Basic principles of fibre optic systems RIGA 29 sept

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WDM Services, Bit Rates

- Ethernet (10 Mb/s)
- IBM Token Ring (16 Mb/s)
- PDH E3 (34 Mb/s)
- DS3 / T-3, Frame Relay (45 Mb/s)
- SONET OC-1 (52 Mb/s)
- FDDI, Fast Ethernet (100 Mb/s)
- T-3D, DS3D (135 Mb/s)
- PDH E4 (140 Mb/s)
- ATM 155, STM-1, OC-3 (155 Mb/s)
- ESCON (200 Mb/s)
- Digital Video (266 Mb/s)
- PDH E5 (565 Mb/s)
- ATM 622, STM-4, OC-12 (622 Mb/s)
- Fibre Channel, FICON, Coupling Link (1.062 Gb/s),
- Gigabit Ethernet, OC-24 (1.25 Gb/s)
- SCSI (max. 1.28 Gb/s)
- HDTV (1.485 Gb/s)
- 2Gb Fibre Channel (2.124 Gb/s)
- ATM 2.5G, STM-16, OC-48 (2.5 Gb/s)
- 4Gb Fibre Channel (4.248 Gb/s)
- STM-64, OC-192, 10GbE (10 Gb/s)
- STM-256, OC-768 (40 Gb/s)

Fibers

Bit-Rate × Length Product

- The Bit-Rate × Length Product ($R_B \times L$) is a convenient measure for the maximum capacity of either fibers or transmission techniques
- $R_B \times L$ can be used for a ranking of fiber types, or transmission techniques – different fiber types and all transmission constraints can be considered
- $R_B \times L$ is the ***maximum*** product of bit-rate R_B and regenerator-less link length L
- **L depends on R_B !!!** (or vice versa)

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Fiber vs. Copper

- Bandwidth vs. Transmission distance
  - VDSL may provide up to ~50 Mb/s at 1 km
  - Fiber’s theoretical limit is in the 25 Tb/s range, the max. regenerator-less link length is several 1000 km
- Environmental stability
  - Copper affected by environment from the moment of installation
  - Optical signals not affected by ambient electrical noise (EMI)
- Glass is a dielectric
  - Virtually eliminates shorting and lightning hazards
- Security
  - Optical signals difficult to “tap” without detection

Fiber Types I

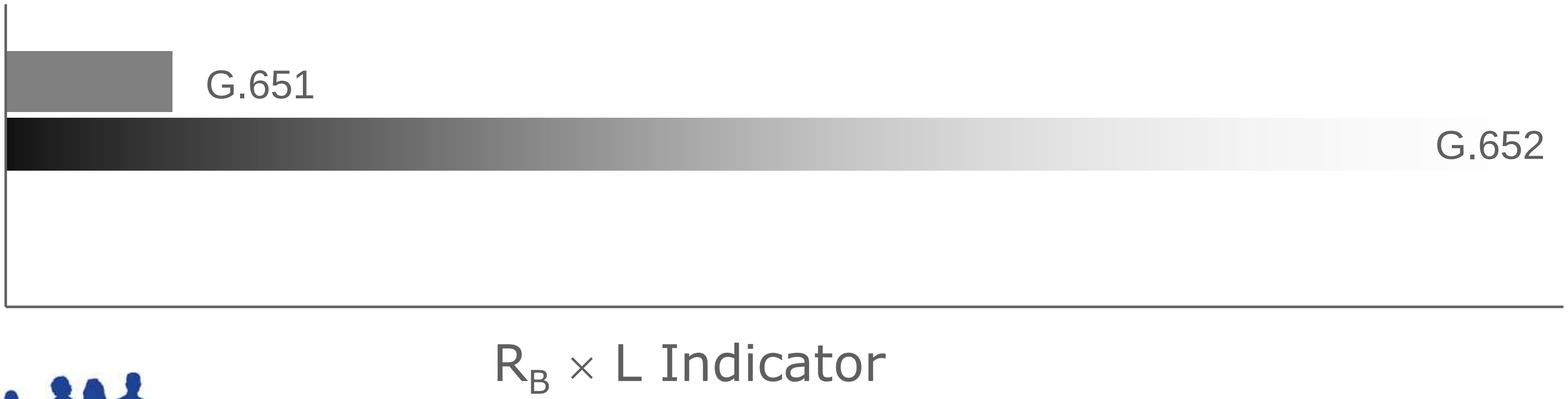
Graded-Index Multi-Mode Fiber

- ITU-T G.651
- Improved Multi-Mode fiber
- Reduces Mode Dispersion through graded refractive index
- Still in use for some LAN applications, e.g. GbE

Fiber Types II

Standard Single-Mode Fiber (SMF)

- ITU-T G.652
- Optimized for (single-channel transmission at) 1310 nm by eliminating dispersion at 1310 nm
- Dispersion at 1550 nm is much greater than at 1310 nm
- Suitable for DWDM transmission at 1550 nm
- Most common fiber deployed today



Fiber Types III

Dispersion Shifted SM Fiber (DSF, DSSM Fiber)

- ITU-T G.653
- Zero dispersion shifted from 1310 nm to 1550 nm
- Great for single channel 1550 transmission at high data rates
- Breeding ground for Four-Wave Mixing –
  Not suitable for high data rate DWDM over long distances

$R_B \times L$ Indicator

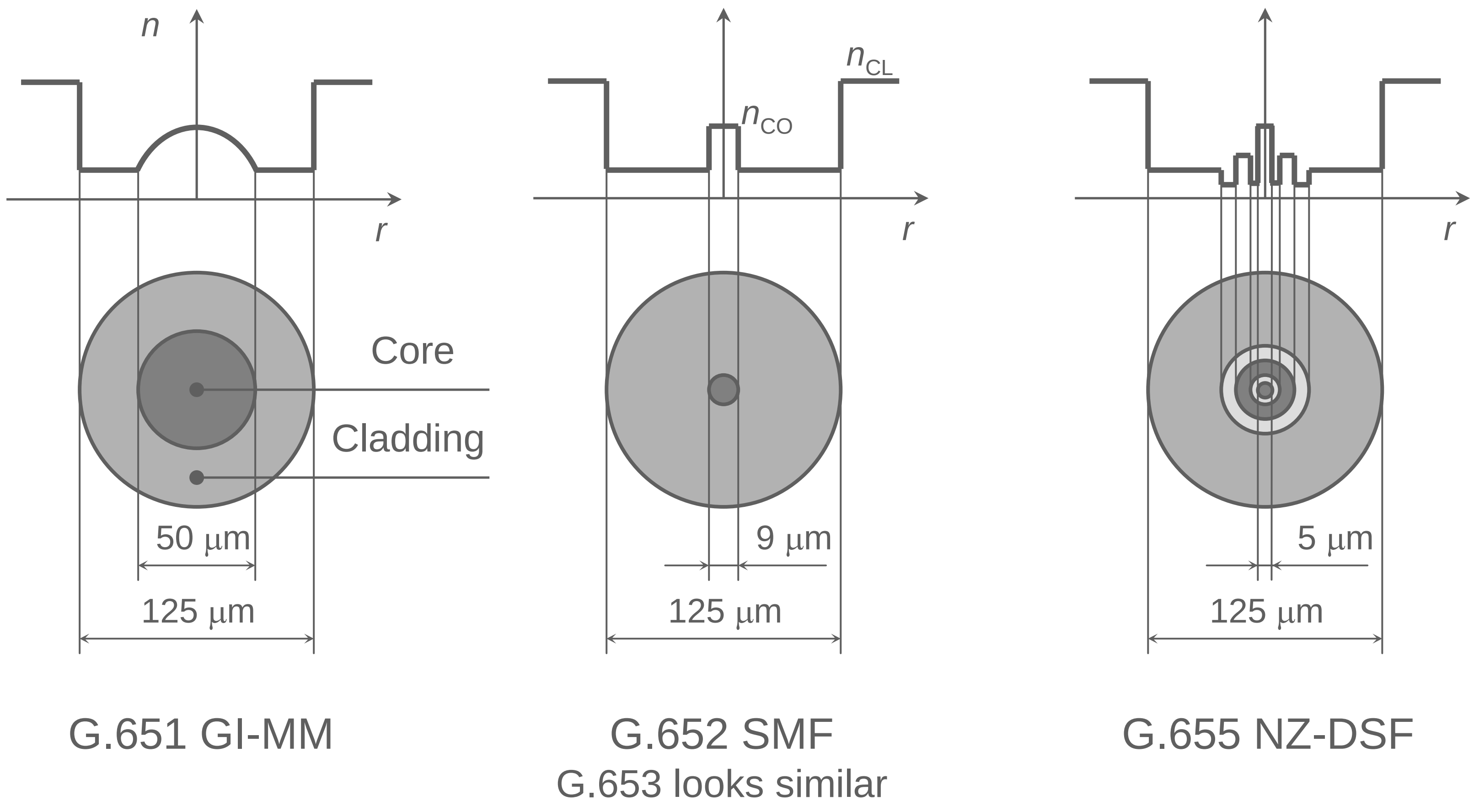
Fiber Types IV

Non-Zero Dispersion Shifted SM Fiber (NZ-DSF)

- ITU-T G.655
- Examples: Corning E-LEAF®, Lucent TrueWave-RS®
- Developed specifically for DWDM
- Compromise between no dispersion for high data rates and enough dispersion to combat FWM
- New fiber or choice for new installations

$R_B \times L$ Indicator

Refractive Index Profile



Weakly guiding single-mode fibers: $n_{CO} \approx n_{CL} \approx 1.45$

Transmission Constraints

Transmission Constraints

Linear and non-linear Effects:

- Linear
  - Attenuation
  - Mode Dispersion, if applicable
  - Chromatic Dispersion
  - Polarization-Mode Dispersion, PMD

- Non-linear
  - Self-Phase Modulation, SPM
  - Cross-Phase Modulation, XPM
  - Four-Wave Mixing, FWM
  - Stimulated Raman-Scattering, SRS
  - Stimulated Brillouin-Scattering, SBS

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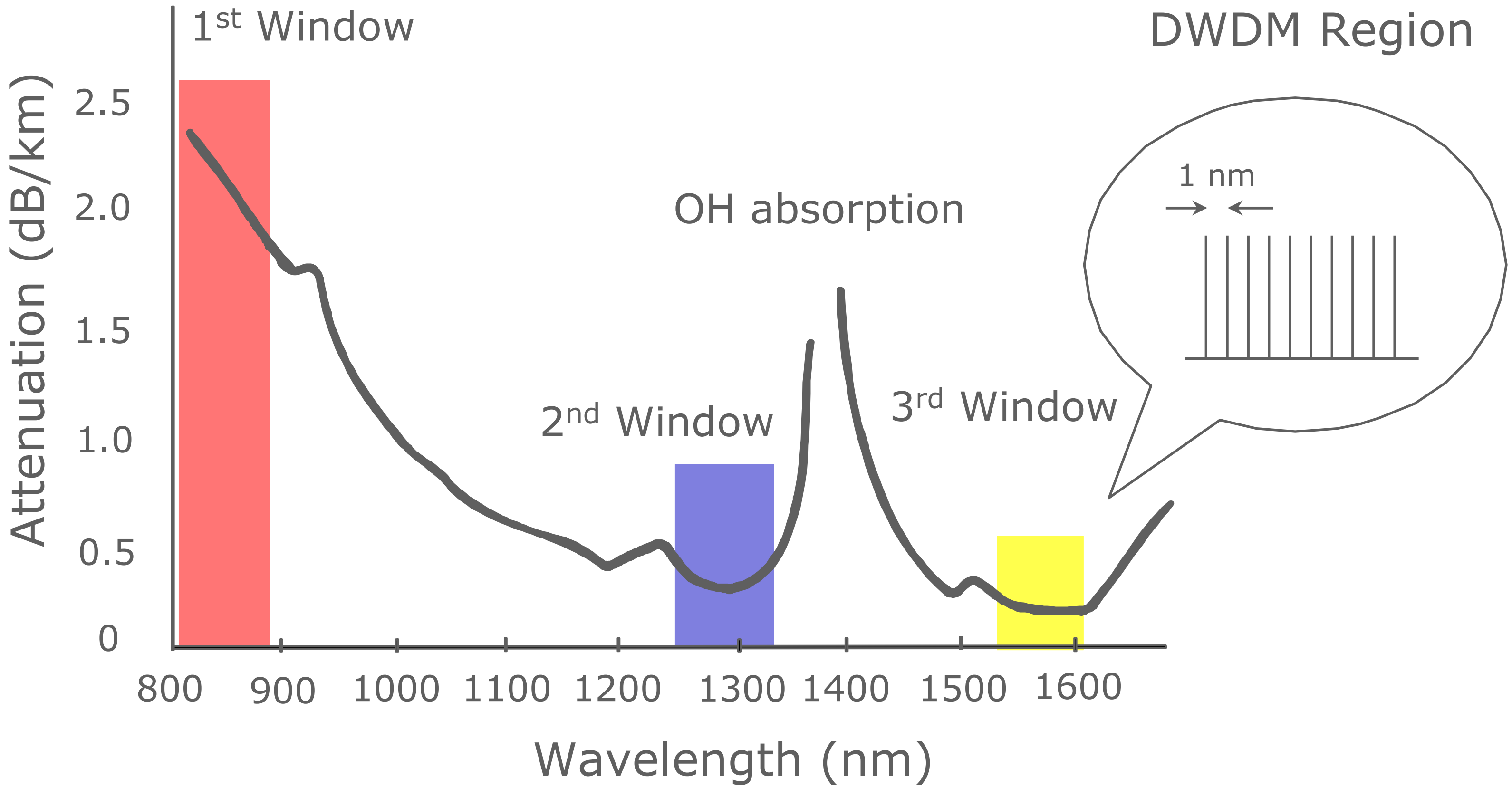
Attenuation



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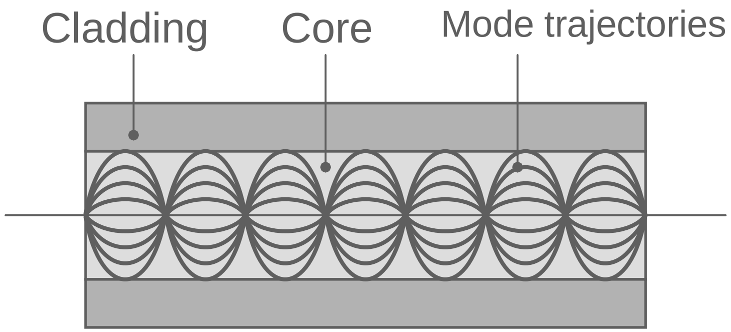
Attenuation

- Signals are attenuated by
  - Rayleigh Scattering (towards shorter wavelengths)
  - Infra-Red Absorption (towards longer wavelengths)
  - Fiber bends for bend radii < 10 mm
  - Micro-Bending, induced by cabling
  - (Connectors)
  - (Splices)
- Attenuation can be compensated by (optical) amplifiers
- Attenuation leads to bit errors through decreased Signal/Noise Ratio (SNR), where noise sources are either receiver electronics, or optical amplifiers

Attenuation

- Attenuation of SMF
  - a = 0,35...0,50dB/km @ 1300nm
  - a = 0,18...0,25dB/km @ 1550nm, industry typical 0.21 dB/km

Mode Dispersion

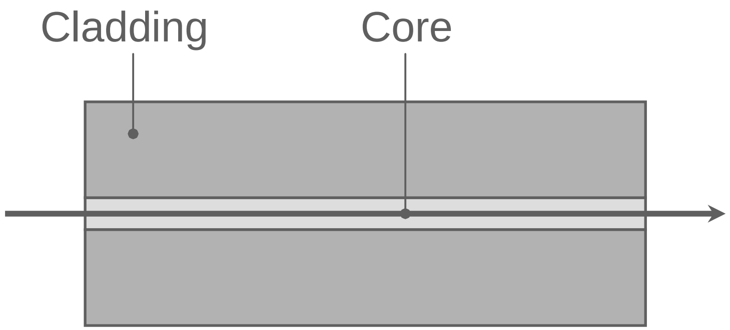


Graded-Index Multi-Mode G.651

Light transmission through refraction

Mode Dispersion ~1 ns/km

$B \times L = 1\ \text{GHz} \cdot \text{km}$



SMF G.652, G.653, G.655

Transmission through wave guidance

No Mode Dispersion

$B \times L > 100\ \text{THz} \cdot \text{km}$

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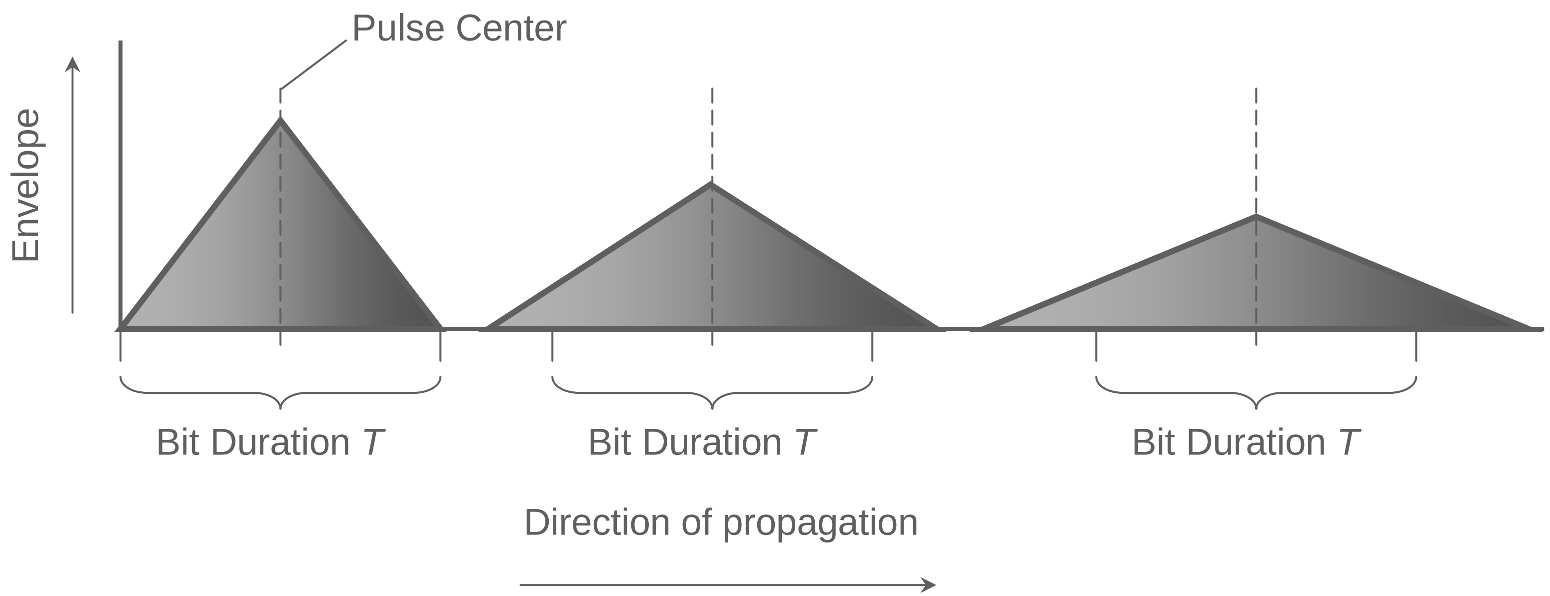
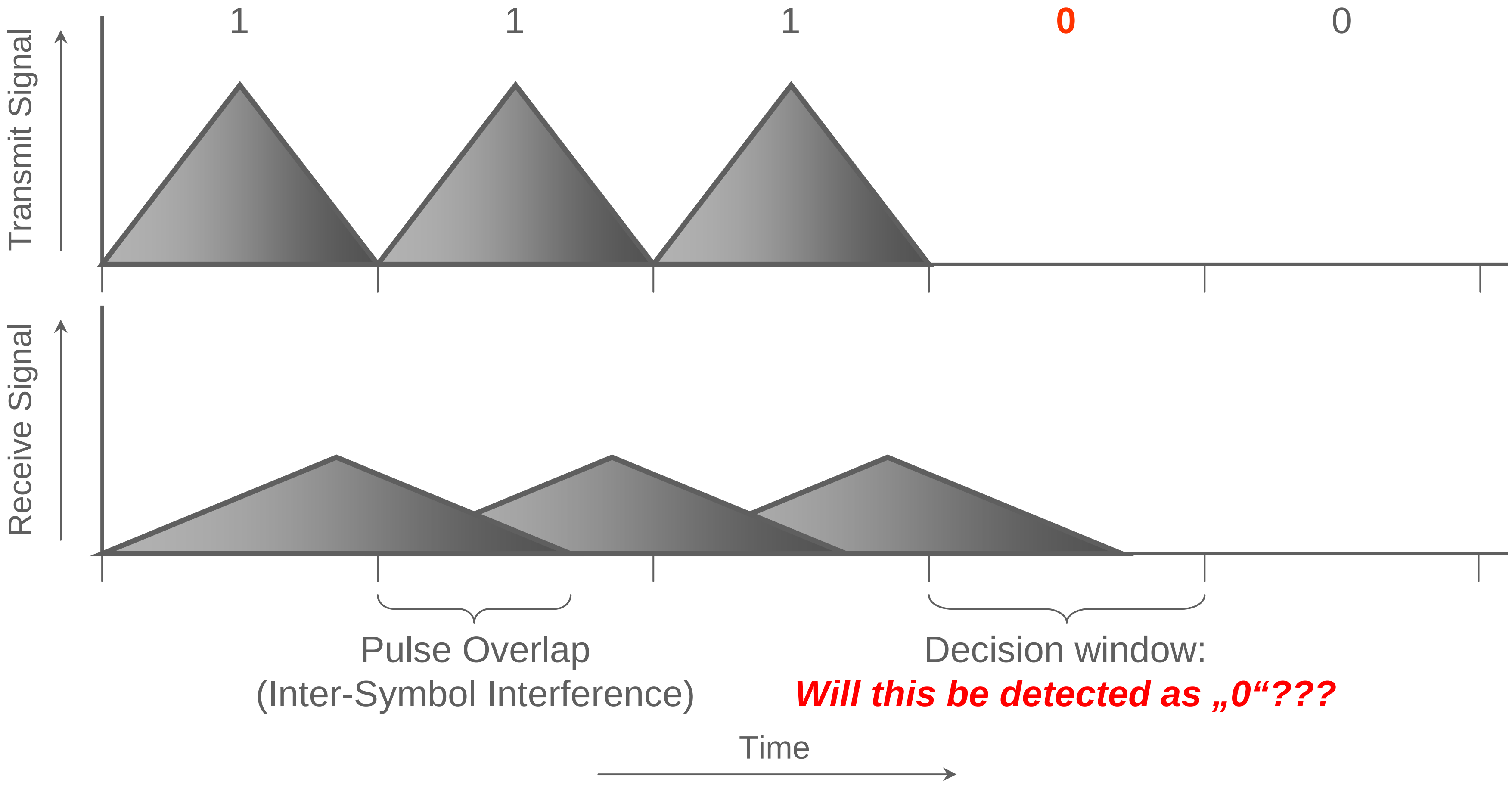
Effect of Dispersion

- All dispersion effects cause pulse spreading
- This leads to pulse overlap and consequently bit errors
- Dispersion (chromatic, PMD) can partly be compensated



Effect of Dispersion



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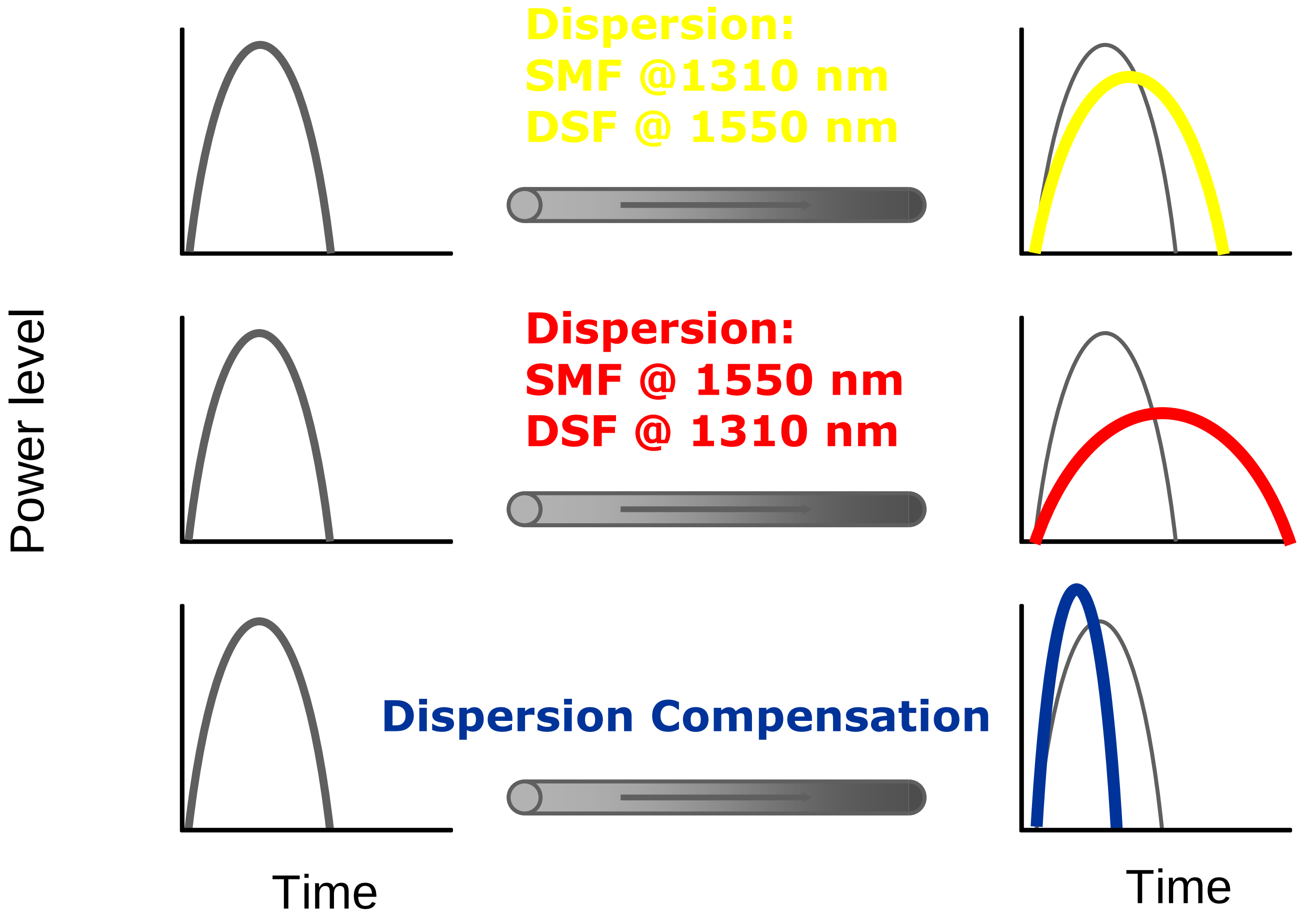
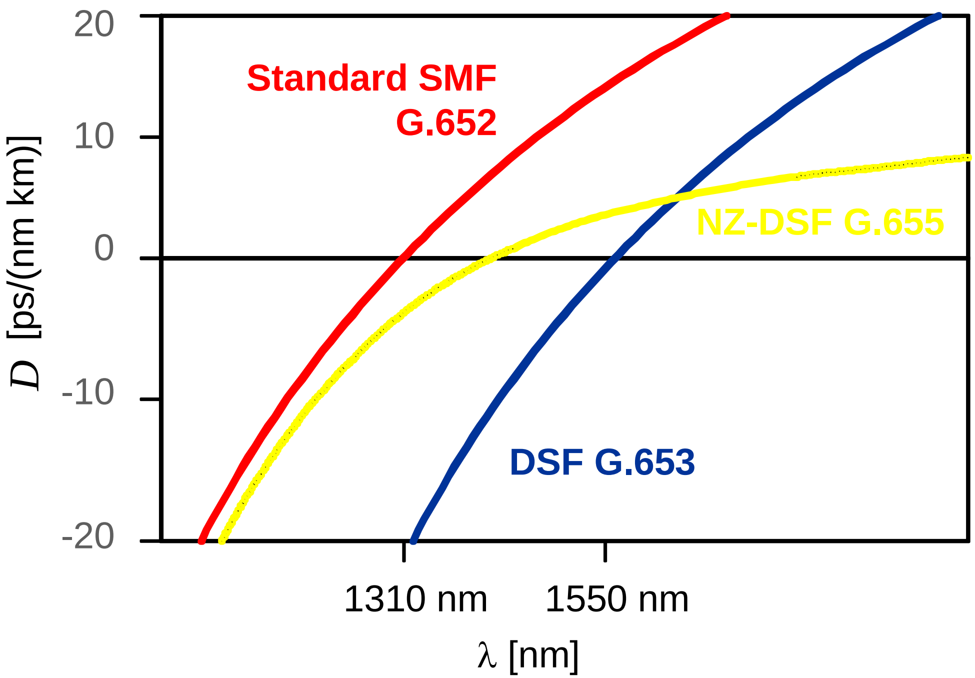
Chromatic Dispersion



Chromatic Dispersion

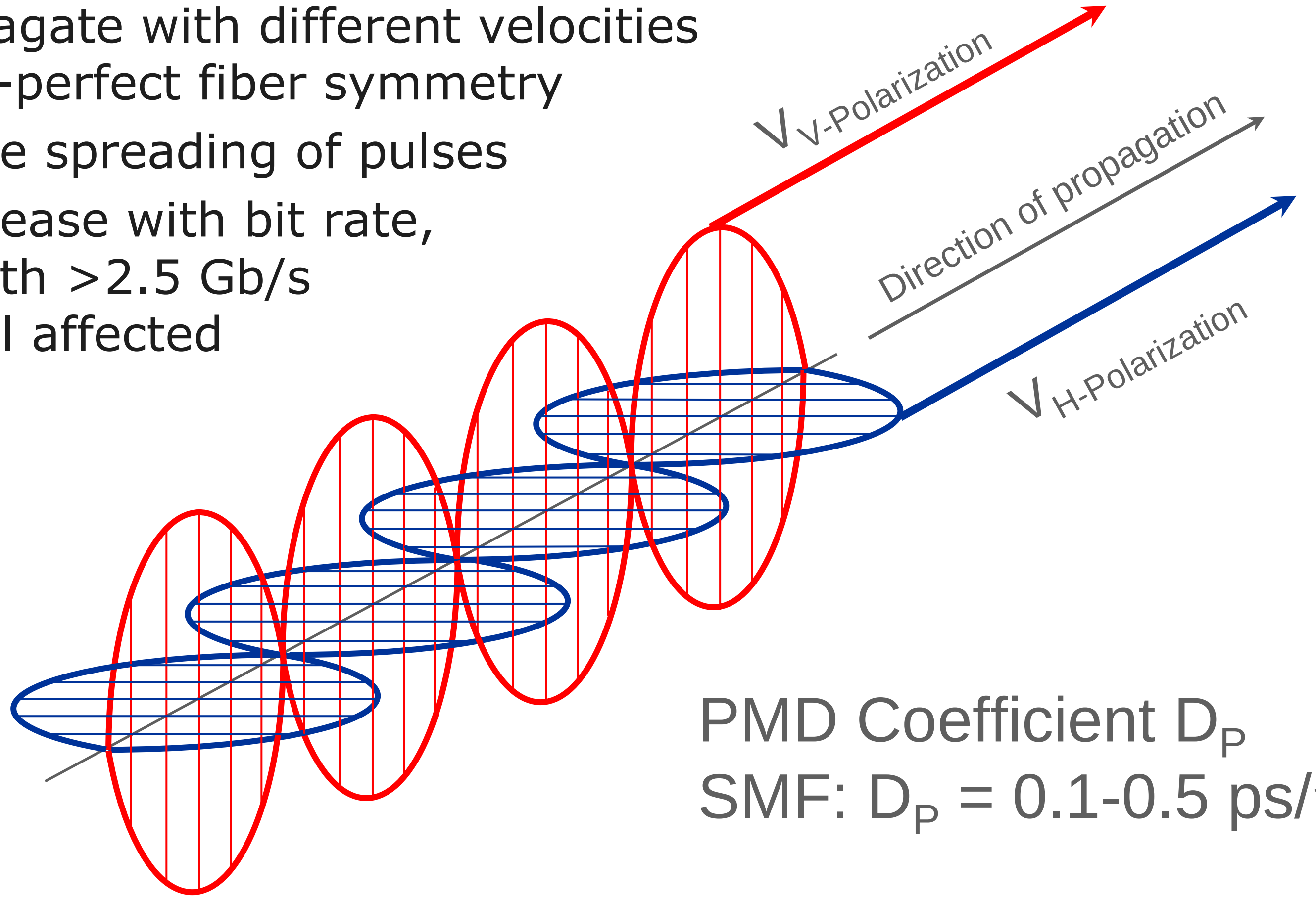
Chromatic Dispersion is described by the Dispersion Parameter ***D***



D states pulse spreading per link length and per bandwidth

Polarization-Mode Dispersion

- Two orthogonal Polarization Modes in SMFs, these propagate with different velocities due to non-perfect fiber symmetry
- Causes time spreading of pulses
- Strong increase with bit rate, systems with >2.5 Gb/s per channel affected



PMD Coefficient D_P

SMF: D_P = 0.1-0.5 ps/√km

Dispersion Compensation

- Dispersion Compensation is necessary for channel bit-rates of >2.5 Gb/s and regenerator-less link lengths of >50 km (e.g. >800 km @ 2.5 Gb/s or >50 km @ 10 Gb/s)

- **Chromatic dispersion** can easily be compensated by means of compensation fibers (change sign of *D* parameter or other dispersive components like Bragg grating fibers

- **PMD** must be considered for systems carrying 10 Gb/s per wavelength or more. Due to its statistical nature it is more difficult to compensate, however compensators based on turnable fiber curls exist…in practise more or less in labs

Fiber Non-linearity

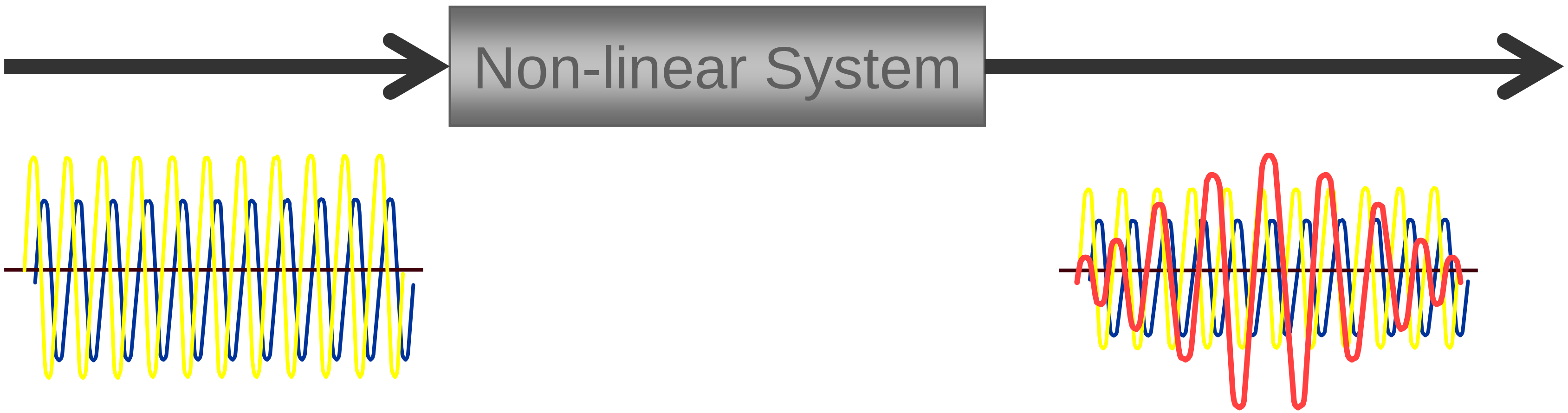
Non-linearity means that new spectral components – noise signals! – can potentially be generated

Input:

$A_1 \cdot g_I(f) + A_2 \cdot g_I(f)$

Output:

$B_1 \cdot g_O(f) + B_2 \cdot g_O(f) + \text{Noise}(f)$



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Non linear effects

Various effects caused by-

-Too high powers

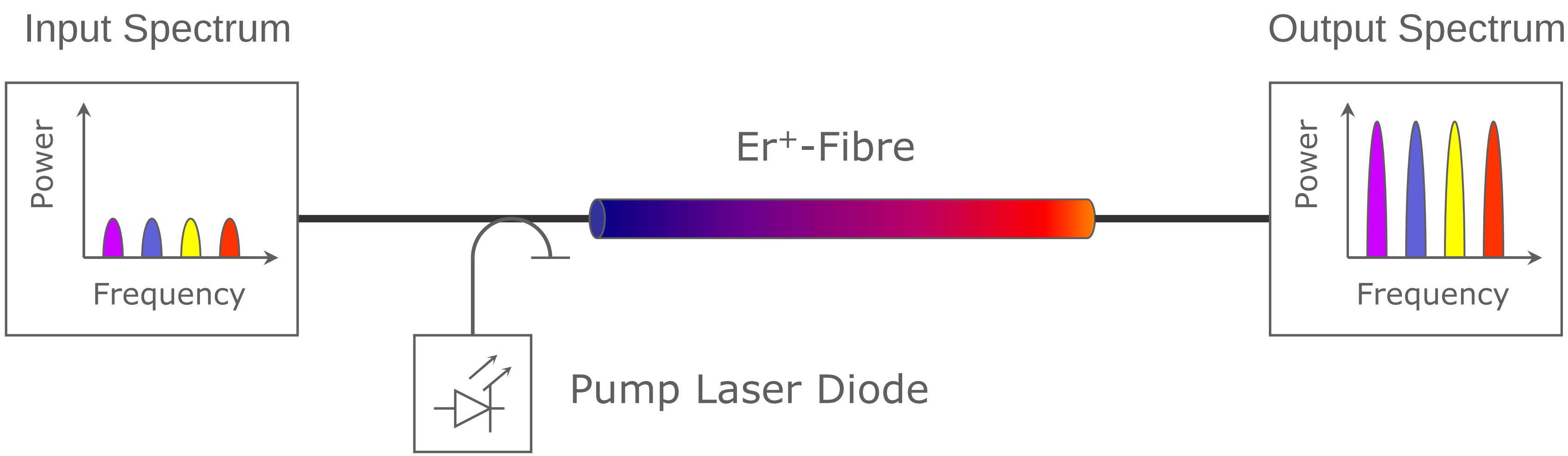
-Not enough dispersion!

Important to realize you cannot do everything in WDM system-and that it is an analogue system!

EDFAs

EDFA Principle

- Based on Er^+-doped fibers
  - Erbium well-suited for 3rd optical window around 1550 nm
  - Erbium leads to very efficient amplifier design
- Traveling-Wave Laser amplifier
- Pump Laser needed for energy supply (980 nm, 1480 nm)



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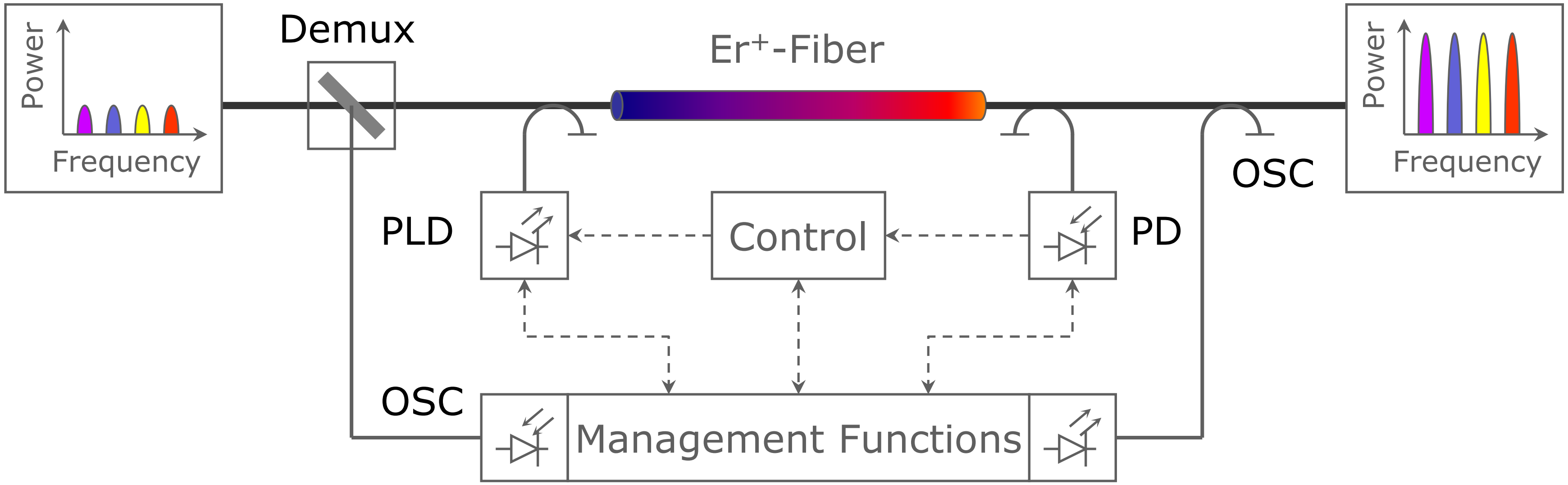
EDFA Characteristics

- Ultra-broadband amplification:
  - ~1530 – 1570 nm (C-Band, ~5 THz)
  - ~1570 – 1610 nm (L-Band, ~5 THz)

- High (small) signal gain, up to 35 dB
- High output power, up to +20 dBm
- Transparent for bit-rate, protocol
- EDFA tilt-important to control (Different amplification at different wavelengths)
- Can lead to crosstalk between WDM channels
  - Power control necessary
  - Cost driver

EDFA Management

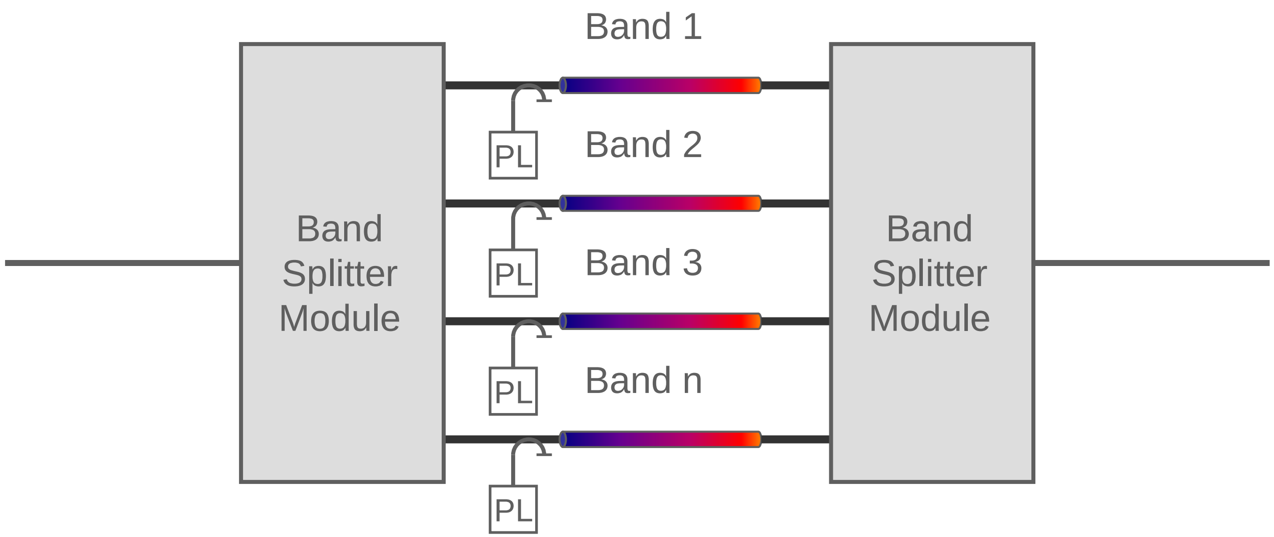
- Multi-channel EDFAs need power control
- In-Line EDFAs need supervisory channel



OSC: Optical Supervisory Channel PD: Photo Diode PLD: Pump Laser Diode

Sub-Band EDFAs

- One EDFA per Sub-Band
- In-Line amplifier needs band splitter
- No power level control necessary
- More robust against channel failures
- Flexible link design possible



WDM

What is WDM?

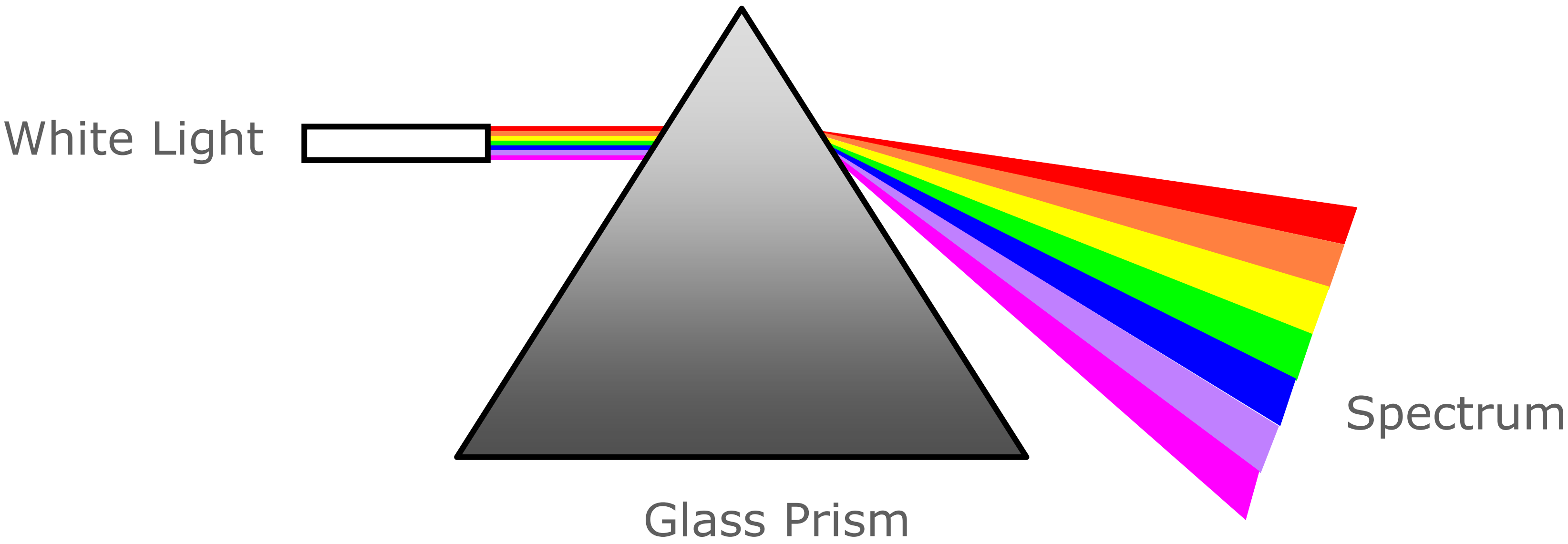
- WDM means ***Wavelength Domain Multiplexing***
- It is Frequency Domain Multiplexing at optical frequencies (~200 THz)
- It can be divided into
  - Dense WDM (DWDM), 200, 100, 50 GHz grid)
  - Coarse WDM (CWDM), channel spacing >> channel bandwidth (e.g. channels at 1470 nm, 14900 nm, …1550 nm,… 1610nm)
    - 8 channels with G652 waterpeak fibre-16 ch with lo/no water peak
    - Funny tricks-you can do 1310 at same time as you do 1550 CWDM..

WDM History

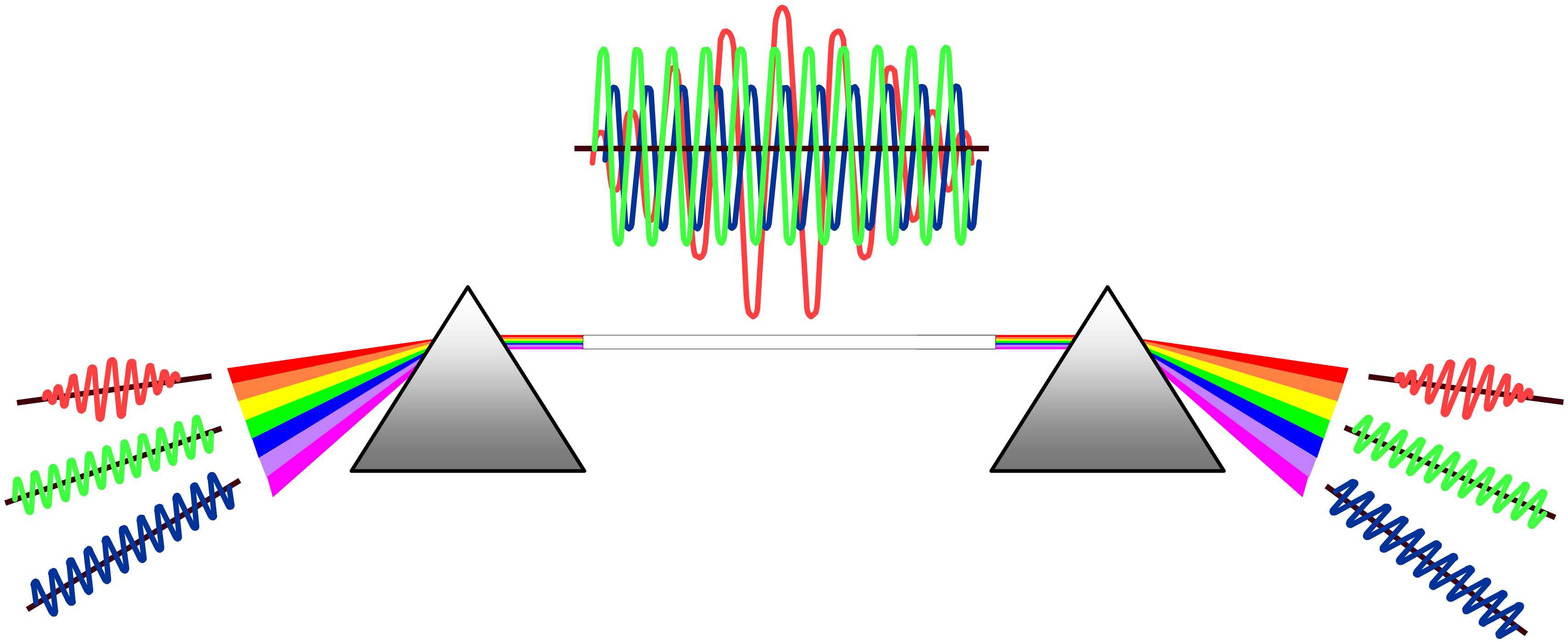
- Early 80's
  - AT&T used dual wavelength CWDM in experiments on Trans-Atlantic cable
- Mid 80's
  - Dual wavelength CWDM in commercial use
  - Field trials Sweden 1987
- 1986
  - EDFA invented
- Early 90's
  - First commercial deployment of DWDM systems-CIENA
- Mid 90's
  - Non-Zero Dispersion Shifted Fiber for long-haul multi-channel transmission
- 2000- 320 *10Gb/s (12.5 GHz) demonstrated
  - ...9/11 killed the real "macho systems"
- 2003 onwards-much more pragmatic approach to whats commercuially feasible

Optical Networking

School Physics Lesson



If we have one at each end...



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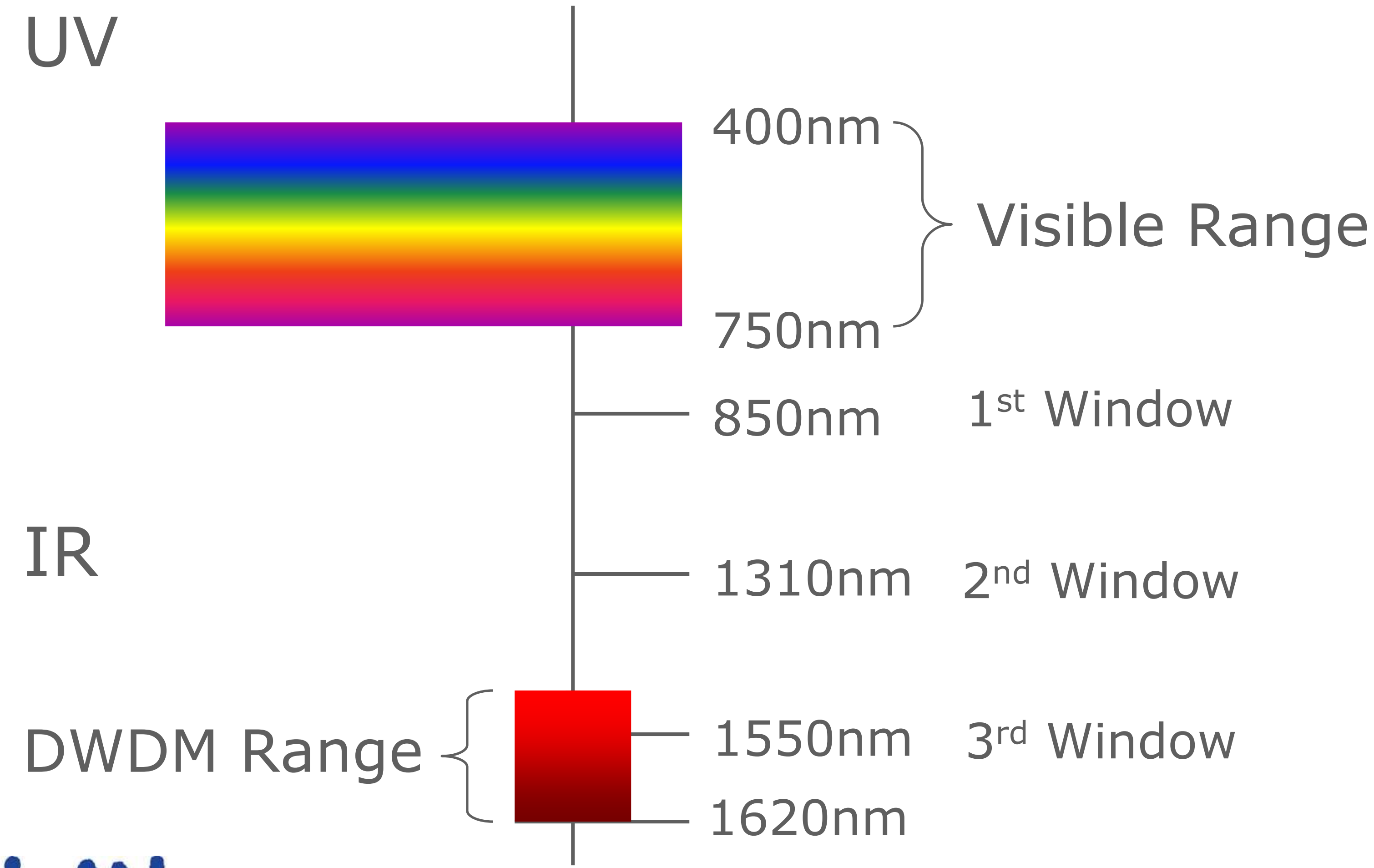
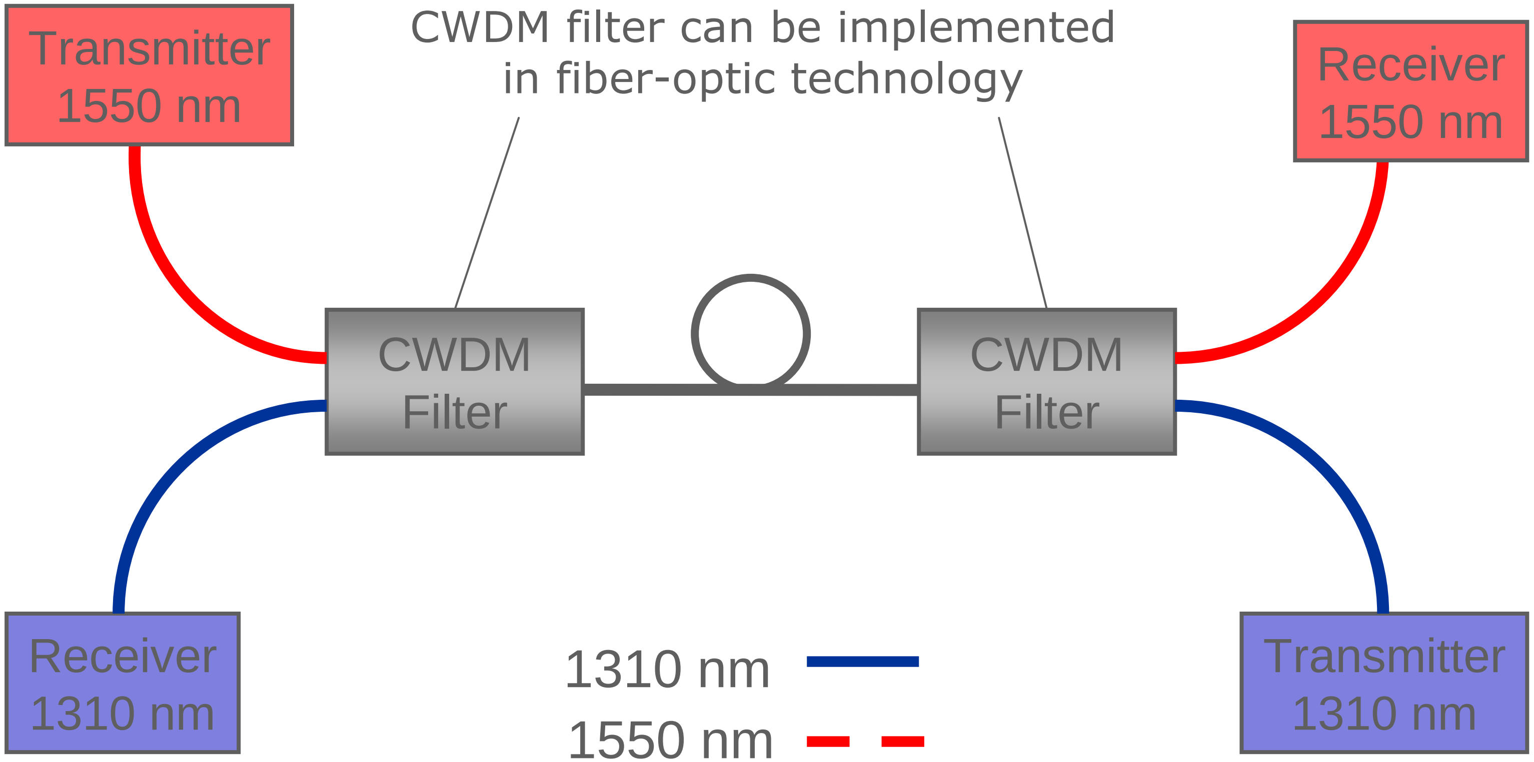
Optical Wavelengths

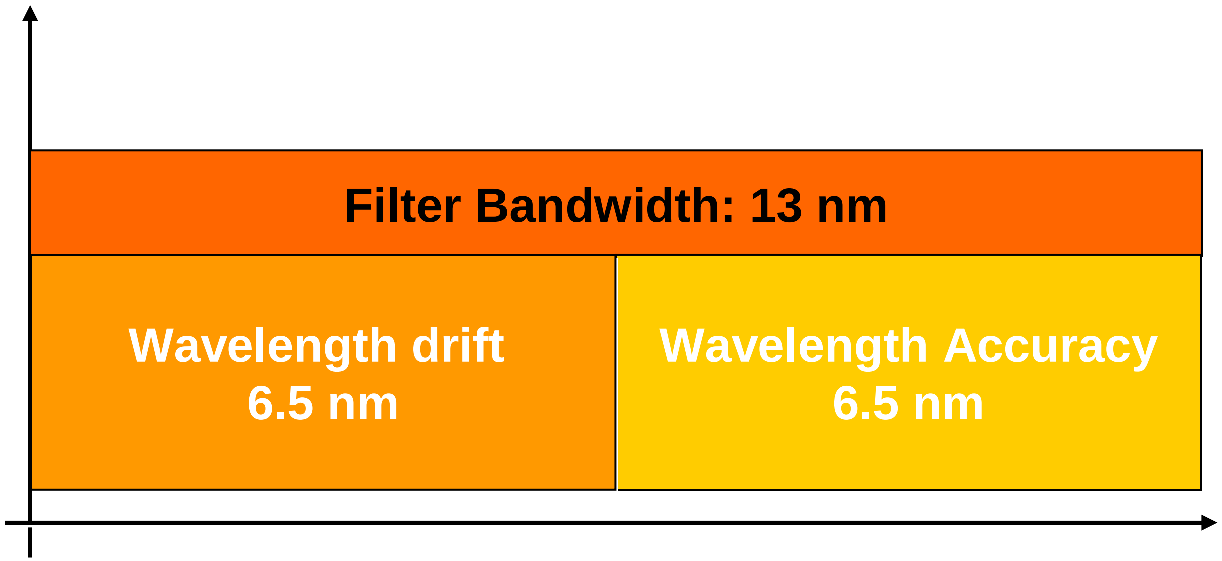


CWDM


Transmitter
1550 nm
CWDM filter can be implemented
in fiber-optic technology
Receiver
1550 nm
CWDM
Filter
CWDM
Filter
Receiver
1310 nm
1310 nm
1550 nm
Transmitter
1310 nm

Why is CWDM such great idea
Wavelength budget

- Standard CWDM filter bandwidth = 13 nm
- Filter bandwidth is allocated between
  - Nominal laser wavelength accuracy
  - Laser wavelength drift



Wavelength budget has implications for laser cost

Wavelength drift due to temperature

- DFB laser wavelength drift: 0.1nm/^{o}C
- Laser operating temperature range: -5 to 60^{o}C
- Total wavelength drift: 6.5 nm
- Lasers do not need temperature control
- Eliminates the need for TEC in laser package

Absence of TEC reduces packaging cost & power consumption

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Cost and power savings on CWDM lasers compared to DWDM devices

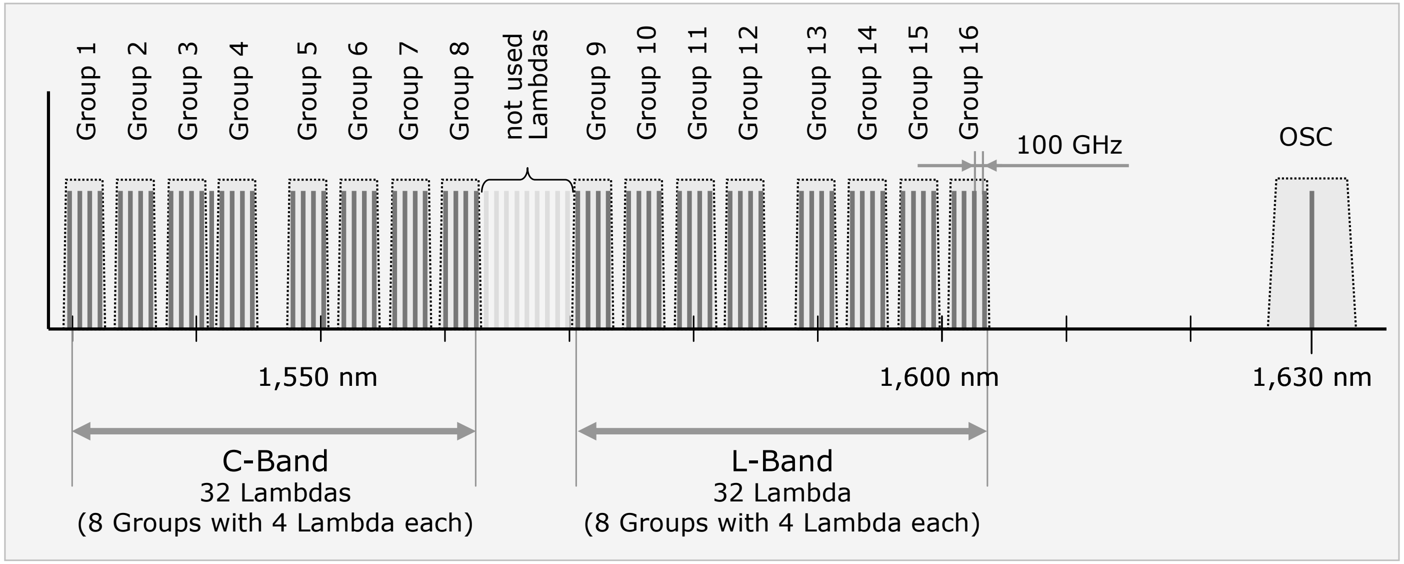
- Total cost savings on laser: ~ 50 %

- Power savings
  - Power consumed by DWDM laser: ~5W
  - Power consumed by CWDM laser: ~0.25W
  - Consider an 8 channel system
    - Power consumed by DWDM lasers: up to 40W
    - Power consumed by CWDM lasers: 2W

- But it really only works below 5 GB/s

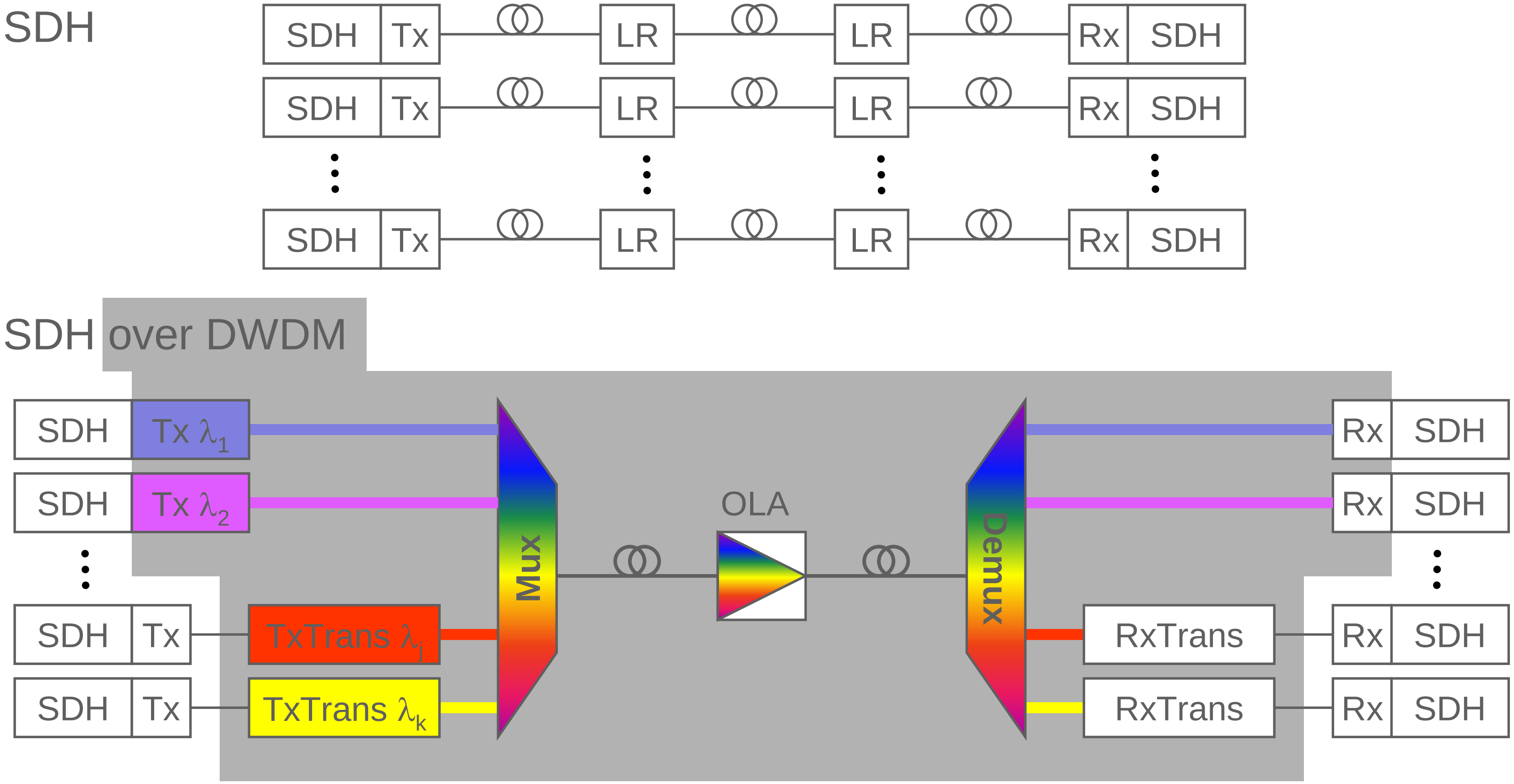
DWDM

Example wavelength grid
32 ch in C-Band, 32 ch in L-band-OSC signal to control amplifiers at 1630 nm



Note- C-band is always cheaper than L-band

Multiple SDH vs. DWDM



TxTrans:	Transmit Transponder
RxTrans:	Receive Transponder
OLA:	Optical Line Amplifier
Mux:	DWDM Multiplexer
Demux:	DWDM Demultiplexer
LR:	SDH Line-Repeater

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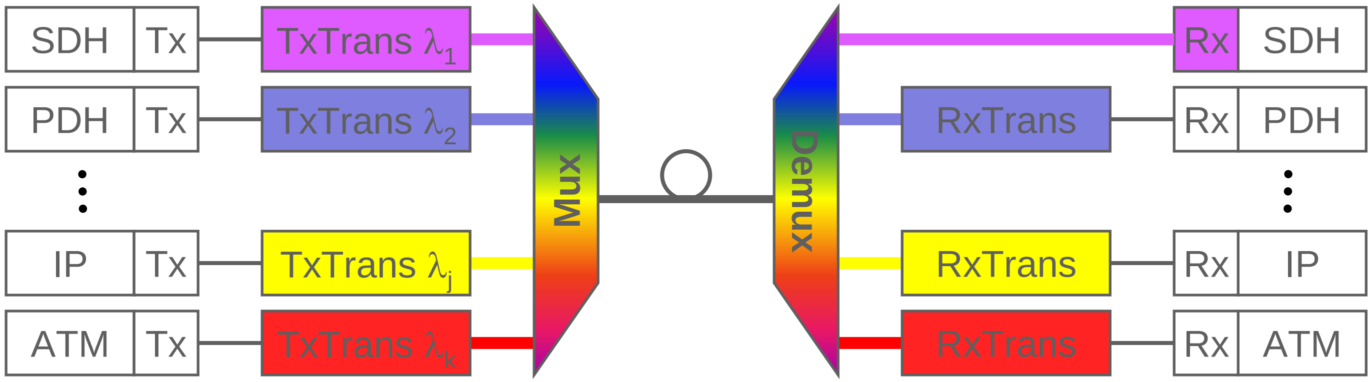
Transponders



- Conversion to ITU-T G.692 wavelength grid in C- and L-Band
- Accepts input at 850, 1310 & 1550 nm (GaAlAs photo diodes)
- Legacy SDH and even PDH equipment can further be used
- All network protocols over same media!!!

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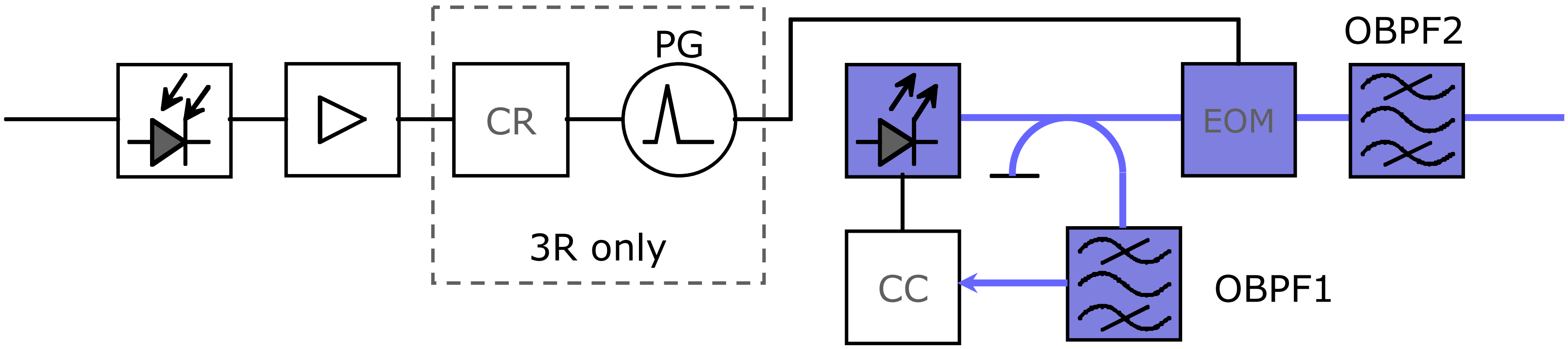
Transponders

2R / 3R Transmit Transponder



CR: Clock Recovery
EOM: External Optical Modulator-Disappearing
CC: Control Circuit
PG: Pulse Generator
OBPF1: Wavelength Locker-gone for 100GHz
OBPF2: Pulse Shaping

Transmit Transponders

Input interface

- Interoffice
- Short-haul
- Long-haul

Functionality

- Non-SDH
  - transparent (2R)
  - transparent (3R)
  - transparent, multi-clock
  - Digital Wrapper
  - FEC (Coder)
- SDH / SONET
  - transparent (2R)
  - transparent (3R)
  - B1 / J0 monitoring
  - FEC (Coder)

Output interface

- Long-haul
- Very-long-haul
- Ultra-long-haul

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Receive Transponders

Input interface

- Long-haul
- Very-long-haul
- Ultra-long-haul

Functionality

- Non-SDH
  - transparent (2R)
  - transparent (3R)
  - transparent, multi-clock
  - Digital (De-) Wrapper
  - FEC (Decoder)
- SDH / SONET
  - transparent (2R)
  - transparent (3R)
  - B1 / J0 monitoring
  - FEC (Decoder)

Output interface

- Interoffice
- Short-haul
- Long-haul

Filters

- Bragg gratings
  - Can be implemented by fiber optics (piece of fiber becomes Bragg grating through UV Laser treatment)
  - Temperature sensitive, need control circuit
  - Excellent selectivity

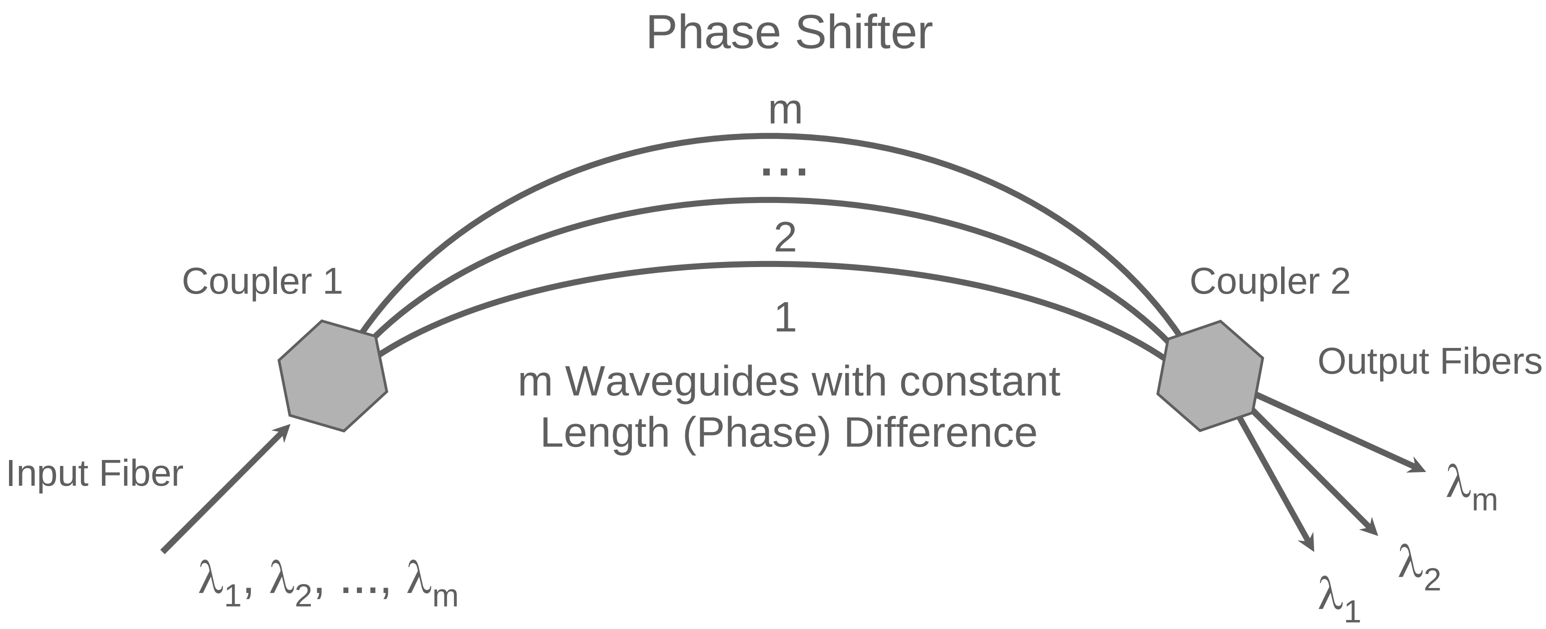
- Thin film
  - Discrete optics
  - Environmentally stable “prisms”
  - Good selectivity

- Arrayed Waveguide grating
  - Can be integrated
  - Thin-film technology
  - Moderately environmentally stable

Filter Types

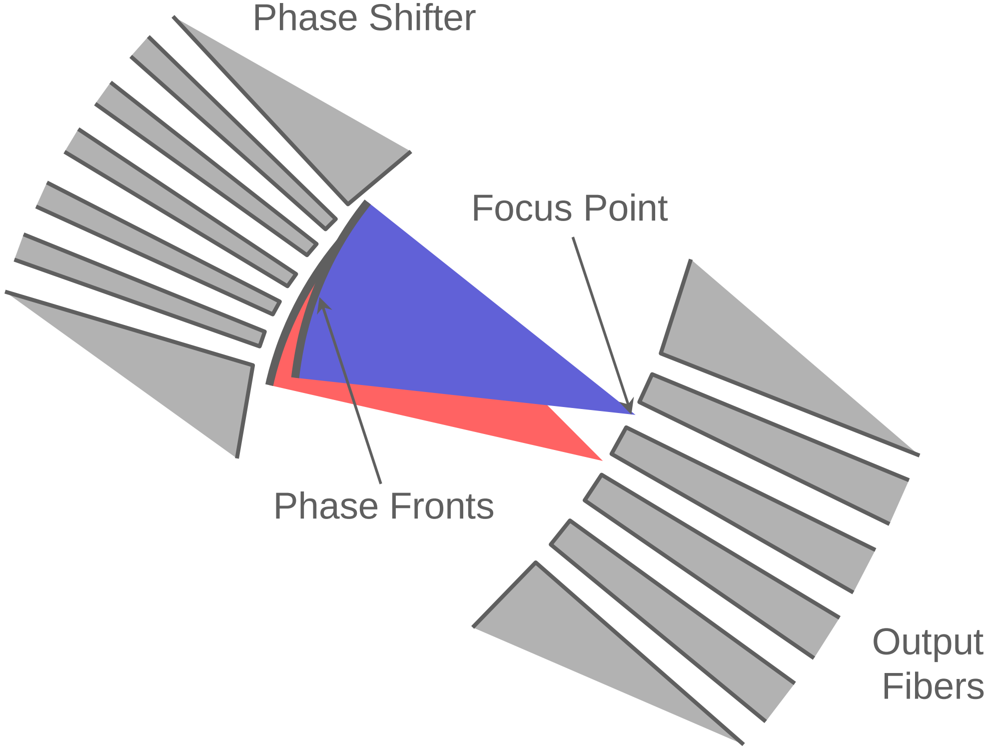
Parameter	Unit	**Arrayed Waveguide Grating**	**Dielectric Filters**	**Fiber Bragg Grating**	**Hybrid Bragg Grating / Filter**
Channel Spacing	GHz	200 / 100 / 50	400 / 200 / 100	200 / 100 / 50	200 / 100 / 50
Insertion Loss	dB	moderate	low	high	moderate
Bandwidth @ -0.5 dB	Nm	narrow	broad	broad	Broad
Bandwidth @ -25 dB	Nm	broad	broad	narrow	Narrow
Sidelobe Suppression	dB	moderate	high	high	High
Passband Ripple	dB	moderate	high	low	Low
Adjacent Channel XT	dB	low	low	very low	very low
Non-adjacent Channel XT	dB	low	very low	very low	very low
PDL	dB	high	low	low	low

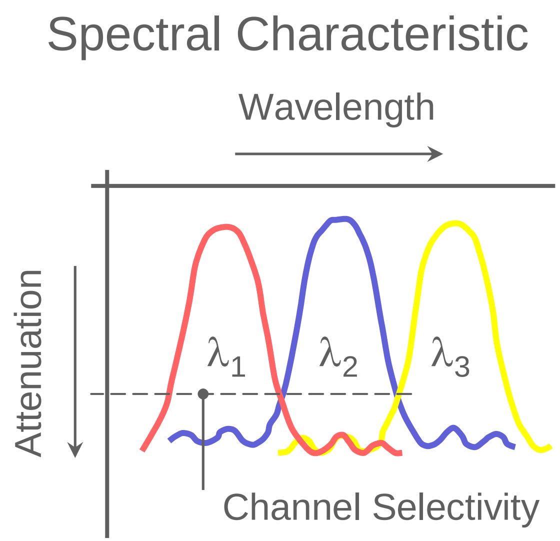
Arrayed Waveguide Filter



- Thin-Film waveguide technology
- Multiplexing / Demultiplexing by constructive and destructive interference of phase-shifted signals

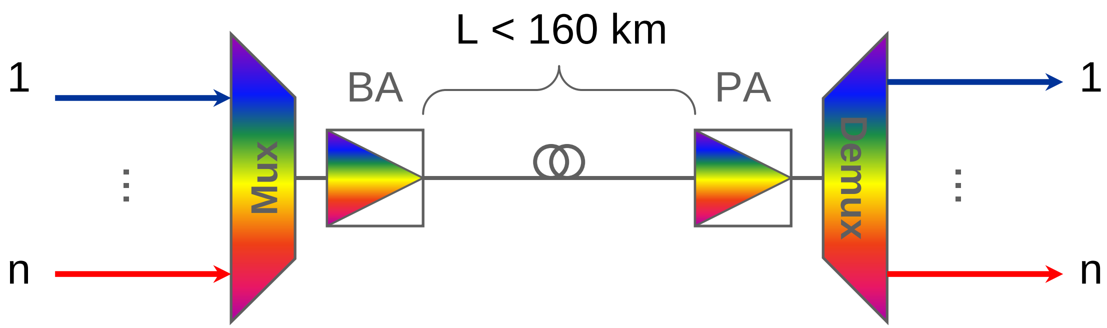
Arrayed Waveguide Filter





DWDM Single-Span

G.692 DWDM Point-to-Point Applications				
Single-Span, long-haul	Single-Span, very long-haul	Single-Span, ultra long-haul	Multi-Span, long-haul	Multi-Span, very long-haul
1 x 80 km	1 x 120 km	1 x 160 km	max. 8 x 80 km	max. 5 x 120 km

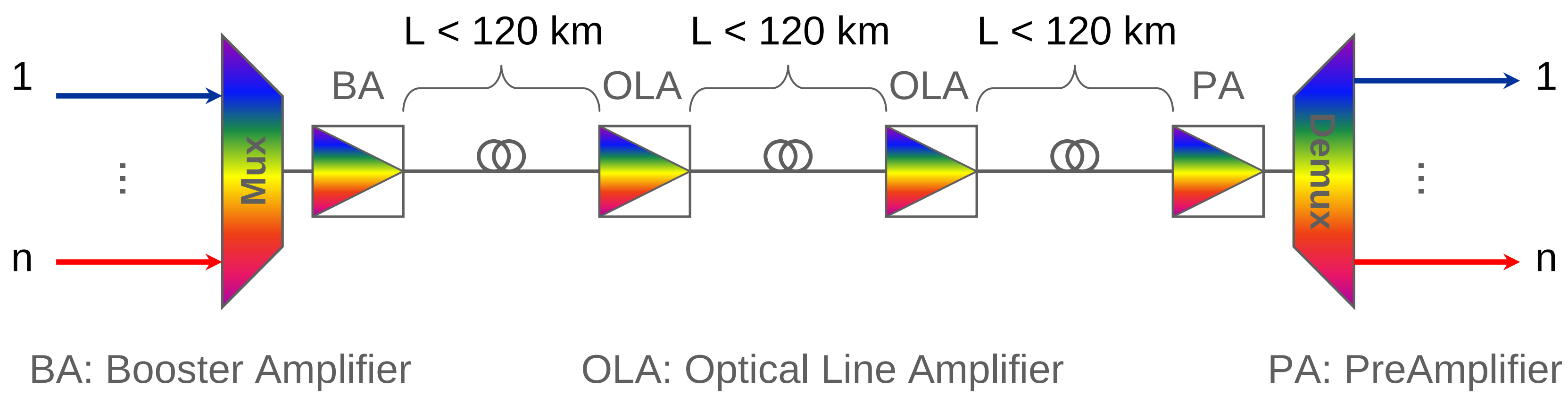


BA: Booster Amplifier

PA: PreAmplifier

DWDM Multi-Span

G.692 DWDM Point-to-Point Applications				
Single-Span, long-haul	Single-Span, very long-haul	Single-Span, ultra long-haul	Multi-Span, long-haul	Multi-Span, very long-haul
1 x 80 km	1 x 120 km	1 x 160 km	max. 8 x 80 km	max. 5 x 120 km



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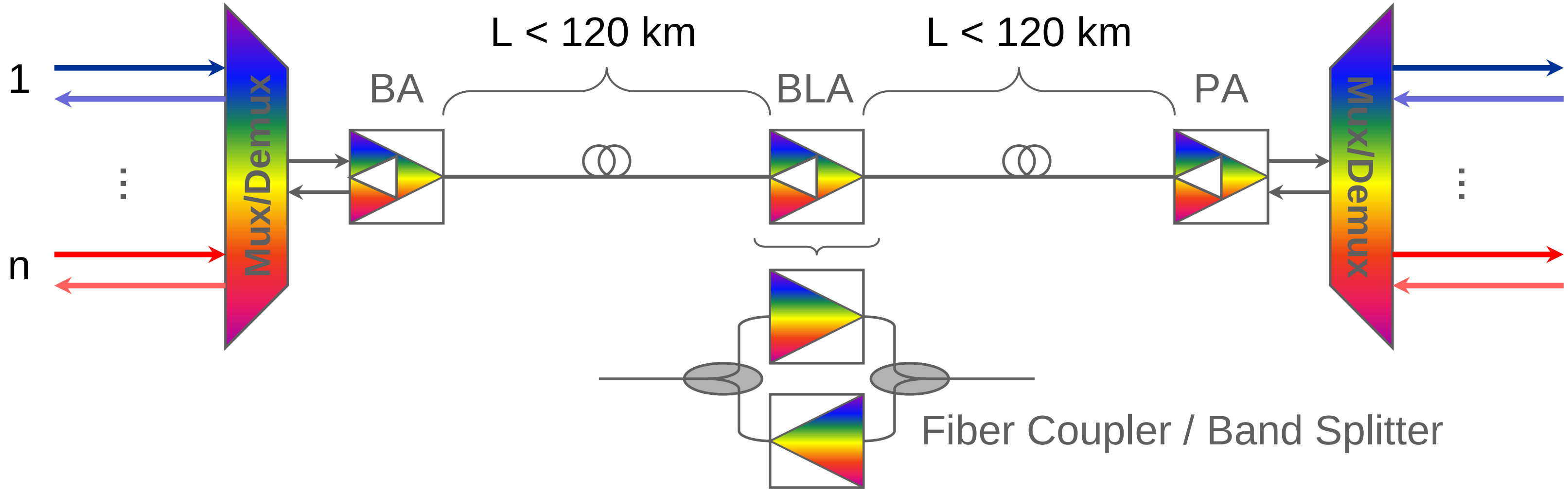
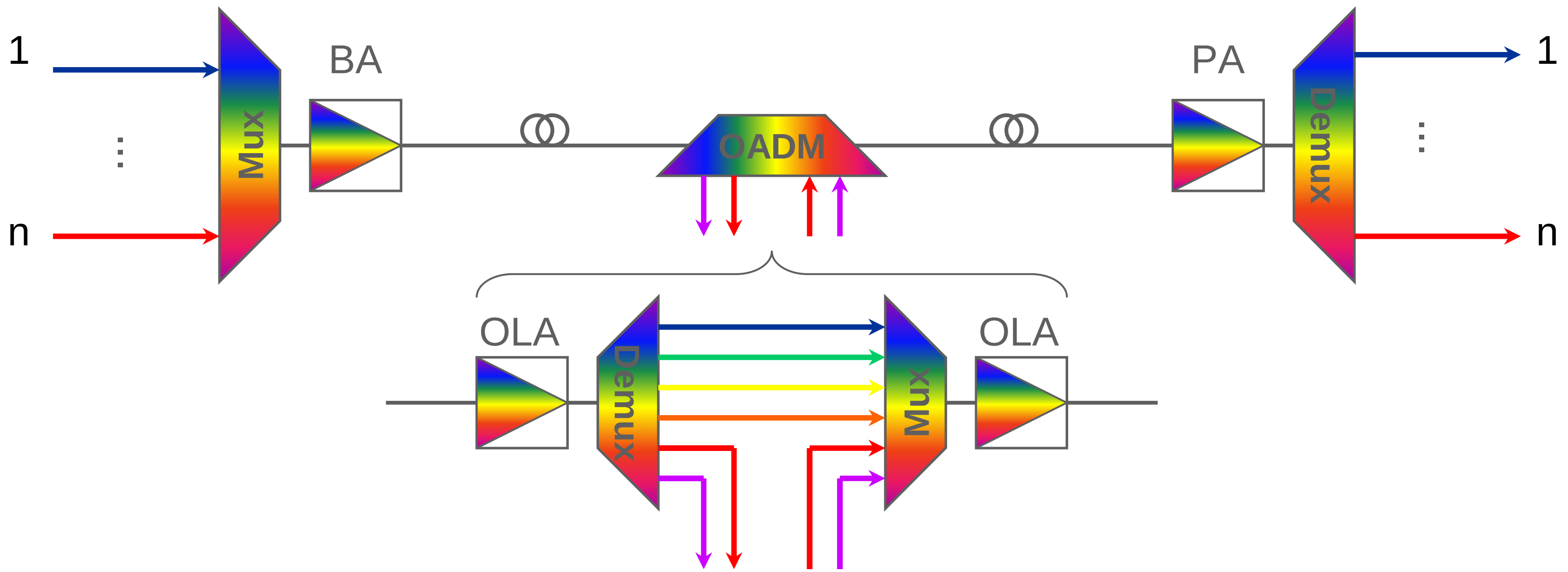
DWDM Single-Fiber Working



BA: Booster Amplifier
BLA: Bidirectional Line Amplifier
PA: PreAmplifier

DWDM Single-Fiber Working can further reduce fiber costs

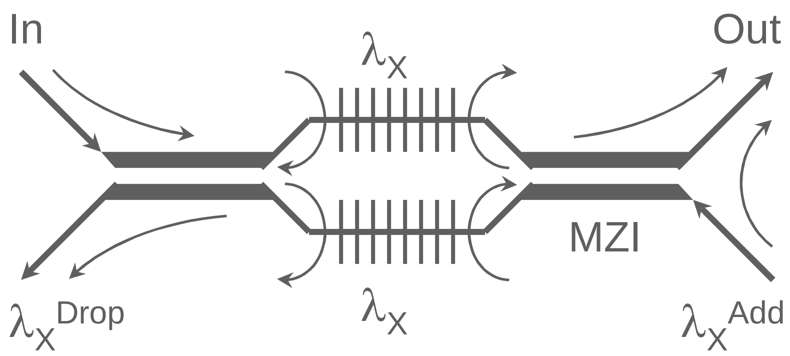
OADM: Principle



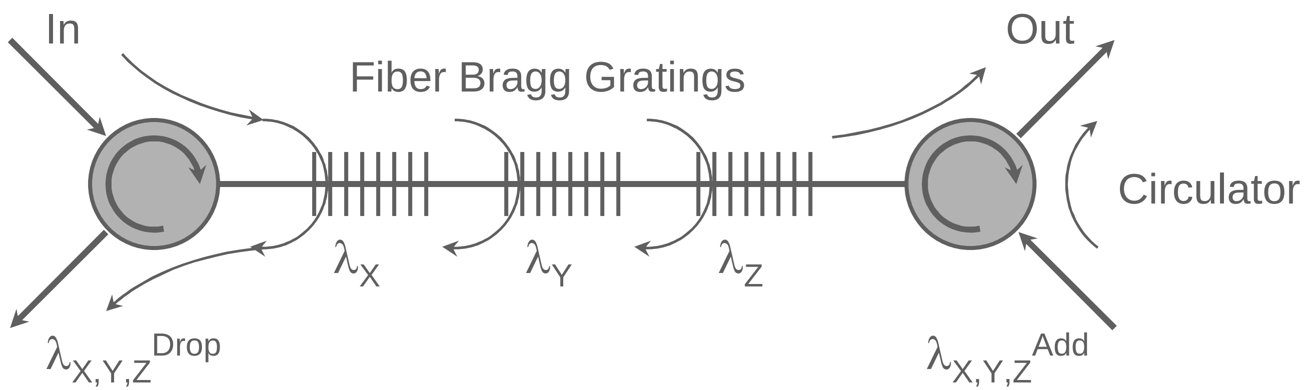
OADM: ***Optical Add / Drop Multiplexer***

- Provides Mid-Span access to up to 50% of all wavelengths
- Avoids expensive Back-to-Back coupling of optical terminal multiplexers
- Currently, wavelengths are selected by fixed-wavelength filters
- *Next-Generation Flexible OADMs will provide for transparent wavelengths routing*

OADM: Fiber Bragg Gratings



- Fiber Bragg Gratings produced by UV Laser radiation
- Circulator is non-reciprocal 3-port
- Alternative: Mach-Zehnder Interferometer (MZI)
- All Add/Drop channels in **1 common fiber**



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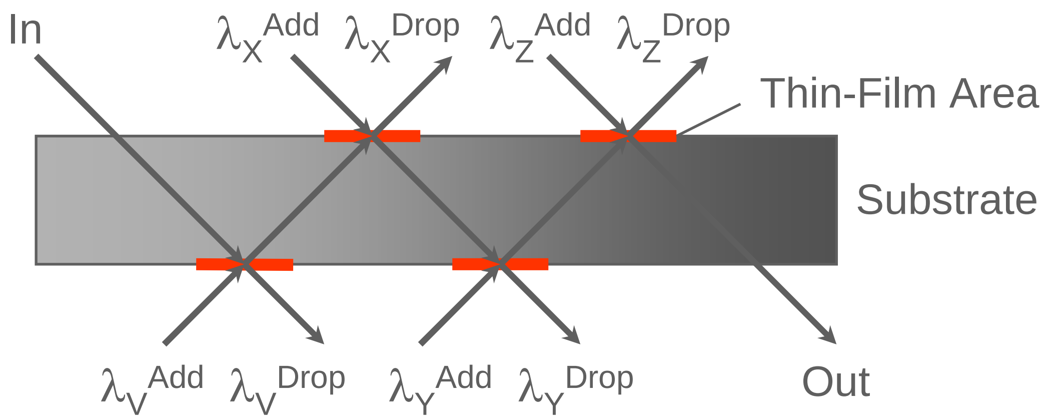
OADM: Thin-Film Technology



- Multiple reflections inside substrate
- Reflection or transmission at thin-film areas
- Add/Drop locations depend on wavelength
- All Add/Drop channels in different fibers

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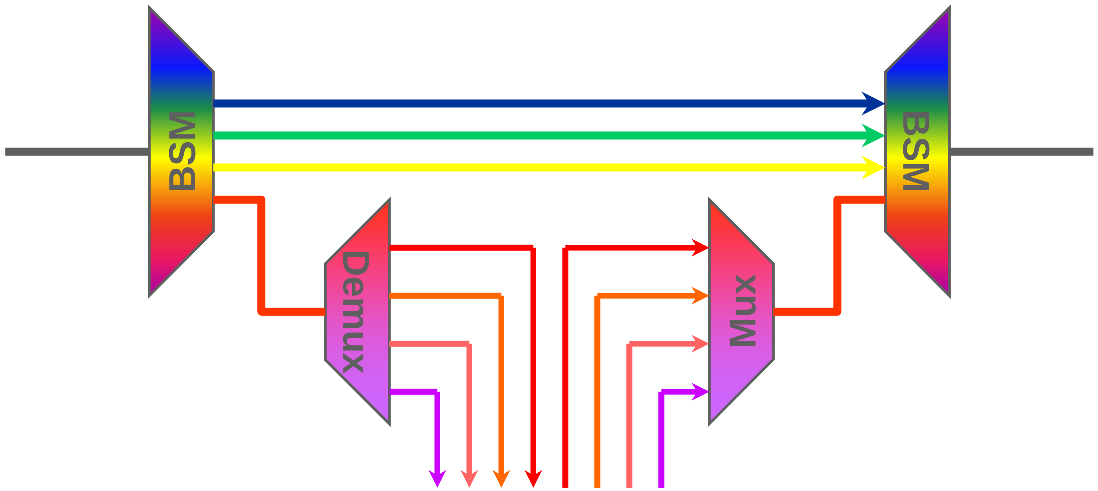
Two-Stage OADM



- Split into Band Splitters / Combiners (BSM) and Mux / Demux
- Can decrease insertion loss of OADMs significantly