 billion times/sec, or 10 Gigabaud.
- But adding bandwidth by increasing clock cycles has limitations.
  - For years, the industry was not able to break through the “10G barrier” caused by increasing chromatic and polarization dispersion impairments.
  - Technology advanced only by packing the channels tighter (160 channels in C-band), and throwing more Nx10G’s at the problem.
- Improving the modulation technique yields more bits per symbol.
  - Quadrature Phase Shift Keying (QPSK) delivers 2 bits per symbol.
  - 8 Quadrature Amplitude Modulation (8QAM) delivers 3 bits per symbol.
  - 16 Quadrature Amplitude Modulation (16QAM) delivers 4 bits per symbol.
  - Etc, etc.



# Polarization Multiplexing

- What is “Polarization Multiplexing”?
  - Light is (among many other things we don’t fully understand yet) actually a wave of electromagnetic energy propagating through space.
  - In 3-Dimensional space (e.g. a cylindrical fiber), you can send two independent orthogonal signals which propagate along a X and Y axis, without interfering with each other.
  - Modern DSPs have made compensating for the changing fiber conditions in real-time practical, allowing dual polarities of light and thus doubling the bandwidth per channel.



# Putting It All Together

- Modern long-haul DWDM systems already deliver:
  - 100Gbps transponders with Dual Polarity (DP) Quadrature Phase Shift Keying (QPSK) of 25GBaud signals, to deliver 3000km reach.
  - 200Gbps transponders with DP-16QAM at 700km reach.
- Further improvements, better DSPs, and better photonics integration onto routers and pluggables, are all expected.

Modulation	Normalized Reach	C-Band Capacity
DP-QPSK	3000 km	8 Tbps
DP-8QAM	1500 km	12 Tbps
DP-16QAM	700 km	16 Tbps
DP-32QAM	350 km	24 Tbps
DP-64QAM	175 km	32 Tbps


# Tools of the Trade

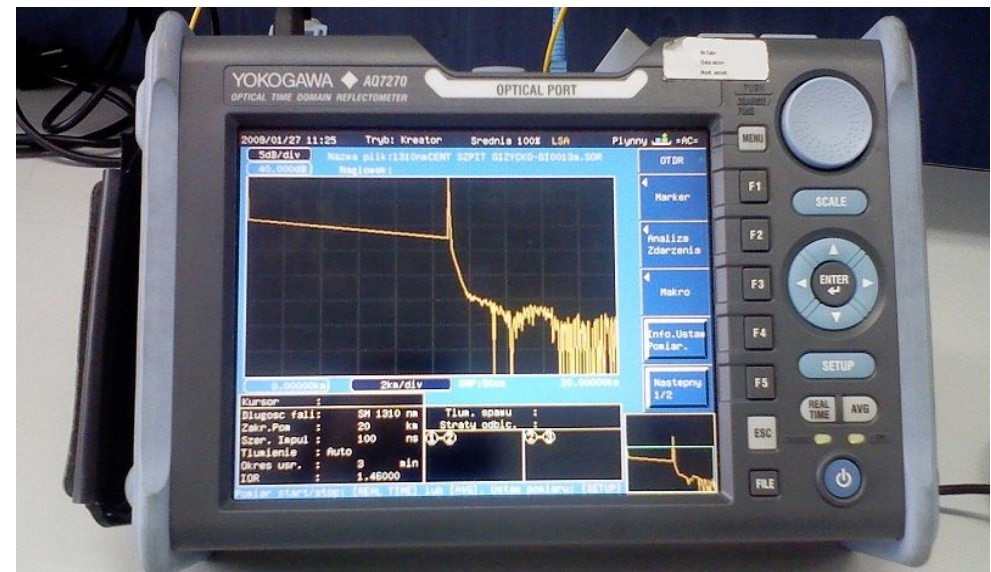
# Fiber Optic Power Meter

- Optical Power Meter (or simply a Light Meter)
  - Measures the brightness of an optical signal.
  - Displays the results in dBm or milliwatts (mW).
  - Most light meters include a “relative loss” function as well as absolute power meter.
    - Designed to work with a known-power light source on the other end, to test the amount of loss over a particular fiber strand.
    - These results are displayed in dB, not dBm.
    - Frequently the source of much confusion in a datacenter, when you use the wrong mode!
    - If I had a nickel for every time someone told me they just measured a +70 signal on my fiber...

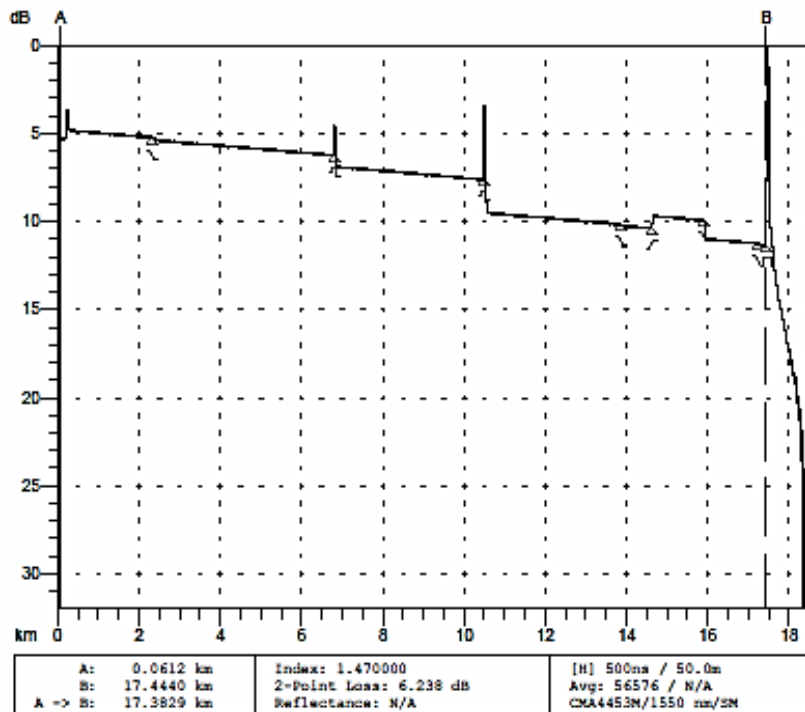


# Optical Time-Domain Reflectometer (OTDR)

- An OTDR is a common tool for testing fiber.
  - Injects a series of light pulses into a fiber strand.
  - Analyzes light that is reflected back.
  - Used to characterize a fiber, with information like:
    - Splice points, and their locations.
    - Overall fiber attenuation.
    - Fiber breaks, and their locations (distance from the end-point).
- 

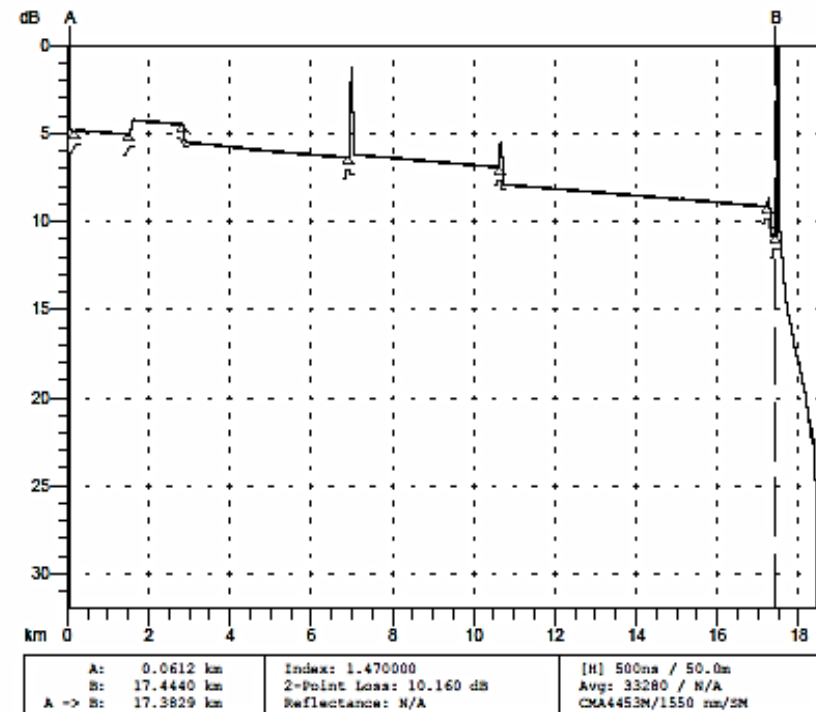


# Example OTDR Output



Feature #/Type	Location (km)	Event-Event (dB) (dB/Km)		Loss (dB)	Refl (dB)
1/N	2.3310	??	??	0.12	
2/R	6.8035	0.91	0.203	0.64	-58.19
3/R	10.4907	0.72	0.196	1.86	-48.24
4/N	13.8639	0.70	0.206	0.06	
5/N	14.6205	0.14	0.188	-0.71	
6/N	15.9114	0.26	0.205	1.06	
7/N	17.2350	0.25	0.193	0.08	
8/E	17.4491	0.05	0.211	>3.00	>-33.55S

Overall (End-to-End) Loss: ??



Feature #/Type	Location (km)	Event-Event (dB) (dB/Km)		Loss (dB)	Refl (dB)
1/N	0.1937	0.02	0.121	-0.06 (2P)	
2/N	1.5194	0.24	0.184	-0.82	
3/N	2.8327	0.26	0.197	0.99	
4/R	6.9421	0.90	0.219	-0.21	>-46.37
5/R	10.6396	0.75	0.203	0.96	-56.69
6/R	17.2269	1.28	0.194	1.61	-61.90
7/E	17.4512	0.04	0.184	>3.00	>-34.48S

Overall (End-to-End) Loss: 5.97 dB

**Question: Can I really blind myself by looking into the fiber?**

# Beware of Big Scary Lasers





# Laser Safety Guidelines

- Lasers are grouped into 4 main classes for safety
  - Class 1 – Completely harmless during normal use.
    - Either low powered, or laser is inaccessible while in operation.
    - Class 1M – Harmless if you don't look at it in a microscope.
  - Class 2 – Only harmful if you intentionally stare into them
    - Ordinary laser pointers, supermarket scanners, etc. Anyone who doesn't WANT to be blinded should be protected by blink reflex.
  - Class 3 – Should not be viewed directly
    - Class 3R (new system) or IIIA (old system)
      - Between 1-5mW, “high power” Internet purchased laser pointers, etc.
    - Class 3B (new system) or IIIB (old system)
      - Limited to 500mW, requires a key and safety interlock system.
  - Class 4 – Burns, melts, destroys Alderaan, etc.

# Laser Safety And The Eye

- Networking lasers operate in the infrared spectrum
  - Infrared can be further classified as follows:
    - IR-A (700nm – 1400nm) – AKA Near Infrared
    - IR-B (1400nm – 3000nm) – AKA Short-wave Infrared
  - Laser safety levels are based on what can enter the eye.
    - And the human eye didn't evolve to see infrared.
    - The cornea actually does a very good job of filtering out IR-B light.
  - So an IR-B laser which transmits 10mW of power may still be a Class 1, because that light can't enter the eye.

# Optical Networking and Safety

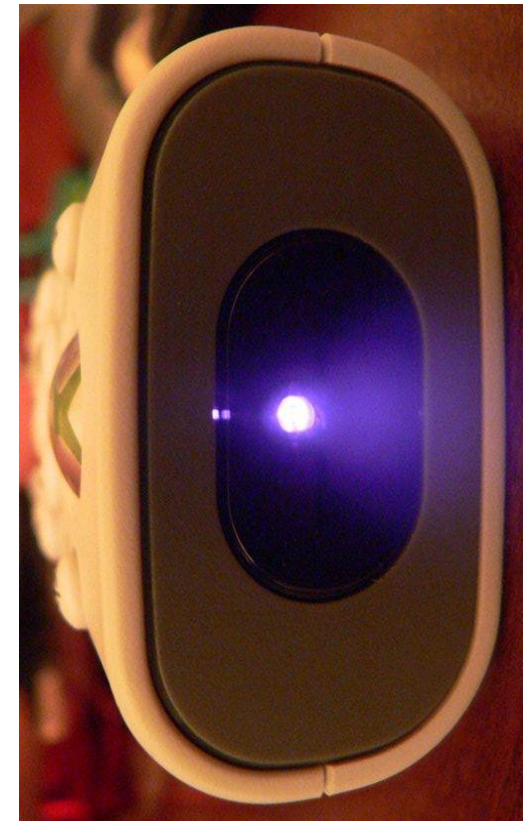
- **Routers**
  - Essentially every single channel laser which can be connected to a router is a Class 1 or Class 1M laser.
  - Even the longest reach 200km+ optics, etc.
- **Optical Amplifiers**
  - Optical amplifiers are capable of putting out enough power to kick a signal into Class 3R (metro) or 3B (long-haul).
- **DWDM Equipment**
  - Total optical power can also increase by muxing together many signals, bringing the total output power into the 3R region even without optical amplification.

# Optical Networking and Safety

- So should I be wearing goggles to the colo?
  - Generally speaking, direct router ports are always Class 1 (completely safe under all conditions).
  - Even on DWDM systems, the light rapidly disperses as soon as it leaves the fiber and travels through air.
  - Wavelengths above 1400nm are IR-B, and are mostly blocked by the human eye. Most high power optics and long-reach systems are in this range.
  - Extremely high-power DWDM systems have safety mechanisms which detect a fiber cut and cease transmitting a continuous high-power signal until it is repaired.

# Why Look Into The Fiber Anyways?

- Can you even see the light at all?
  - No, the human eye can only see between 390 – 750nm.
  - No telecom fiber signal is directly visible to the human eye.
- But, I looked at 850nm and I saw red?
  - What you're seeing are the sidebands of an imperfect signal generation, not the main 850nm signal itself.
  - However, most digital cameras can actually see in infrared.
  - One trick to check for light in a fiber is to hold it up to your camera phone.
    - You can try this on your TV's remote control.



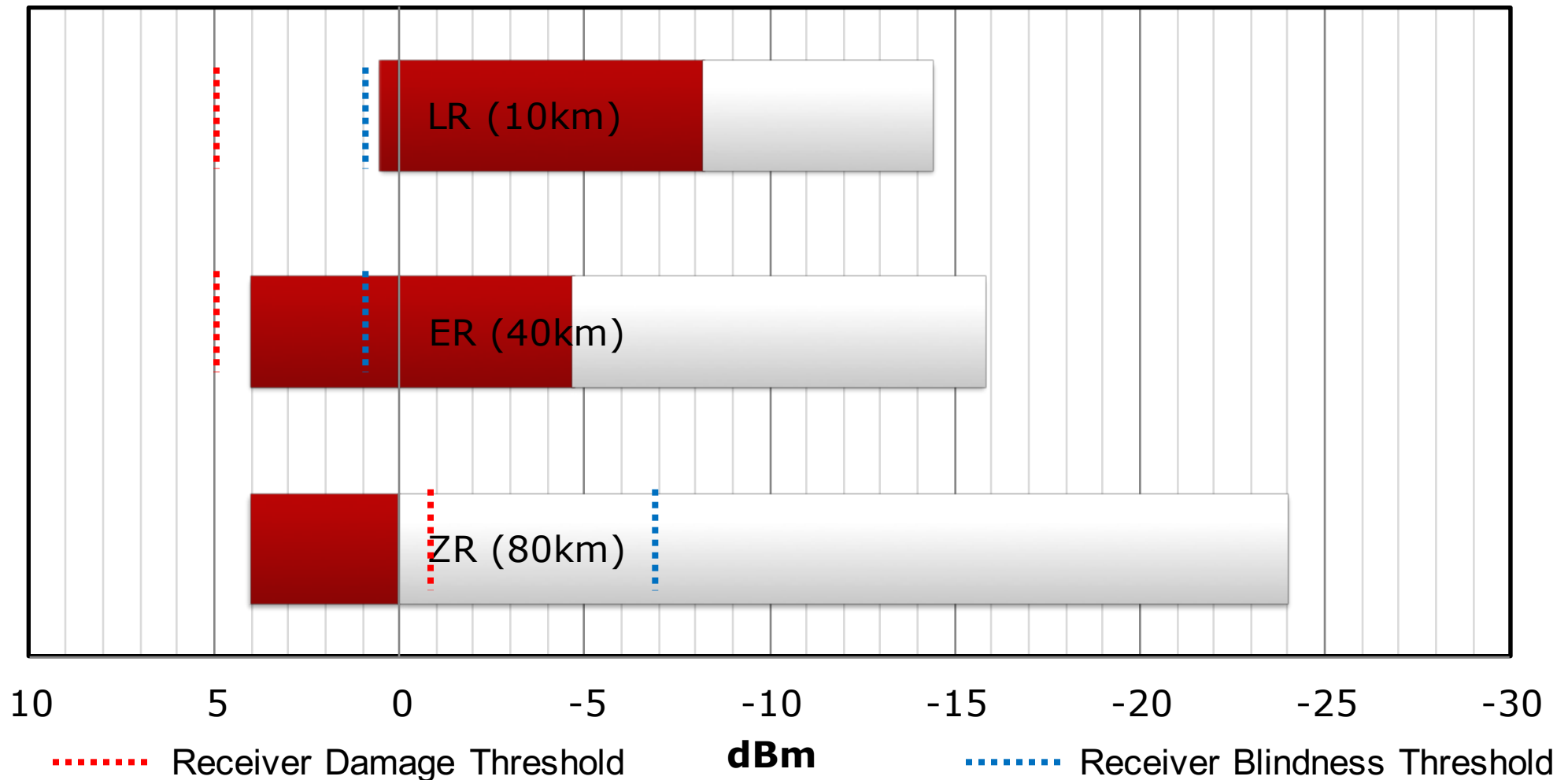
**Question: Can optical transceivers be damaged by over-powered transmitters?**

# Damage by Overpowered Transmitters?

- Well, yes and no.
  - Actually, most optics transmit at roughly the same power.
    - The typical output of 10km vs 80km optics are within 3dB.
  - Long reach optics achieve their distances by having extremely sensitive receivers, not stronger transmitters.
    - 80km optics may have a 10dB+ more sensitive receiver than 10km
    - These sensitive receivers are what are in danger of burning out.
  - There are two thresholds you need to be concerned with.
    - Saturation point (where the receiver is “blinded”, and takes errors).
    - Damage point (where the receiver is actually damaged).
    - The actual values depend on the specific optic.
    - But generally speaking, only 80km optics are at risk.

# Tx and Rx Optical Power Ranges

■ Tx Window    ■ Rx Window





**Question: Do I really need to be concerned about bend radius?**

# Is Bend Radius Really A Concern?

- Yes, bend radius is a real issue.
  - Remember that total internal reflection requires the light to hit the cladding below a “critical angle”.
  - Bending the fiber beyond it's specified bend radius causes light to leak out.
  - In fact, they even make “macro-bend light meters” which clamp onto the fiber.
  - There are “bend insensitive” fibers for use in residential or office environments which have less bend sensitivity, but they usually trade some performance under normal conditions to achieve this.



**Question: Can two transceivers on different wavelengths talk to each other?**

# Can You Mismatch Transceiver Freqs?

- Between certain types of optics, yes.
  - Essentially all optical receivers are wide-band.
    - Though the level of sensitivity may differ for some frequencies.
    - Laser receivers see everything between 1260nm – 1620nm.
    - But they won't be able to see a 850nm LED, for example.
  - Many DWDM networks are build around this premise.
    - By using one wavelength going A->B and other going B->A, you can achieve a bidirectional system over a single fiber strand.
    - The DWDM filters (muxes and OADMs) provide hard cut-offs of certain frequencies, but the transceivers can receive any color.
  - The only “gotcha” is optical power meters will be wrong.
    - A meter that is calibrated to read a 1310nm signal will see a 1550nm signal just fine, but it's power reading will be a few dB off.

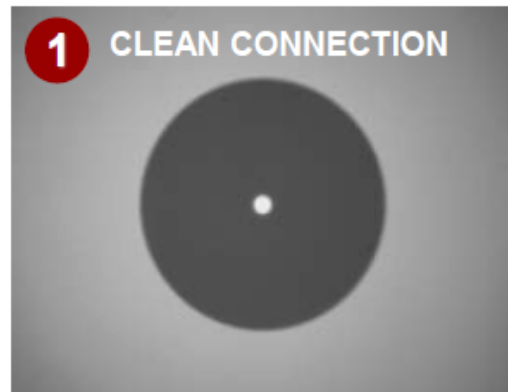
# Can You Mismatch Transceiver Freqs?

- Obscure Optical Networking Trick #738:
  - You may be able to achieve nearly as much distance with a LR/ER (1310nm 10km / 1550nm 40km) pair as with an ER/ER pair.
  - 1550nm has a much lower attenuation rate than 1310nm.
    - Around 0.2dB/km vs 0.35dB/km depending on fiber type.
    - So the LR side receives a much stronger signal than the ER side.
  - The ER optic has a much greater RX sensitivity than the LR.
    - So it will be able to hear the 1310nm signal much better.
- Result:
  - You may only *need* a long reach optic on one side.

**Question: Do I Really Need to Clean the Fiber to have it work right?**

# Do I Really Need to Clean the Fiber?

[http://www.fols.org/fols\\_library/presentations/documents/brown.pdf](http://www.fols.org/fols_library/presentations/documents/brown.pdf)



Back Reflection = **-67.5 dB**  
Total Loss = **0.250 dB**



Back Reflection = **-32.5 dB**  
Total Loss = **4.87 dB**

## Fiber Contamination and Its Effect on Signal Performance



## Clean Connection vs. Dirty Connection

OTDR trace illustration of the significant decrease in signal performance after mating dirty connectors

## **Other Misc Fiber Information**



# How Fast Does Light Travel In Fiber?

- Ever wondered how fast light travels in fiber?
  - The speed of light is 299,792,458 m/sec
  - SMF28 core has a refractive index of  $\sim 1.468$
  - Speed of light / 1.468 = 204,218,296 m/sec
  - Or roughly 204.2 km/ms, or 126.89 miles/ms
  - Cut that in half to account for round-trip times.
    - So approximately 1ms per 100km (or 62.5 miles) of RTT.
- Why do you see a much higher value in real life?
  - Remember, fiber is rarely laid in a straight line.
  - It is often laid in rings which take significant detours.
  - Dispersion compensation can add extra distance too.

**Send questions, comments, complaints to:**

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