# 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 at a routing/packet conference?

- Everything we do on "The Internet" largely revolves 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, and remember, I omitted almost all the math.
- The purpose of this tutorial is to touch on a bit of every topic, from the mundane to the advanced and unusual.
- But it helps to have a basic understanding of how and why things work, even if you aren't designing fiber networks yourself.

# The Basics of Fiber Optic Transmission

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

Fiber is ultimately just a "waveguide for light".

- Basically: light that goes in one end, comes out the other end.
- Most commonly made of glass/silica, but it can also be plastic.

So why do we use fiber in the first place?

- Glass is an extremely low-cost material to produce and install.
- Very light (relative to copper), flexible, high-density material.
- Carries tremendous amounts of information (76.8 Tbps+ today).
- It can easily carry large numbers of completely independent signals over the same fiber strand, without interference.
- Can carry signals thousands of kilometers without regeneration.
- 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

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, written as "*c*".
- For shorthand math, you can round this up to 300,000 km/s.

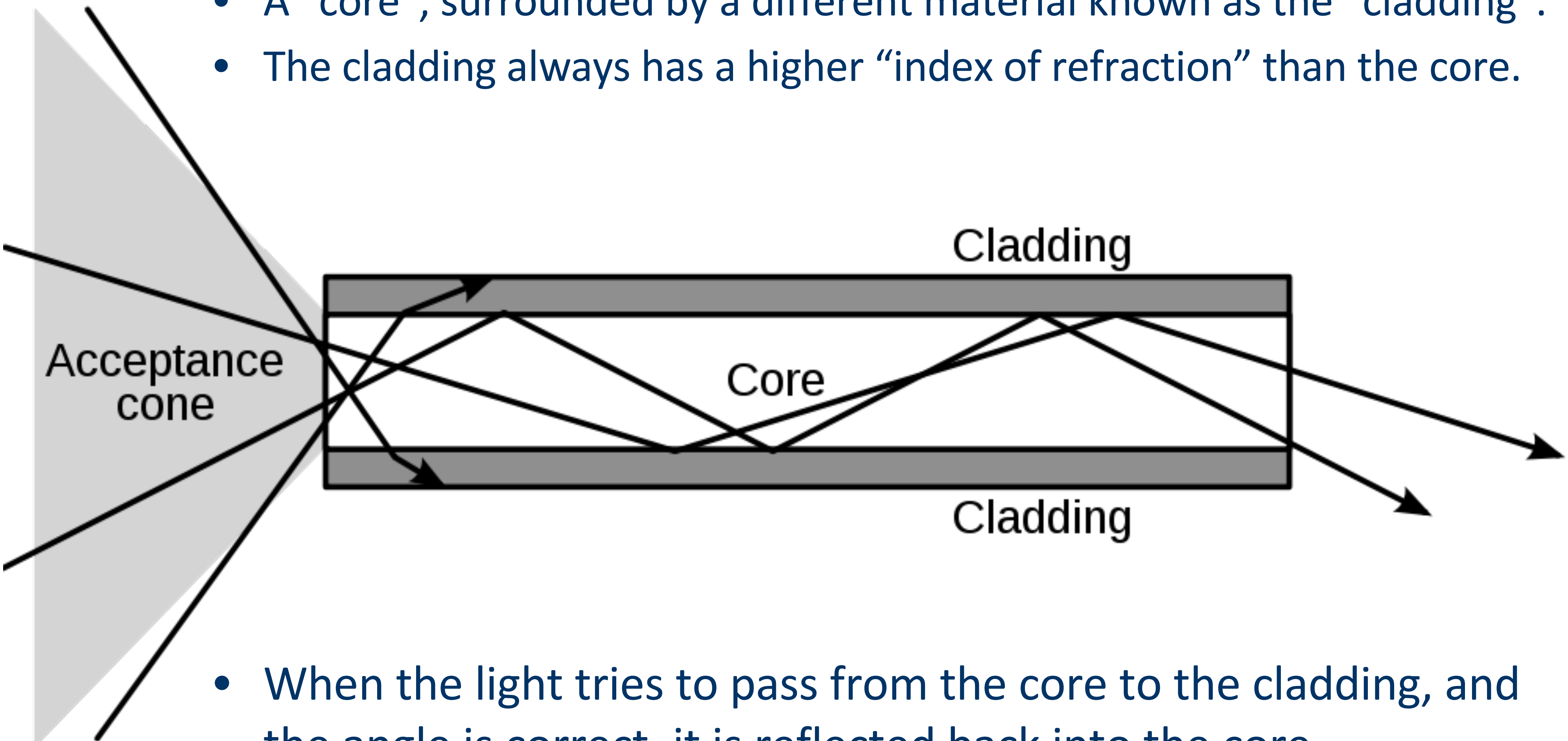
But when light passes through materials that **aren't** a perfect vacuum, it actually propagates much slower than this.

- The speed of light in any particular material is expressed as a ratio relative to "*c*", known as that material's "refractive index".
- 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 looking up from under water.

# Fiber Works by “Total Internal Reflection”

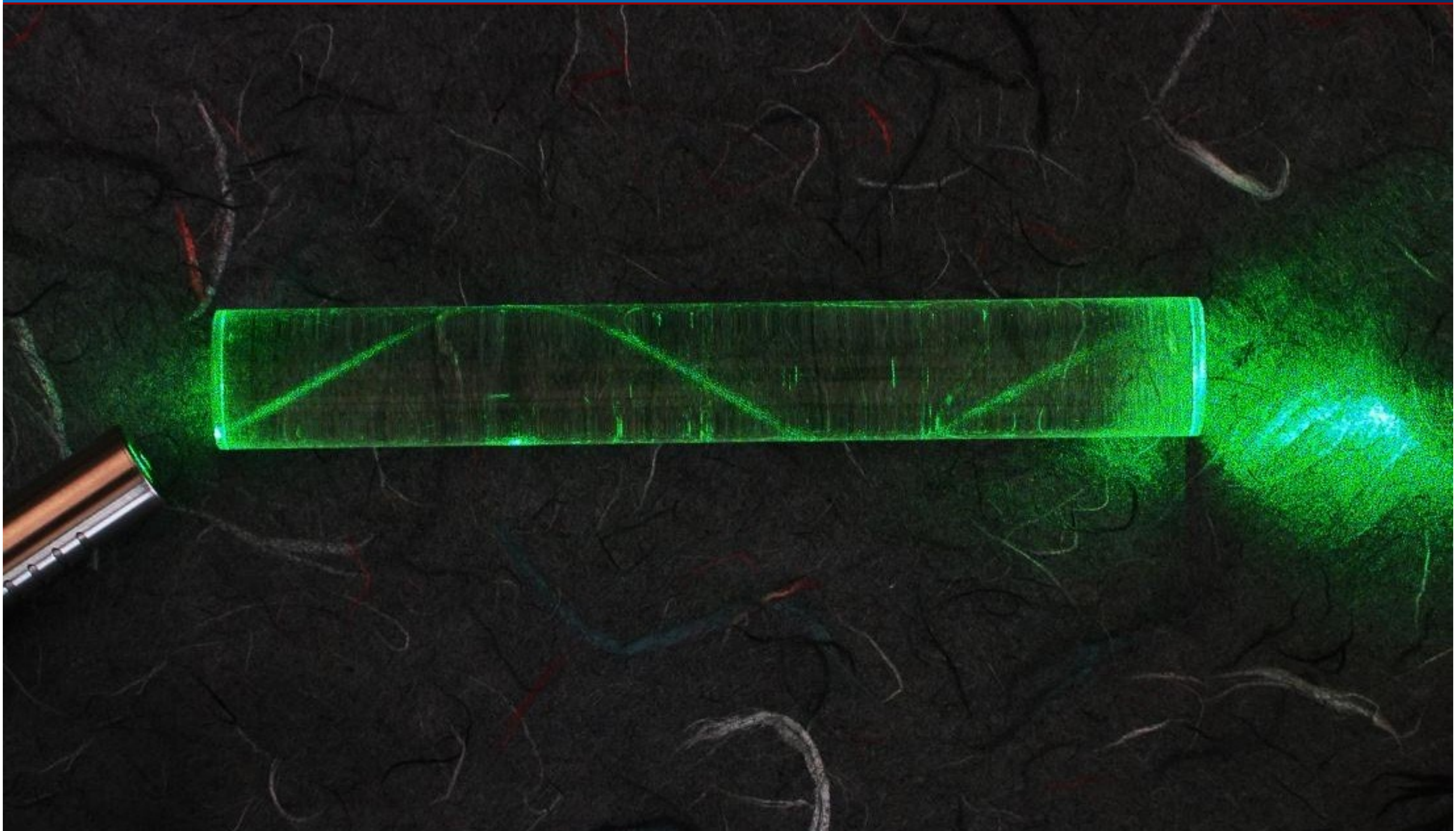
Fiber optic cables are internally composed of two layers.

- 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



# Duplex vs Simplex Operation

- The vast majority of deployed fiber optic systems are “duplex”.
  - One “pair” of fiber is used for each point-to-point link.
  - One strand is used to transmit a signal, the other to receive one.
  - This results in the simplest/cheapest optical components.

- But fiber itself is perfectly capable of carrying many signals, in both directions, over a single strand.
  - It just requires more expensive optical components to do so.

- Which system we use is largely a question of economics.
  - When fiber is cheap, we typically just throw burn extra strands.
  - But where the fiber is expensive or constrained (e.g. out of riser capacity, long-haul, etc) we use more advanced techniques.

# The Most Basic Distinction in Fiber: Multi-Mode vs Single Mode

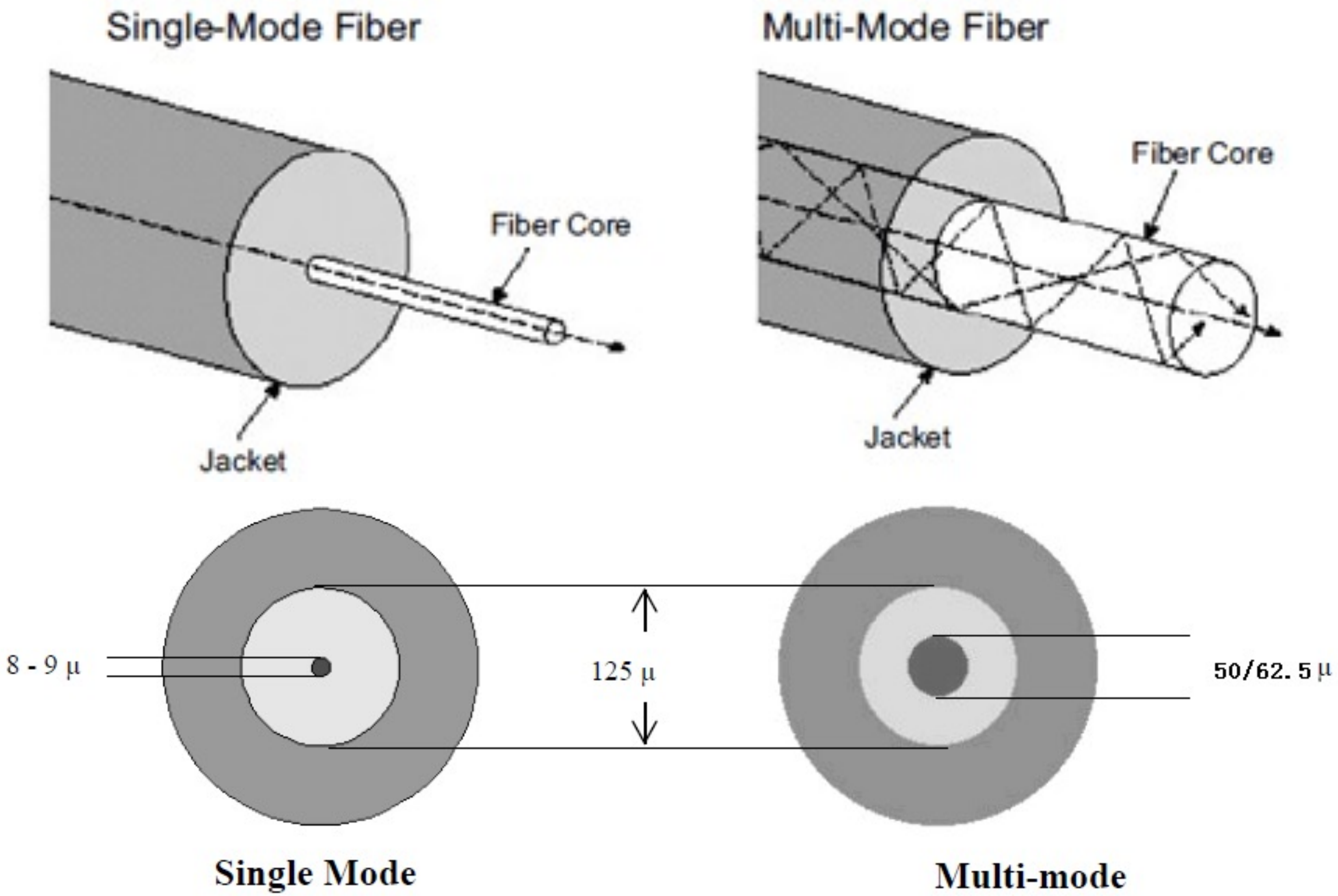
# Multi-Mode Fiber (MMF)

- Specifically designed for use with "cheaper" light sources.
  - Has an extremely wide core, allowing the use of less precisely focused, aimed, and calibrated light sources.
  - But this comes at the expensive of long-distance reach.
    - Fiber is so named because it allows multiple "modes" of light to propagate.
    - "Modal dispersion" typically limit distances to "tens to hundreds" of meters.
- Types of Multi-Mode
  - OM1/OM2 aka "FDDI grade": found with orange fiber jackets.
    - OM1 has a 62.5 micron (µm) core, OM2 has a 50µm core.
    - Originally designed for 100M/1310nm signals, starts to fail at 10G speeds.
  - OM3/OM4 aka "laser optimized": found with "aqua" fiber jackets.
    - Specifically designed for modern 850nm short reach laser sources.
    - Supports 10G signals at much longer distances (300-550m, vs 26m on OM1).
    - Required for 40G/100G signals (which are really 10G/25G signals), 100-150m.

# Single Mode Fiber (SMF)

- The fiber used for high bandwidths, and long distances.
  - Has a much smaller core size, between 8-10 microns (µm).
  - No inherent distance limitations caused by modal dispersion
    - Typically supports distances of ~80km without amplification.
    - With amplification, can transmit a signal several thousand kilometers.
- SMF has an even broader array of types than MMF.
  - Also has “OS1” and “OS2”, but they’re packaging, not fiber type.
    - OS1 ”tight buffered” for indoor use, OS2 “loose” to be blown into ducts.
  - ”Classic” SMF can be called “SMF-28” (a Corning product name)
  - But it comes in many different formulations of Low Water Peak Fiber (LWPF), Dispersion Shifted Fiber (DSF), Non-Zero Dispersion Shifted Fiber (NZDSF), Bend Insensitive Fiber, etc.

# Single Mode vs Multi-Mode Fiber



# Fiber Cables and Connectors

# Basic Optical Terms and Concepts

# Optical Power and Attenuation

Quite simply, the brightness (or "intensity") of the light.

- As light travels through fiber, some of its energy is lost.
  - Scattered by microscopic imperfections in the fiber.
  - Or absorbed by residual OH+ or dopants and converted to heat.
- This loss of intensity is called "attenuation".
  - No matter how good the fiber, eventually the light will be lost.

- We typically measure optical power in "Decibels"
  - A decibel (dB, $1/10^{th}$ 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 a logarithmic ratio between two values

- -10dB is 1/10th the signal, -20dB is 1/100th the signal, etc.
- Another easy one: +3dB is double, -3dB is half.
- But remember, this doesn't tell you "double of what?"

To express an absolute value, we need a reference.

- In optical networking, this is known as a "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 probably the single biggest mistake made in optical networking!

# Why Do We Measure Light in Decibels?

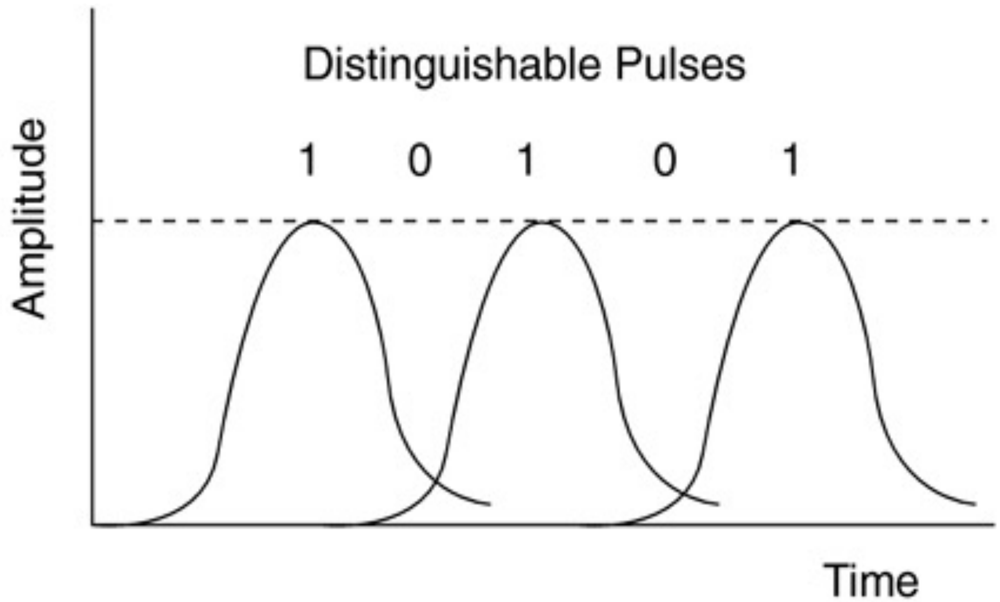
- Light, like sound, follows the “inverse square law”.
  - The signal is “inversely proportional to the distance squared”.
    - A signal travels distance X, and loses half of its intensity.
    - The signal travels another distance X, and loses another half.
      - At 2X, only 25% remains.
      - At 3X, only 12.5% remains.
      - At 4X, only 6.25% remains.
- A logarithmic scale vastly simplifies our calculations.
  - A 3dB change is approx. 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, etc.
- This lets us to use elementary school math.
  - Which is much easier for the humans to work with.

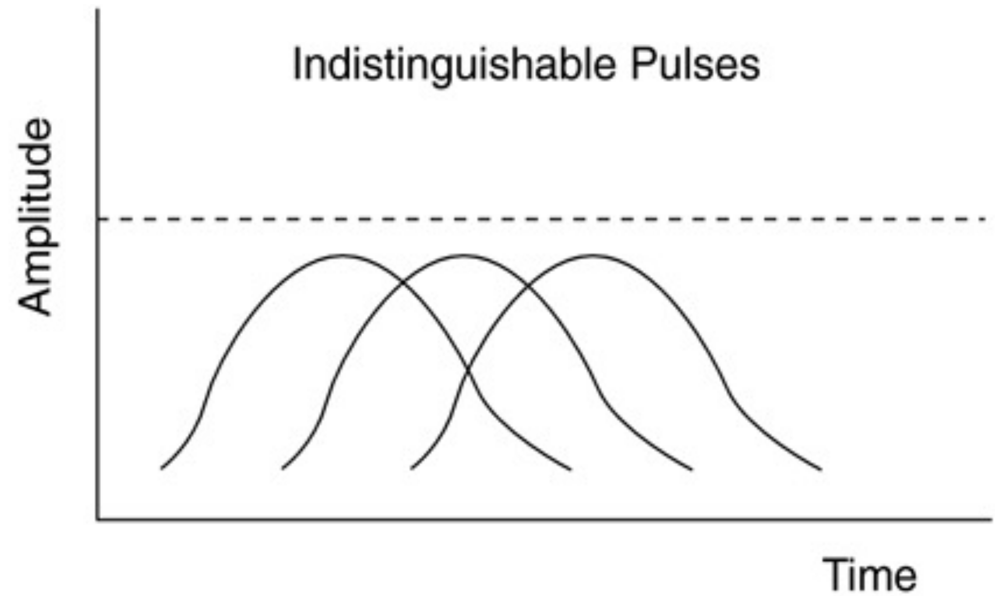
# Decibel to Power Conversion Table

| *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

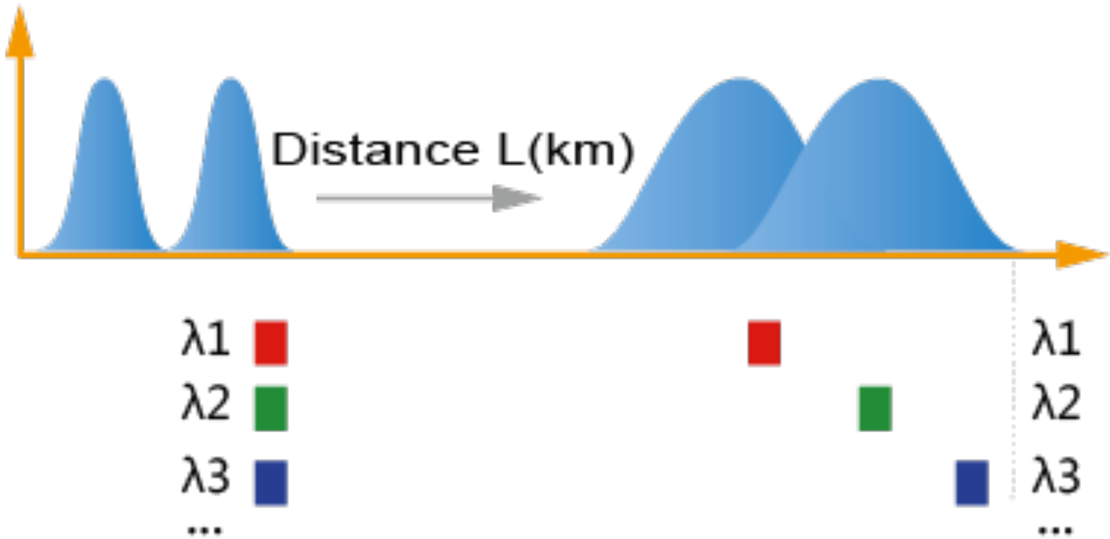
- Dispersion simply means “to spread out”.
  - In optical networking, this results in signal degradation.
  - Eventually, it is no longer distinguishable as individual pulses at the receiver.
- We’re primarily concerned with two types of dispersion:
  - “Chromatic Dispersion” (CD), and “Polarization Mode Dispersion” (PMD).



# Chromatic Dispersion (CD)

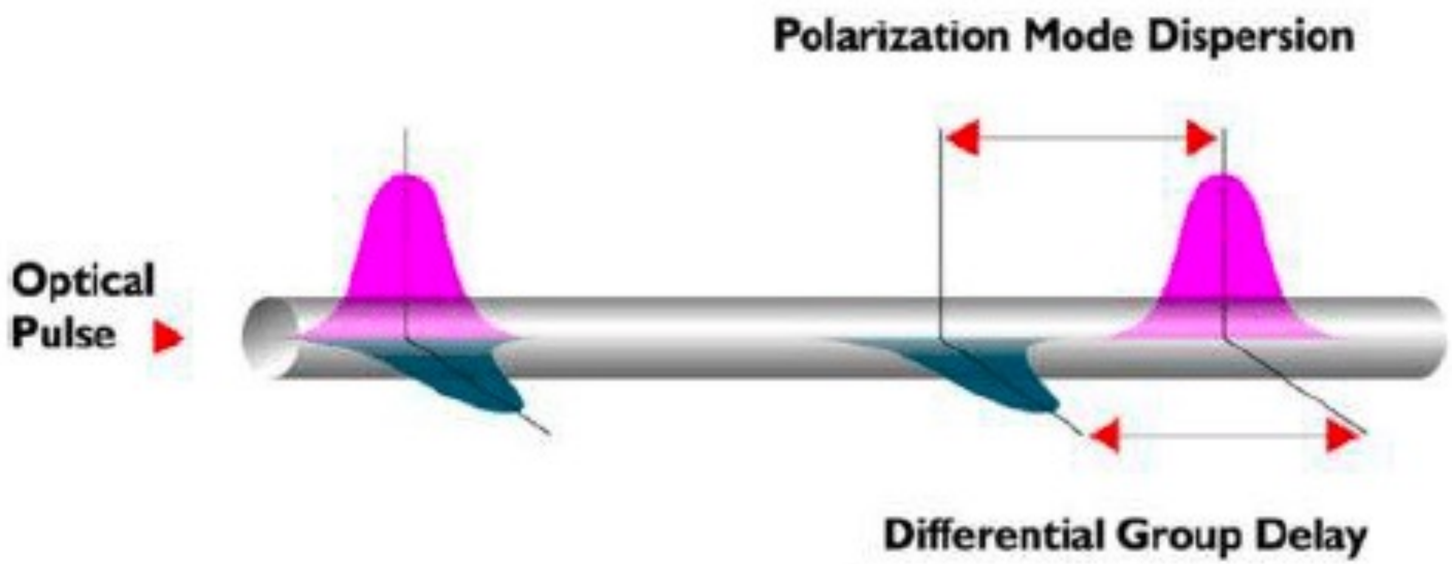
- Different frequencies of light propagate through a non-vacuum at different speeds.
  - This is how rainbows and optical prisms work.
  - Eventually, your signal stops arriving at the same time, and become indistinguishable.




- Chromatic Dispersion has historically been a huge limiting factor.
  - The faster your symbol rates, the wider your signal linewidths.
  - The wider the signal linewidth, the worse CD affects your signal.
  - CD impacts increase at the square of the baud rate.
  - We measure CD in “picoseconds per nanometer” (ps/nm).

# Polarization Mode Dispersion (PMD)

- Polarization Mode Dispersion (PMD) results when the light of one polarization arrives at a different time than the other.
  - This is caused by imperfections in the cylindrical shape of the fiber.

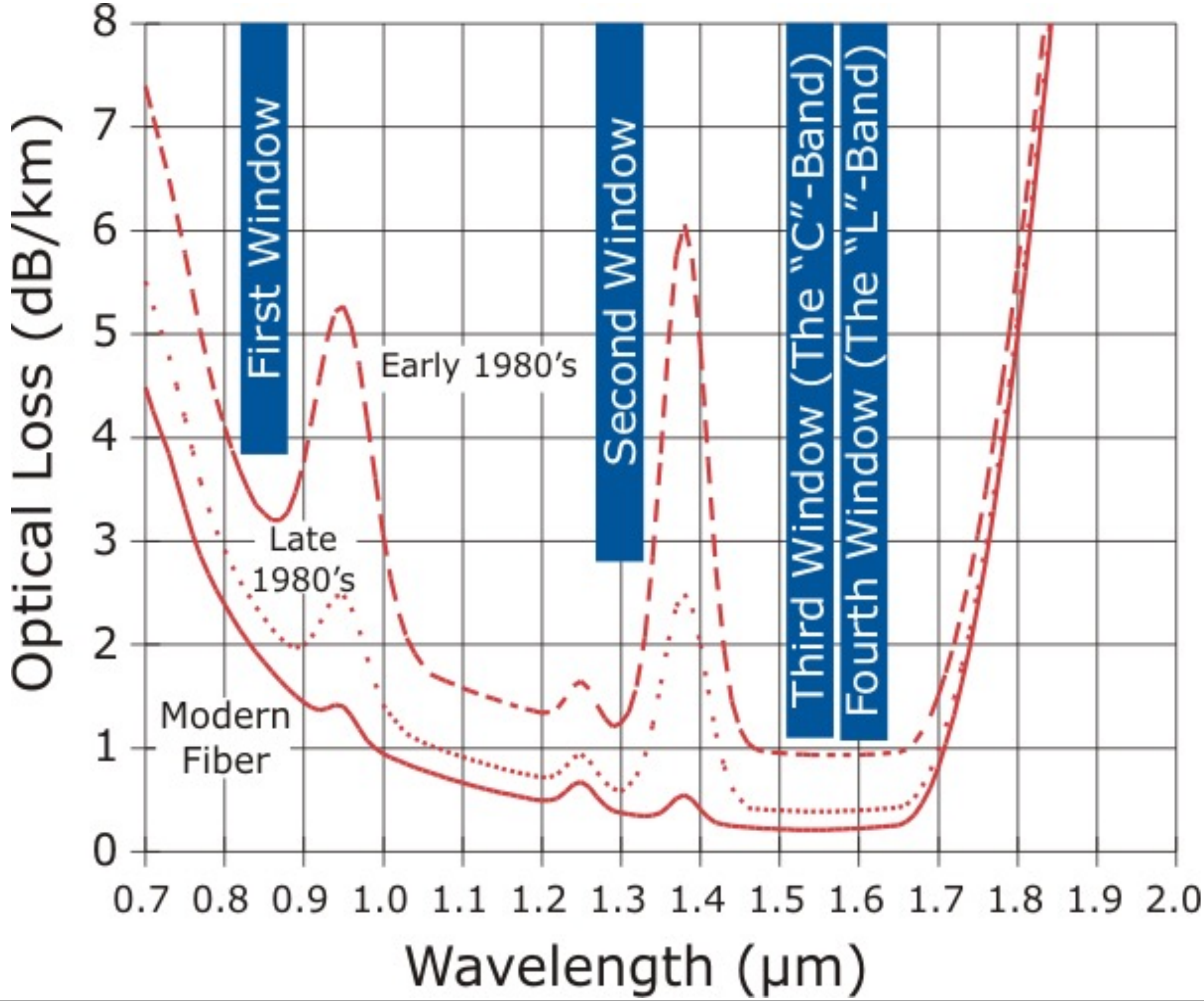



- The difference in arrival time between the polarizations is called “Differential Group Delay” (DGD), measured in picoseconds (ps).

# Fiber Optic Transmission Bands

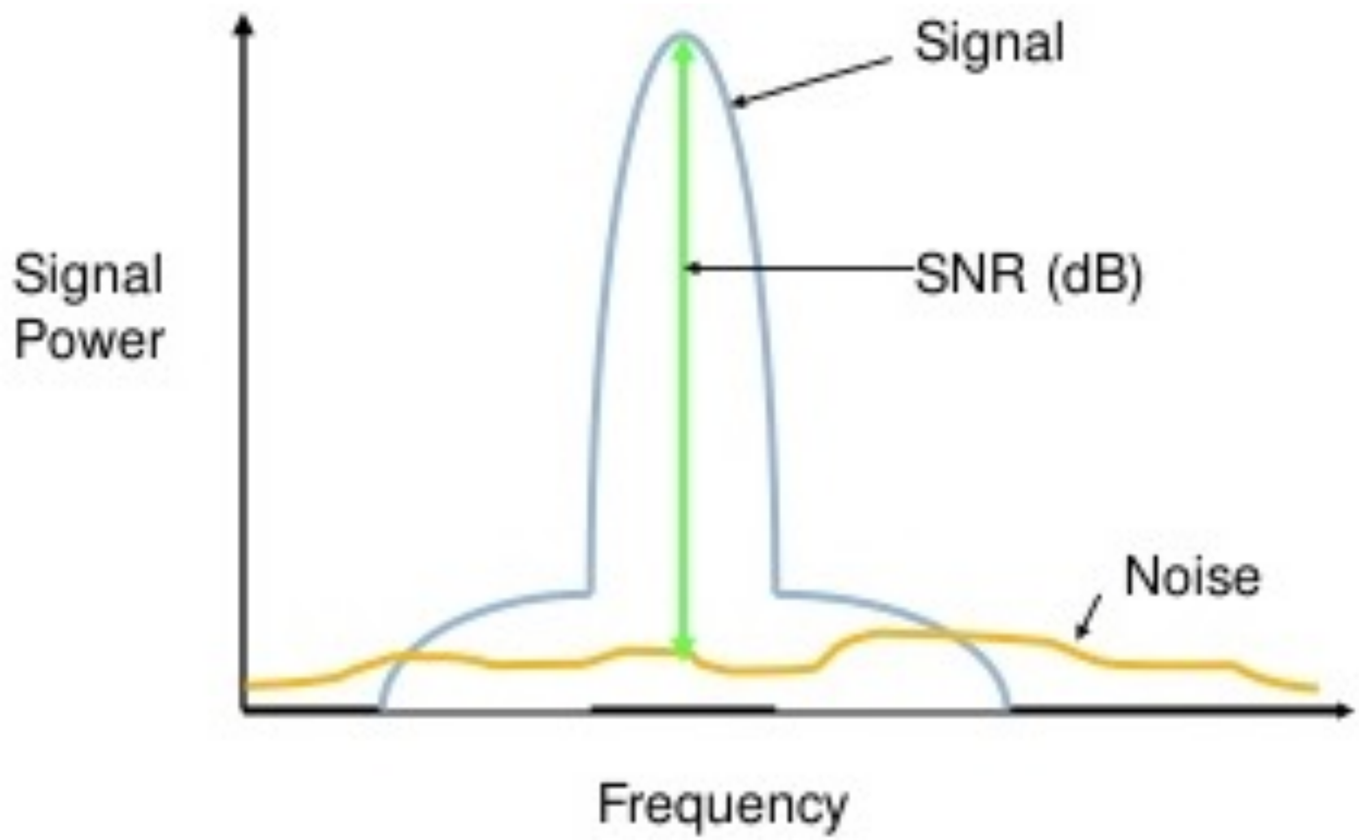
- 850nm –
  - Highest attenuation, only used for short-reach applications.
- 1310nm – O-Band (Original Band)
  - Covers 1260nm-1360nm, 1310nm is the center frequency.
  - Point of lowest dispersion on classic SMF, but higher attenuation.
  - Primarily used for intermediate-reach applications (2-10km) today.
- 1550nm – C-band (Conventional Band)
  - Covers 1530nm – 1565nm, 1550nm is the center frequency.
  - Lowest rate of attenuation, but higher chromatic dispersion.
  - Used for almost all long-reach and DWDM applications today.
- L-band (Long Band)
  - Covers 1565nm – 1625nm, 60nm of total spectrum.
  - Acts as an “extension” to C-band, with many similar properties.
  - Different amplification techniques are required.
  - Typically only used when fiber is extremely constrained/valuable.

# Fiber Optic Transmission Bands



# Optical Signal to Noise Ratio (OSNR)

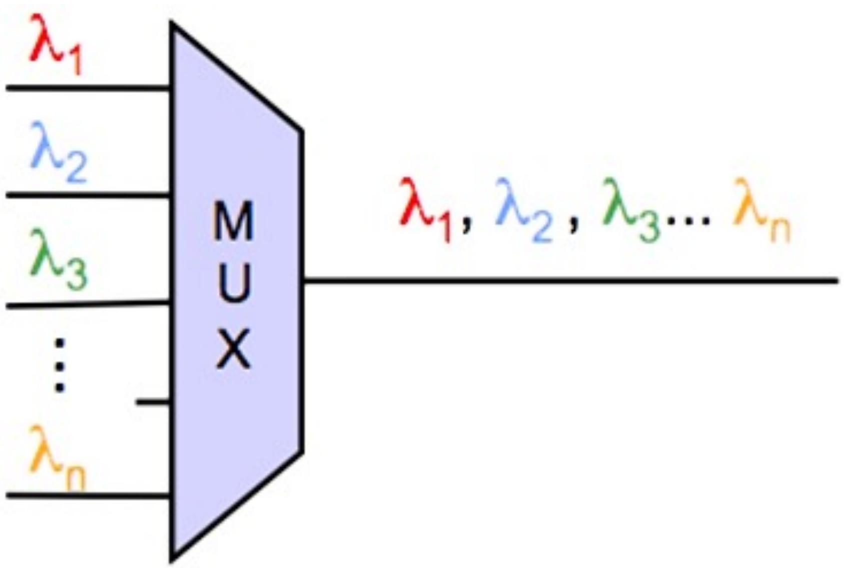
In amplified long-reach systems, OSNR becomes the single most important limiting factor.

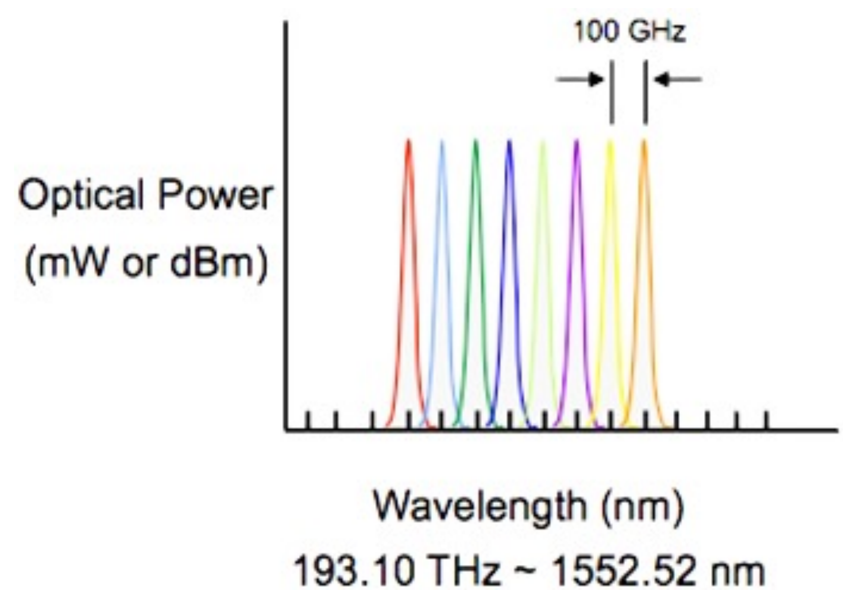


# Wave Division Multiplexing

# Wave Division Multiplexing (WDM)

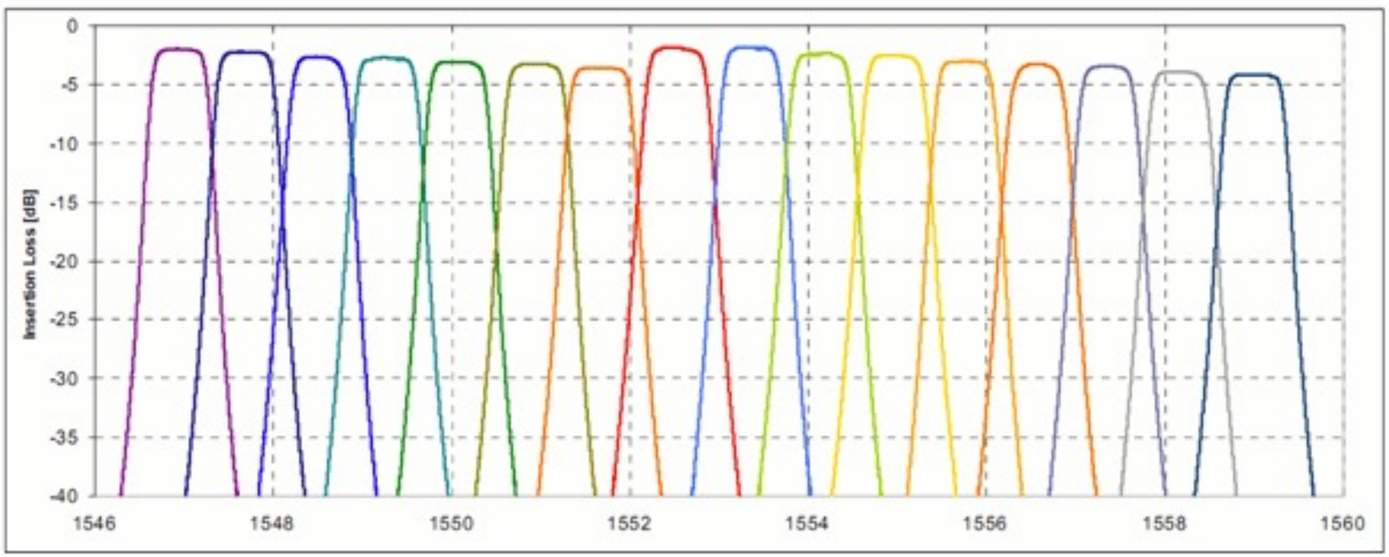
- We know that light comes in many different "colors".
  - What we perceive as "white" is just a mix of many wavelengths.
- These different colors can be combined on the same fiber.
- The goal is to put multiple signals on the same fiber without interference ("ships in the night"), thus increasing capacity.



# Coarse Wave Division Multiplexing (CWDM)

- 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

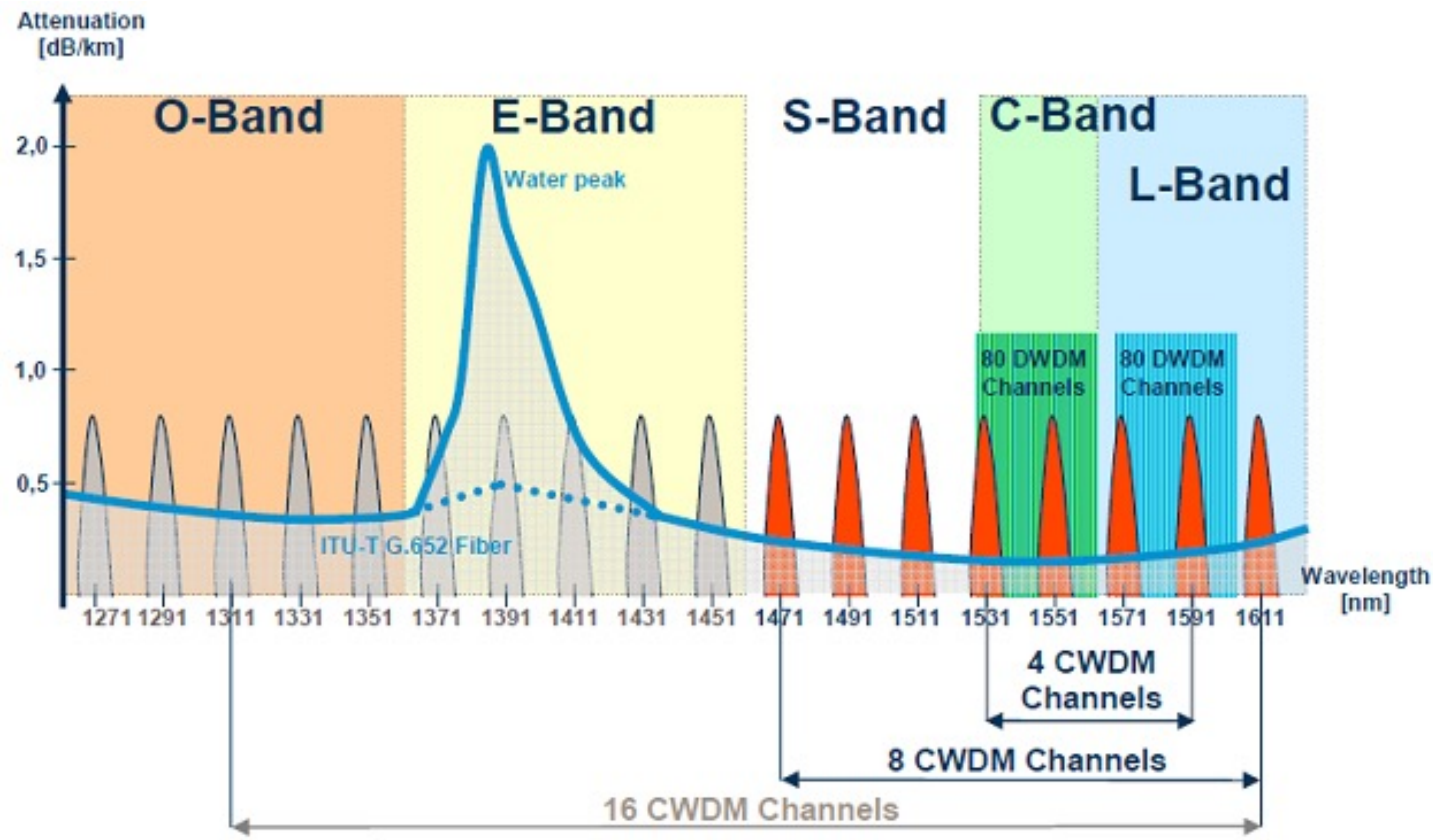



  - With Low Water Peak fiber, another 10 channels are possible
    - Centered on 1270/1290/1310/1330/1350/1370/1390/1410/1430/1450.
  - Can also be used to refer to a simple 1310/1550nm mux.

# Dense Wave Division Multiplexing (DWDM)

- Defined by the ITU-T G.694.1 as a "grid" of specific channels.
- Within C-band, the follow channel sizes are common:
  - 200GHz – 1.6nm spacing, 20-24 channels in C-band
  - 100GHz – 0.8nm spacing, 40-48 channels in C-band
  - 50GHz – 0.4nm spacing, 80-96 channels in C-band
  - 25GHz – 0.2nm spacing, 160-192 channels in C-band
- A rough guideline to the technology:
  - 200GHz is "2000-era" old tech, rarely seen in production today.
  - 100GHz is still quite common for metro DWDM tuned pluggables.
  - 50GHz is common for commercial, long-haul, and 100G systems.
  - 25GHz was used briefly for high-density 10G systems, before the move to coherent 100G systems shifted everything back to 50GHz.
  - Modern systems can be flexible, in 6.25GHz increments or smaller.

# WDM Channel Size Comparison



# What Are The Advantages to Each?

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 more easily stay within the window.

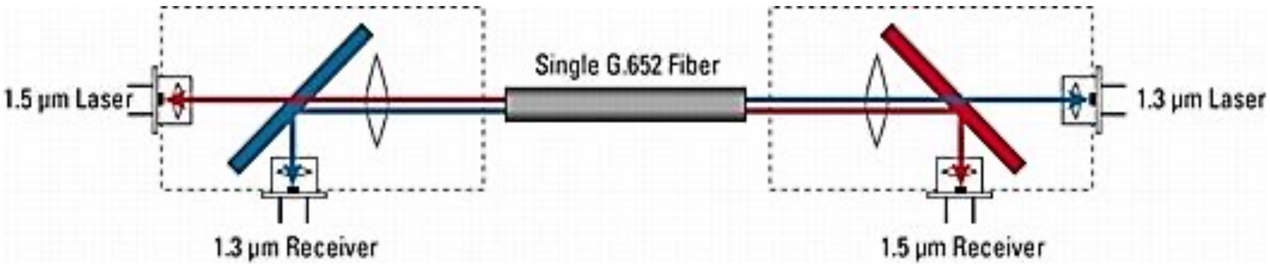
DWDM

- Far more channels are possible within the same fiber.
  - 96 channels (at 50GHz) in 32nm of spectrum, vs. 8ch in 160nm.
- Can stay completely within the C-band
  - Where attenuation and dispersion are far lower.
  - And where simple Erbium Doped Amplifiers (EDFAs) work.
- But can also be duplicated within the L-band for expansion.

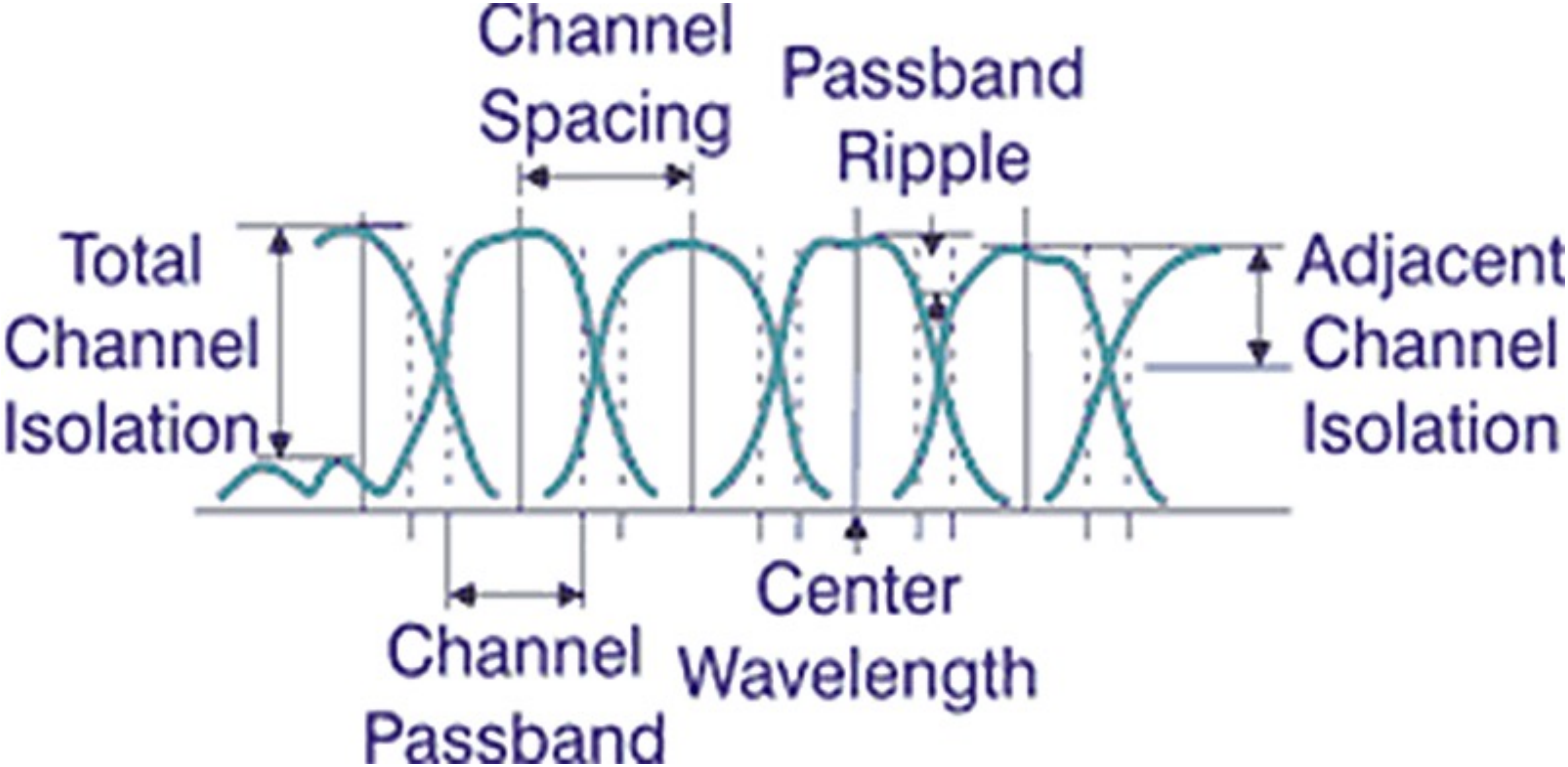
# Other Uses of Wave Division Multiplexing

But other forms of WDM exist as well

- Simple 1310/1550 muxes.
- 4-lane “Grey” Optics
  - New high-speed interfaces often start using WDM lanes.
    - They’re cheaper to implement, or can support older fiber technology.
  - 10GE had 10GBASE-LX4 (4x 2.5G channels, rather than 1x 10G)
  - 40GE has LR4 (4x 10G, 1270nm / 1290nm / 1310nm / 1330nm)
  - 100GE has LR4 (4x 25G, 1295nm / 1300nm / 1305nm / 1310nm)
- Single Strand Optics (BX “bidirectional” standards)
    - E.g. 1310 / 1490nm mux integrated into a pluggable transceiver.



# DWDM Channel Terminology



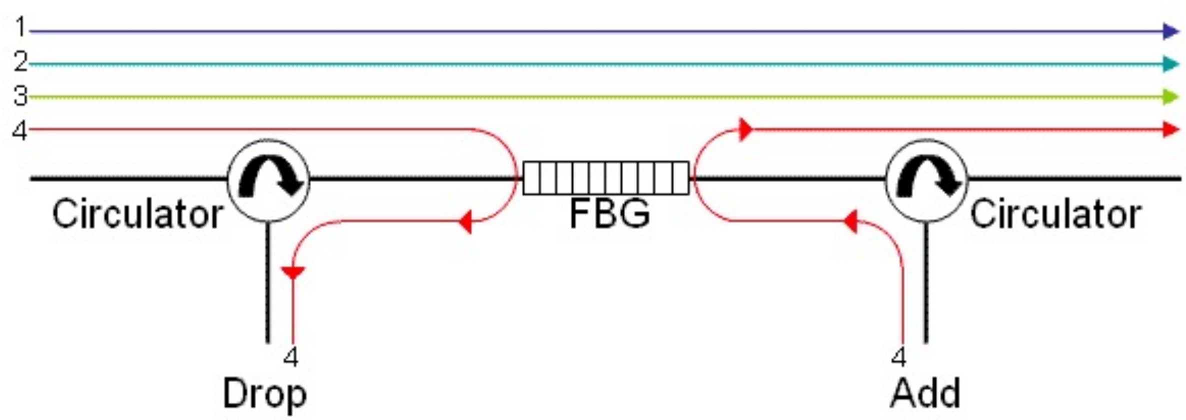
# WDM Networking Components

# WDM Mux/Demux

- A simple, passive (unpowered) device, which combines/splits multiple colors of light to/from a single "common" fiber.
- Short for "multiplexer", sometimes called a "filter", or "prism".
  - A "filter" is how it actually works, by filtering specific colors.
  - But people conceptually understand that a prism splits light into its various component frequencies.
- A complete system requires both a mux and a demux, for the TX and RX operation.
- Typically sold as a single package containing both units, for simplicity (and use on duplex fiber).

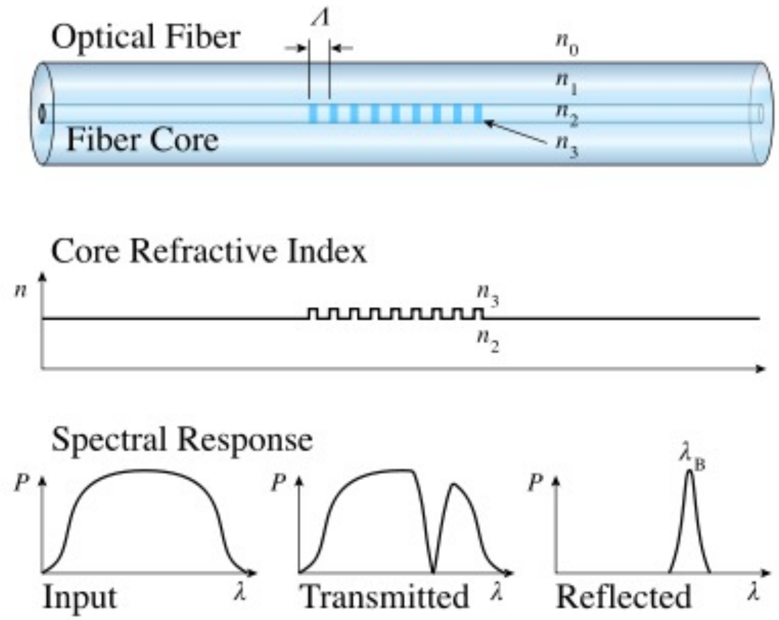
# Optical Add/Drop Multiplexer (OADM)

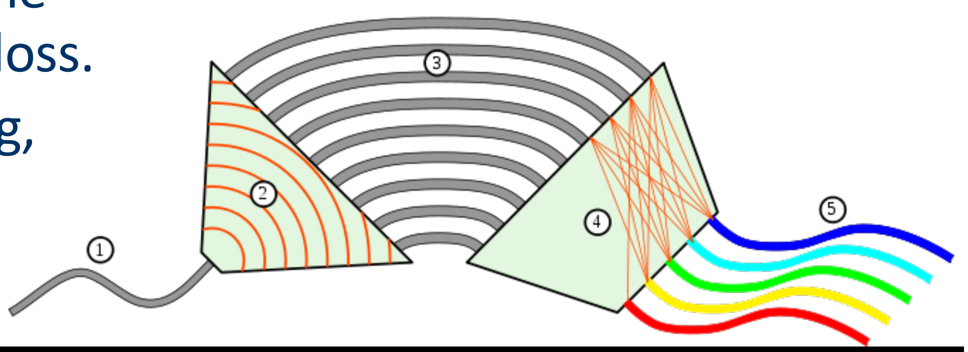
- Selectively Adds and Drops certain WDM channels, while passing other channels through without disruption.
- While muxes often used at major end-points to break out all channels, OADMs are often used at mid-points within rings.
- A well-constructed OADM ring can reach any other node in the ring optically, potentially reusing some wavelengths multiple times on different portions of the ring.
- This is also an entirely passive and unpowered device.



# Passive Optical Filter Technology

- FBG (Fiber Bragg Grating)
  - An “etched” fiber core, which causes a certain frequency to be reflected.
  - Does one channel at a time.
- Thin Film Filter (TFF)
  - Used for medium channel counts, < 16
- AWG (Arrayed Waveguide Grating)
  - Typically used for 40+ channel systems.
  - Essentially a very fancy interferometer.
  - For high channel counts, these are the cheapest and have lowest insertion loss.
  - Early versions required active cooling, but most units today are athermal (AAWG).

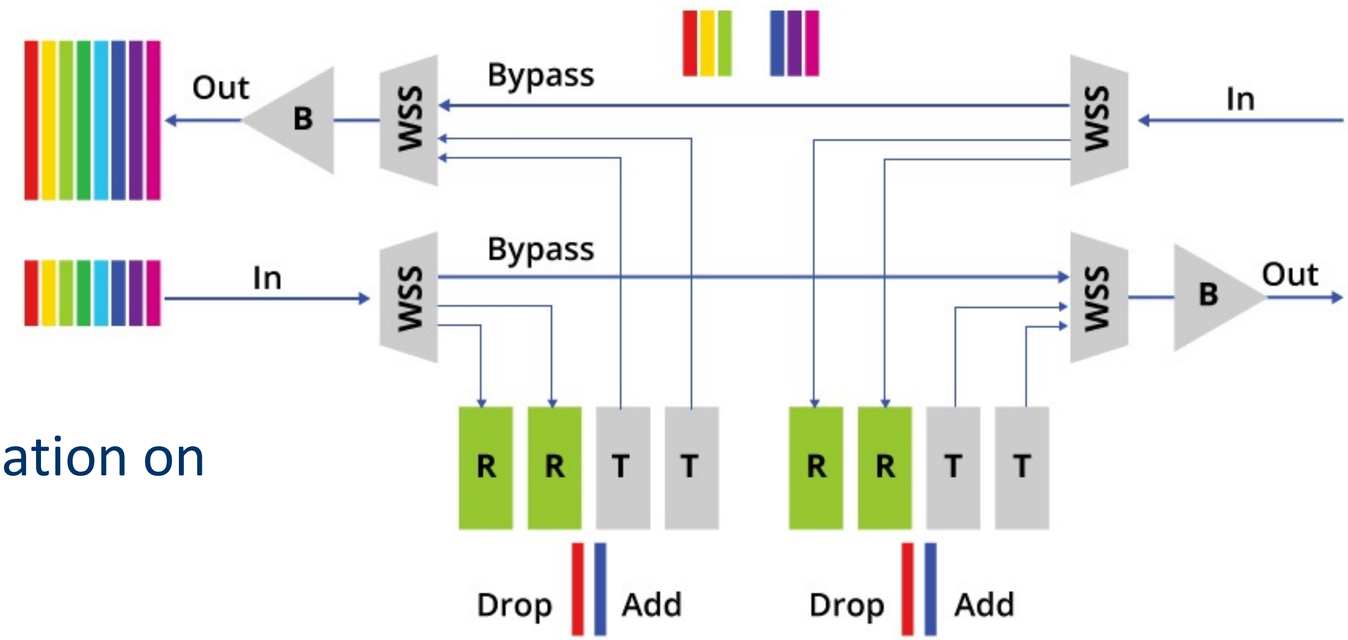


# Reconfigurable OADM (ROADM)

A ROADM is a software reconfigurable OADM

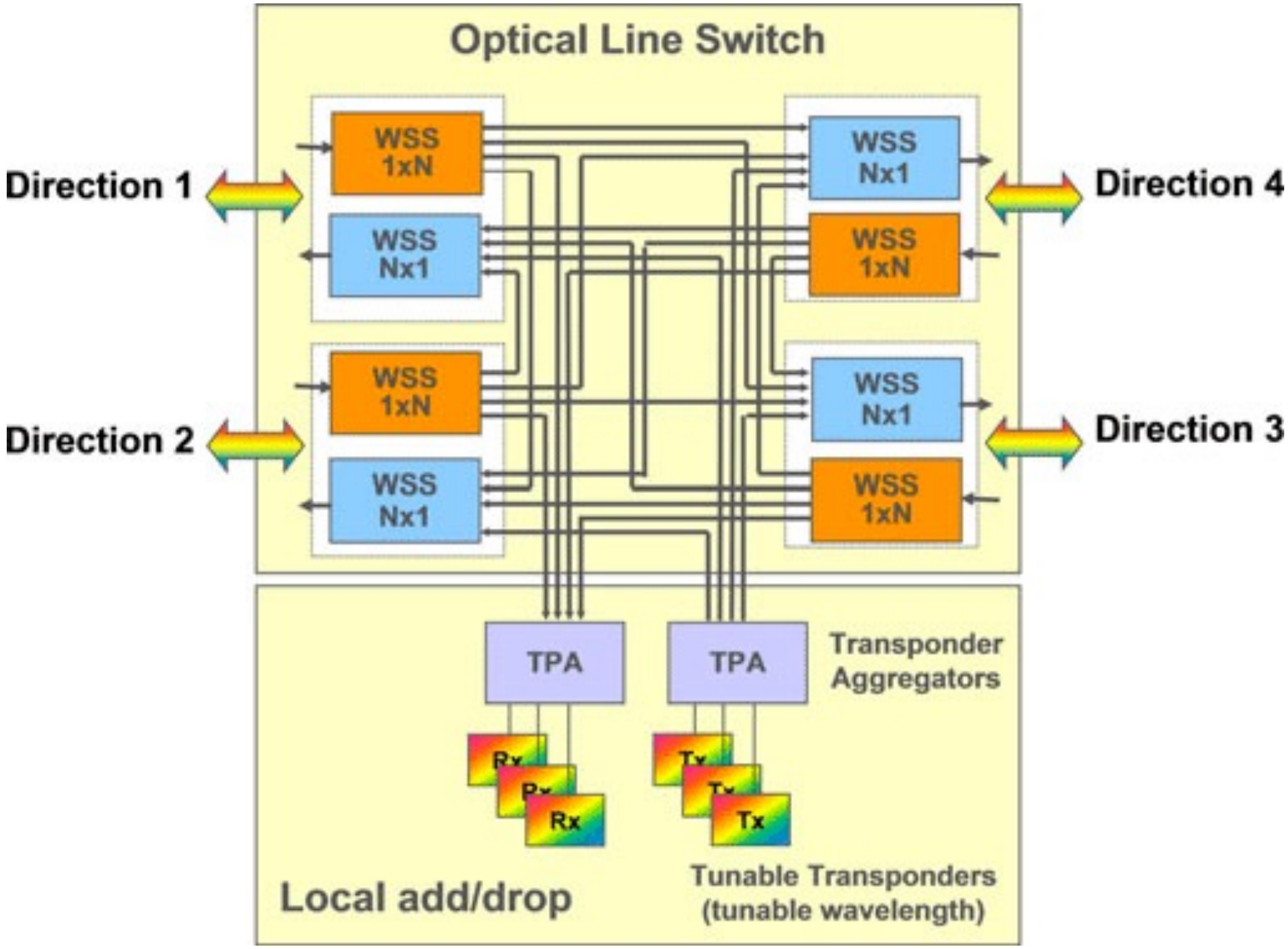
- Built around a WSS (Wavelength Selective Switch).
- Common Architectures:
  - Broadcast and Select: A 1xN Passive Splitter on TX, and WSS on RX
  - Route and Select: A WSS on TX, and WSS on RX




- Plus a lot of amplification on all sides!

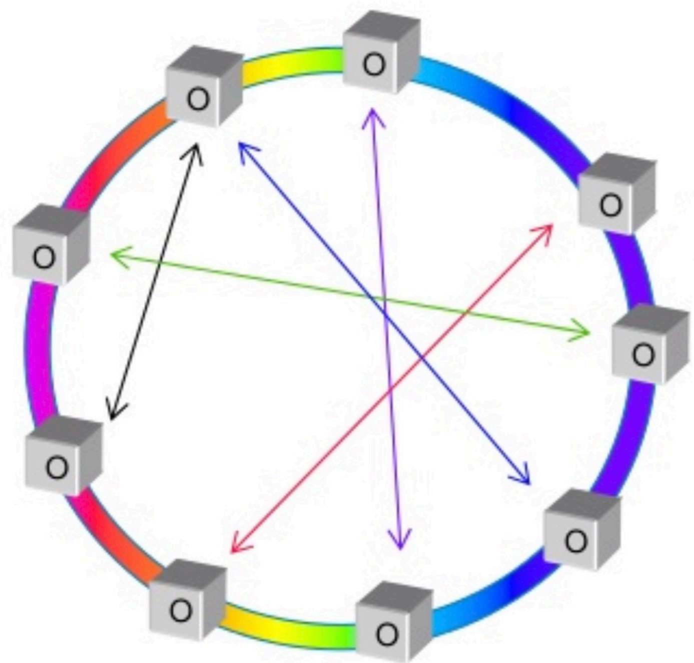
# ROADM Degrees

A ROADM “degree” is one possible direction light can be steered.



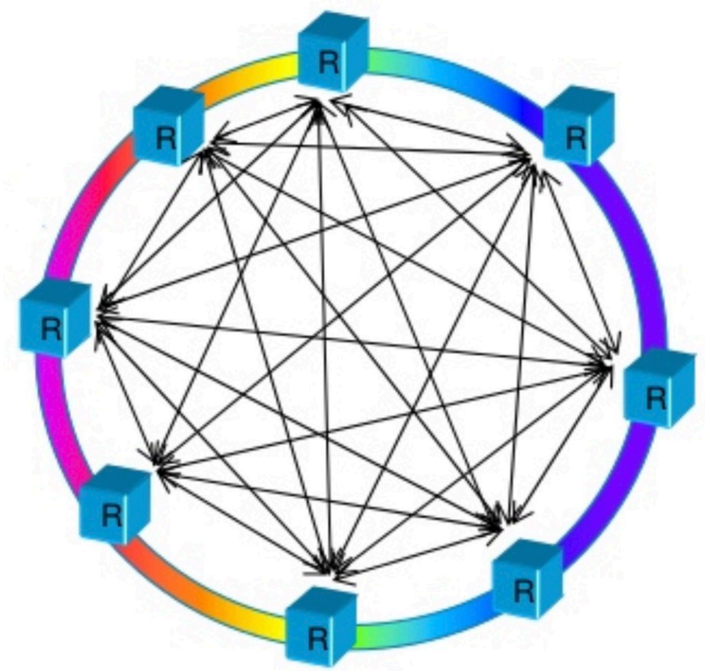
# Fixed OADM (FOADM) vs ROADM Rings

## Fixed OADM



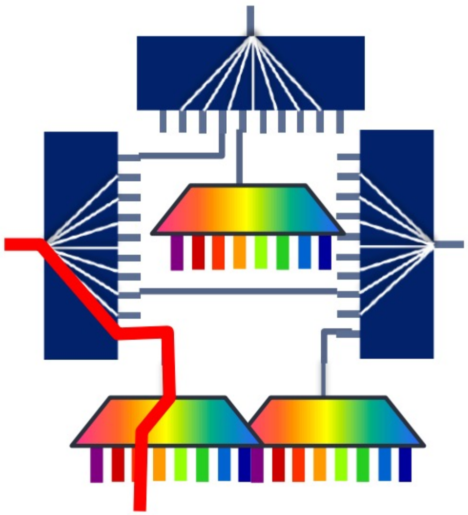
- Optical connections between nodes are static, not reconfigurable without hw swap.
- Requires extensive man hours to support.
- But incredibly cheap and built on simple passive components.

## ROADM



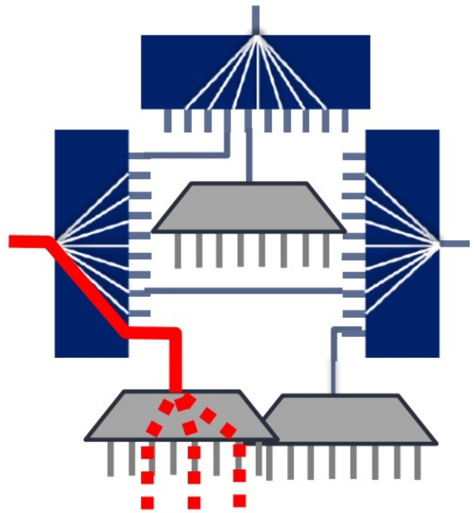
- Dynamically connects any point to any point optically, using only software.
- Can be run from a point-and-click GUI.
- But built on incredibly complex and expensive pieces of equipment.

# The Evolution of the ROADM



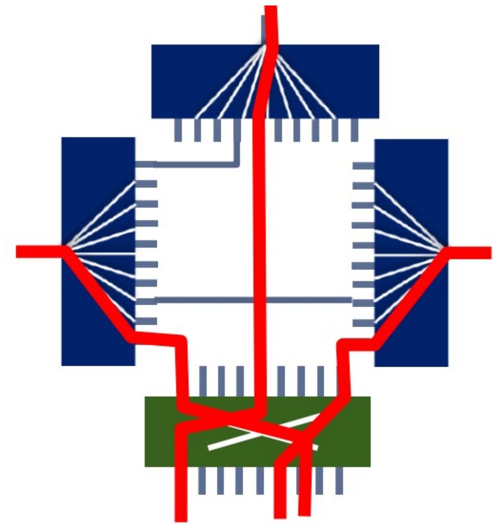
Basic ROADM

- Reconfigurable, but add/drop still goes to a standard fixed mux.
- Specific frequencies must be connected to specific ports.
- The network must be recabled in order to change or move frequencies.



Colorless ROADM

- Eliminates the need to map specific frequencies to specific ports.
- But still limited to muxing in one direction at a time.



CDC ROADM

- Colorless – Any channel can be add/dropped on any port.
- Directionless – Any channel can be sent to any direction.
- Contentionless – The same channel can be reused in different directions without causing internal contention in the ROADM.

# Modern Networking and the CDC ROADM

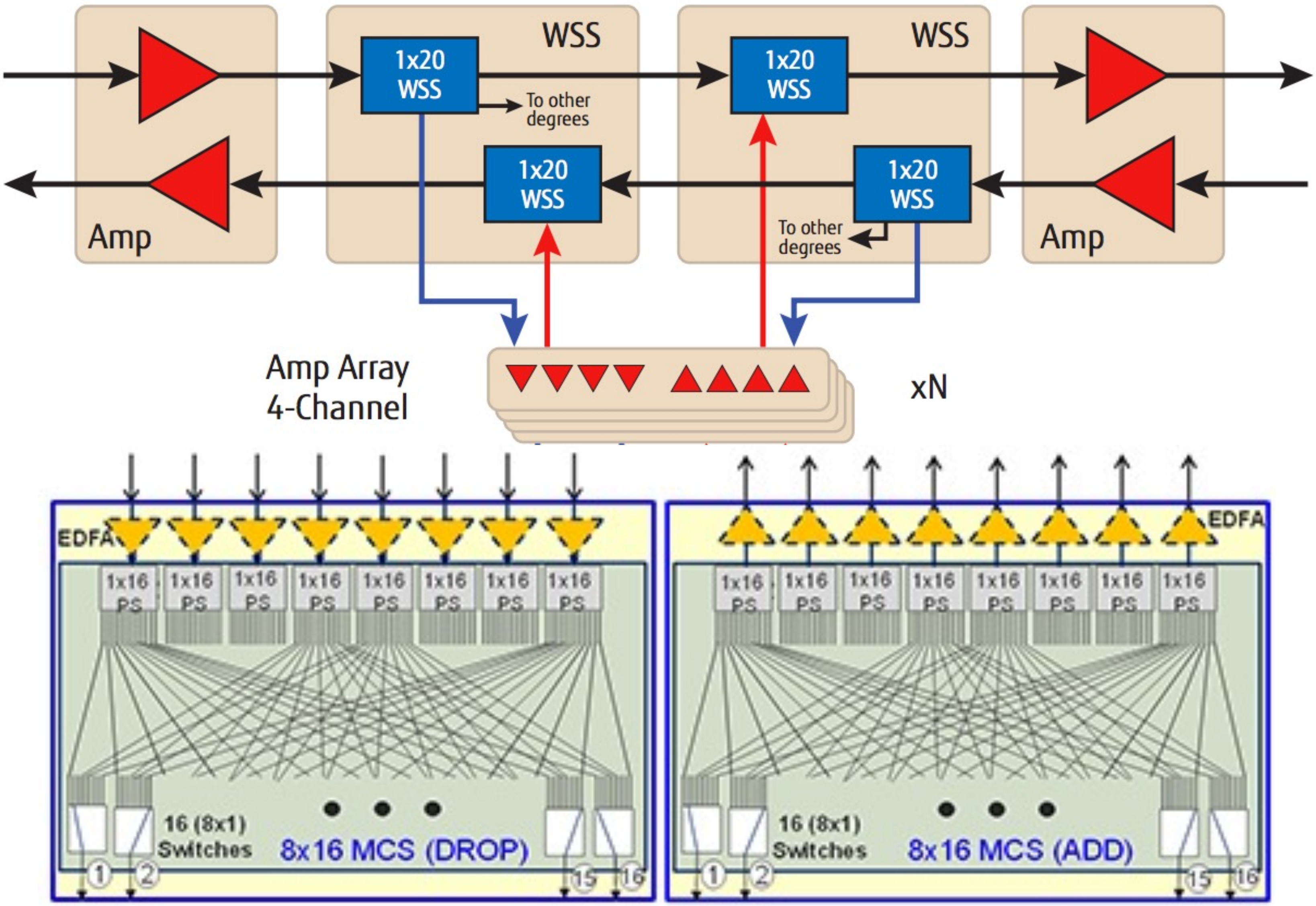
The goal is to move optical channels entirely in software.

- Transponders can be reallocated onto different physical paths as traffic patterns change (due to time-of-day changes, or during fiber cuts), potentially increasing efficiency and reducing costs.
- Eliminates the need to physically move cables to reconfigure.
- Allows dynamic bandwidth allocation at an optical level.

Potentially the entire process can be automated.

- IETF pushing for vendor interoperability and signaling via mechanisms like PCEP (Path Computation Element Protocol).
- Routers could "request" additional bandwidth from a pool of underlying transponders, based on real-time traffic requirements.

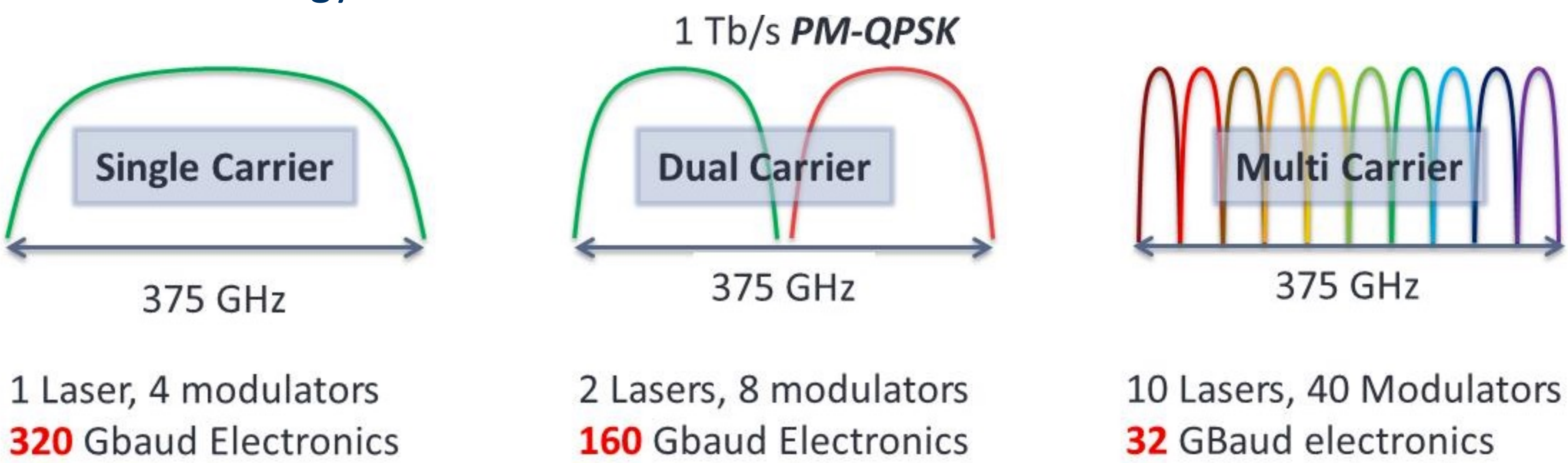
# What Goes Into a Modern CDC ROADM



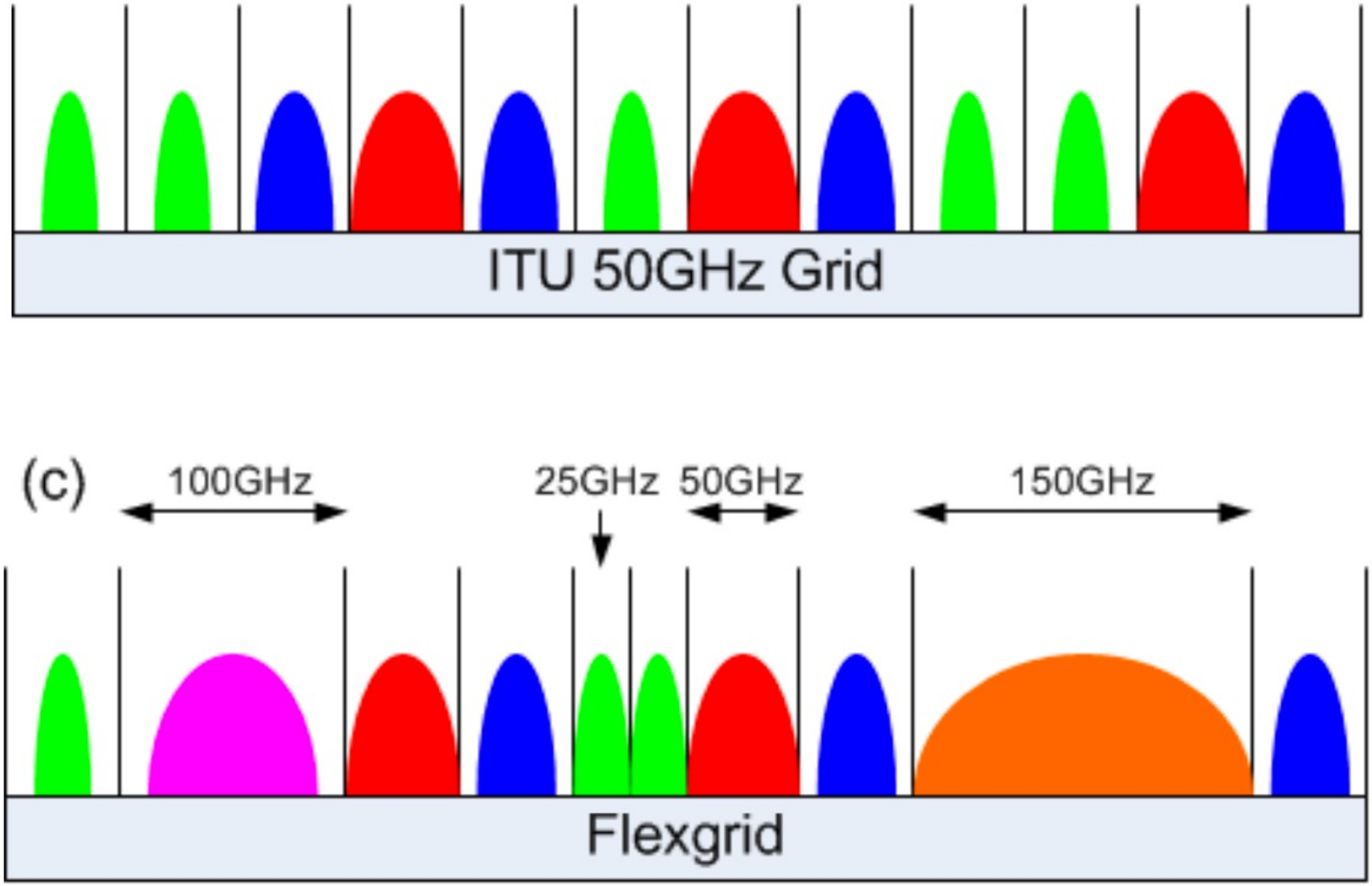
# DWDM Superchannels

What if we want performance that a single carrier can't deliver?

- Superchannels pack multiple carriers together in a single channel.
- Often you can pack the carriers together tighter than if you were using standard channels too, increasing spectral efficiency.
- In this example, we deliver 1 Tbps using off the shelf 10x100G technology.



# The Evolution of DWDM Channels



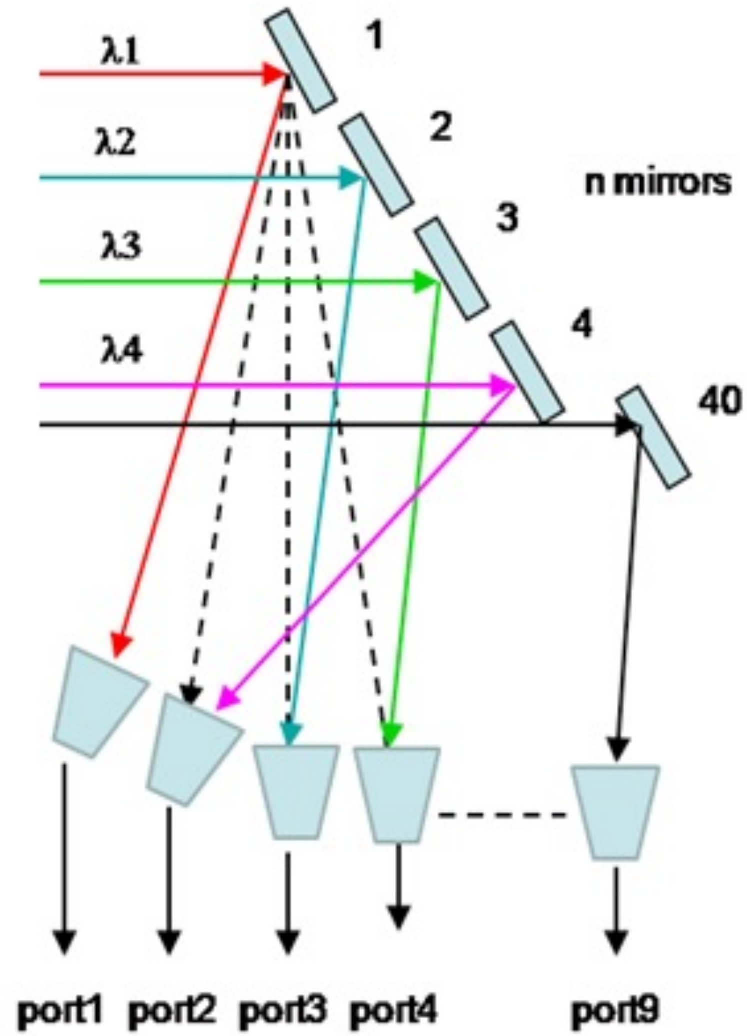
# Other Optical Networking Components

# Dispersion Compensation Units (DCU/DCM)

- Originally, just a big spool of fiber in a box.
  - Designed to cause dispersion in the opposite direction (opposite ”slope”) as the transmission fiber.
  - Passing through this spool reverses the effects of dispersion caused by the transmission fiber.
  - But it also adds fiber distance (typically 20%), and latency.
  - Usually deployed at amp sites.
- Newer designs are FBG based.
  - Reduces insertion loss, eliminates the latency overhead and physical bulk of a fiber spool-based design.
  - But also specific to channel plan, does not align well wider channels.

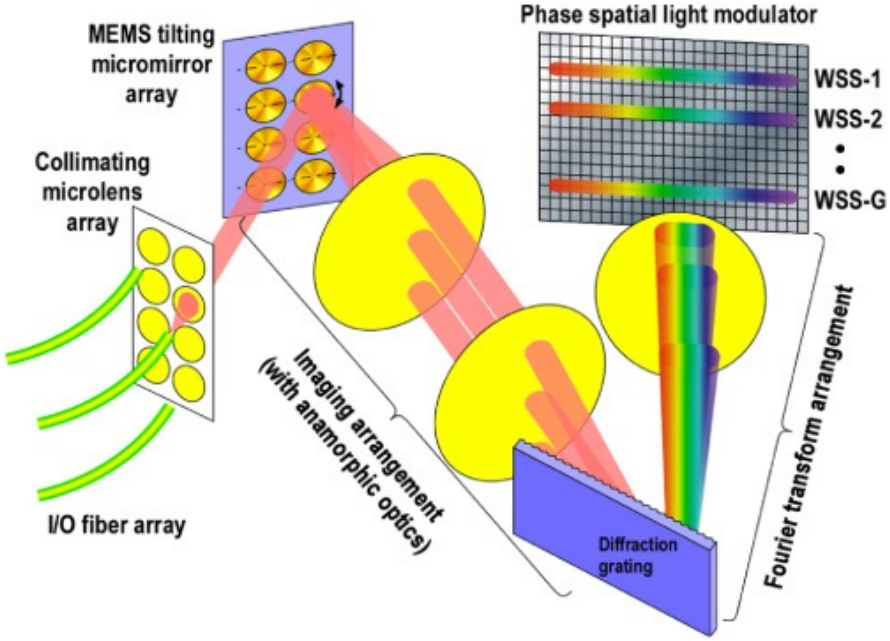
# Optical Switches

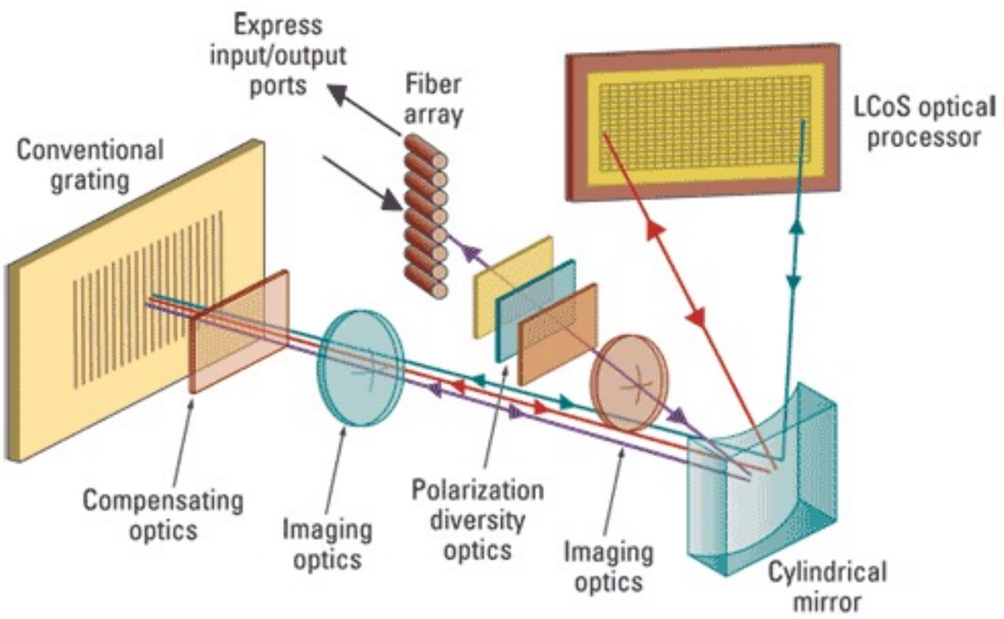
- Optical Switches
  - Let you direct light between ports, without doing O-E-O conversion.
  - Built with an array of tiny mirrors, which can be moved electrically.
  - Allows you to connect two fibers together optically in software.
  - Becoming popular in optical cross-connect and fiber protection roles.



# Wavelength Selective Switch (WSS)

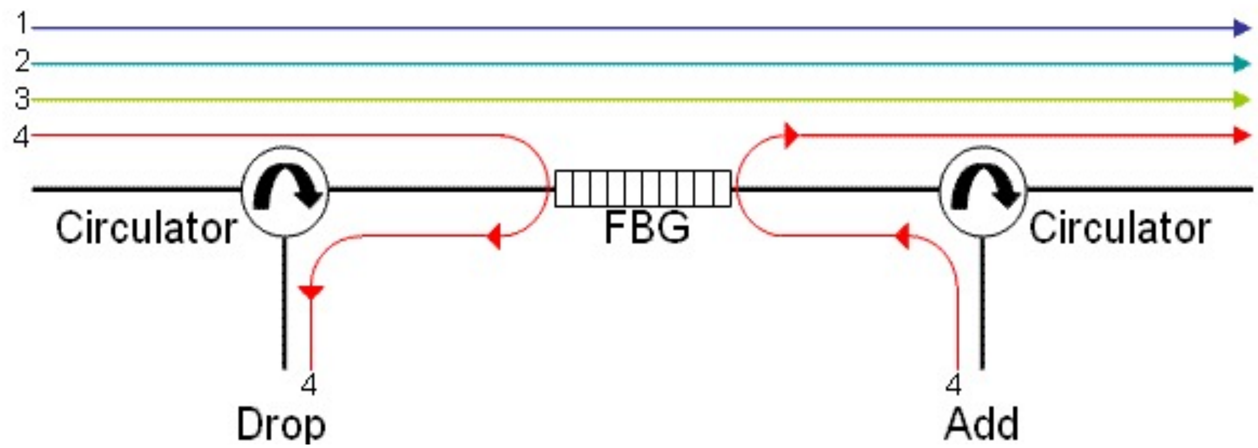
- Lets you "route" an individual wavelength between ports
  - The WSS is a key component inside of a ROADM.
  - First generation WSS' used 3D MEMS optical switches.
  - Modern WSS' use Liquid Crystal on Silicon (LCoS).



# Circulator

- A component typically not seen by the end user.
  - A circulator has 3 fiber ports.
    - Light coming in port 1 goes out port 2.
    - Light coming in port 2 goes out port 3.
  - Frequently used inside other popular components.
    - Bragg grating based components, like OADMs and small muxes.
    - Dispersion compensation spools, amplifiers, etc.
    - Very useful when building single-strand bidirectional systems too.



# Optical Splitters

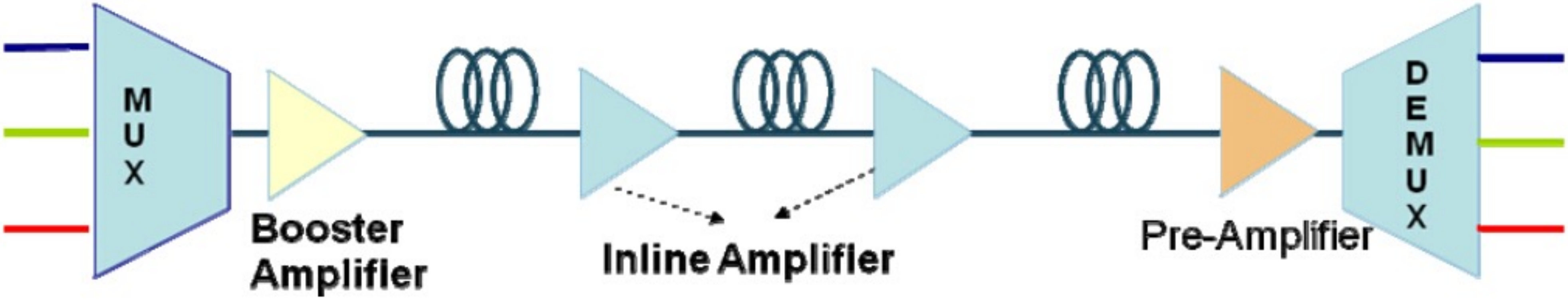
- Do exactly what they sound like they do, split a signal.
- Some common examples of splitters are:
  - A 50/50 Splitter
    - Often used for simple "optical protection".
    - Split your signal in half and send down two different fiber paths.
    - Use an optical switch with power monitoring capabilities 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, 98/2, or 95/5 Splitter
    - Often used for "Optical Performance Monitoring".
    - Tap a small % of the signal and send it to a spectrum analyzer.
  - A 1xN Splitter (e.g. 1x32)
    - Used in multipoint signal distribution, e.g. Cable TV

# Optical Amplification

# Optical Amplifiers

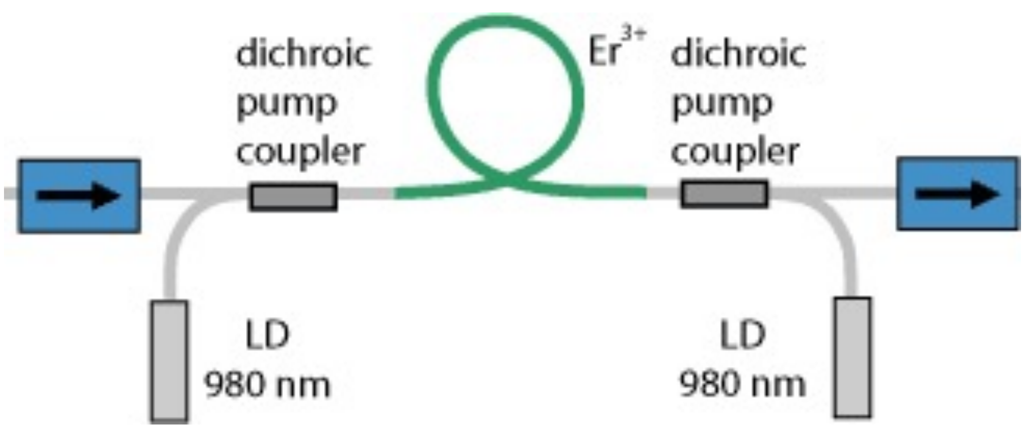
Optical amplifiers increase the intensity of a signal

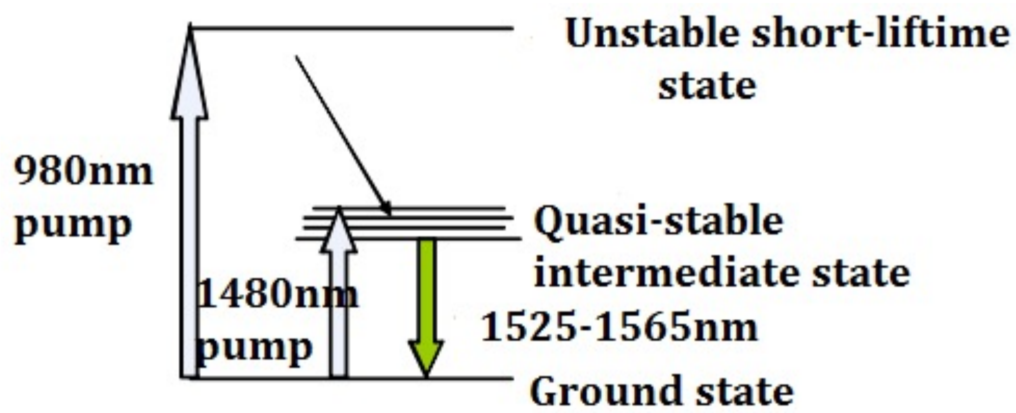
- Purely optical way to extend signal reach, no regeneration.
- There are different types, for different frequencies of light.
- And different designs, for different positions within the span.
  - Booster Amplifiers are designed for high total output powers.
  - Pre-Amplifiers are designed for low input powers with minimal noise.
  - Inline Amplifiers strike a balance between the two.



# Erbium Doped Fiber Amplifier (EDFA)

- The most basic/common fiber amplification system.
  - In an EDFA, a piece of fiber is "doped" with Erbium ions ($Er^{3}$+).
  - Another laser (980/1480nm) is pumped in via a coupler.
  - Pump laser puts Erbium electrons into higher energy state.
  - C-band frequency photons cause the Erbium electrons to decay to their ground state, and emits a clone of the original photon.

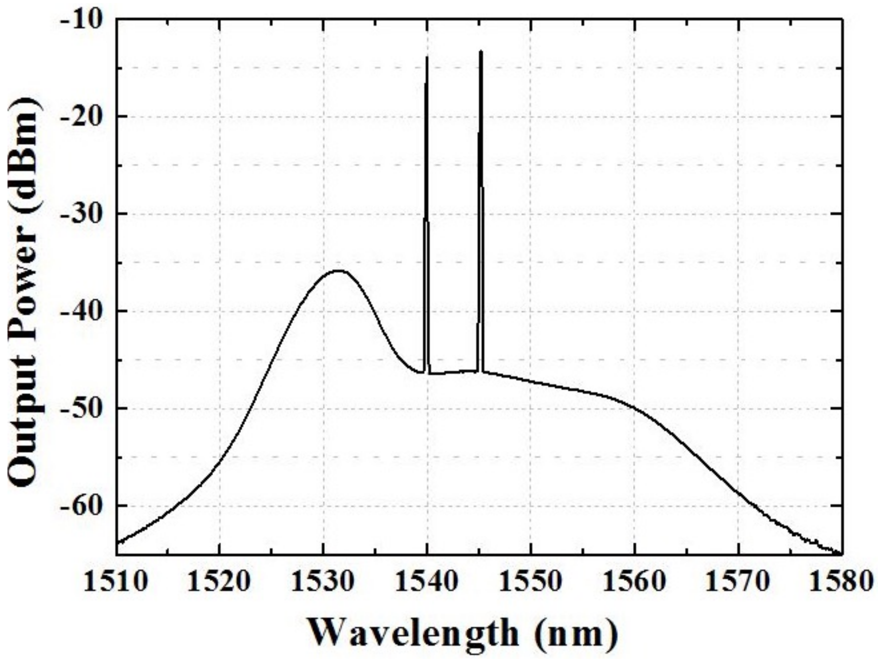


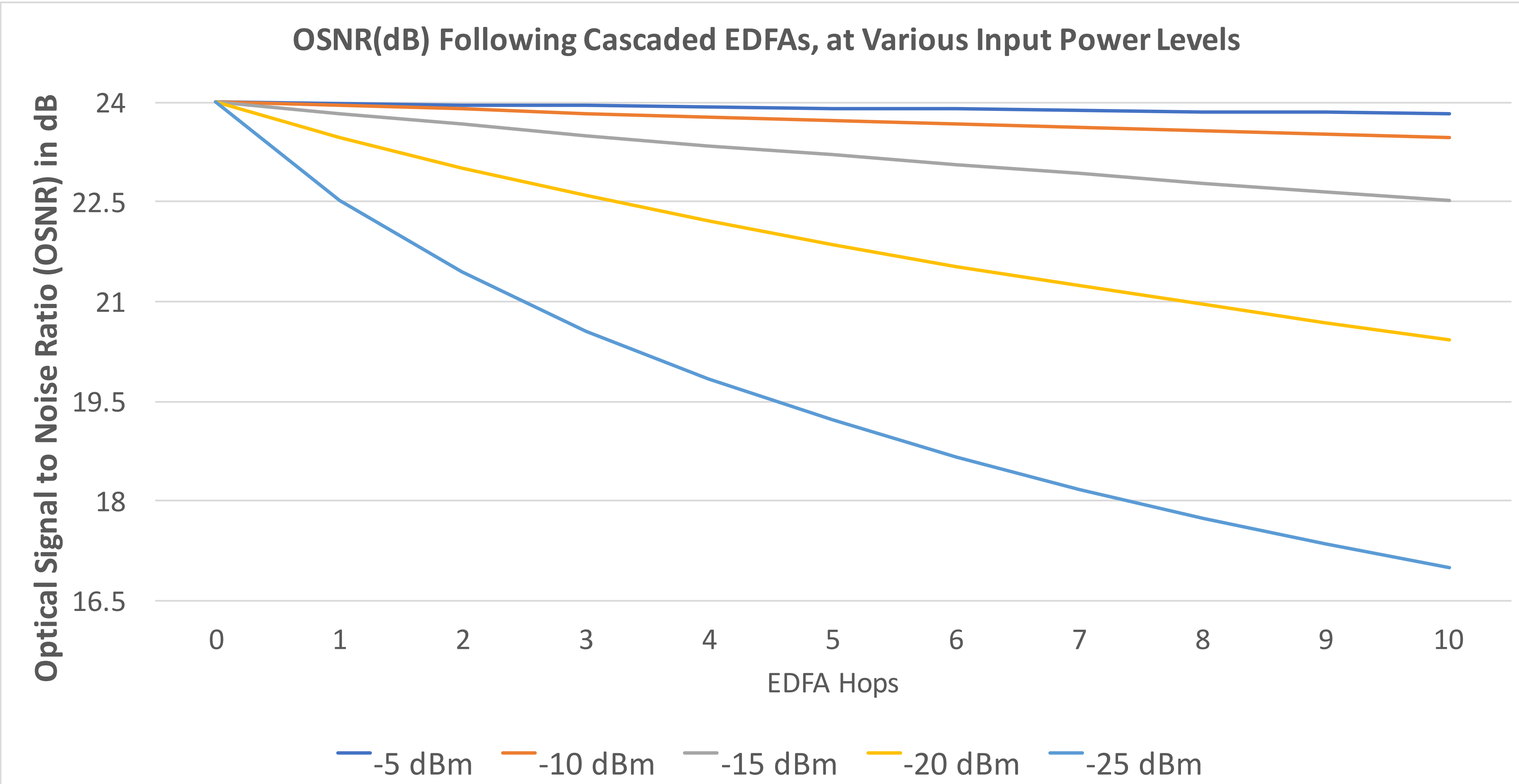
# EDFA Noise

So why can't we use this to boost a signal forever?

- In addition to the intended boosting of signal, EDFAs also generate noise ("Amplified Spontaneous Emission", ASE).
- Whenever an excited Erbium electron fails to encounter a "good" photon within ~10ms, it falls back to its ground state spontaneously, and emits a "noise" photon.
- Once generated, this noise is indistinguishable from the original signal.
- After enough amplifications, the noise ruins the original signal.

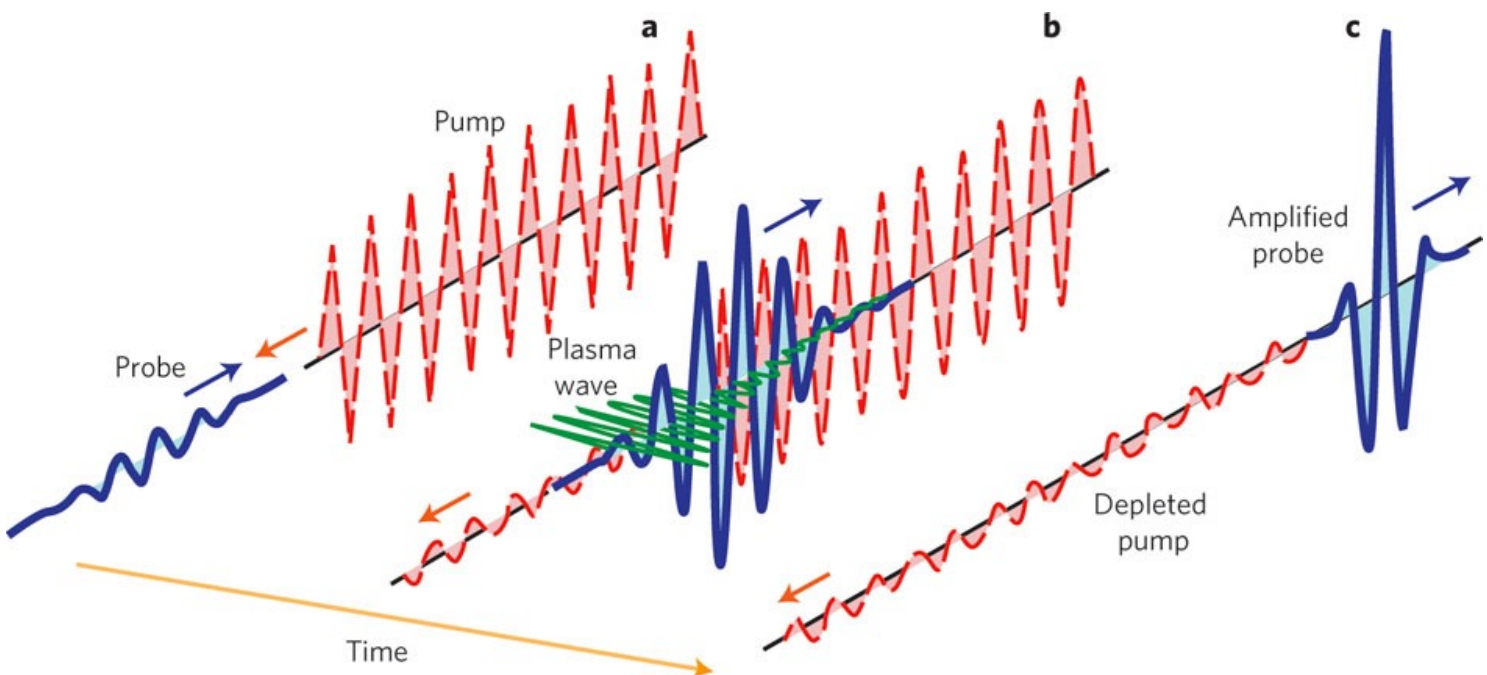


# EDFA Noise – Why Input Power Matters

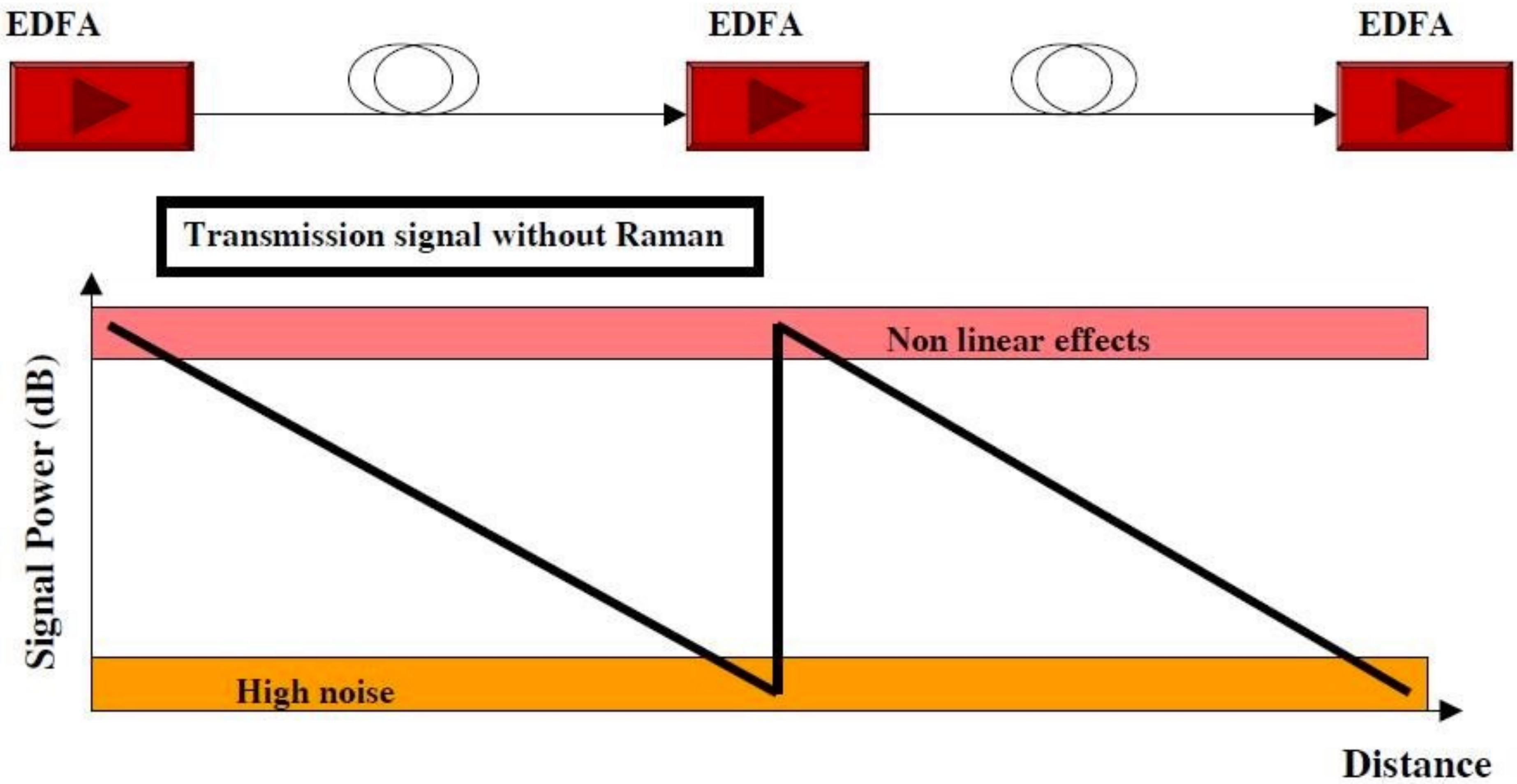


# Raman Amplification

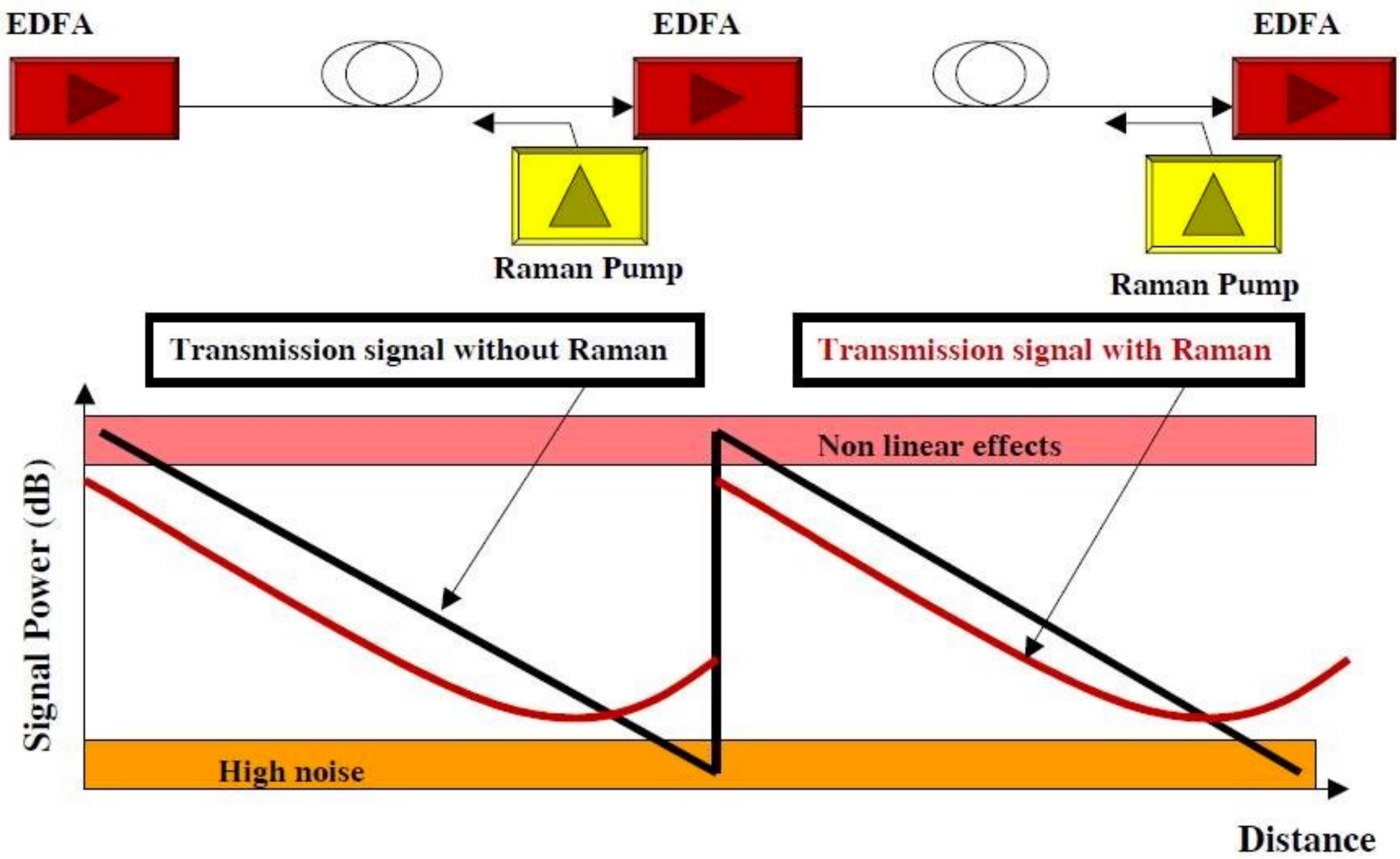
- Works on a principal of “Stimulated Raman Scattering”.
- Requires very high-power pump lasers, long gain mediums.
  - EDFAs used “lumped” design, gain media of 1-20 meters.
  - Raman usually use “distributed” design, gain medium 20+ km.
- Best used “counter-propagating” (facing backwards towards signal)



# EDFA Only Amplification



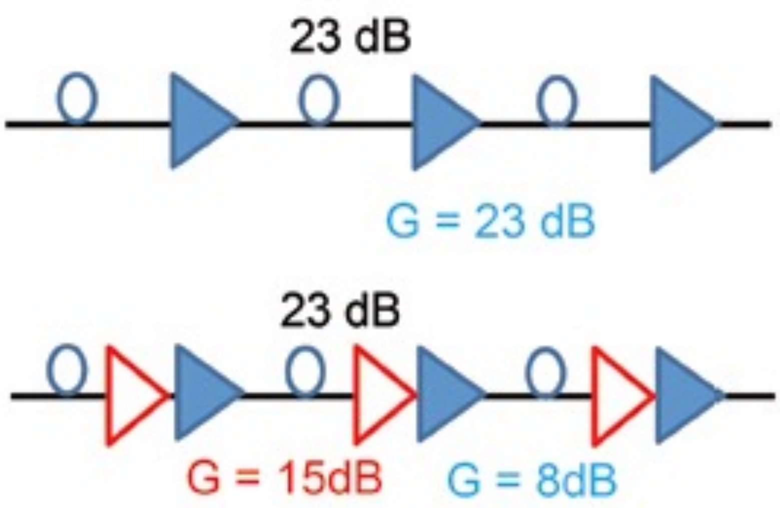
# Hybrid EDFA + Raman Amplification

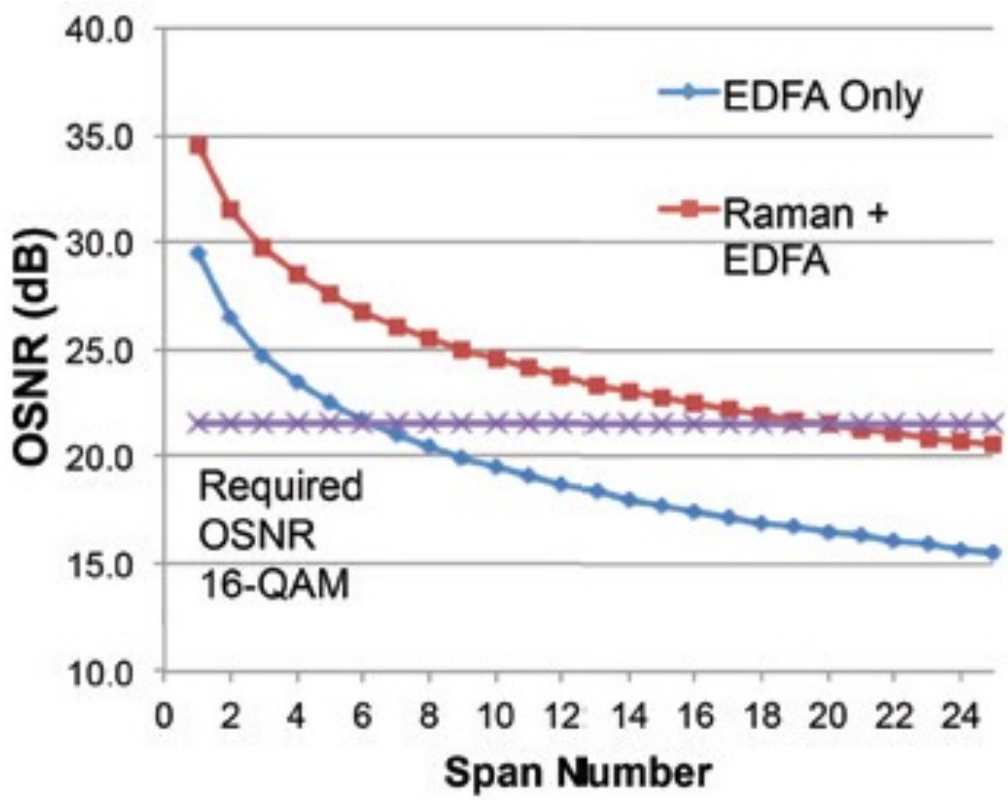


# Hybrid EDFA + Raman Performance

## Adding Raman extends EDFA reach significantly!

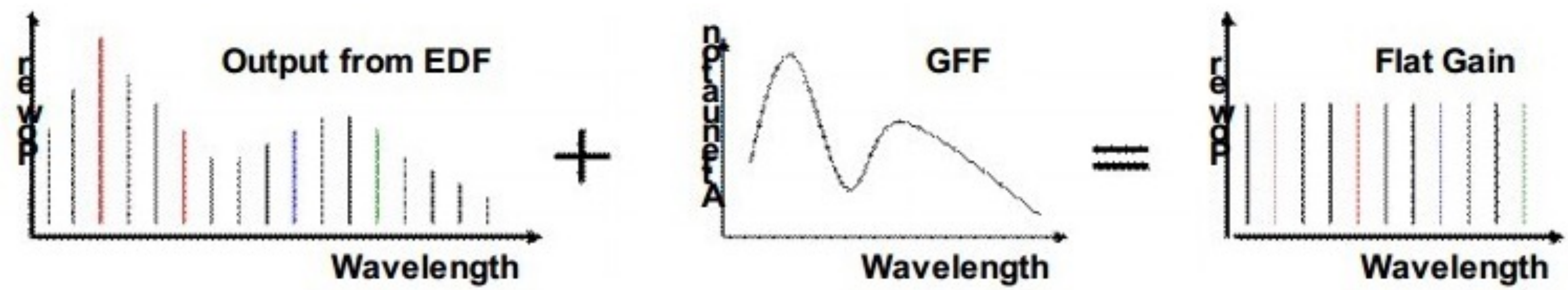
- In this example (21dB OSNR): from 7 hops to 20 hops
- At 100km/each, we go from only 700km to doing 2000km.



# Amplifiers and Power Balance

- Amplifiers introduce some of their own unique issues
  - Unbalanced channel power causes OSNR penalties.
  - Amplifier gain often varies significantly across frequencies
    - Gain Flattening Filters try to compensate for this property.
    - Typical gain variations between channels (“ripple”) are still < 1dB.




- Even small power variations can add up after several hops.
  - Dynamic Gain Equalization (“DGE”) is required periodically.
  - ROADMs are often used in this role, to balance every channel.

# Amplifiers and Total System Power

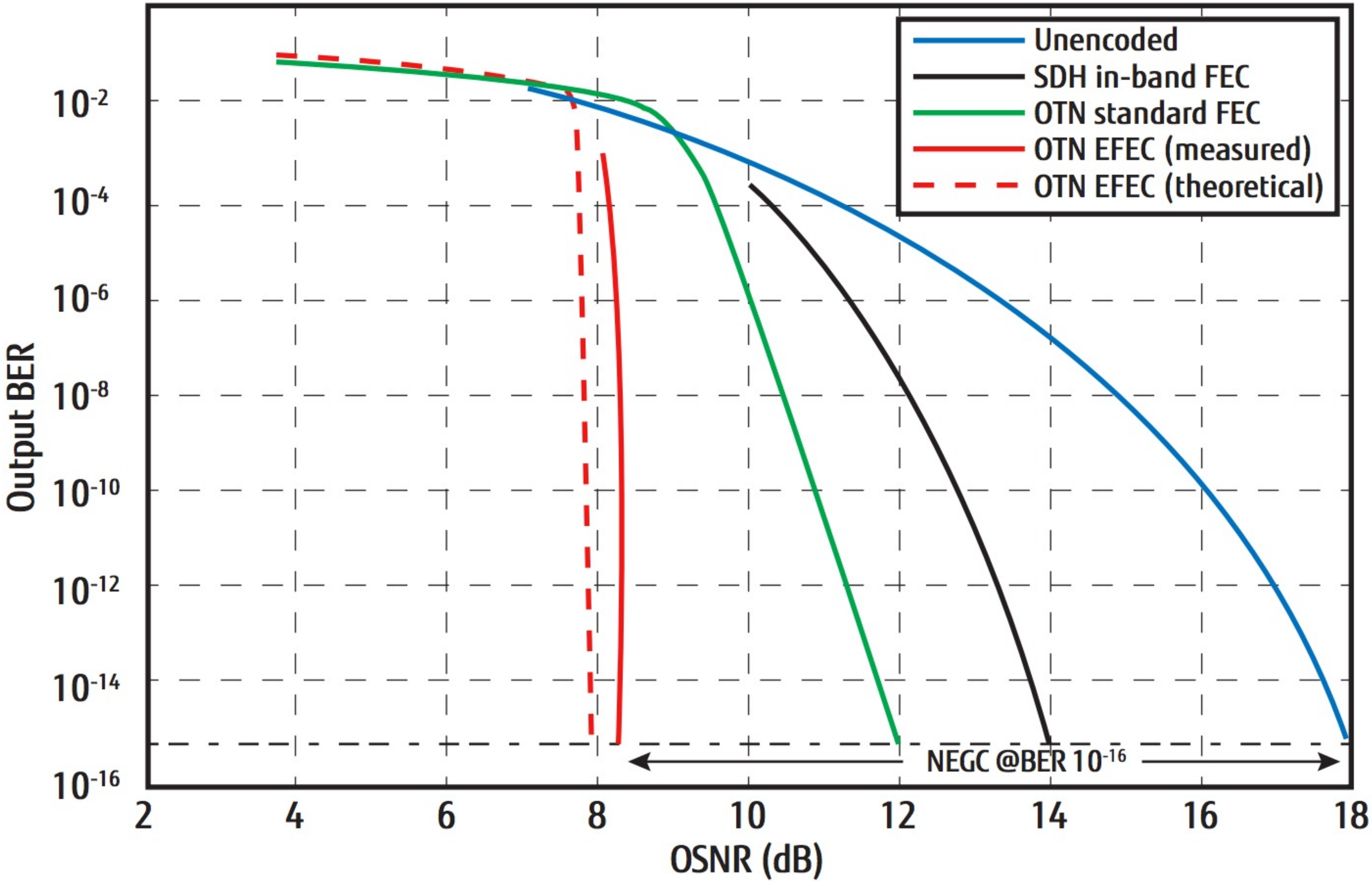
- Amplifiers also have limits on their total system power
  - Both what they can output, and what they can take as input.
  - And the total input power changes as you add channels!
    - A single channel at +0 dBm is only 1mW of input power.
    - 40 DWDM channels at +0 dBm/each is 40mW, or +16dBm of power.
    - 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 significantly.
    - A good EDFA needs to constantly monitor and adjust power levels.
    - The best EDFAs will communicate with others on the line system.

# Other Optical Networking Concepts

# Forward Error Correction

- FEC adds extra/redundant information to the transmission, so the receiver can computationally “recover” from any errors.
- In practice, FEC works by lowering the required OSNR, which can help an otherwise unusable signal function normally.
  - Using clever math, padding a 10.325Gbps signal to 11Gbps (7% overhead) can extend a signal from 80km to 120km or beyond.
  - This can really matter when upgrading older DWDM systems.
    - Since it usually isn’t practical to move amp sites closer on a live system.
  - FEC has evolved significantly as well.
    - 1st Gen – RS-FEC – 6% overhead for ~6dB of net coding gain.
    - 2nd Gen - EFEC – 7% overhead for ~8-9dB of net coding gain.
    - 3rd Gen – SD-FEC – 20-25% overhead for 10-11dB coding gain.
      - It might not seem worth it, but a 1-2dB gain in OSNR can hugely increase optical reach.
  - FEC is key to many standards like 100GBASE-SR4 as well.

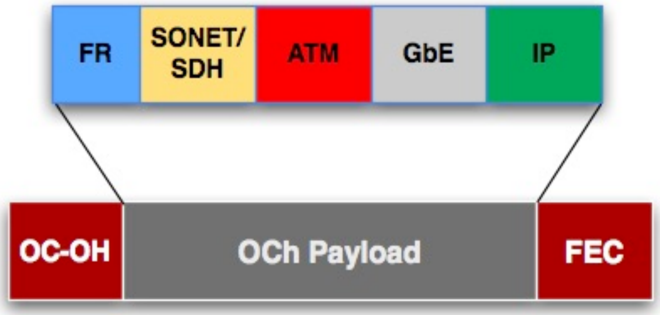
# The Benefits of Forward Error Correction



# OTN Digital Wrapper Technology (G.709)

## OTN stands for Optical Transport Network

- Replacement for SONET/SDH, with support for optical networking.
  - A standard for the generic transport of any protocol across a common optical network, with TDM mux/demux capabilities.
  - Implemented as a "wrapper" around other protocols.
- Why is this needed?
  - Pure optical channels only make sense for high-speed protocols.
    - Example: A single 100GE service, delivered over a 100G wave.
  - Low speed services still need to be aggregated.
    - Example: 10x10GE services on a 100G wave.
  - OTN lets the optical network be completely transparent to underlying protocols.
  - Can also help with troubleshooting.



# 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 many different types of SMF.
- The most common types are:
  - "Standard" SMF (ITU-T G.652) A.K.A. SMF-28
  - Full Spectrum (Low Water Peak) Fiber (ITU-T G.652.C/D)
  - Dispersion Shifted Fiber (ITU-T G.653)
  - Cutoff Shifted Low-Loss Fiber (ITU-T G.654)
  - Non-Zero Dispersion Shifted Fiber (ITU-T G.655)
  - Bend Insensitive Fiber (ITU-T G.657)

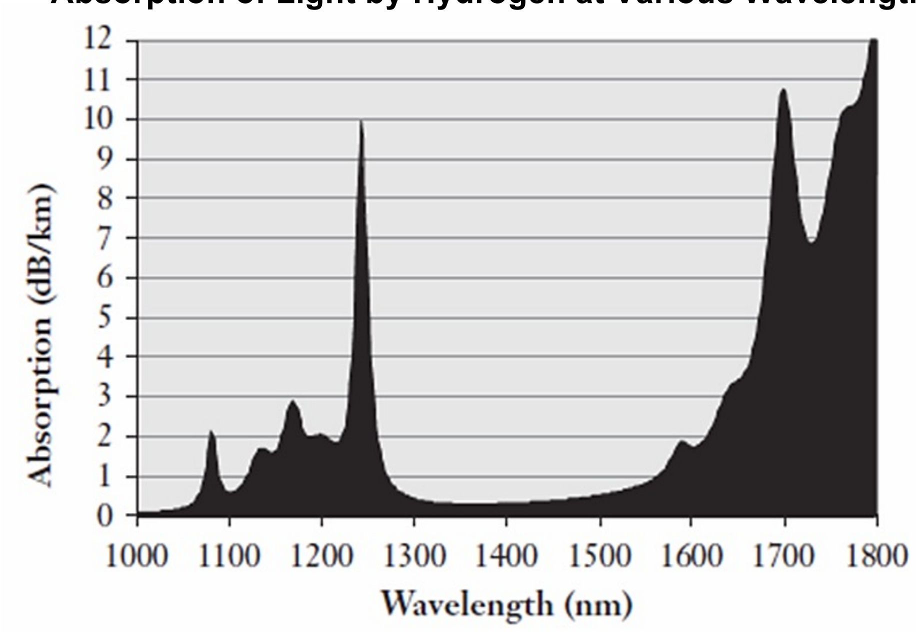
# “Standard” Single-Mode Fiber (G.652)

- One of the original fiber cables.
  - Deployed widely throughout the 1990s.
- Frequently called “SMF-28”, or simply “classic” SMF.
  - SMF-28 is actually a Corning product name.
  - 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.
- Ironically, has come full circle to again being the best choice for modern high-speed DWDM systems.

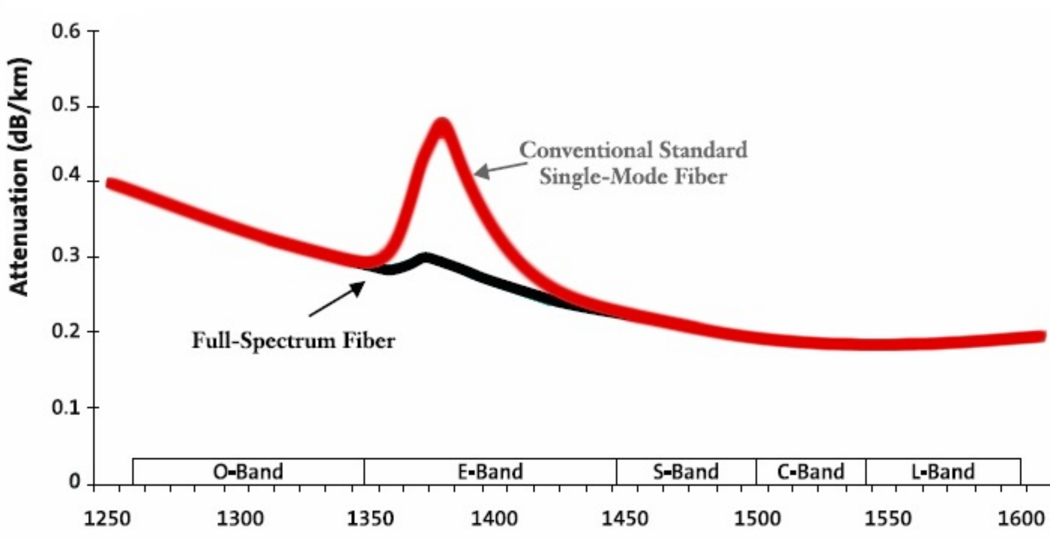
# Low Water Peak Fiber (G.652.C/D)

- 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 changes depending on the frequency of light.
    - The point of lowest dispersion in G.652 occur around 1310nm.
    - 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 huge problems.
  - It worked well for simple, single channel systems.
  - But running DWDM signals over DSF causes huge amounts of non-linear interactions at higher powers.
  - 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 just outside of C-band.
  - This leaves a small amount of dispersion, which helps avoid the non-linear impairments caused by DSF.

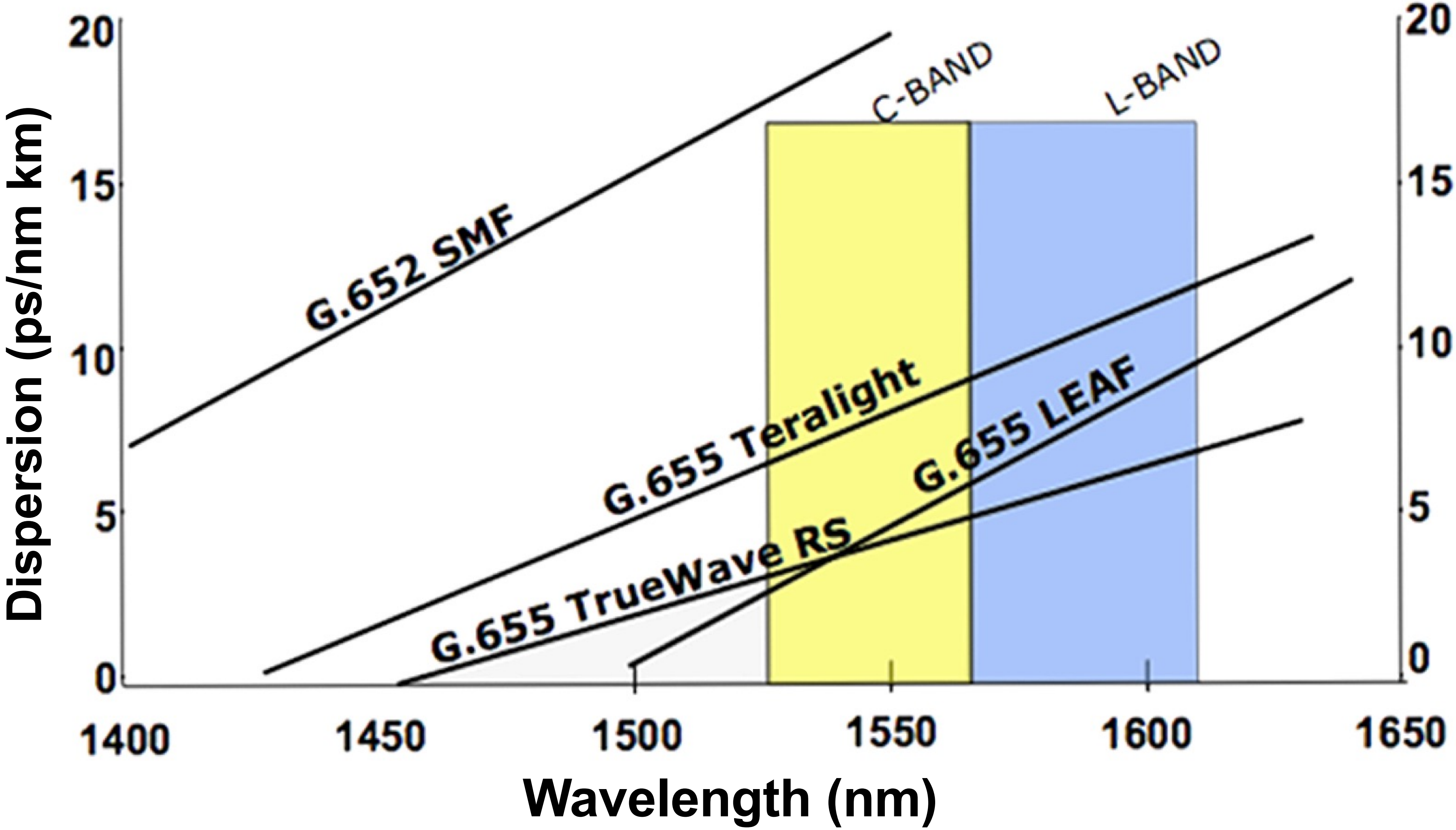
- To manage dispersion, NZDSF comes in 2 types
  - NZD+ and NZD-, with opposite dispersion "slopes".
    - The "transmission fiber" still spreads out 1550nm just a bit.
    - Then "compensation fiber" compresses it in the opposite direction.
  - By switching between the two slopes, the original signal can be maintained even over extremely long distances.

# Other Single-Mode Fiber Types

- G.654
  - Ultra low attenuation, high power capable fiber.
  - Designed for ultra-long reach 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 patch cable use, where a perfect bend radius may not be practical.

- Modern fibers are often better than these specs.
  - But much of what’s actually in the ground is old fiber.

# Dispersion Rates of Commercial Fibers



# Non-Linear Impairments

# Non-Linear Impairments

- Might be better described as “high power problems”.
  - If you don’t transmit at high powers, you’ll never see them.
    - But if you care about reach, you’ll probably be trying to push this.
    - What is “high power”? “Depends”, but usually above +4dBm / carrier.
- Non-Linear Impairments can be categorized as:
  - Stimulated Scattering
    - Stimulated Brillouin Scattering (SBS)
    - Stimulated Raman Scattering (SRS)
  - Kerr Effect
    - Intense light causes changes to the refractive index of the fiber.
    - Four Wave Mixing (FWM), Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM)

# Stimulated Brillouin Scattering (SBS)

- Excessive power transmitted into the fiber causes acoustic vibration at an atomic level within the lattice structure of the glass.
  - These vibrations set up Bragg grating effects, causing reflections.
  - Past a certain point, power is reflected back rather than forwards.
  - This limits power, causes errors, and can damage the transmitter.
- SBS is highly dependent on the “power density” in the fiber.
  - Wider linewidths spread the optical power out over more freq.
  - SBS suppression techniques include “dithering” to a wider signal.
  - Coherent helps quite a bit here, higher baud rates do too.
- SBS impact also largely requires long distances of fiber.
  - Putting high power through a very short span may not hurt you.
  - Typical “effective length” maxes out at around 20km.

# Stimulated Raman Scattering (SRS)

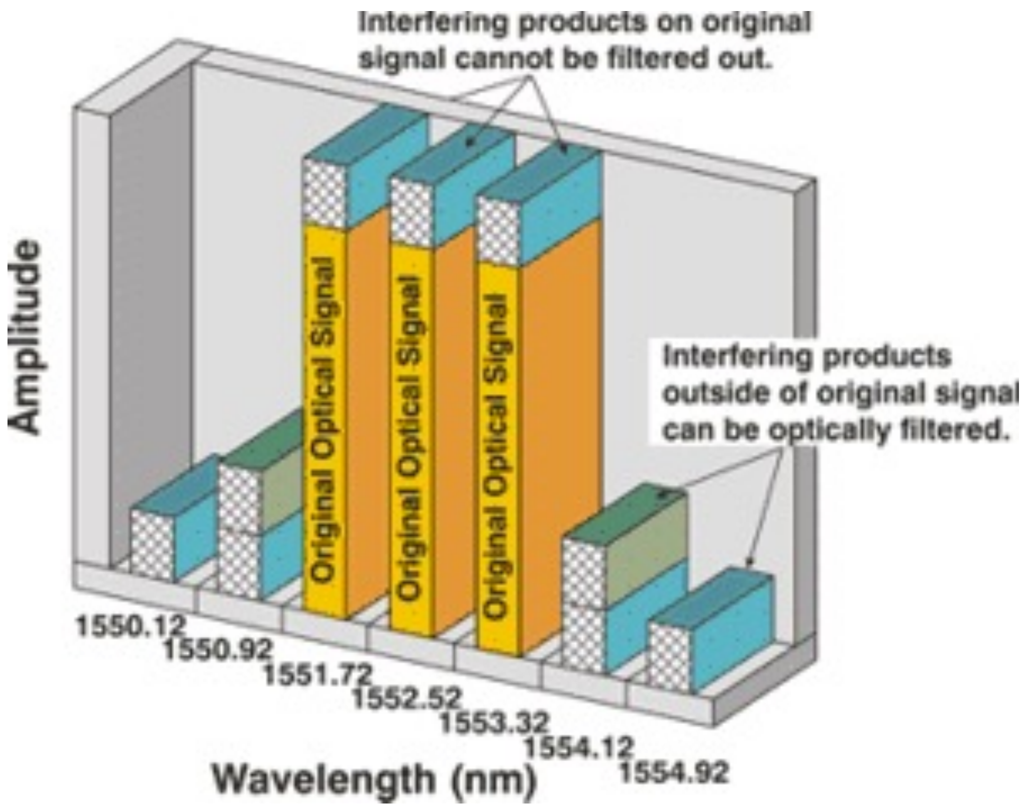
- SRS is related to the SBS phenomenon.
  - Used intentionally, this is what makes Raman amplification work.
  - Unintentionally, it causes power transfer from one wave to another
- Tighter channel spacing actually reduces SRS effects.
  - But adding more total channels increases them.

Example max launch powers, in G.655 NZDSF fiber:

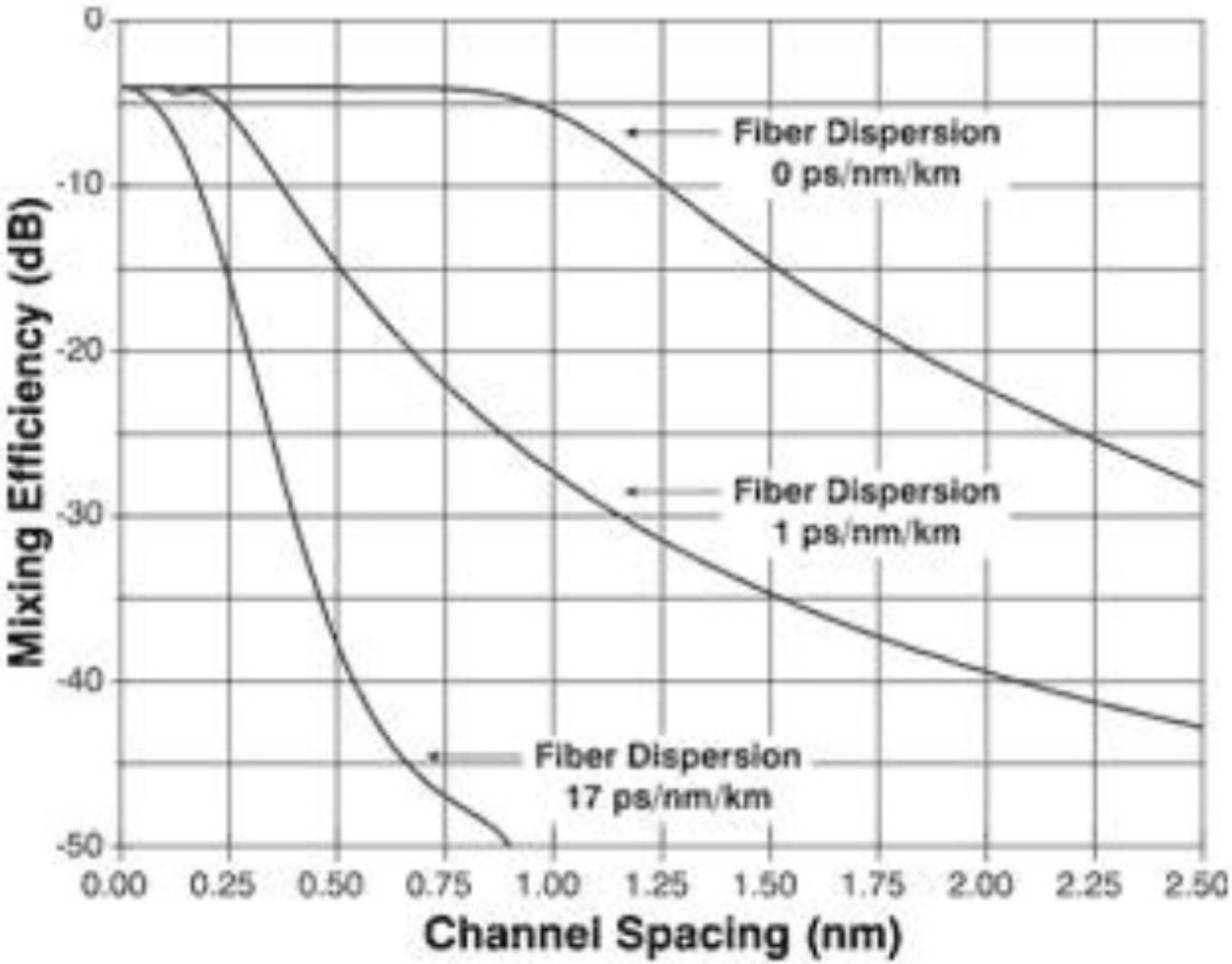
| Channel Count | 200GHz Spacing | 100GHz Spacing | 50GHz Spacing |
|---|---|---|---|
| 8 | 15 dBm / ch | 18 dBm / ch | 21 dBm / ch |
| 16 | 8.6 dBm / ch | 11.6 dBm / ch | 14.7 dBm / ch |
| 32 | 2.5 dBm / ch | 5.5 dBm / ch | 8.5 dBm / ch |
| 40 | 0.5 dBm / ch | 3.6 dBm / ch | 6.6 dBm / ch |
| 80 | -5.5 dBm / ch | -2.5 dBm / ch | 0.5 dBm / ch |

# Four Wave Mixing (FWM)

- Regularly spaced signals can interact with each other, to create harmonics in other frequencies.
- The closer they're spaced, the worse the effects.
- Transmission rate independent behavior.
- Uneven channel spacing can reduce the effects.
- FWM is most prevalent in low dispersion fibers.



# Four Wave Mixing Efficiency



# Four Wave Mixing Examples

| DWDM Channels | | Fiber Chromatic Dispersion Coefficient | | |
|---|---|---|---|---|
| | | 2 ps/(nm·km) | 5 ps/(nm·km) | 10 ps/(nm·km) |
| Number of Channels | Channel Spacing (GHz) | Max Signal Power (dBm) | Max Signal Power (dBm) | Max Signal Power (dBm) |
| 8 | 10 | –11 | –6 | –4 |
| | 25 | –3 | 1 | 4 |
| | 50 | 3 | 7 | 10 |
| | 100 | 9 | 13 | 15 |
| 16 | 10 | –13 | –10 | –6 |
| | 25 | –5 | –1 | 1 |
| | 50 | 0 | 4 | 8 |
| | 100 | 6 | 10 | 14 |
| 32 | 10 | –14 | –10 | –6 |
| | 25 | –6 | –1 | 1 |
| | 50 | 0 | 4 | 8 |
| | 100 | 6 | 10 | 13 |

# Interchannel Effects (XPM, SPM)

- Cross-Phase Modulation (XPM)
  - One wavelength of light can affect the phase of another.
  - Can cause inter-channel cross-talk on DWDM systems.
  - Also caused by mixing NRZ and Coherent systems.
    - Coherent systems actually modulate on phase, so neighboring NRZ channels cause XPM penalties in coherent channels.
    - A 100GHz (minimum) to 200GHz (best) guard band helps this.
  - High CD helps prevent XPM.
- Self-Phase Modulation (SPM)
  - Occurs when the change in signal power between a 0 and 1 is so strong that it triggers Kerr effect.
  - Low CD helps prevent SPM.

# Nonlinear Effects and Effective Area

- All nonlinearities are related to the energy “density”.
  - This is why CD helps nonlinearities, it spreads the power out.
  - A “larger fiber” (technically a larger “Mode Field Diameter”) also spreads the power over a larger area, reducing peak intensity.
  - This measurement is called a fiber’s “Effective Area” ($A_{eff}$).
    - If not specified in the fiber specs, use MFD and $\pi * r^2$
  - Larger effective area fiber reduces all non-linear effects.
  - Some common examples:
    - Standard G.655 NZ-DSF – 50 $\mu m^2$
    - LEAF or TrueWave XL NZ-DSF– 75 $\mu m^2$
    - Standard G.652 “SMF28”-based NDSF – 80 $\mu m^2$
    - Submarine Fiber (e.g. Corning Vascade) - 150 $\mu m^2$
- One tradeoff: Larger Effective Area = Less Raman Gain

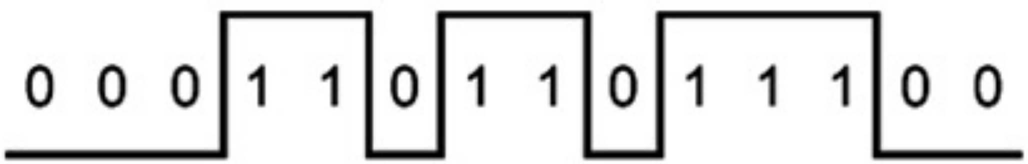
# What We Transmit Over Fiber

# Modulation

- At the end of the day, we live in an analog world.
  - Digital signals must still be encoded into analog waves.
  - And light is just another type of electromagnetic wave.
- The simplest form of modulation is called "IM-DD".
  - Which stands for "Intensity Modulation with Direct Detection".
  - The most common version is "NRZ", or "Non-Return to Zero".
  - Also called "Amplitude Shift Keying" (ASK).
  - Which is just a fancy way of saying "bright for a 1, dim for a 0".
  - "Direct Detect" means only a photodiode is needed to RX.
- Historically, fiber optic systems were purely NRZ based.
  - All 10G and below optical technology is based around NRZ.

# Background: Baud

- The “rate” at which you modulate a signal is the “baud”.
  - Technically defined as the “symbol rate per second”.
  - 10 Gbps means flashing bright/dim, 10 billion times/sec.
  - A.K.A. 10 GigaBaud (10GBaud)
- If you only encode 1 bit per baud, this is your bit rate.
  - Two states (bright or dim) means we represent 1 bit per symbol.
- Scaling the baud rate worked very well, to a point.
  - We built very successful networks using 10G technology.
  - And when that ran out, we built more parallel 10G links using DWDM over a single fiber.
  - But it was never enough.



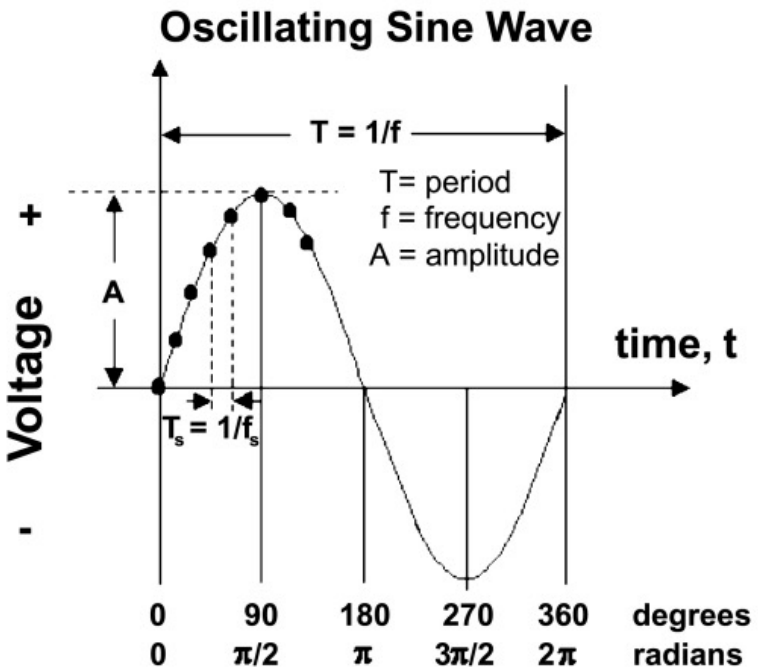
# So Where Do We Go From There?

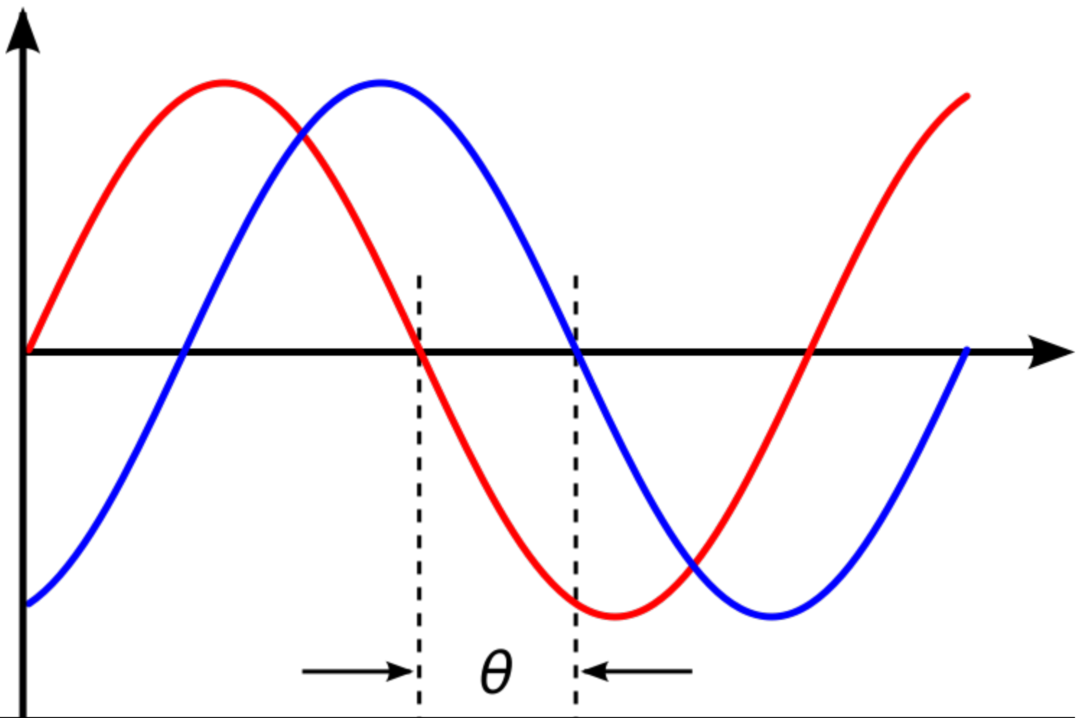
- So what’s a sad Internet to do when baud rates stop keeping up with our demand for cat pictures?
  - Increase the number of bits of information that can be encoded per symbol change (aka per baud)!

- There are a few methods to accomplish this.
  - Amplitude Shift Keying (ASK)
    - Have more than 2 ”states”, e.g. have “bright” and “really bright”.
  - Phase Shift Keying (PSK)
    - Modulate on an additional property of an analog signal, the “phase” of the signal over time.

# Phase Shift Keying (PSK)

- An analog signal can be represented as a sine wave.
  - A sender and receiver both agree on a specific frequency.
  - The sender transmits this frequency, but modulates the wave by “offsetting” it forwards/backwards to encode data.



# Intro – Coherent Optical Technologies

- So what exactly is "Coherent" technology?
  - The introduction of Phase Shift Keying in optical.
  - Named after it's ability to track phase changes in optical signals (a concept called "phase coherence").
  - Coherent provided an entirely new way to modulate signals, breaking the long-standing 10Gbps barrier.
- So how exactly does it do that?
  - By introducing a concept called a "local oscillator".
  - AKA it uses a laser on the RECEIVE side of the signal.
  - Phase information can be computed from this reference, by comparing the received signal to the local reference laser.

# Tying It All Together

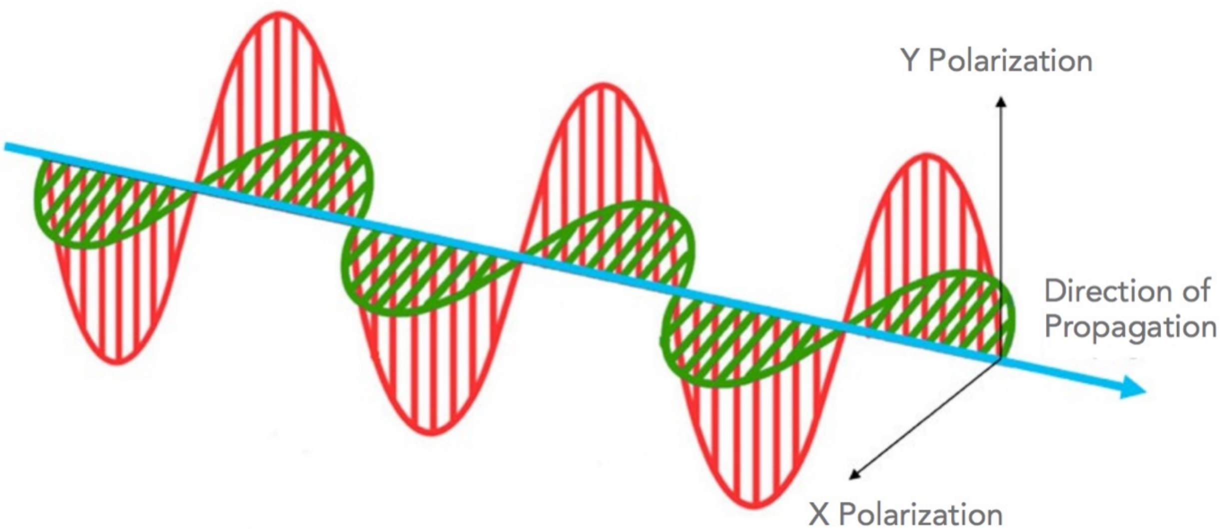
- Doing Phase Shift Keying isn't as easy as it sounds.
  - With ASK all we needed we a photodiode to "see" the light.
  - But Coherent technology is actually built around the "DSP".
    - The "Digital Signal Processor", an advanced purpose-built microprocessor, specifically designed for real-time processing of numeric data representing analog signals.
    - These DSPs tie all the signals together, recovering useful data.
- But Coherent technologies delivered in spades:
  - Significantly improved bandwidth (jumped from 1.6 Tbps to 9.6 Tbps)
  - Delivered true 100G optical signals, not just Nx10G signals.
  - Eliminated the need for physical Dispersion Compensation.
  - Enabled high bandwidths over massive distances.

# Where Does One Go From PSK?

- Quadrature Amplitude Modulation (QAM)
  - Effectively a combination of ASK and PSK.
  - Take two amplitude modulated carriers, and send them at the same time, over the same frequency, with a phase offset (a sine and a cosine).
  - Rely on your DSP to computationally recover the signal.
- More and more complex versions can be created.
  - Adding new possible states and increasing the amount of information that can be encoded per symbol.
  - 8QAM, 16QAM, 32QAM, 64QAM, 128QAM, 256QAM....

# Polarization Multiplexing

- Light is (among many other things we don't fully understand yet) a wave of electromagnetic energy, propagating through space.
- In 3-Dimensional space (e.g. a cylindrical fiber), you can send two independent orthogonal waves which propagate along a X and Y axis, which theoretically do not interfere with each other.
- Modern DSPs make it possible to compensate for changing fiber conditions in real time, effectively doubling bandwidth.



# BPS = Polarization * Baud * Modulation

- Total transponder bandwidth is a combination of:
  - Polarization – Today dual polarization, to double capacity.
  - Baud – Higher baud needs wider channel sizes, better DACs.
  - Modulation – Higher modulation needs better OSNR levels.

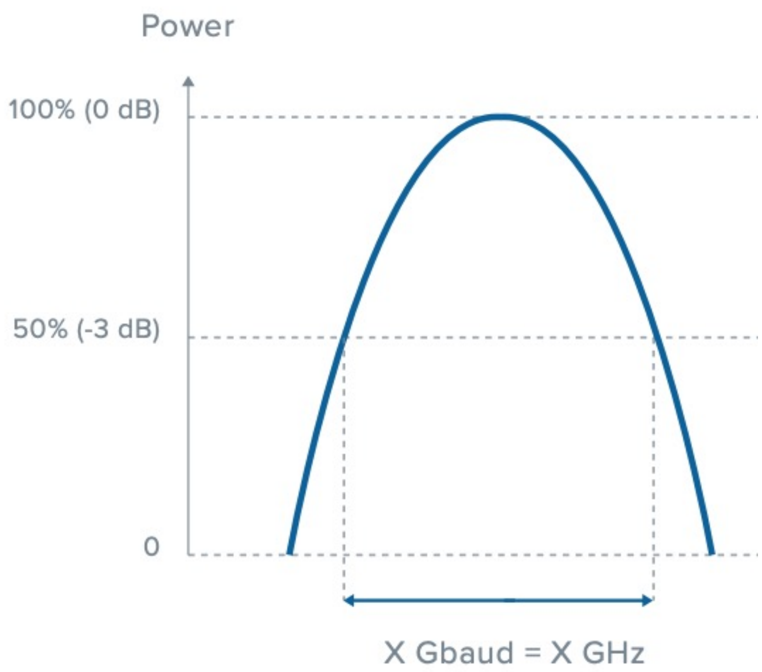
| Data Rate | Baud Rate | Polarities | Modulation Format | Channel Size | Raw BW (with FEC) | Efficiency (bits/s/Hz) | OSNR Required |
|---|---|---|---|---|---|---|---|
| 100G | 32G | 2 | DP-QPSK | 37.5GHz | 128G | 2 | 10.5 dB |
| 150G | 32G | 2 | DP-8QAM | 37.5GHz | 192G | 3 | 16.0 dB |
| 200G | 32G | 2 | DP-16QAM | 37.5GHz | 256G | 4 | 19.5 dB |
| 200G | 56G | 2 | DP-8QAM | 62.5GHz | 224G | 3 | 17.5 dB |
| 400G | 56G | 2 | DP-32QAM | 62.5GHz | 560G | 5 | 23.0 dB |
| 200G | 64G | 2 | DP-QPSK | 75GHz | 256G | 4 | 14.5 dB |
| 400G | 64G | 2 | DP-16QAM | 75GHz | 512G | 4 | 21.0 dB |
| 600G | 64G | 2 | DP-64QAM | 75GHz | 768G | 6 | 25.0 dB |

# Flexibility of an Acacia AC1200 DSP

| | QPSK | 8QAM | 16QAM | 32QAM | 64QAM |
|---|---|---|---|---|---|
| 100G | 34.5 Gbaud | | | | |
| 150G | 51.75 Gbaud | 34.5 Gbaud | | | |
| 200G | 69 Gbaud | 46 Gbaud | 34.5 Gbaud | | |
| 250G | | 57.5 Gbaud | 43.125 Gbaud | 34.5 Gbaud | |
| 300G | | 69 Gbaud | 51.75 Gbaud | 41.4 Gbaud | 34.5 Gbaud |
| 350G | | | 60.375 Gbaud | 48.3 Gbaud | 40.25 Gbaud |
| 400G | | | 69 Gbaud | 55.2 Gbaud | 46 Gbaud |
| 450G | | | | 62.1 Gbaud | 51.75 Gbaud |
| 500G | | | | 69 Gbaud | 57.5 Gbaud |
| 550G | | | | | 63.25 Gbaud |
| 600G | | | | | 69 Gbaud |

# Baud Rates vs Higher Order Modulation

- Consider two possible ways to get to 200Gbps
  - 2 polarities * 32 Gbaud * 16QAM = 200G
    - Requires a 19.5dB OSNR, but fits in a 37.5GHz channel
  - 2 polarities * 64 Gbaud * QPSK = 200G
    - Works down to 14.5dB OSNR, but requires a 75GHz channel
- As baud rate increases, channel size requirements increase proportionally.
- If you can afford the additional spectrum, trading baud rate for modulation can significantly increase optical reach.
- But many brownfield networks with fixed channel sizes and ROADMs will not be able to fully utilize this capability.



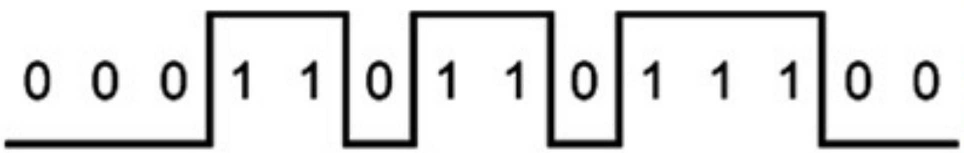
# More About Coherent

- Other Advantages of Coherent
  - Need for dispersion compensation all but eliminated.
    - Coherent DSPs eat CD for lunch - 200,000 ps/nm or more.
    - In fact, Coherent systems performance BETTER with CD.
  - Coherent can “lock on” to one specific frequency.
    - You may not need a “mux” to filter out specific channels.
    - This enables “Colorless Directionless Contentionless” ROADMs.

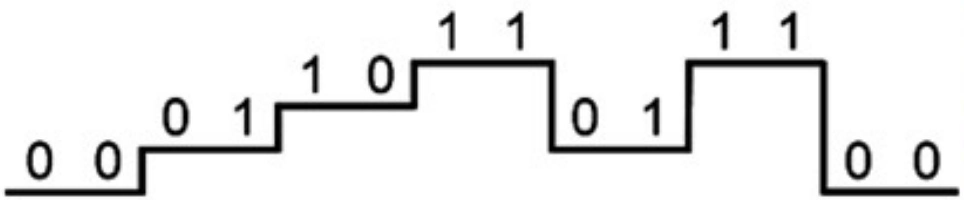
- But there are some major downsides too.
  - Many components, and expensive / power hungry DSP.
  - Very difficult to integrate into high-density “pluggables”.

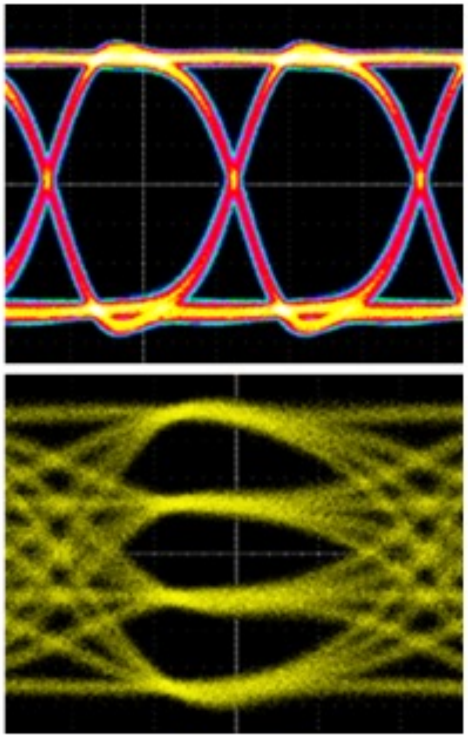
# PAM2 vs PAM4

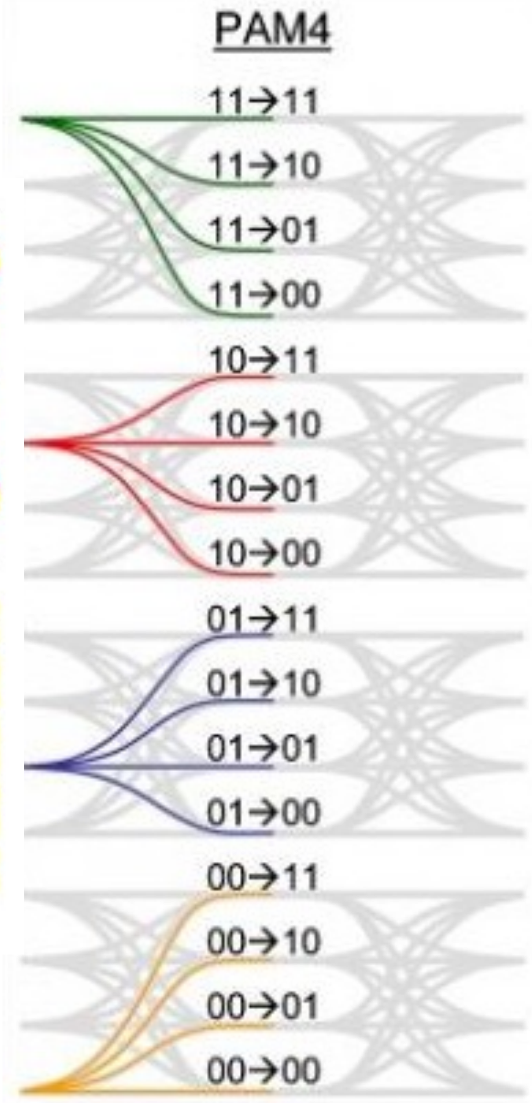
PAM2-NRZ




PAM4





# 400G ZR

- An attempt to get Coherent technology into a pluggable.
  - An exceptionally difficult challenge, still very much in the specification development and R&D phase as of this writing.
- Why? Overhead reduction vs external DCI transponders.
  - If all you're doing with your external DCI platform is providing bandwidth to your routers, you can eliminate some platform complexity and client-side optics overhead by putting your DWDM directly onto the router (e.g. "IPoDWDM").
  - Router vendors have been trying this with "coherent line-cards", mostly with limited success.
  - 400G ZR is an industry attempt to create the necessary scale and traction to cram high stripped-down coherent technology into a 400G pluggable.

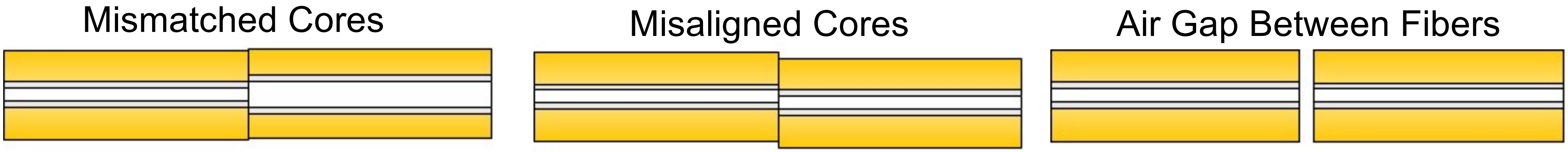
# PAM4 DWDM

- Another commercially available solution today is DWDM tuned QSFP28s based on PAM4.
  - 2x56G PAM4 encoded wavelengths at +/- 25GHz offset.
  - Can be significantly lower cost per bit than coherent.
  - Deployable in increments of 100G vs 1.2T w/coherent.
  - Can support distances of 80-120km point-to-point.
- But this comes with a great many caveats.
  - Needs special flat-top muxes with 75GHz+ passbands.
  - Must dispersion compensate to within +/- 100 ps/nm.
  - Must amplify +10dB just to link back-to-back optics.
  - Very high OSNR requirement, can never use a ROADM.

# Engineering an Optical Network

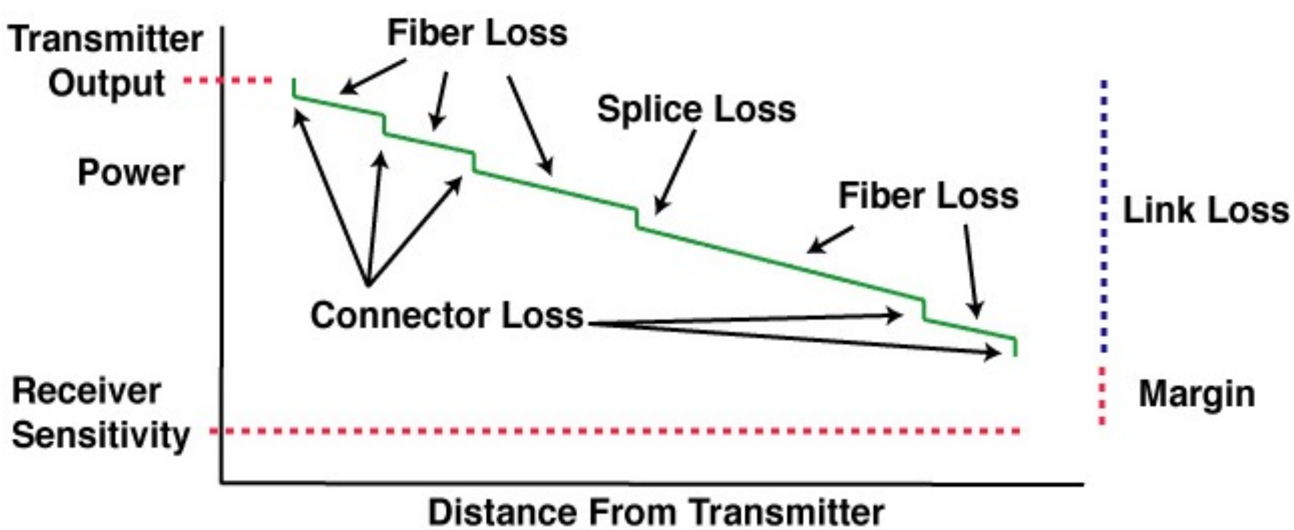
# Insertion Loss

- 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:
    - 40-channel DWDM 100GHz Mux/Demux: 3.5dB
    - 80-channel DWDM 50GHz Mux/Demux: 9.5dB
      - Effectively just 2x 100GHz muxes (even+odd) plus an interleaver.



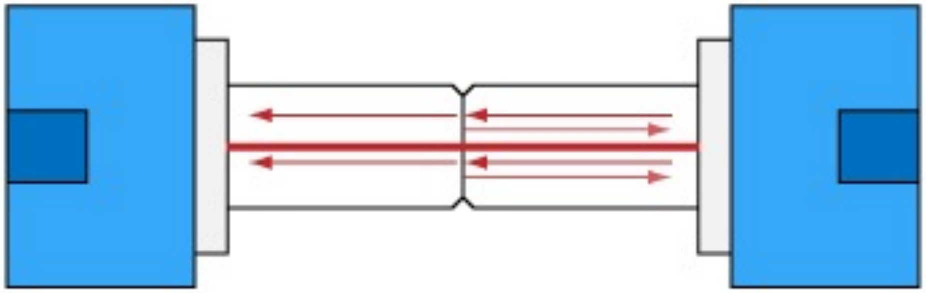
# Balling On An (Optical) Budget

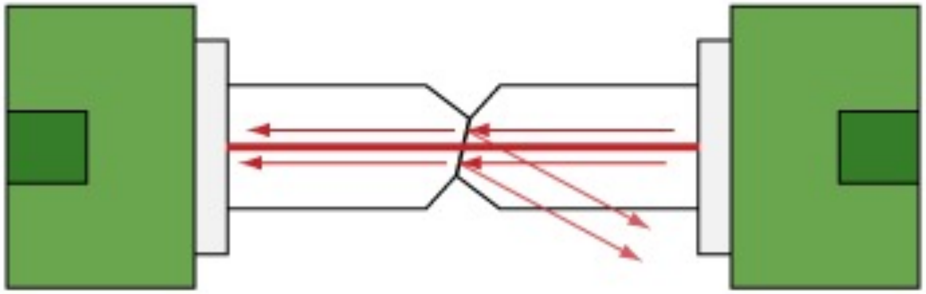
- To plan your optical network, you need a budget.
  - When an optic says "10km", this is only a guideline.
  - Actual distances can be significantly better or worse.
  - It's also smart to leave some margin in your designs.
    - Patch cables get bent and moved around, optic transmitters will cool with age, a fiber cut and repaired will add more loss, etc.



# PC/UPC vs APC

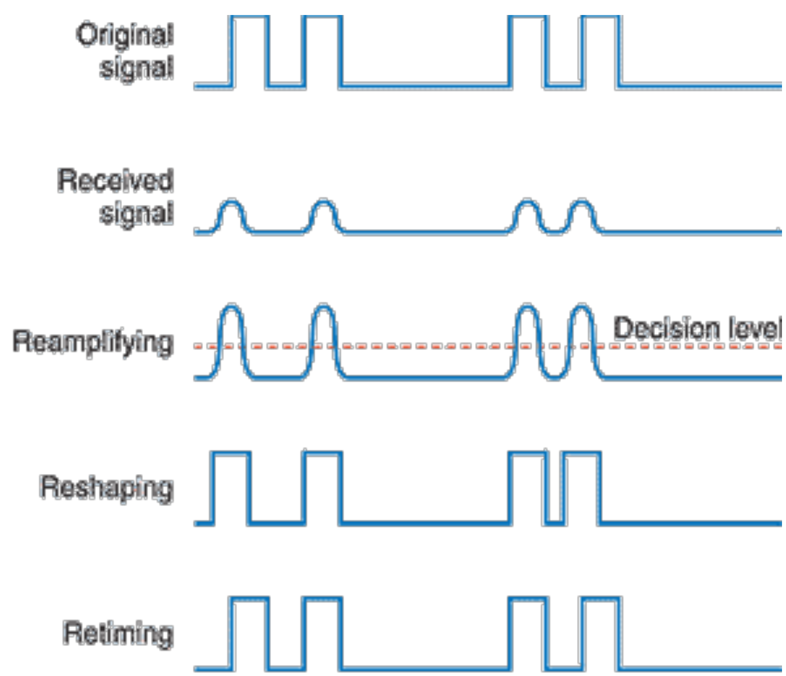
- Beware of the different types of ferrule connectors.
  - (Ultra) Physical Contact
    - Blue Connectors
    - PC - < -30dB Back Reflection
    - UPC - < -55dB Back Reflection
  - Angled Physical Contact
    - Green Connectors
    - 8˚ angle on the ferrule
    - < -65dB Back Reflection
    - Incompatible with PC / UPC!
    - Useful for high power applications
  - Why? When disconnected, even UPC reflects massively.
    - On a high-powered amplifier, reflections could cause damage.





# 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.

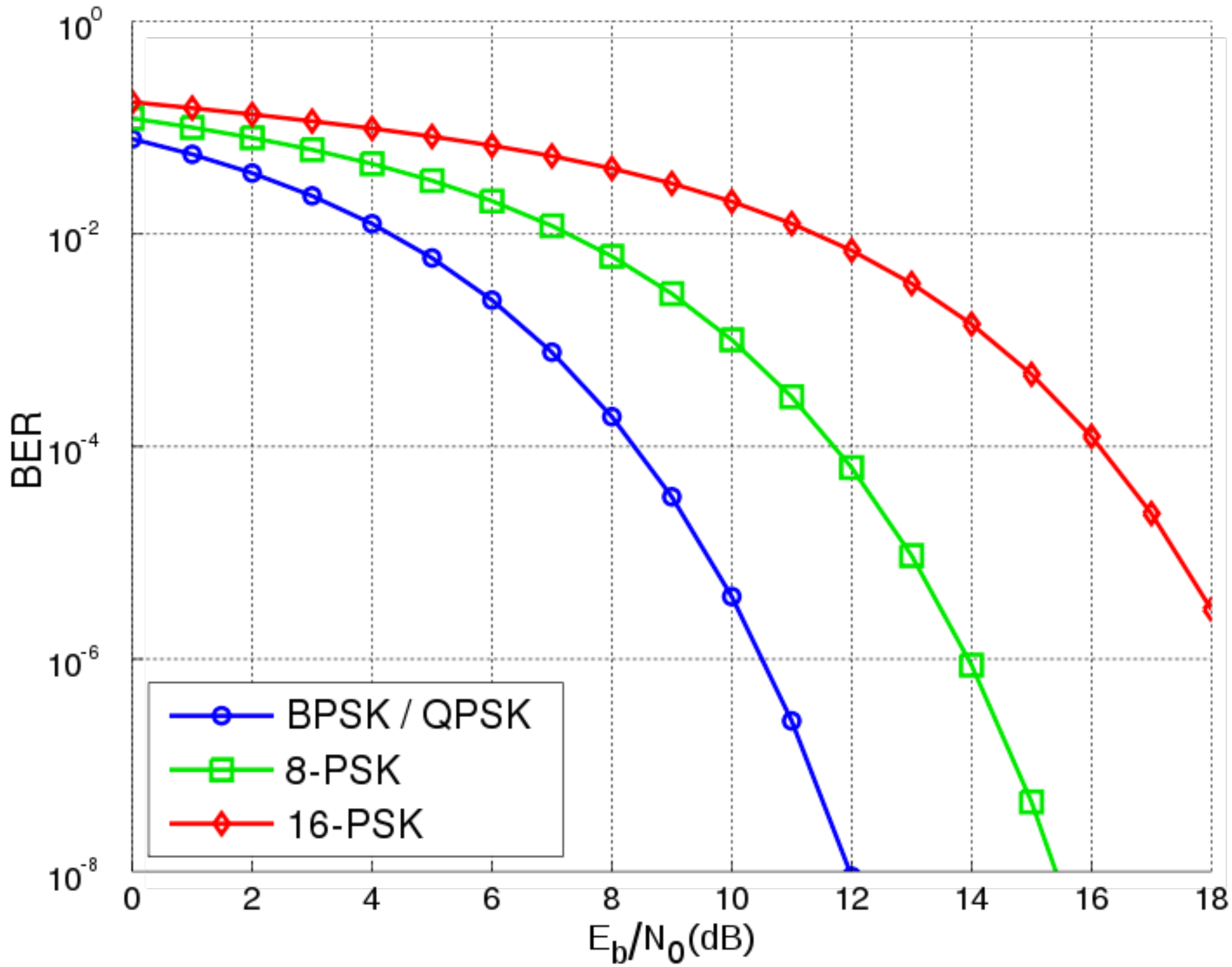


# Bit Error Rates (BER)

- As optical impairments add up, links don't just "die".
  - They start taking bit errors, at progressively higher rates.
  - The probability that this will happen is the Bit Error Rate.
- For 99% confidence (100 bit error samples), test:

| Date Rate | BER $10^{-9}$ | BER $10^{-11}$ | BER $10^{-12}$ | BER $10^{-13}$ |
|---|---|---|---|---|
| 100 Gbps | 1 sec | 2 min | 21 min | 3 hr 29 min |
| 40 Gbps | 3 sec | 6 min | 53 min | 8 hr 47 min |
| 10 Gbps | 13 sec | 21 min | 3 hr 30 min | 1d 10 hr 58m |
| 1 Gbps | 2 mins | 3 hr 30 min | 1d 10 hr 58 min | 14d 13 hr 33m |

# OSNR(dB) and Bit Error Rates



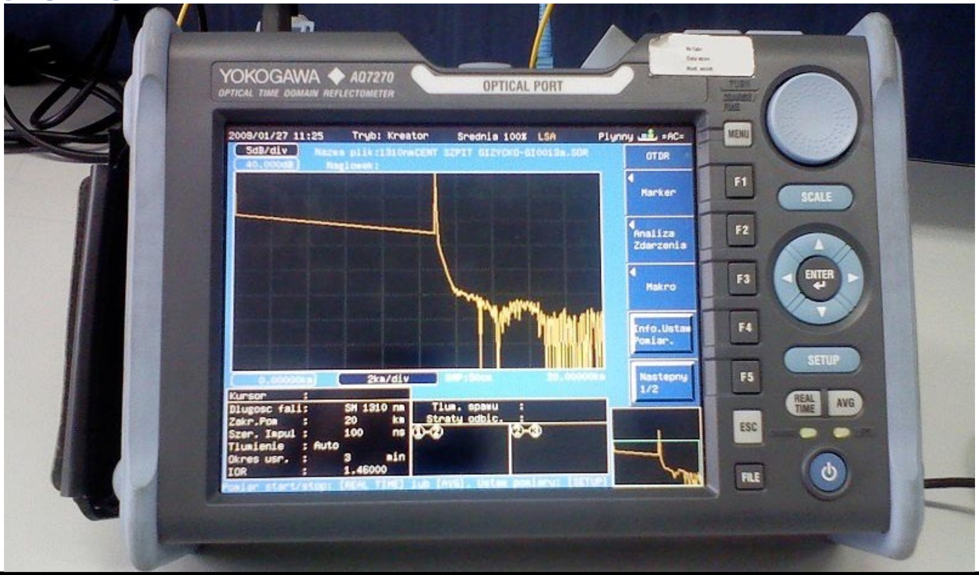
# Tools of the Trade

# Optical Power Meter (or Light Meter)

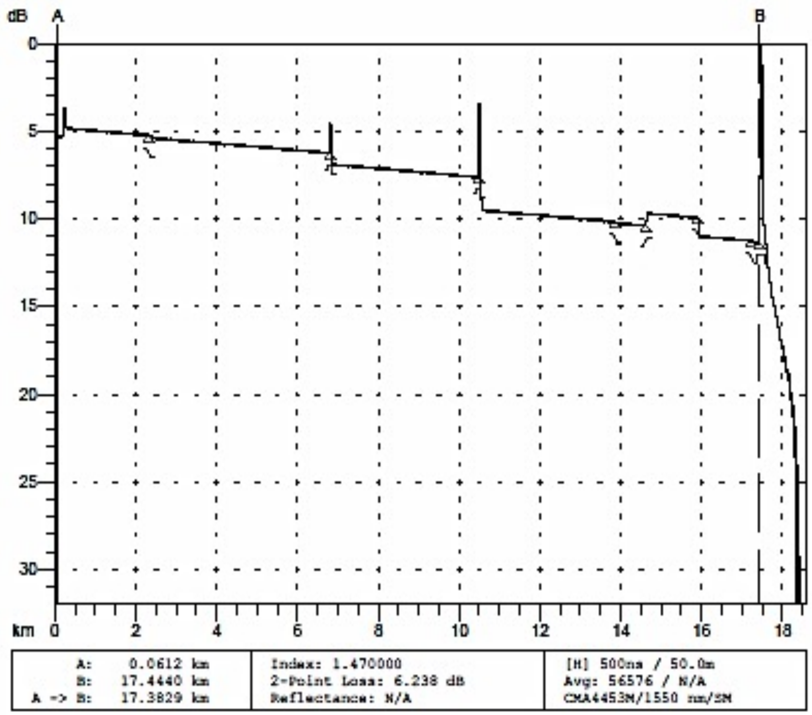
- Measures the brightness of an optical signal.
- Displays the results in dBm or milliwatts (mW).
- Most light meters also include a "relative loss" function, as well as absolute power meter.
  - Designed to work with a known-power light source on the other end, to test the amount of loss over a particular 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 the 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).

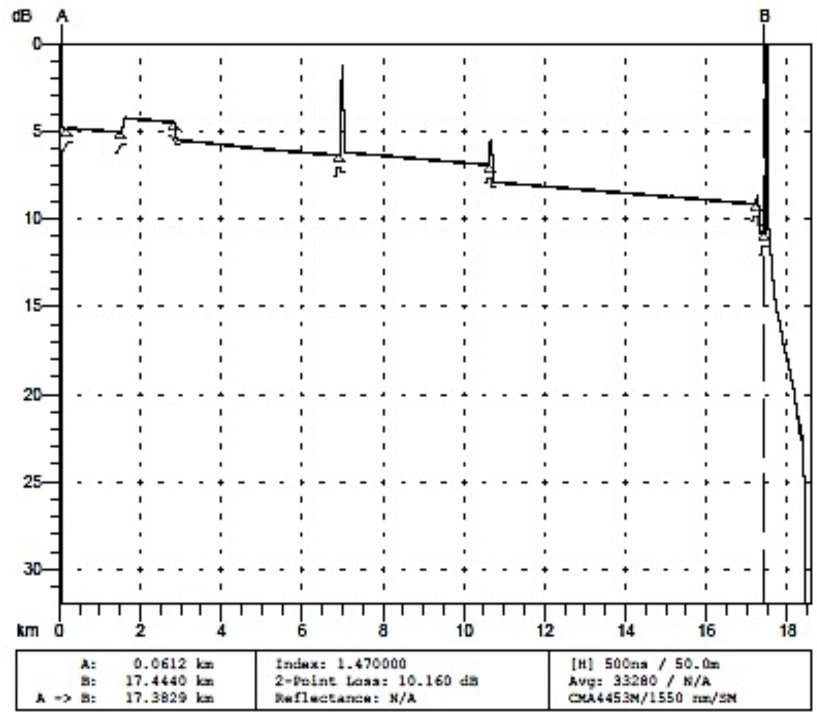


# Example OTDR Output




| 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?

# Or - 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.
    - Remember, the human eye didn’t evolve to see infrared.
    - The cornea actually does a good job of filtering out IR-B light.
    - So IR-B has much higher safety limits than visible light.

Max power (continuous, without auto-shutdown features) for IR-B:

| Class 1 | Class 3R | Class 3B | Class 4 |
|---|---|---|---|
| < 10 dBm | < 17 dBm | < 27 dBm | > 27dBm |

# Optical Networking and Safety

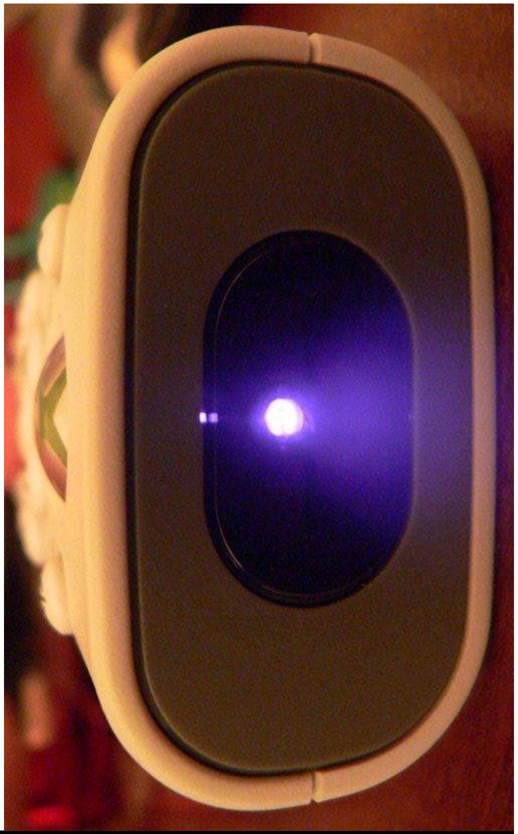
- Routers
  - Essentially every single-channel laser that can be connected to a router is a Class 1 or Class 1M laser.
  - Even “long reach” 200km+ optics are no exception:
    - A multi-lane optic can have the highest output, e.g. 40G LR4 = 8mW
- Optical Amplifiers
  - Can easily have output powers of 3R (metro) or 3B (long-haul).
  - Raman amplifiers are almost always Class 4.
  - But they all have Automatic Power Reduction/Shutdown too.
- DWDM Equipment
  - Total output power is the sum of all muxed input signals.
  - This can put the total output power into the 3B territory even without amplification, and often has no auto-shutdown feature.

# Optical Networking and Safety

- So should I be wearing safety goggles in the colo?
  - Generally speaking, your standard client optics are always Class 1 (completely safe under all conditions).
  - Even on amplified/DWDM systems, 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.
  - High-power systems are legally required to have auto-shutdown safety mechanisms if they detect a cut.
- But, don't hold a DWDM mux directly to your eye.
- And be extra careful with a fiber microscope.

# 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.
  - Many digital cameras can see 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.
    - Except newer/nicer ones filter IR, for picture quality. iPhone started blocking IR as of 4S/5.

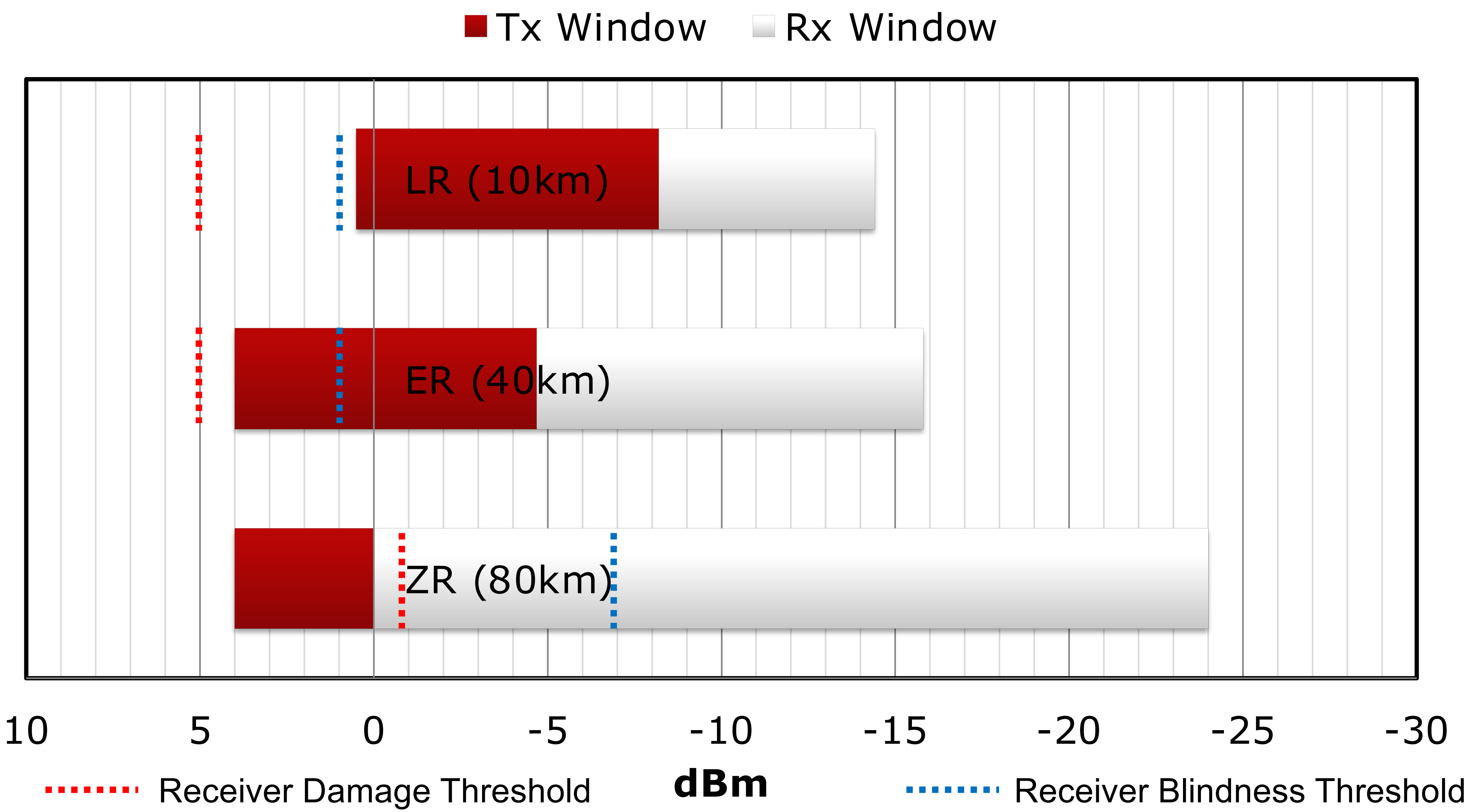


## Question: Can optical transceivers be damaged by over-powered transmitters?

# Damage by Overpowered Transmitters?

- 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 more sensitive receivers, not stronger transmitters.
  - 80km optics may have a 10dB+ more sensitive RX 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 (the receiver is "blinded", and takes errors).
  - Damage point (the receiver is actually damaged).
  - The actual values depend on the specific optic.
  - But generally speaking, only 80km optics are at risk.

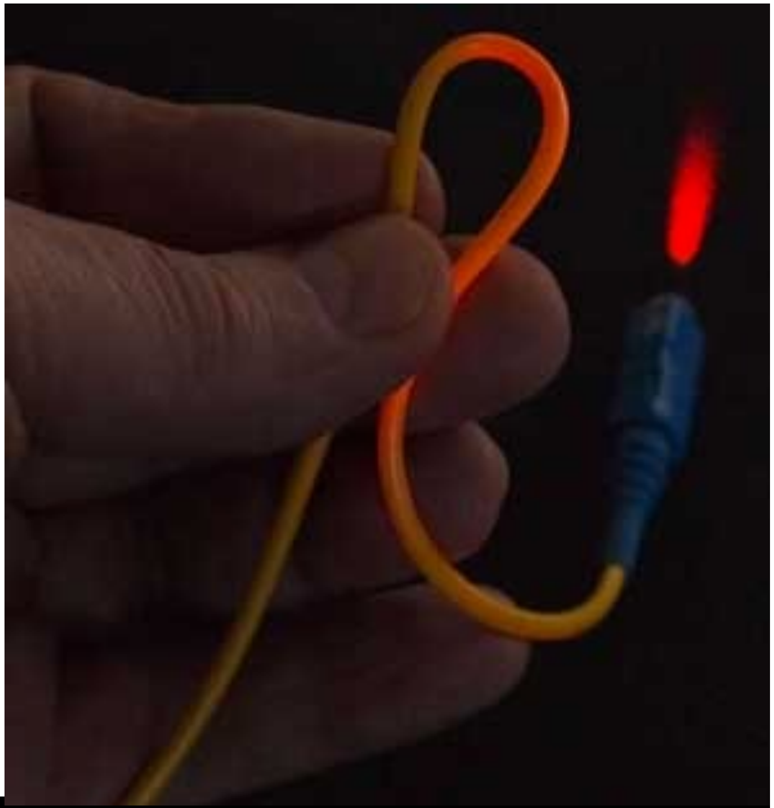
# Tx and Rx Optical Power Ranges



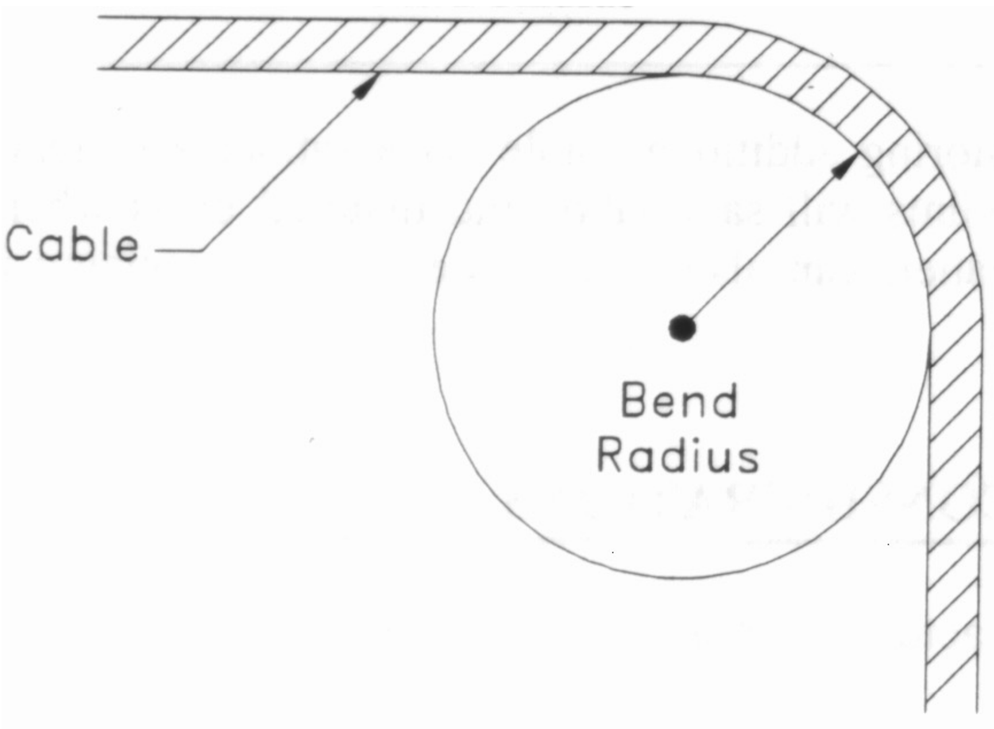
# Question: Do I really need to be concerned about bend radius?

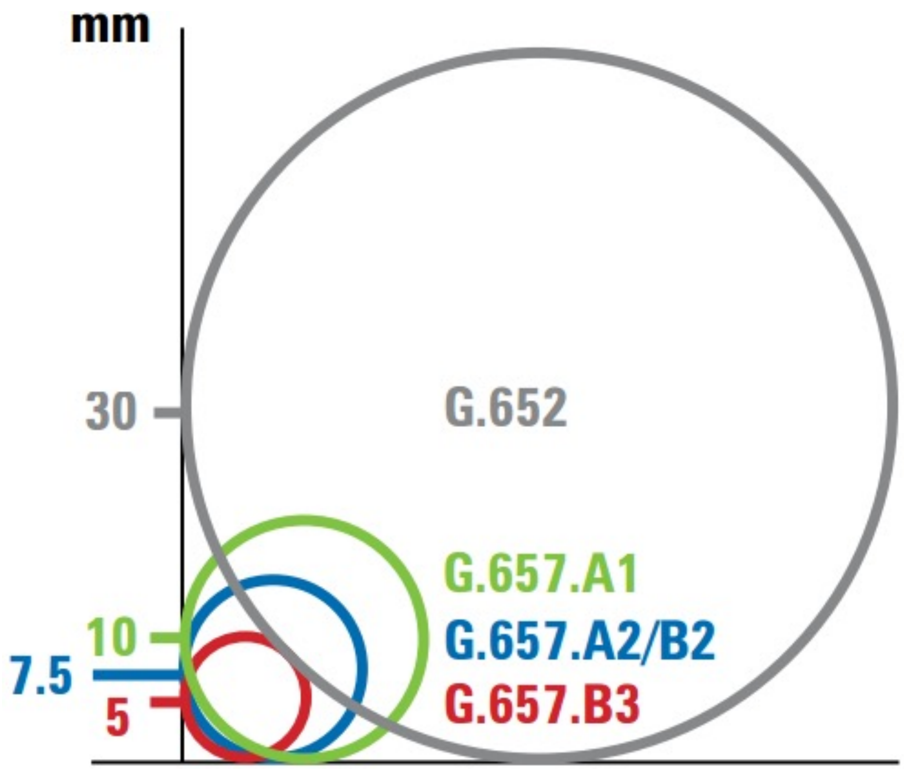
# Is Bend Radius Really A Concern?

- 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 its specified bend radius causes the light to "leak" out.
  - There are "bend insensitive" fibers, though they usually trade some level of performance for this.
  - These are pretty useful in datacenter applications, when humans don't do the right thing.



# Practical Bend Radius Examples (SMF)



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

# Can You Mismatch Transceiver Freqs?

- Between certain types of optics, yes.
  - All optical receivers have wideband photodetectors.
    - Laser receivers “see” everything between 1260nm – 1620nm.
    - But they won’t be able to see a 850nm LED, for example.
    - Coherent receivers can even “lock on” to one specific frequency.
  - 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 its power reading will be a few dB off.

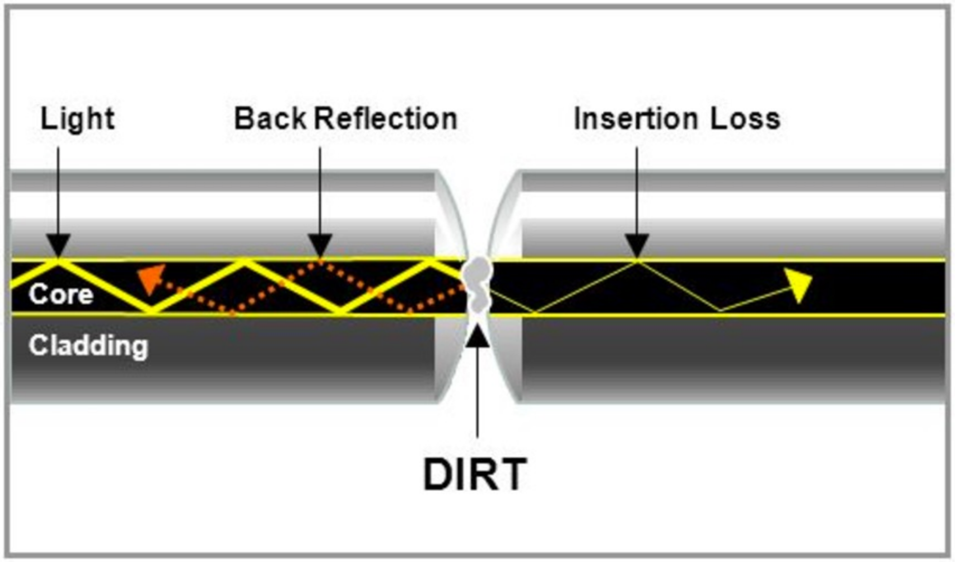
# Can You Mismatch Transceiver Freqs?

- You can also mismatch frequencies for added reach.
  - You can achieve nearly as much distance with an LR/ER pair (1310nm 10km / 1550nm 40km) as with an ER/ER pair.
    - The ER transmits at 1550nm, which has a lower rate of attenuation.
      - 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.
    - And the ER optic has a much greater RX sensitivity than the LR.
      - So it will be able to hear the 1310nm signal much better than an LR optic would in the same position.
- Result:
  - You may only *need* a long reach optic on one side.

## Question:
## Do I Really Need to Clean the Fiber?

# Do I Really Need to Clean the Fiber?

- Dirt can actually DAMAGE the connector permanently.
  - A mating force of 2.2lb, over a 200µm surface area...
  - Results in 45,000 lbs per square inch of pressure.
  - This can permanently pit and chip your fiber cables!
- Buy a cheap cleaning kit!




# 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 1.4679
  - Speed of light / 1.4679 = 204,232,207 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:

Richard A Steenbergen <ras@petabitscale.com>