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

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Purpose of This Tutorial

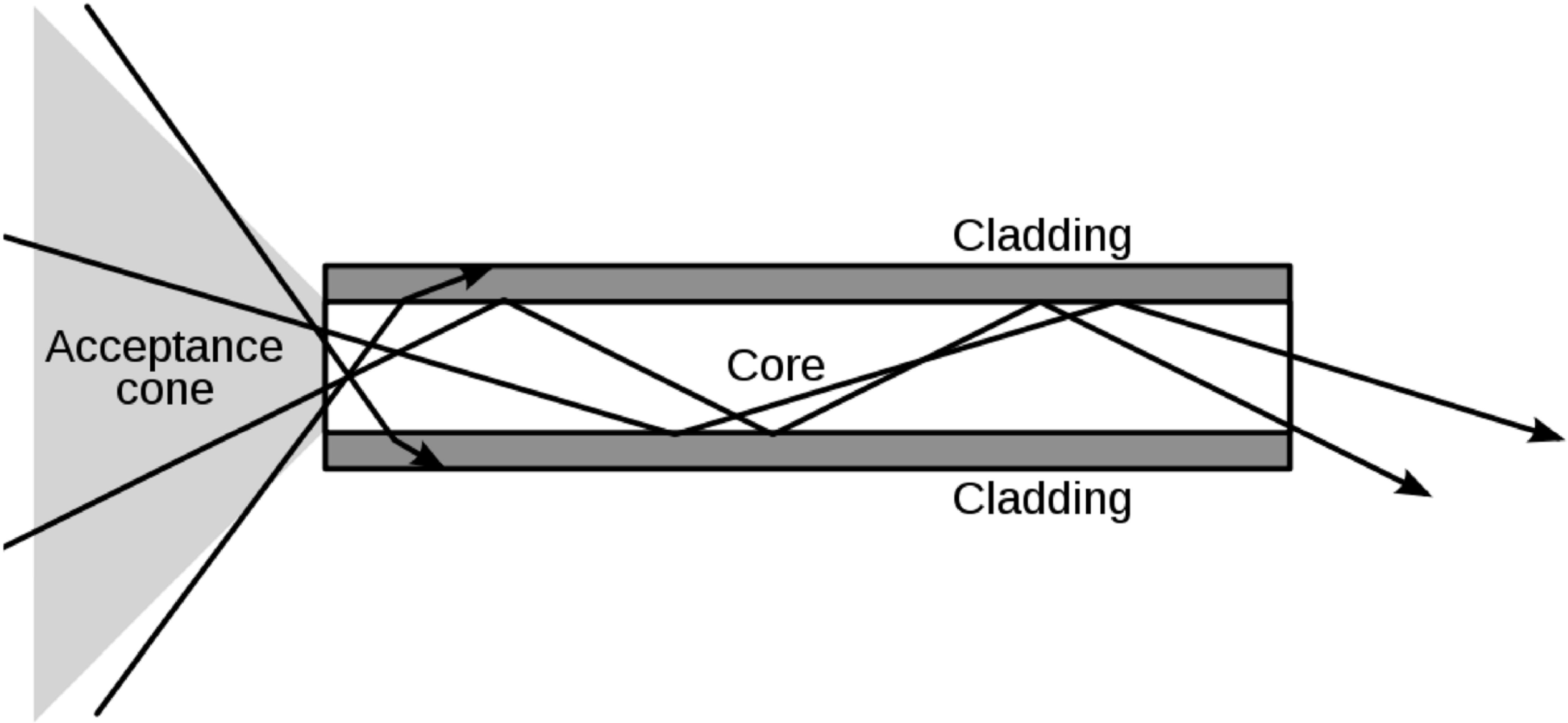
- Why talk about optical networking?
  - The Internet as an industry is largely based around fiber.
  - Yet many router jockeys don’t get enough exposure to it.
  - This leads to a wide variety of confusion, misconceptions, and errors when working with fiber optic networks.
- Will this presentation make 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

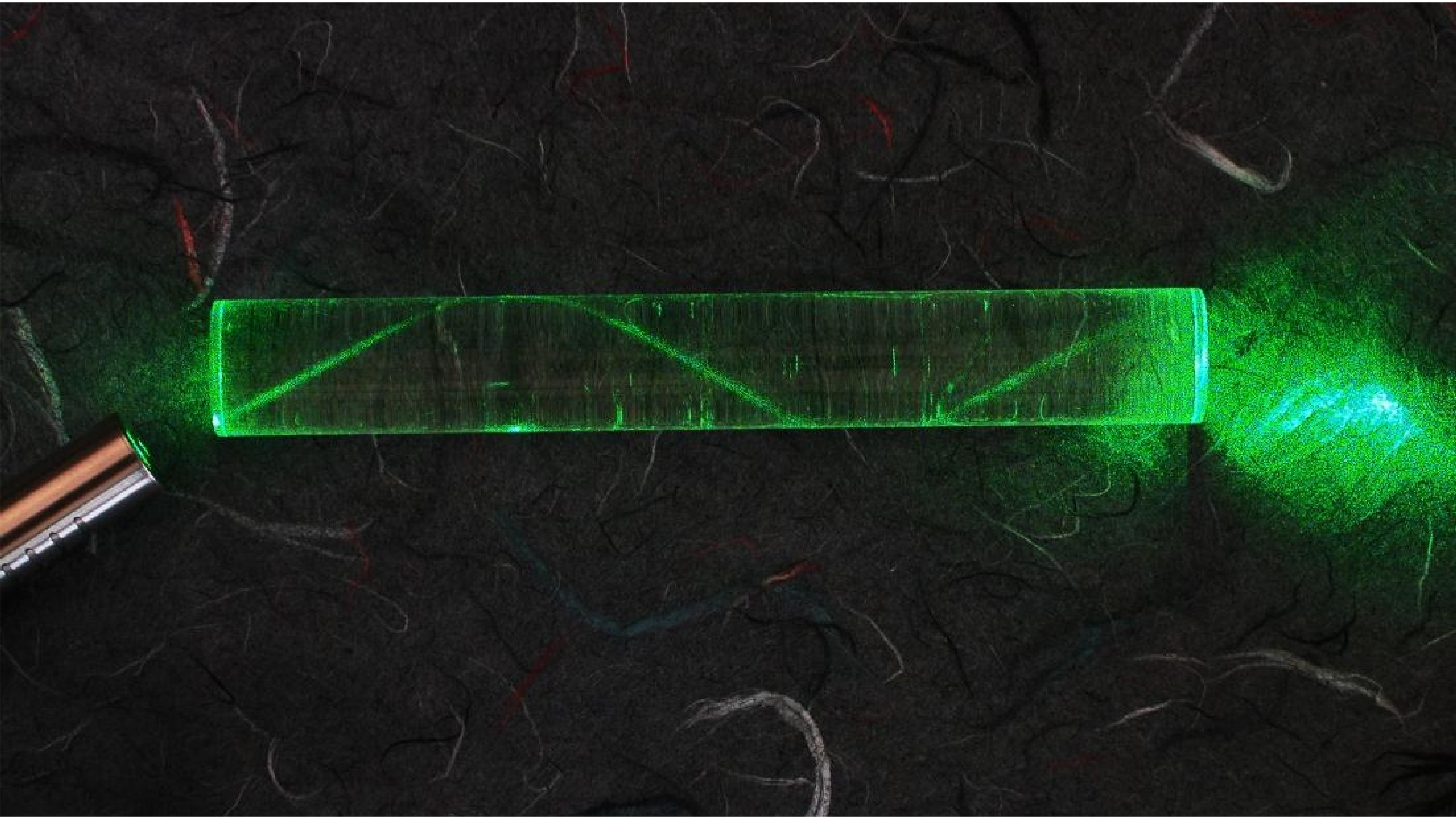
How Does Fiber Work?

- Fiber is essentially a waveguide for light.
- Using a principal known as “Total Internal Reflection”
  - Fiber cables are internally composed of two layers.
    - Known as the “core” and the “cladding”.
  - The core layer is surrounded by the cladding layer.
    - And the cladding layer has a higher index of refraction than the core.
  - When light tries to pass from a lower to a higher index of refraction, at the correct angle, it is reflected back instead.
  - This causes light to be continuously reflected back into the core, allowing the light to travel to the other end of the fiber.

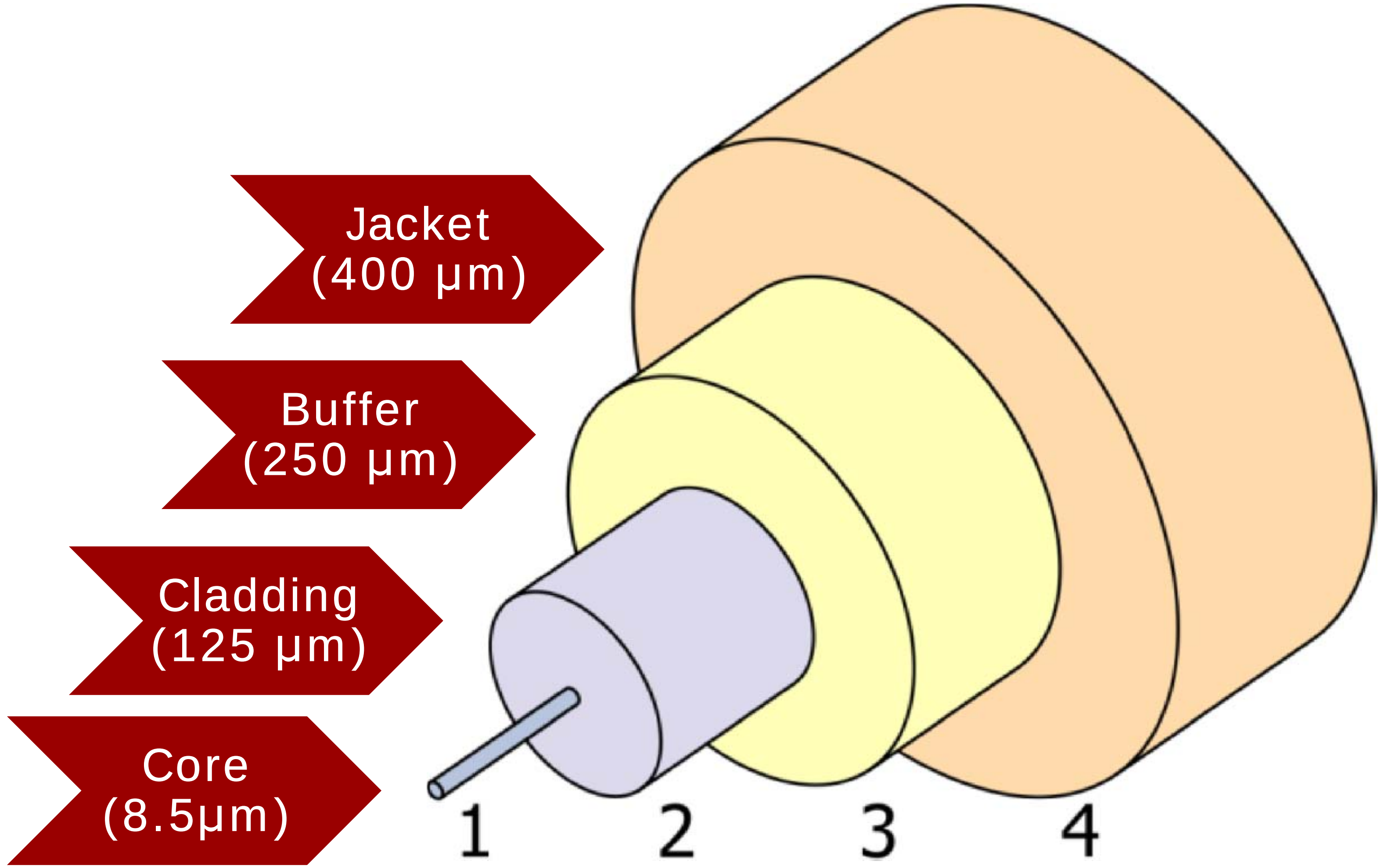
Diagram Showing Internal Reflection



Gratuitous Example Image From Wikipedia

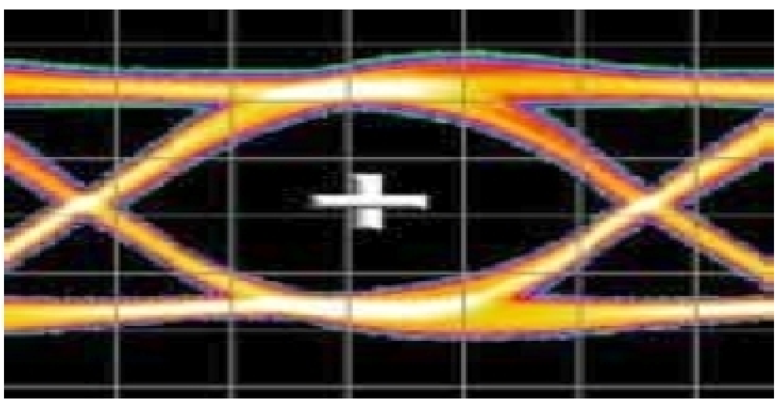


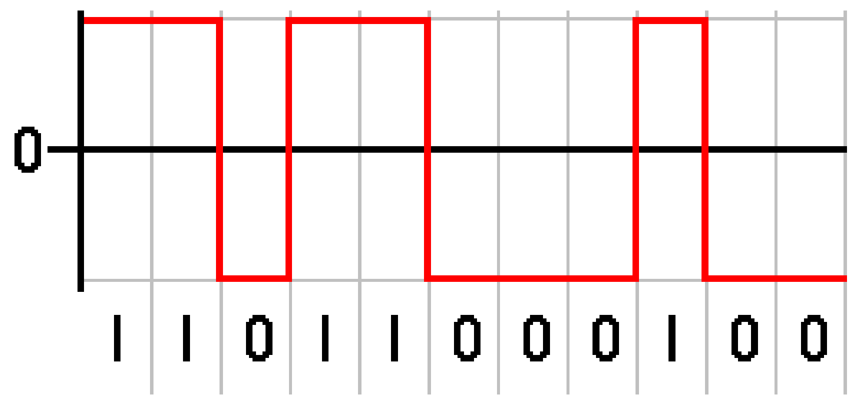
The Inside of a Single-Mode Fiber Cable



What We Transmit Over Fiber

- Digital signals are encoded in analog pulses of light.
  - Today, primarily via a method known a Non-Return to Zero (NRZ) modulation.
- Most fibers operate in duplex (pairs)
  - One fiber is used to transmit, the other is used to receive.
  - But it is possible to send both signals over a single strand.





Basic Fiber Types

Fiber Types

- Network fiber can be classified into two main types
  - Single Mode Fiber (SMF)
  - Multi-Mode Fiber (MMF)
- The difference is primarily in the size of the core
  - Multi-mode fiber has a wide core, allowing multiple modes of light to propagate.
  - Single-mode fiber has a narrow core, allowing only a single mode of light to propagate.

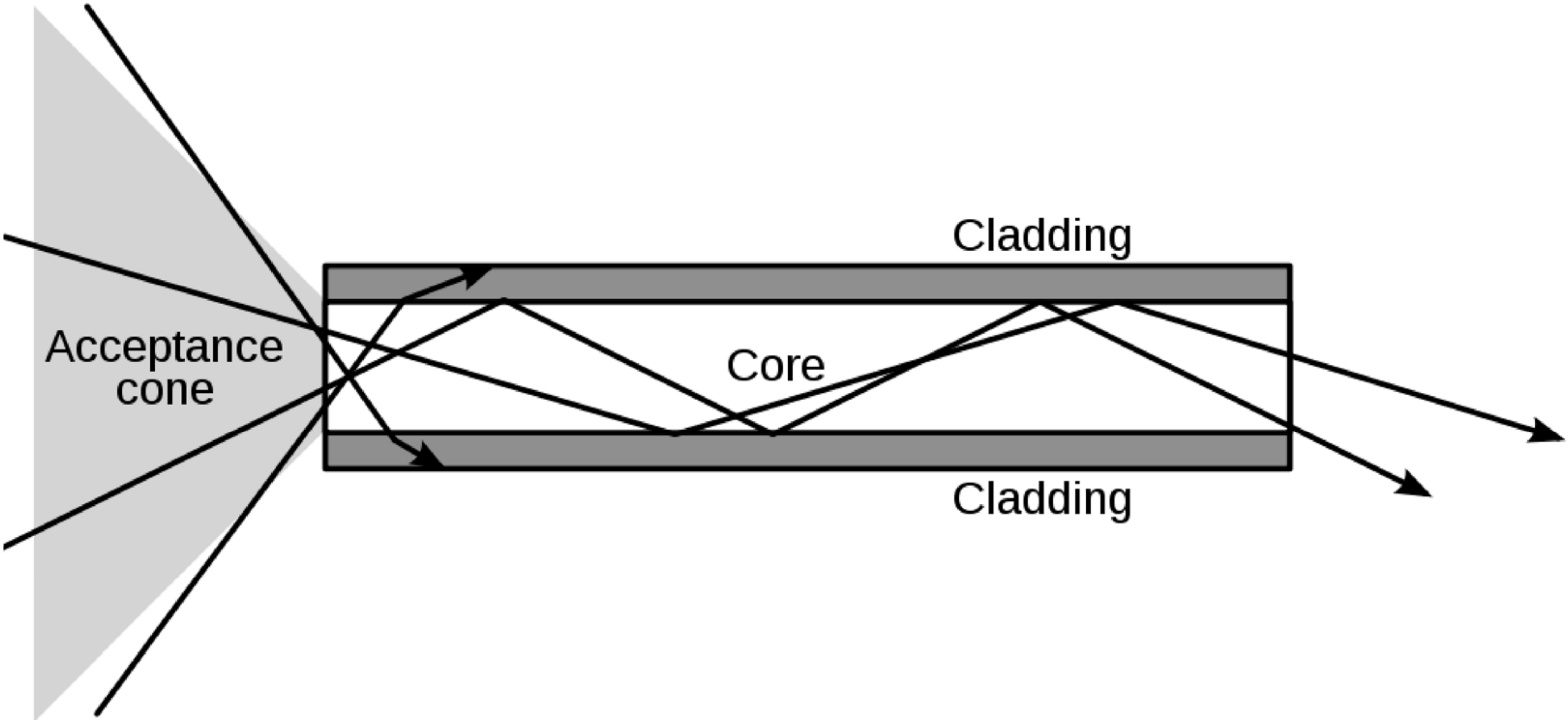
Multi-Mode Fiber

- Multi-Mode Fiber
  - Has two common core sizes (62.5µm OM1, or 50µm OM2)
  - Specifically designed for use with “cheaper” optics
    - The wide core lets you use incoherent LED light sources.
    - Or cheaper, less precisely aimed lasers.
    - Typically operates at 850nm or 1310nm.
  - But this comes at the expense of long-distance reach
    - Modal distortion significantly limits the maximum distance.
    - Typically limited to between “tens to hundreds of meters”.
  - Recently augmented with “laser optimized” (OM3) MMF
    - Uses aqua colored cables, rather than the traditional orange.
    - Designed to achieve 10Gbps at 300 meters with VCSEL lasers.

Single-Mode Fiber

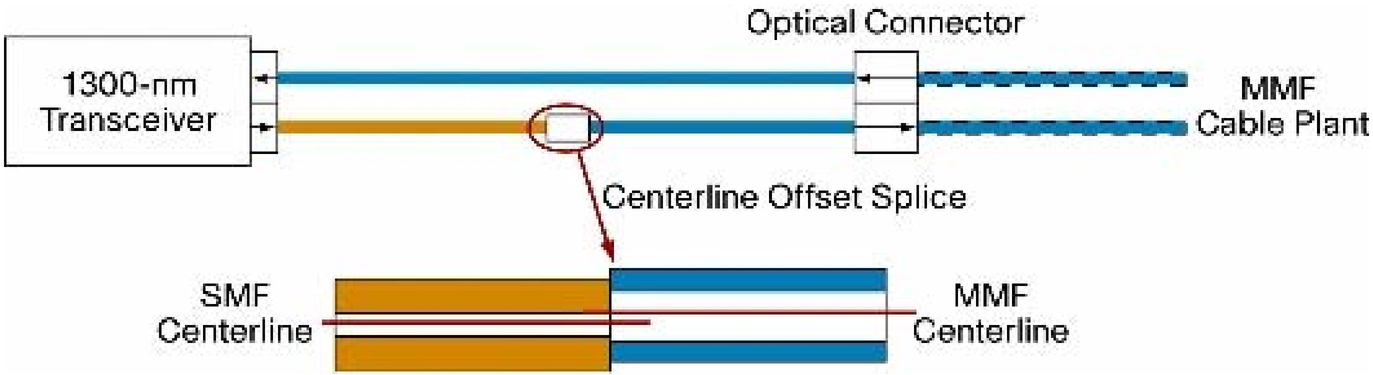
- Single-Mode Fiber
  - Has a core size of between 8-10 microns (μm)
  - SMF supports distances up to several thousand kilometers
    - With appropriate amplification and dispersion compensation.
  - But requires more expensive, coherent laser light sources.
    - Typically in the 1270nm – 1625nm range.
  - “Classic” Single-Mode Fiber is frequently called SMF-28
    - 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.

Modal Distortion in Multimode Fiber

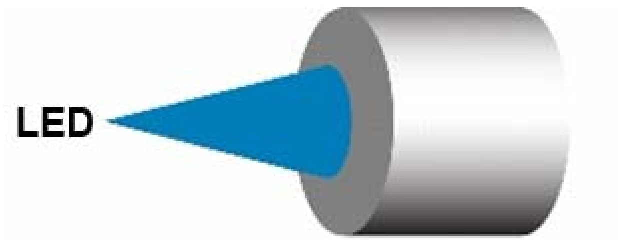


Mode Conditioning Cables

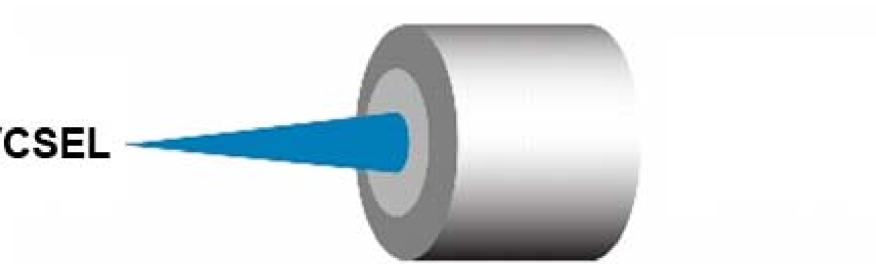
- What happens to a “narrow” laser inside “wide” MMF?
  - It gets bounced around, causing modal distortions.
- This can be improved with a Mode Conditioning Cable
  - A manufactured splice between the SMF and MMF cables, precisely setting the angle of the light sent into the MMF.
  - By controlling the angle, modal distortions can be reduced, allowing greater distances to be achieved over MMF.
    - For example, a 1GE LX over MMF would go from 300M to 550M.



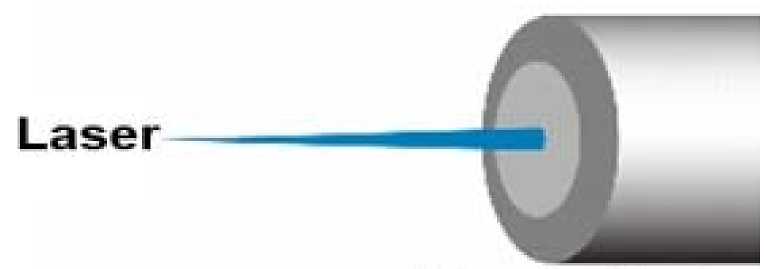
Different Optical Transmitter Types



Light Emiting Diode
FDDI



Vertical Cavity Surface Emitting Laser (VCSEL)
Gigabit Ethernet SX



Single Mode
Gigabit Ether

What Happens When You…?

Transmit Optic Type	Multimode Fiber	Single-mode Fiber
LED Source (traditional 850nm/SX Gigabit optics, 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).

Fiber-Optic Pluggable Transceivers

- Previously discussed at great length
  - NANOG 29, Oct 2003, 1G Pluggable Transceivers
    - http://www.nanog.org/meetings/nanog29/presentations/wodelet.pdf
  - NANOG 42, Feb 2008, 10G Pluggable Transceivers
    - http://www.**nanog**.org/meetings/nanog42/presentations/pluggables.pdf
    - Some updates from 2 years later:
      - SFP+ is now shipping in large quantities, at pretty reasonable prices too.
      - 10GBASE-SR, LR, LRM optics are now available from the router vendors.
      - Longer reach optics (ER, ZR) are in the pipeline too, ER is shipping soon.
      - Some no-name vendors are even advertising 18-channel CWDM 40km.
      - No DWDM optics on the horizon yet, but it's only a matter of time.
      - SFP+ is the "format of choice" for new, high density, enterprise-grade boxes.
      - Still not a complete replacement for XFP, but attractive on 32/48-port blades.

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.
    - Either absorbed by the glass particles and converted to 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, 1/10th 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 itself is simply a ratio between 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

- So 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 addition when measuring gains/losses.

Decibel to Power Conversion Table

Table 1 - Decibel to Power Conversion

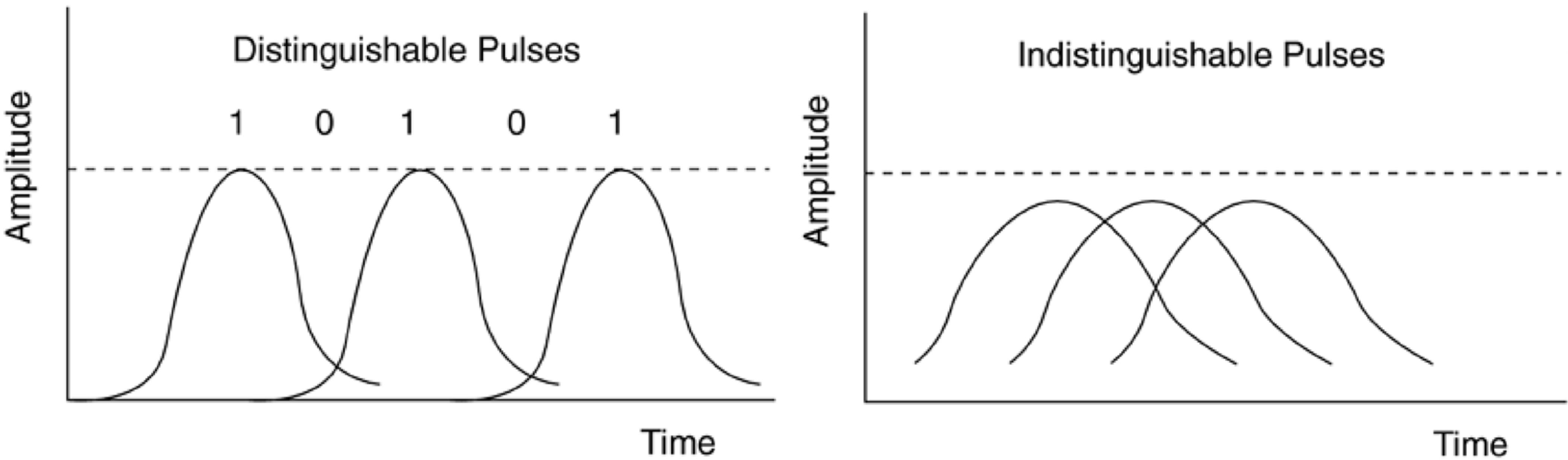
dB (loss)	Power Out as a % of Power In	% of Power Lost	Remarks
1	79%	21%	---
2	63%	37%	---
3	50%	50%	1/2 the power
4	40%	60%	---
5	32%	68%	---
6	25%	75%	1/4 the power
7	20%	80%	1/5 the power
8	16%	84%	1/6 the power
9	12%	88%	1/8 the power
10	10%	90%	1/10 the power
11	8%	92%	1/12 the power
12	6.3%	93.7%	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 how 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

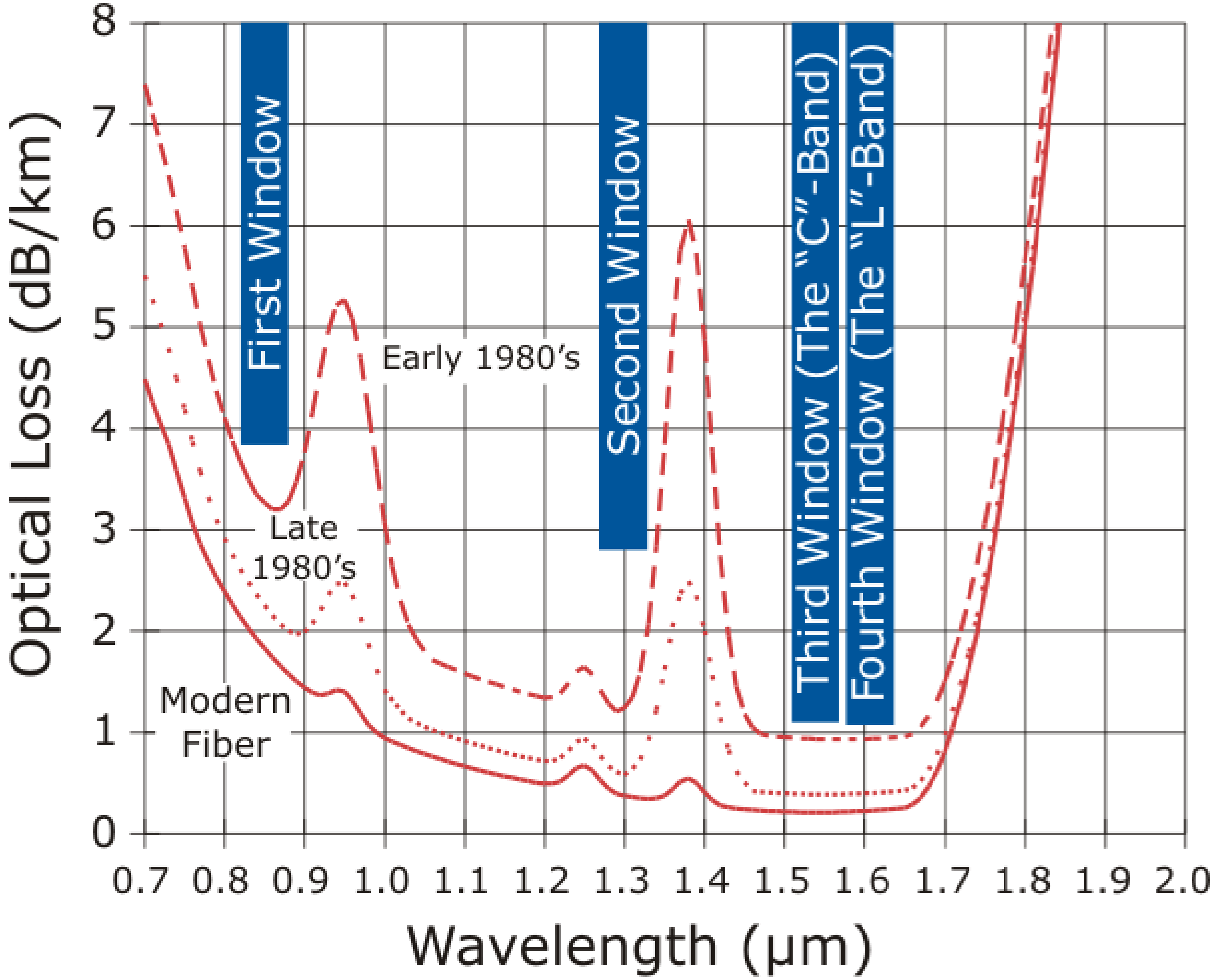
- As the signal is dispersed, it is no longer distinguishable as individual pulses at the receiver.



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.

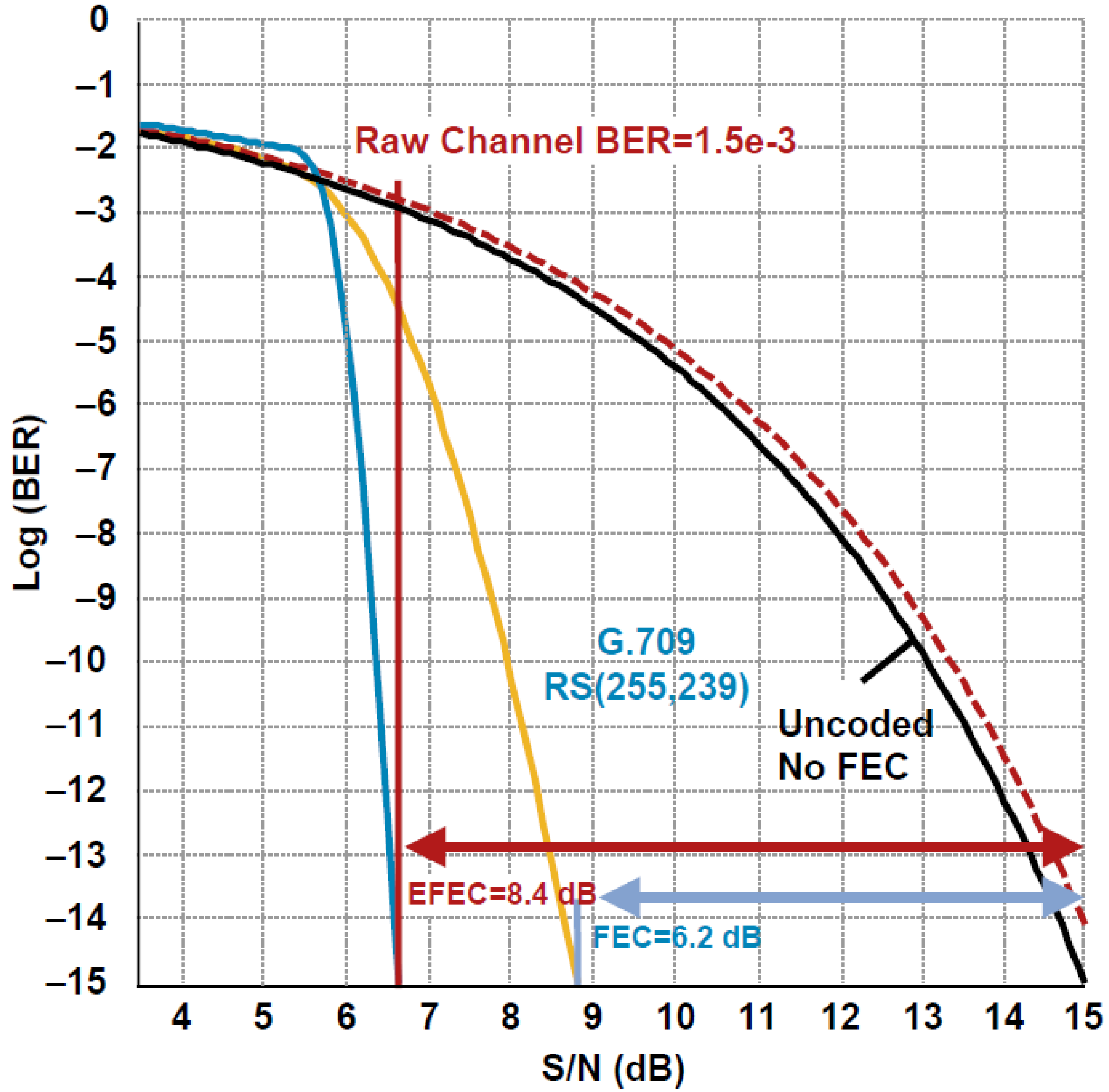
Fiber Optic Transmission Bands



Forward Error Correction

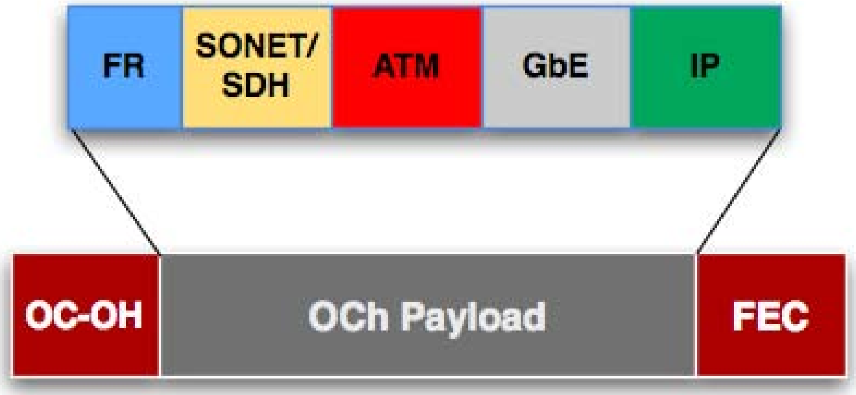
- Forward Error Correction
  - Adds extra/redundant information to a transmission so that a receiver can “recover” from small errors.
  - Think of it like RAID5 for your wavelengths. Even if you lose some data, you can still recover it computationally.
  - FEC works by extending the receiver sensitivity 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)

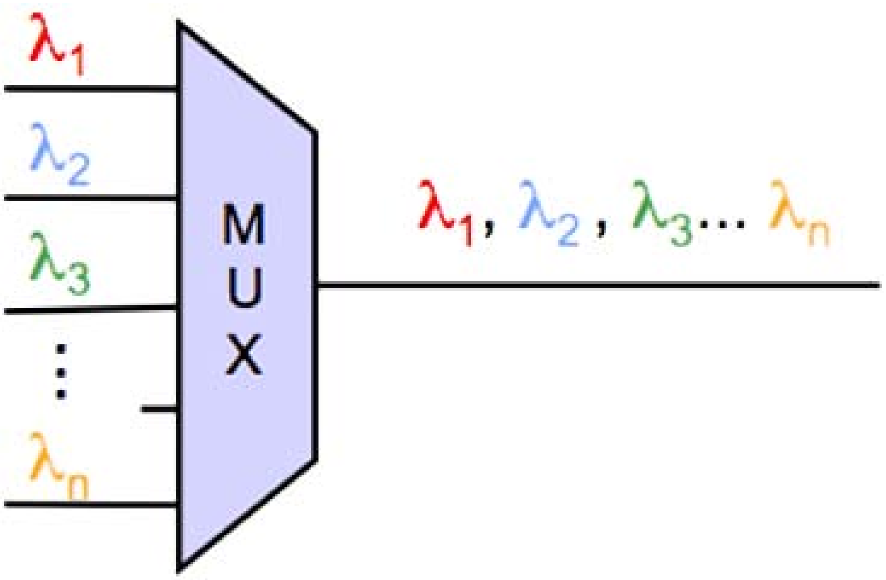
- OTN stands for Optical Transport Network
  - A set of standards which allow interoperability and the generic transport of any protocol across an optical network.
  - Implemented as a "wrapper" around another protocol.
  - Why is this needed?
    - So the optical network can be completely transparent.
    - 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 network operator to troubleshoot with OTN instead.

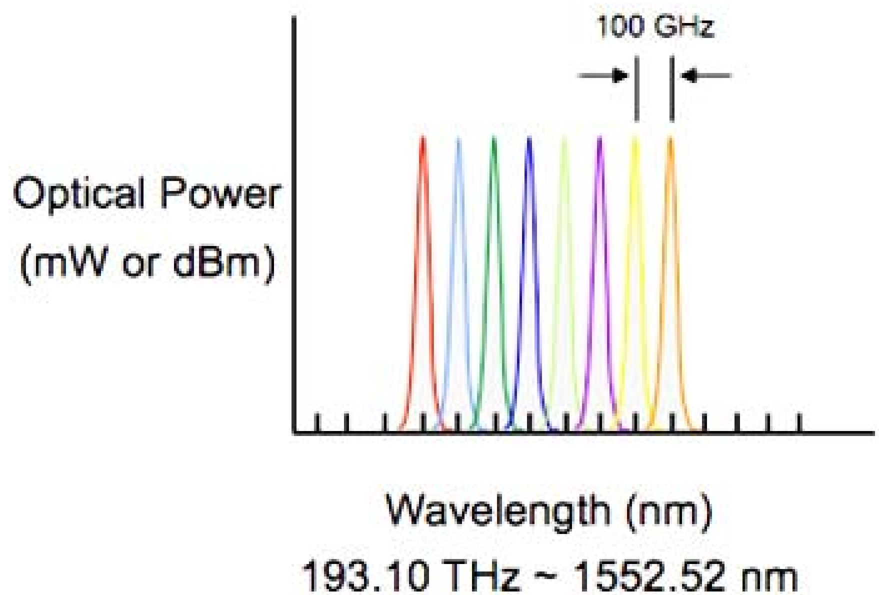


Wave Division Multiplexing

Wave Division Multiplexing (WDM)

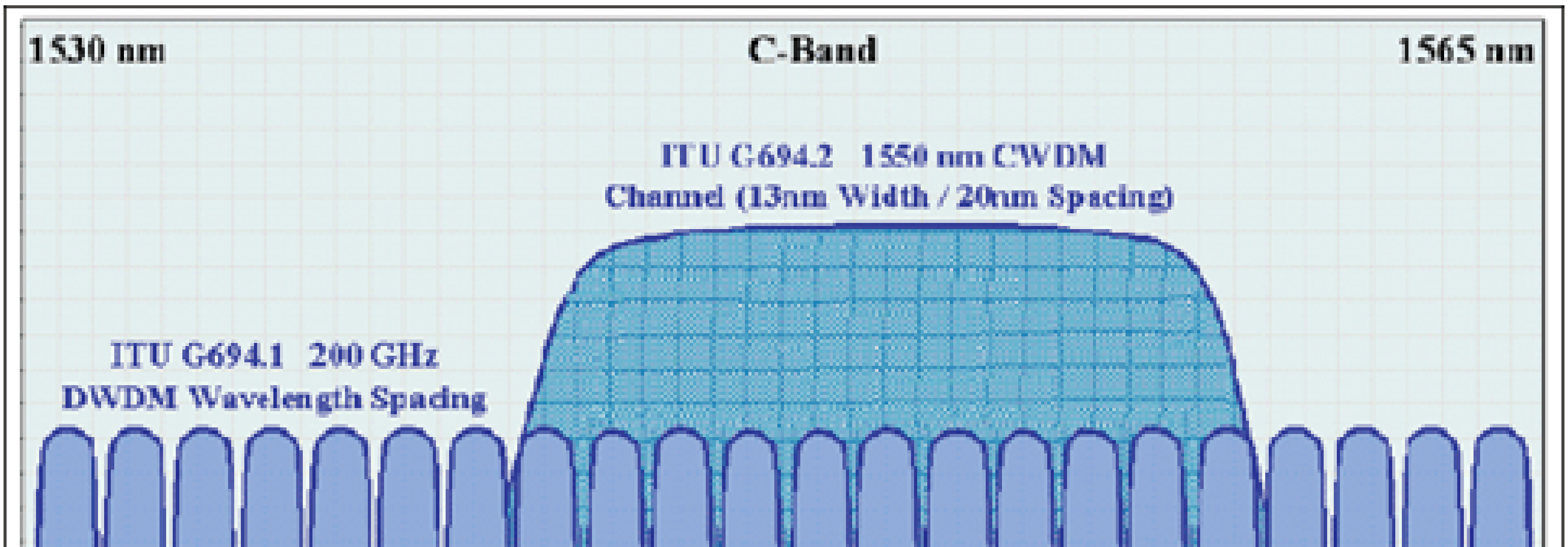
- What is Wave Division Multiplexing (WDM)?
  - We know that light comes in many different colors.
  - These different colors can be combined on the same fiber.
  - The goal is to have signals not interfere with each other.
    - “Ships in the night” approach.





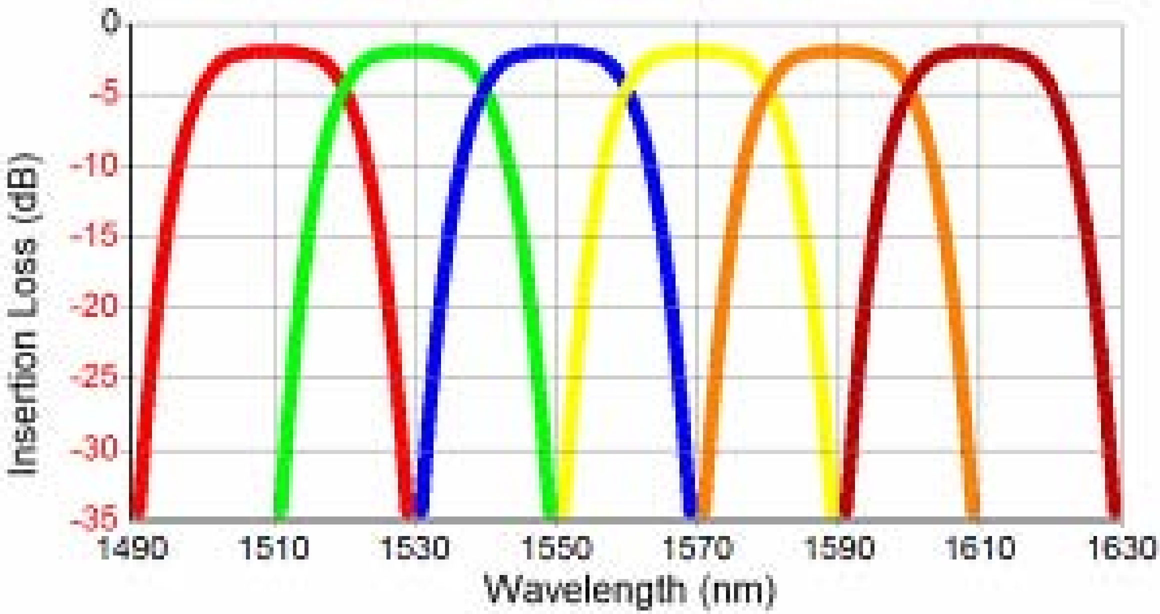
Different Types of WDM

- 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 the range of the optical spectrum they typically cover.



Coarse Wavelength-Division Multiplexing

- CWDM is loosely used to mean anything not DWDM
  - The most “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.

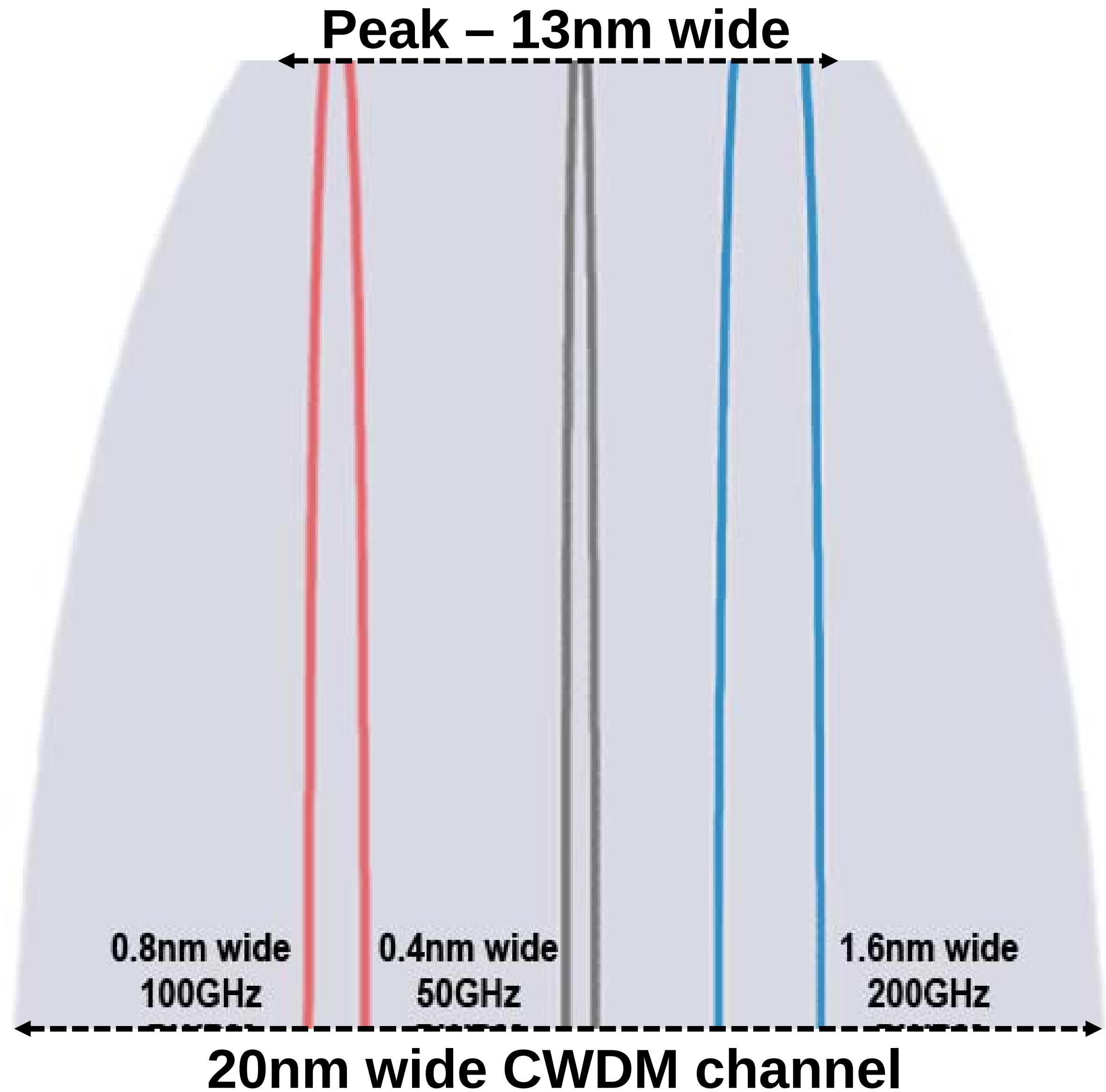
Dense Wavelength-Division Multiplexing

- What exactly is Dense WDM (DWDM)?
  - A much more tightly packed WDM system.
  - Typically used for commercial long-haul systems.
  - And typically based in the C-band.
  - Specific channel sizes are standardized in an “ITU Grid”.
  - Within C-band, these channel spacings are common:
    - 200GHz – 1.6nm spacing, 20 channels possible
    - 100GHz – 0.8nm spacing, 40 channels possible
    - 50GHz – 0.4nm spacing, 80 channels possible
    - 25GHz – 0.2nm spacing, 160 channels possible
  - 200GHz is “2000-era old tech”, 100GHz is common on pluggables or cheaper systems, 50/25GHz are “modern”.

What Are The Advantages?

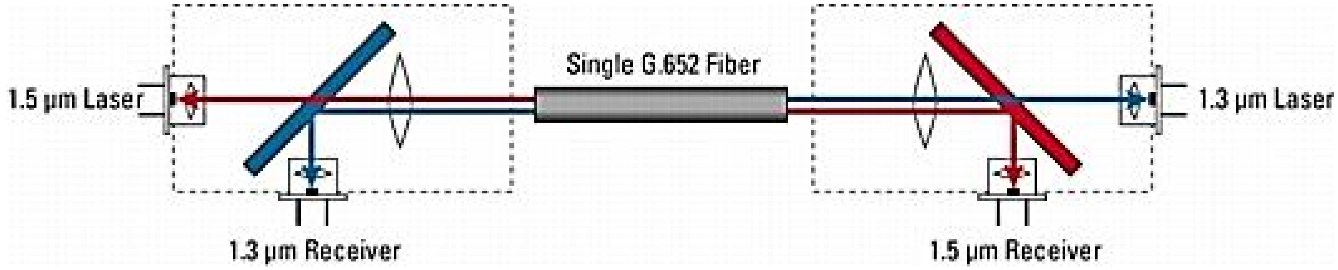
- CWDM
  - Cheaper, less precise lasers can be used.
    - The actual signal in a CWDM system isn't really any wider.
    - But the wide channel allows for large temperature variations.
    - Cheaper, uncooled lasers, can more easily stay within the window.
- DWDM
  - Far more channels are possible within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

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

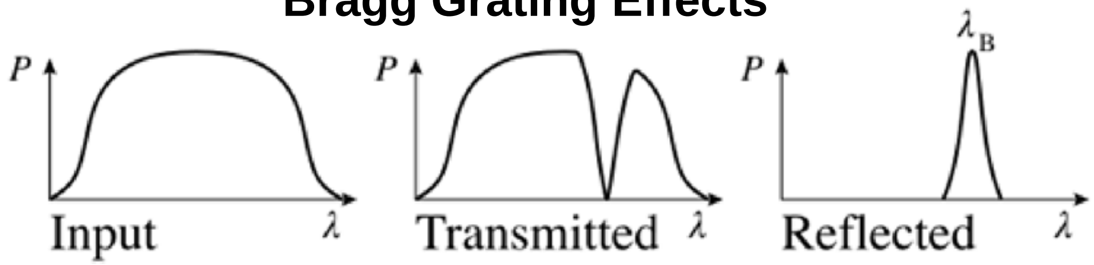
WDM Mux/Demux

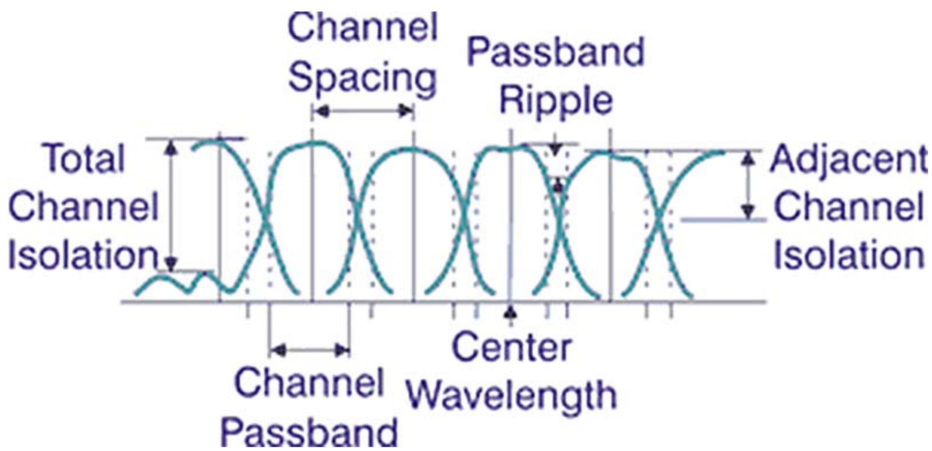
- The Mux/Demux
  - Short for “multiplexer”, sometimes called a “filter” or “prism”.
    - The term “filter” is how it actually works, by filtering specific colors.
    - But most people understand a “prism” splitting light into spectrums.
  - A simple device which combines or splits multiple colors 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.

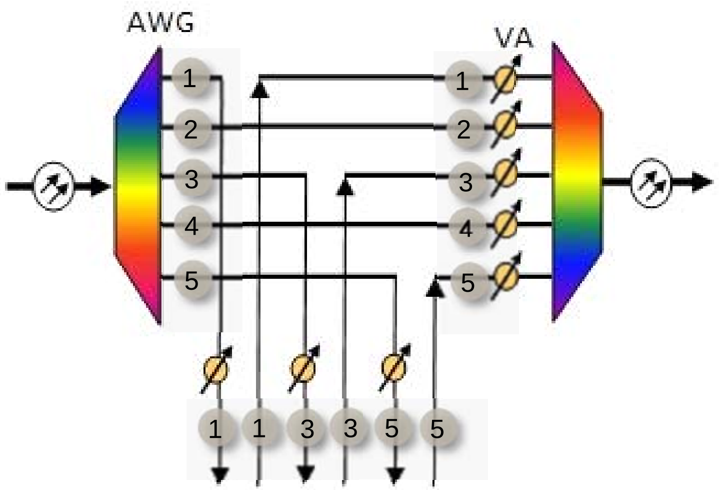
Bragg Grating Effects





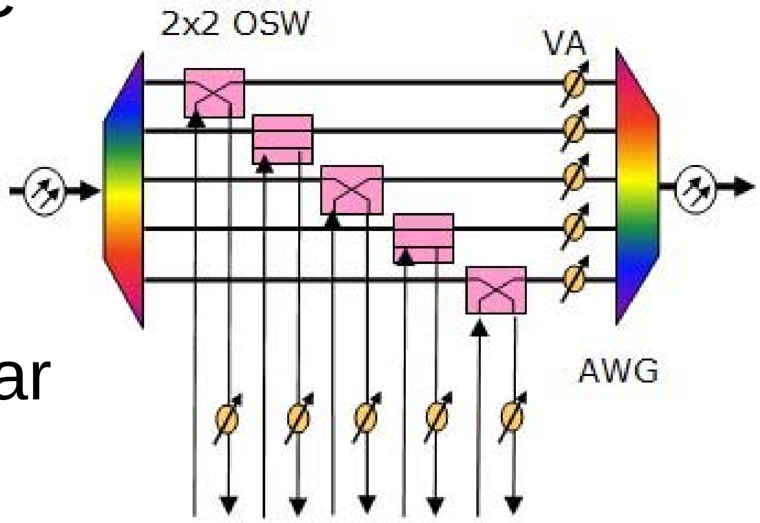
The Optical Add/Drop Multiplexer (OADM)

- 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.



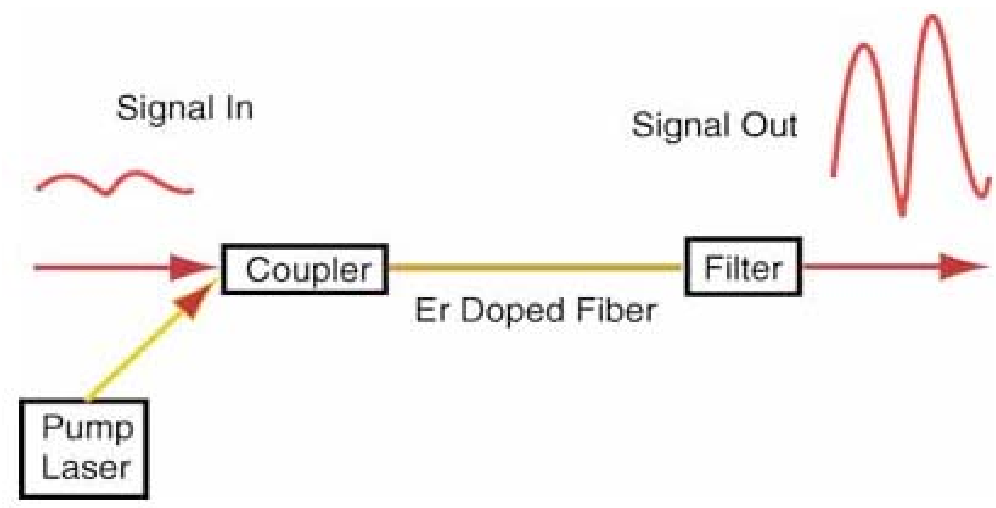
The ROADM

- 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

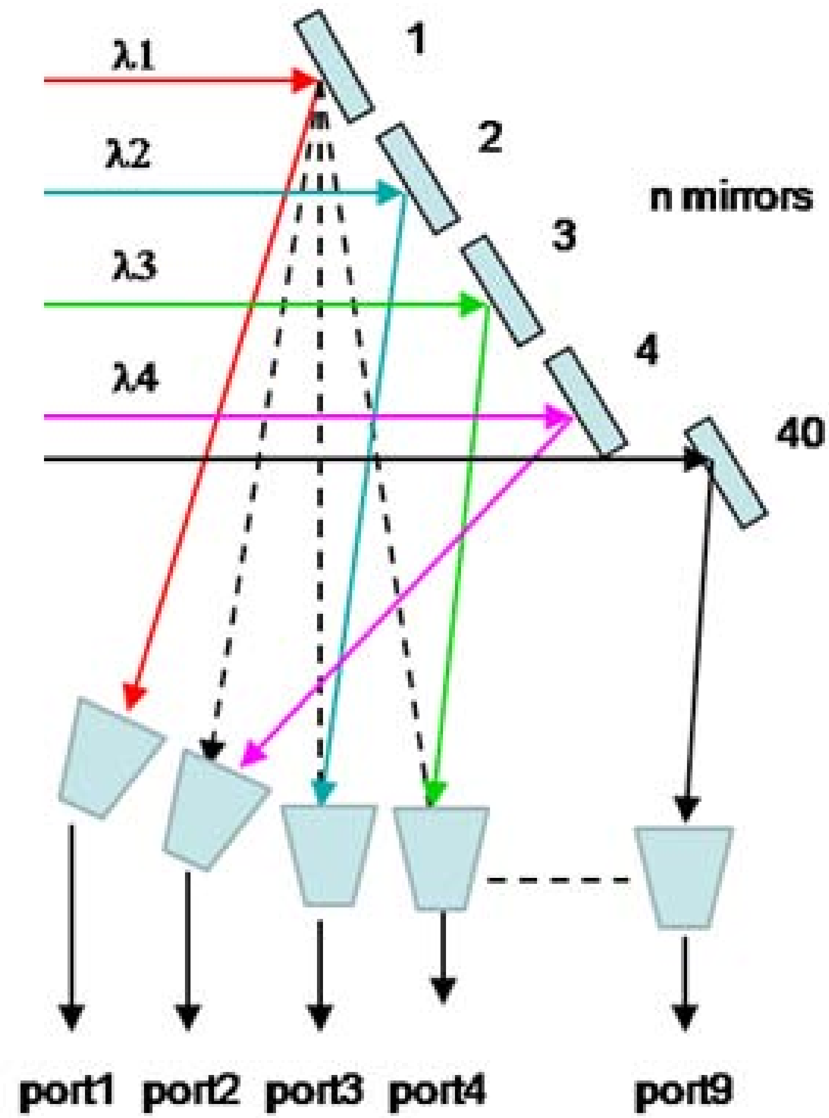
- Optical amplifiers increase the intensity of a signal
  - There are different types, for different spectrums of light.
  - The most common is the Erbium Doped Fiber Amplifier.
    - Another method is Raman Amplification, typically for ultra long-haul.
  - In an EDFA, a piece of fiber is “doped” with 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.

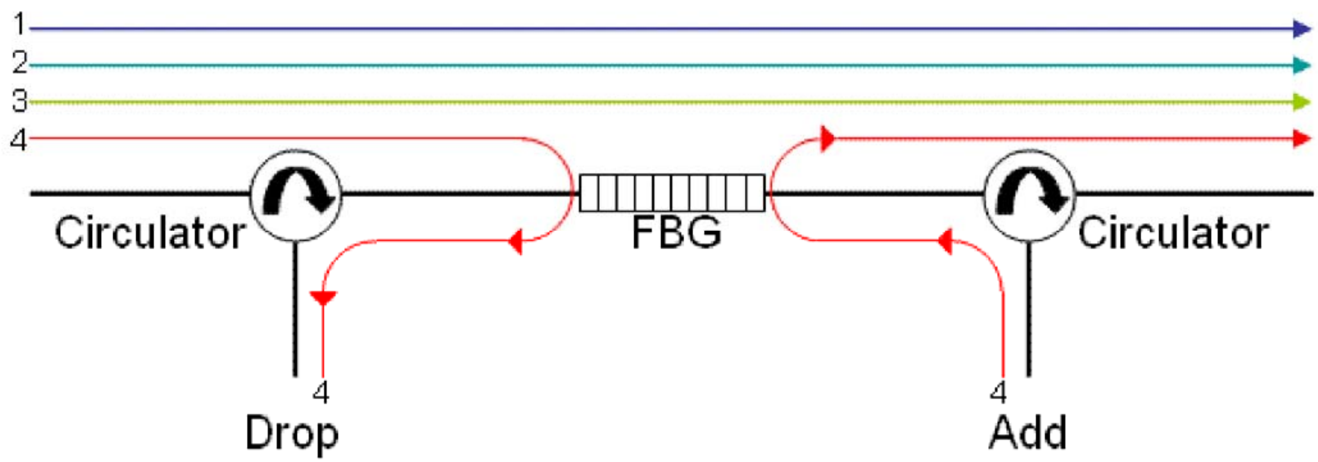
Optical Switches

- 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)

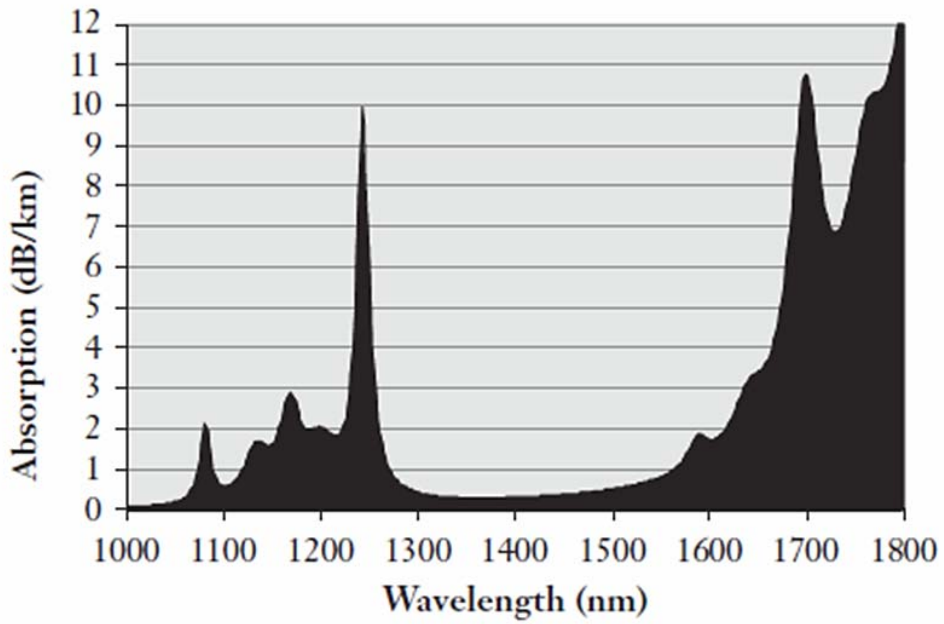
“Standard” Single-Mode Fiber (G.652)

- The original and mode widely deployed fiber.
- Frequently called “SMF-28”, or simply “classic” SMF.
  - SMF-28 is actually a product name from Corning.
- Optimized for the 1310nm band.
  - Lowest rate of dispersion occurs in this band.
  - Attenuation is lower at 1550nm, but more dispersion there.

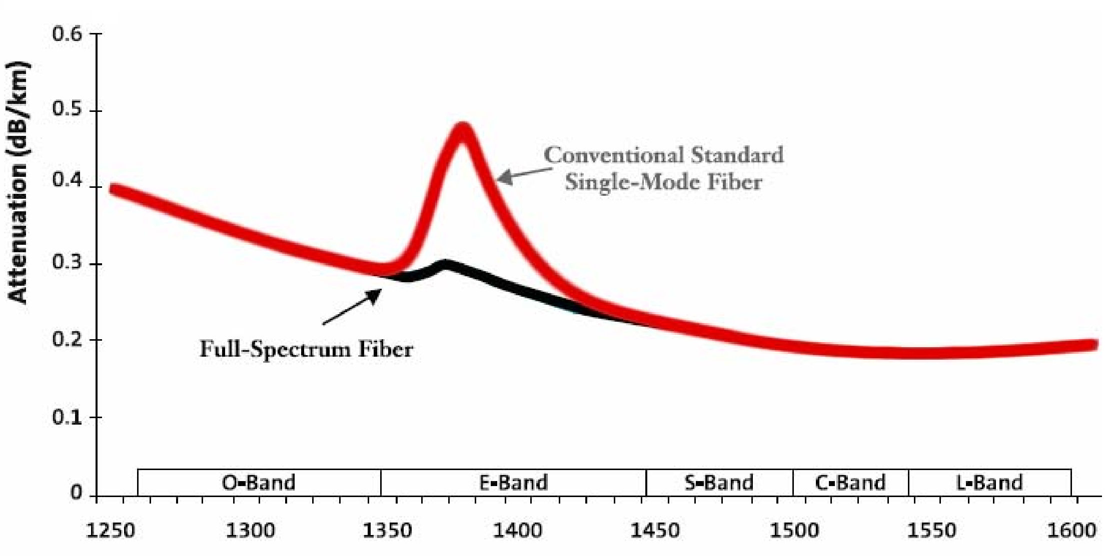
Low Water Peak Fiber (G.652.C/D)

- 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 fiber.
  - 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 across different frequencies of light.
  - The natural point of zero dispersion occurs at 1300nm.
  - But this is not the point of lowest attenuation.
  - DSF shifts the point of zero dispersion to 1550nm.
- But this turned out to cause big problems.
  - Running DWDM over DSF causes non-linear interactions.
  - The notable example is called Four Wave Mixing
    - 3 equally spaced wavelengths interact to produce a 4^{th} wavelength.
  - As a result, this fiber is rarely used today.

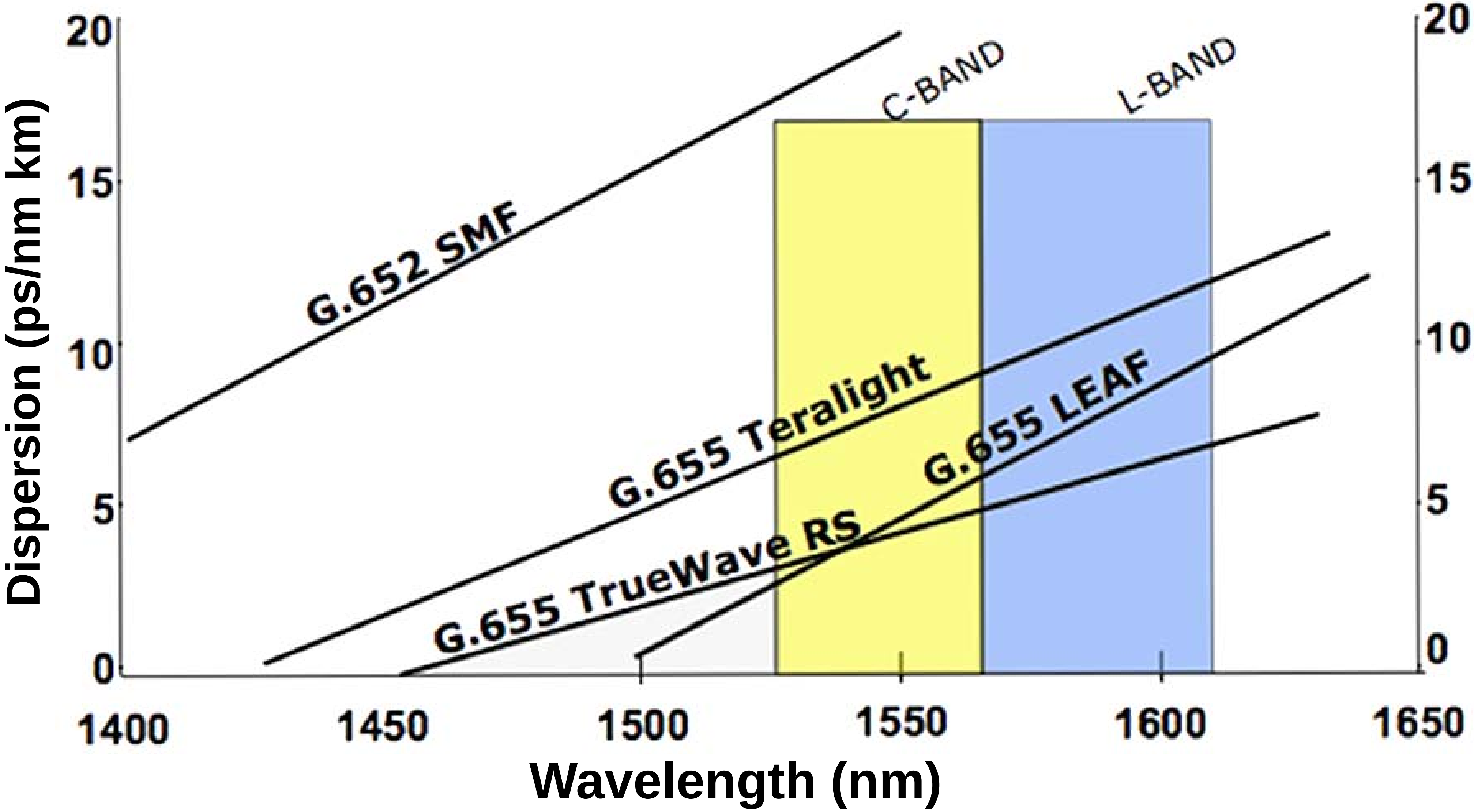
Non-Zero Dispersion Shifted Fiber

- 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 in the ground is old fiber.

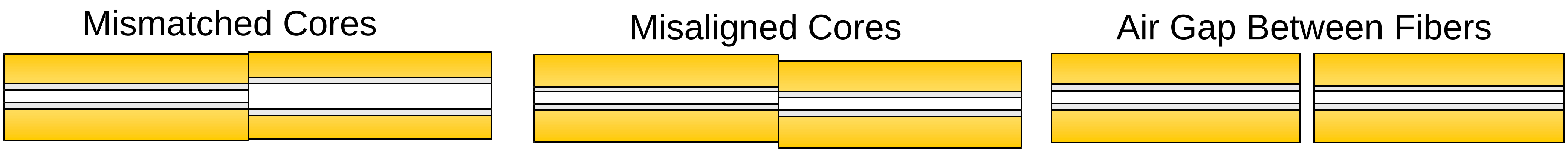
Dispersion Rates of Commercial Fibers



Engineering an Optical Network

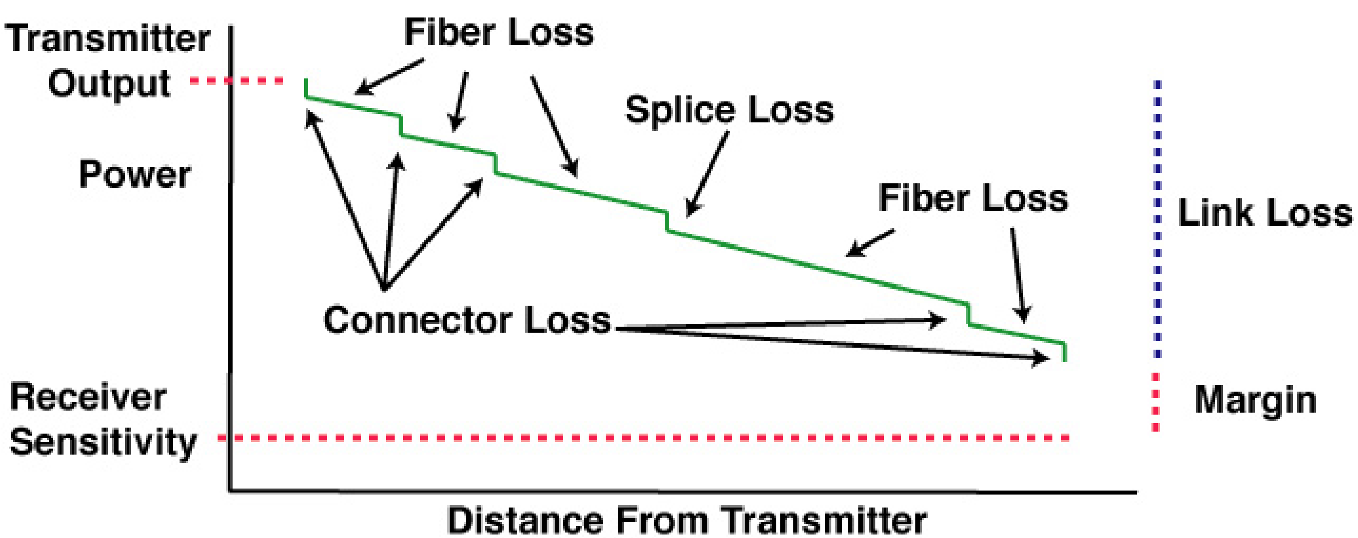
Insertion Loss

- 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



Optical Budgets

- 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 cool with age, a fiber cut fix will add more splices, etc.

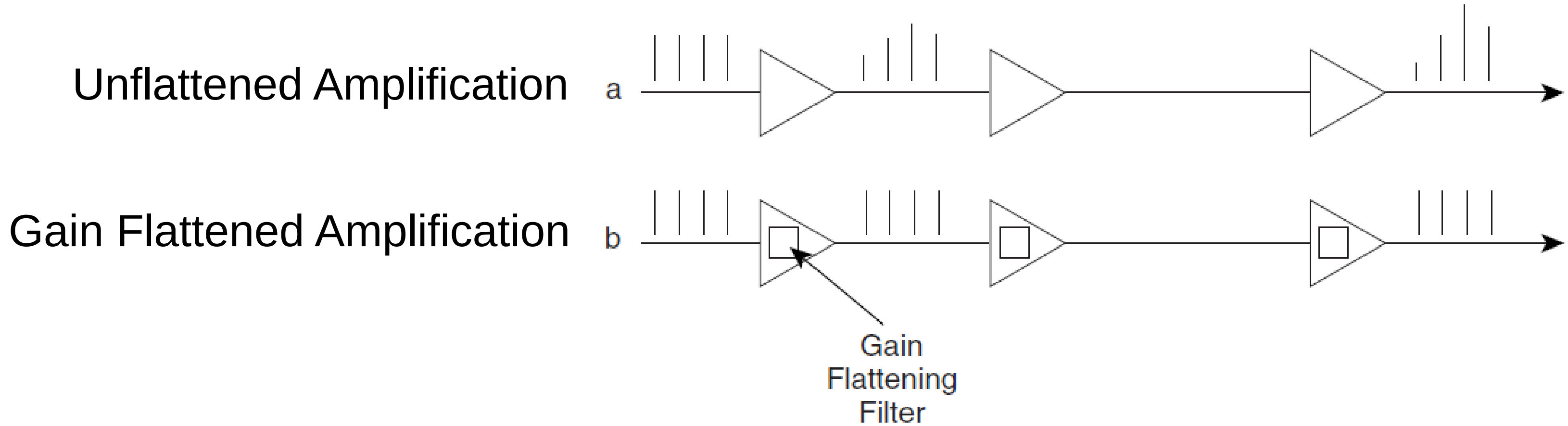


Balling On A (Optical) Budget

Event	Typical Loss	Worst Case Loss
Factory made connector	0.1 – 0.2 dB	0.75 dB
Field terminated connector	0.3 – 1.0 dB	1.0+ dB
Fusion splice	0.05 dB	0.3 dB
Mechanical splice	0.1 dB	
G.652 Loss @ 1310nm		
G.652 Loss @ 1550nm		
G.655 Loss @ 1310nm		
G.655 Loss @ 1550nm	0.2 dB/km	

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 OADMs, 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

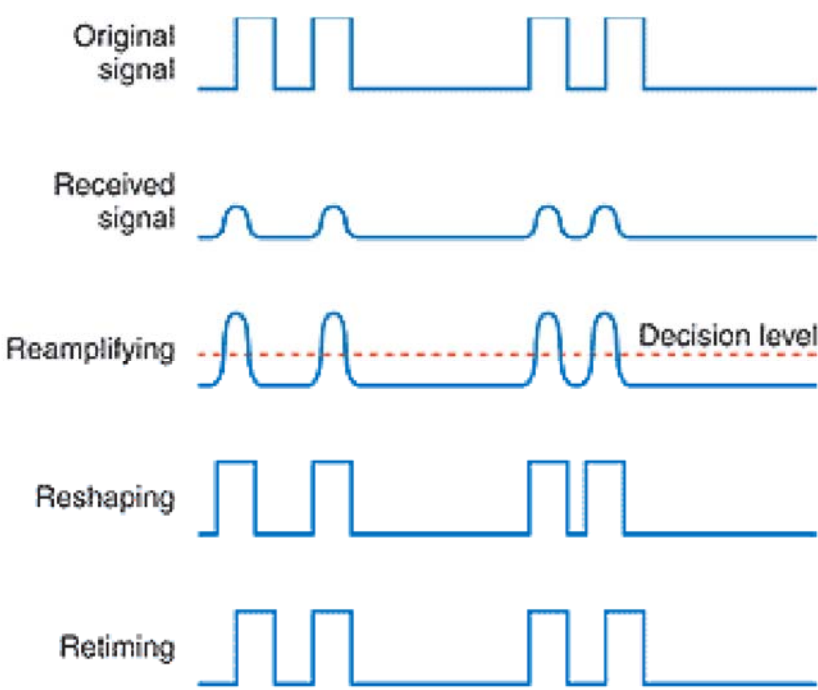
- Dispersion Compensating Fiber
  - Essentially just big a spool of fiber.
    - Designed to cause dispersion in the opposite direction (with the opposite “slope”) as the transmission fiber used.
    - Passing the signal through this spool reverses the effects of dispersion caused by transmission through 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 are used to reduce the total amount of fiber needed.

Dealing with Dispersion

- Electronic Dispersion Compensation
  - Technology is getting better all the time.
  - Dispersion which used to completely ruin a signal can now be compensated for electronically in the receiver.
  - EDC is being integrated into pluggable optics.
  - And is largely responsible for the 300 meter ranges which can now be achieved over MMF with modern optical standards like 10GBASE-LRM.
  - Will be essential in future 40G and 100G optical technology.

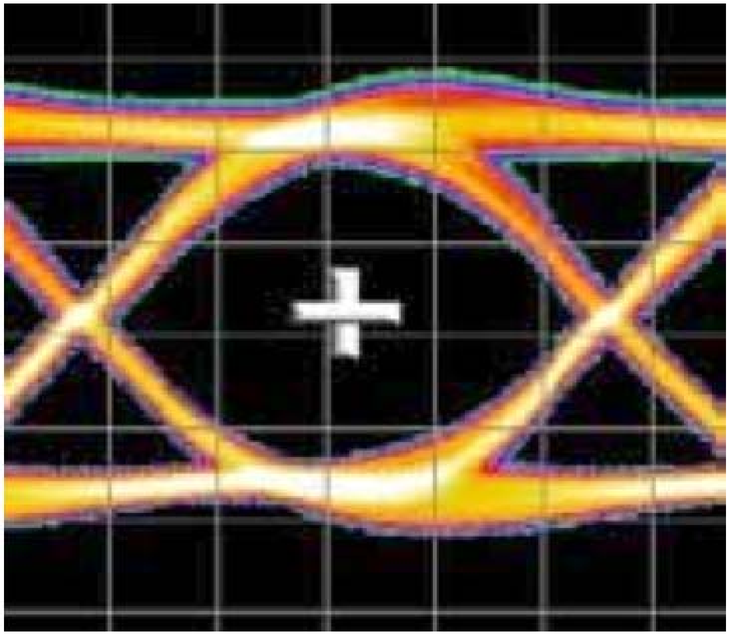
Re-amplifying, Reshaping, and Retiming

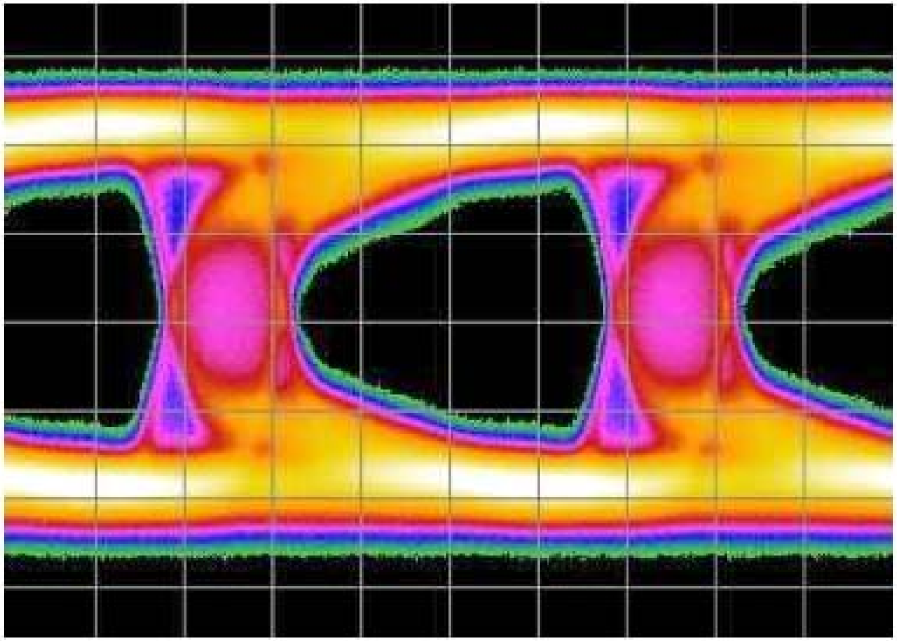
- Signal Regeneration (Repeaters)
  - Different types are described by the “R’s” that they perform.
  - 1R – Re-amplifying
    - Makes the analog signal stronger (i.e. makes the light brighter)
    - Typically performed by an amplifier.
  - 2R – Reshaping
    - Restores the original pulse shape that 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.



Eye Diagrams

- An oscilloscope display of a digital signal.
  - Representative of the impairments affecting the signal.
  - As the signal is distorted, the original digital encoding can no longer be correctly interpreted.





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.

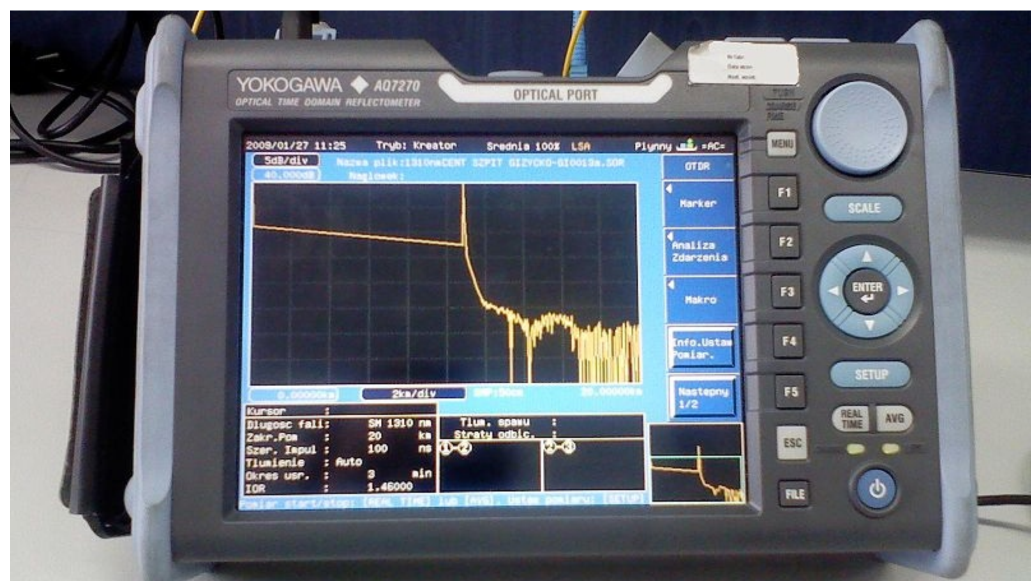
Tools of the Trade

Fiber Optic Power Meter

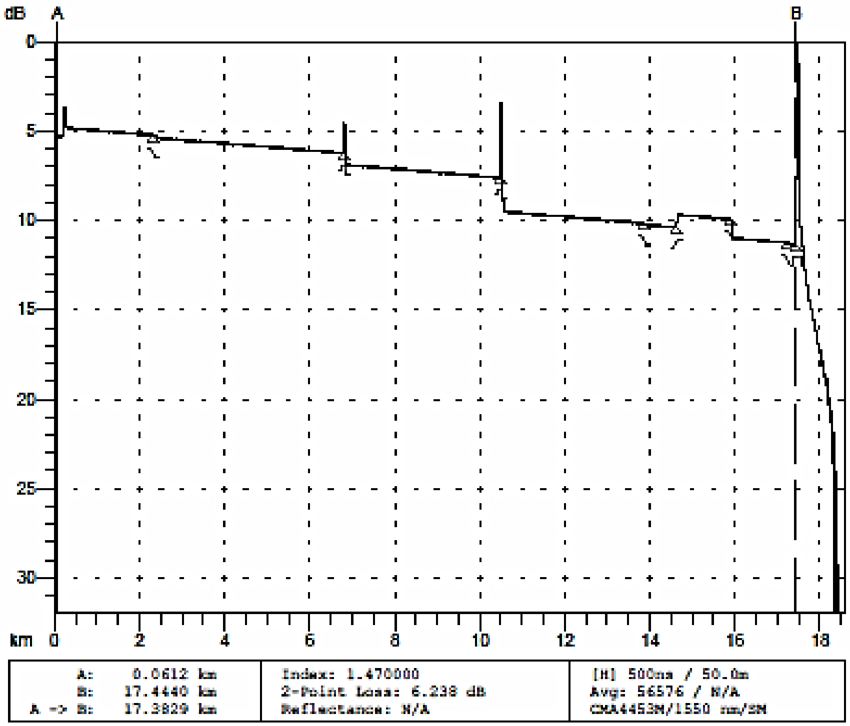
- Optical Power Meter (or simply a Light Meter)
  - Measures the brightness of an optical signal.
  - Displays the results in dBm or milliwatts (mW).
  - Most light meters include a “relative loss” function as well as absolute power meter.
    - Designed to work with a known-power light source on the 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).

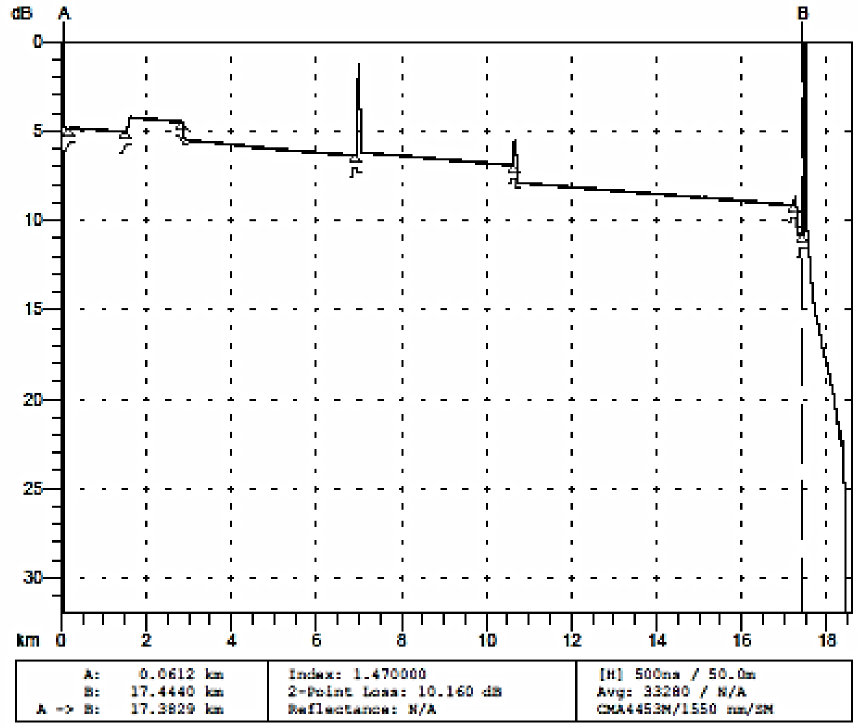


Example OTDR Output



Feature #/Type	Location (km)	Event-Event (dB)	Event-Event (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)	Event-Event (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" 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, sets things on fire, 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 wasn't meant to see in IR.
  - It actually does a good job of filtering out IR-B light.
  - So an IR laser which transmits 10mW of power may still be a Class 1 because that light can't enter the eye.

Optical Networking and Safety

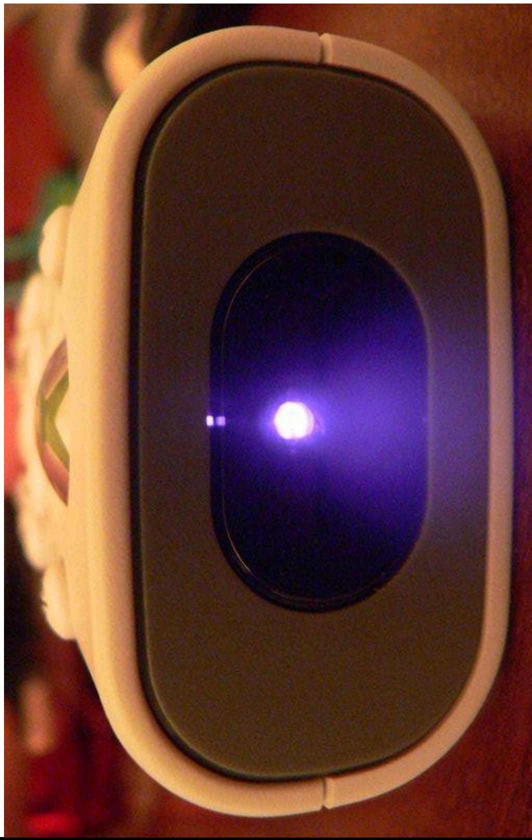
- Routers
  - Essentially every single channel laser which can be connected to a router is a Class 1 or Class 1M laser.
  - Even the longest reach 200km+ optics, etc.
- Optical Amplifiers
  - Optical amplifiers are capable of putting out enough power to kick a signal into Class 3R (metro) or 3B (long-haul).
- 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 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 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.
    - If you're bored, try it on your TV's remote control.

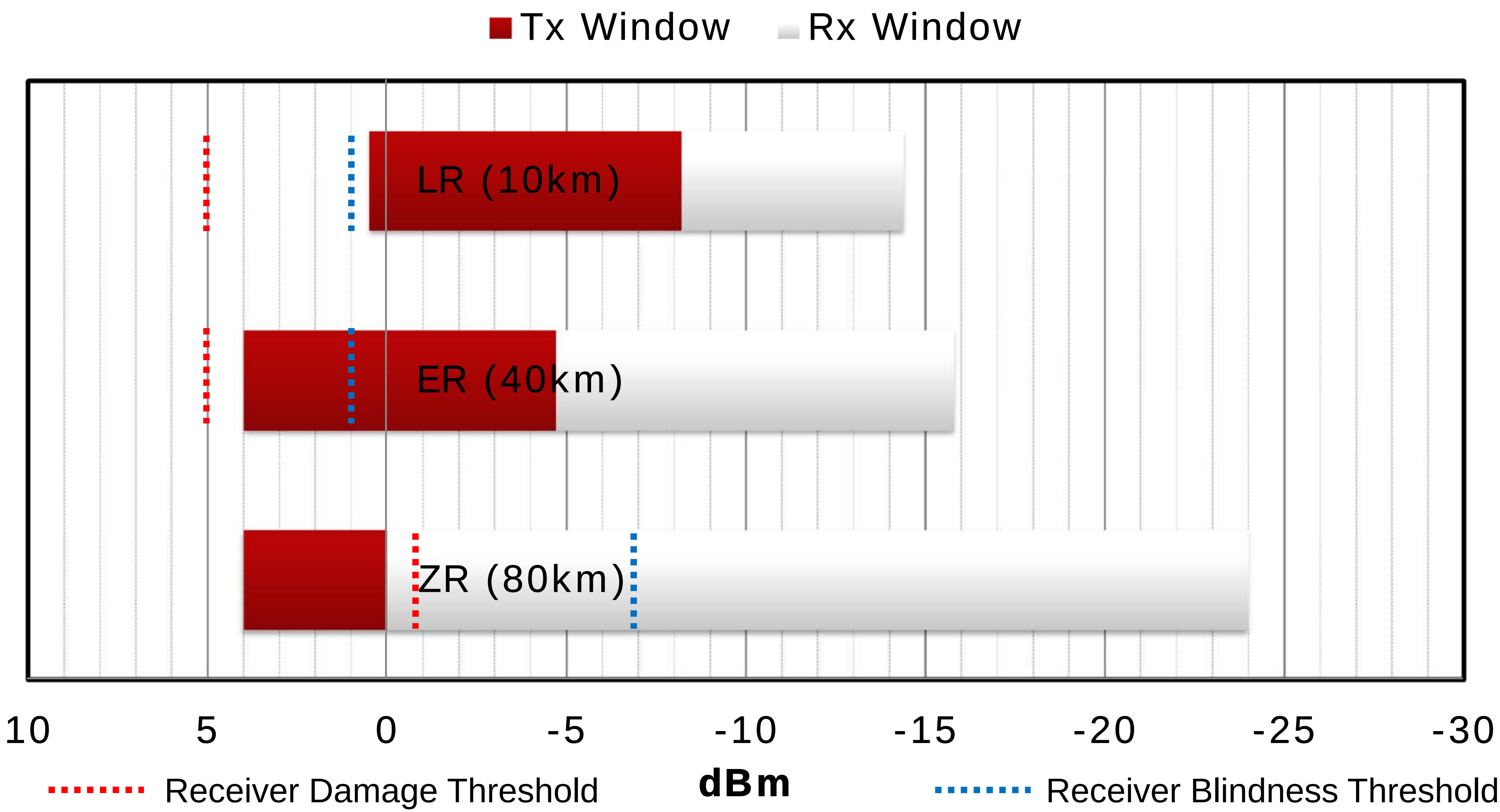


Question: Can optical transceivers be damaged by over-powered transmitters?

Damage by Overpowered Transmitters?

- Well, yes and no.
  - Actually, most optics transmit at roughly the same power.
    - The typical output of 10km and 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



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?

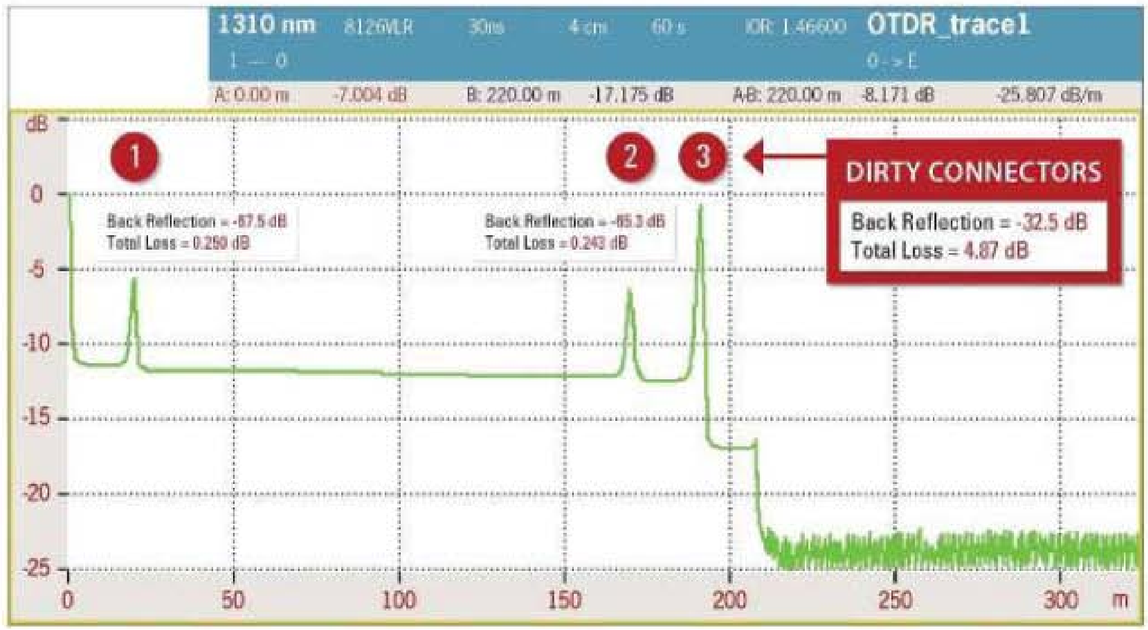
Do I Really Need to Clean the Fiber?

http://www.fols.org/fols_library/presentations/documents/brown.pdf

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

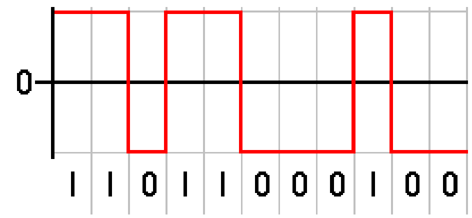
How Fast Does Light Travel In Fiber?

- 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 ~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 spools add extra distance too.

The Future of Optical Networking Technology

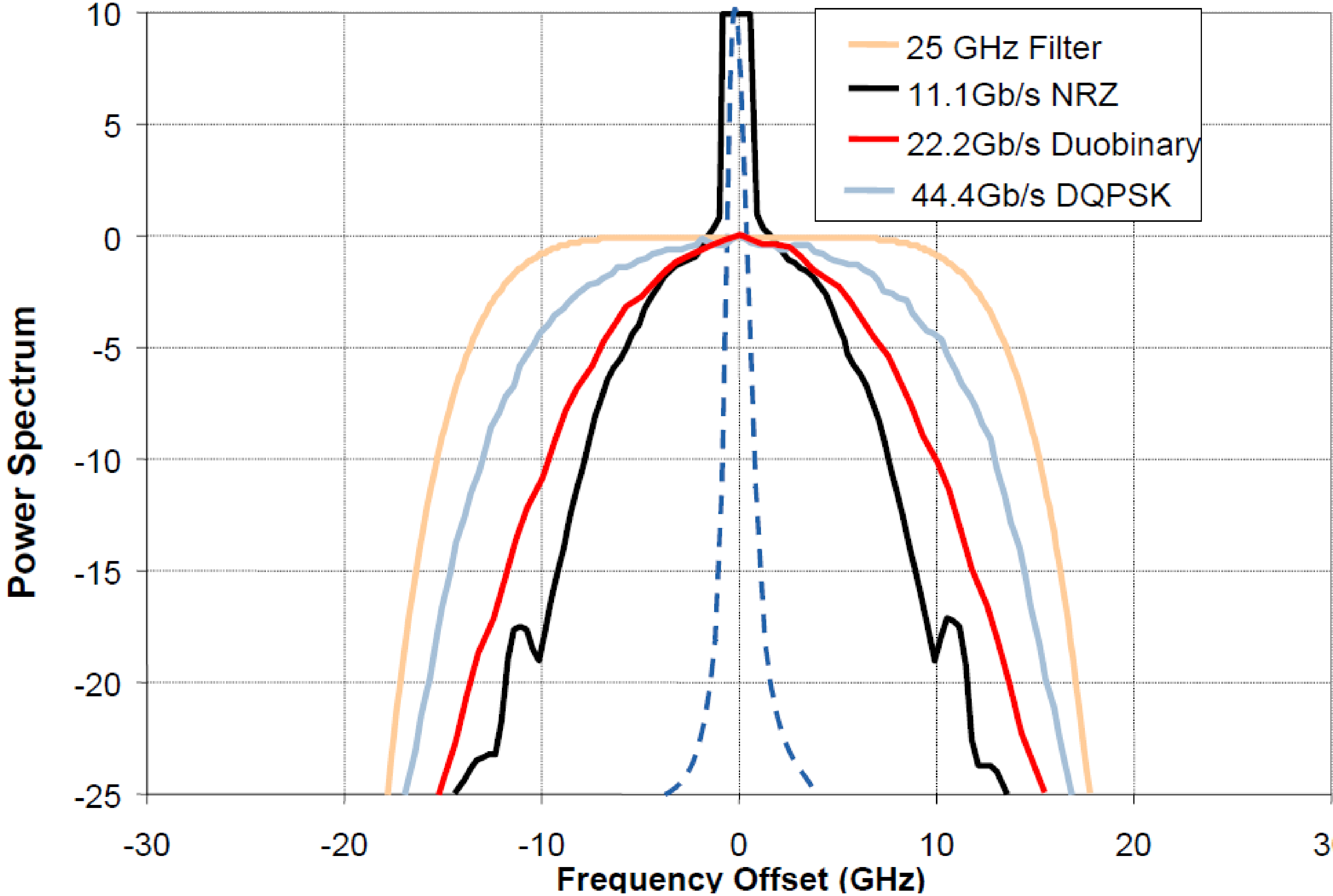
Better Modulation Techniques

- Classic systems use a relatively simple modulation
  - Called “Non-Return to Zero” (NRZ).
    - Each symbol encodes 1 bit worth of data.



- But there are other more efficient modulations
  - If we can’t signal faster, carry more data in each signal.
  - Some modulation schemes currently being adopted are:
    - Duo-binary
    - DPSK (Differential Phase Shift Keying)
    - DQPSK (Differential Quaternary Phase-Shift Keying)
  - For more information about alternative modulations, see:
    - http://www.stupi.se/Opinions/bbq4.pdf

Alternative Modulation Techniques



Alien Wavelengths

- “Normally” a DWDM system is run by a single entity.
  - I run DWDM on my fiber, but when I want to hand off to you I convert the signal to a “standard” 1310/1550nm first.
    - This presents obvious inefficiencies and added costs.
    - What if you could just talk to my fiber with your own DWDM signals?
- This concept is called Alien Wavelengths.
  - But without the standard->DWDM conversion layer, I no longer have control over what goes into my DWDM fiber.
    - As we discussed under amplifier management, not having consistent power levels can cause problems.
    - One channel could also inject enough light to harm other channels.
    - Many networks are looking for ways to safety implement support for alien wavelengths. In the future, this will become more popular.

Send questions, comments, complaints to:

Richard A Steenbergen ras@nlayer.net