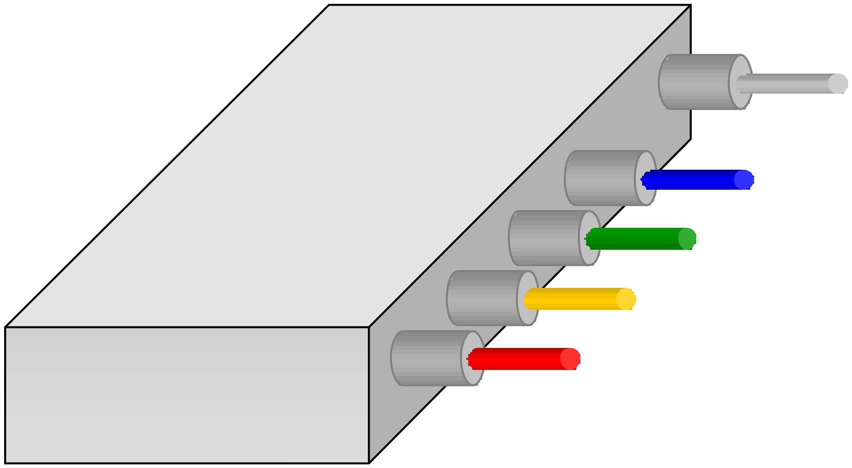
LW Technology

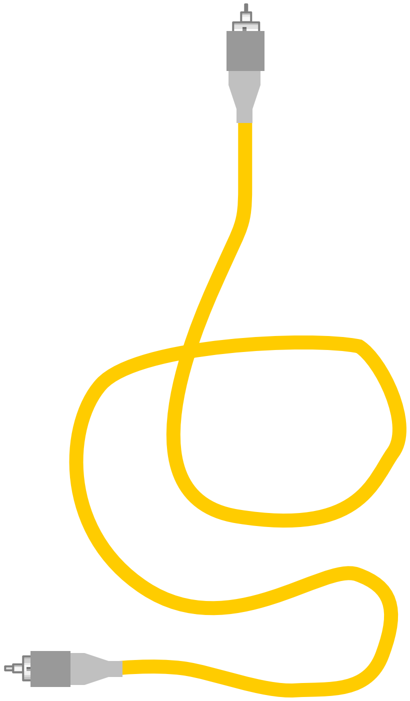


Passive Components

Revision 1.1
December 11, 2000

Patchcords

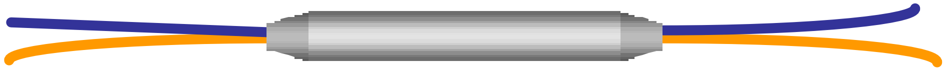
- “Jumper cables” to connect devices and instruments
- “Adapter cables” to connect interfaces using different connector styles
- Insertion loss is dominated by the connector losses (2 m fiber has almost no attenuation)
- Often yellow sheath used for single-mode fiber, orange sheath for multimode



Wavelength-Independent Couplers

- Wavelength-Independent coupler (WIC) types:
  - couple light from each fiber to all the fibers at the other side
  - 50% / 50% (3 dB) most common 4 port type
  - 1%, 5% or 10% taps (often 3 port devices)

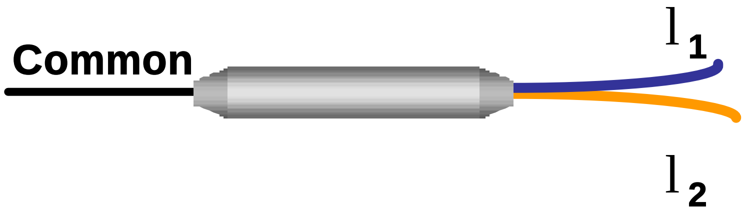
- Excess Loss (EL):
  - Measure of power “wasted” in the component



$$EL = -10 \bullet \log_{10} \frac{\sum P_{out}}{P_{in}}$$

Wavelength-Dependent Couplers

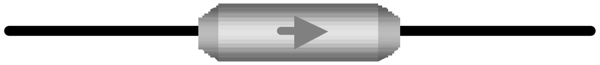
- Wavelength-division multiplexers (WDM) types:
  - 3 port devices (4th port terminated)
  - 1310 / 1550 nm (“classic” WDM technology)
  - 1480 / 1550 nm and 980 / 1550 nm for pumping optical amplifiers (see later)
  - 1550 / 1625 nm for network monitoring



- Insertion and rejection:
  - Low loss (< 1 dB) for path wavelength
  - High loss (20 to 50 dB) for other wavelength

Isolators

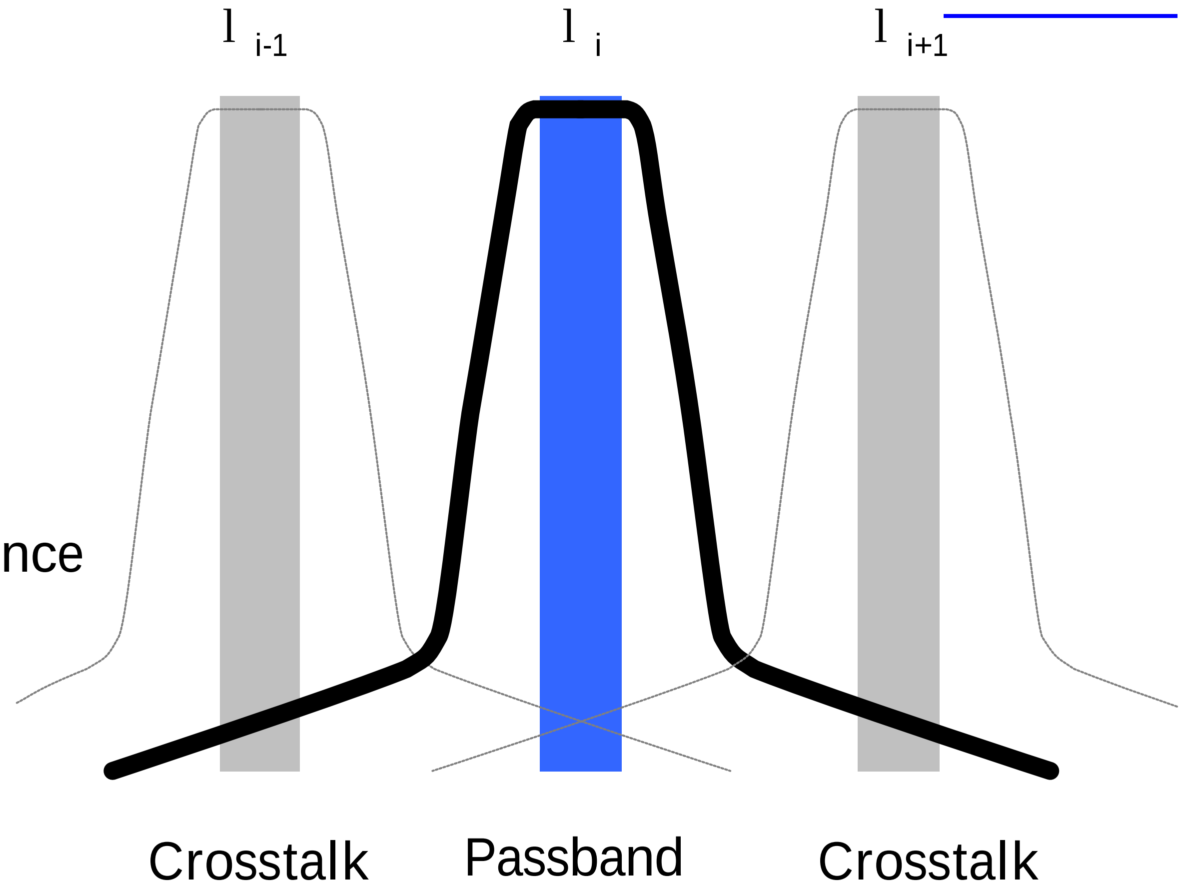
- Main application:
  - To protect lasers and optical amplifiers from light coming back (which otherwise can cause instabilities)



- Insertion loss:
  - Low loss (0.2 to 2 dB) in forward direction
  - High loss in reverse direction:
    20 to 40 dB single stage, 40 to 80 dB dual stage)
- Return loss:
  - More than 60 dB without connectors

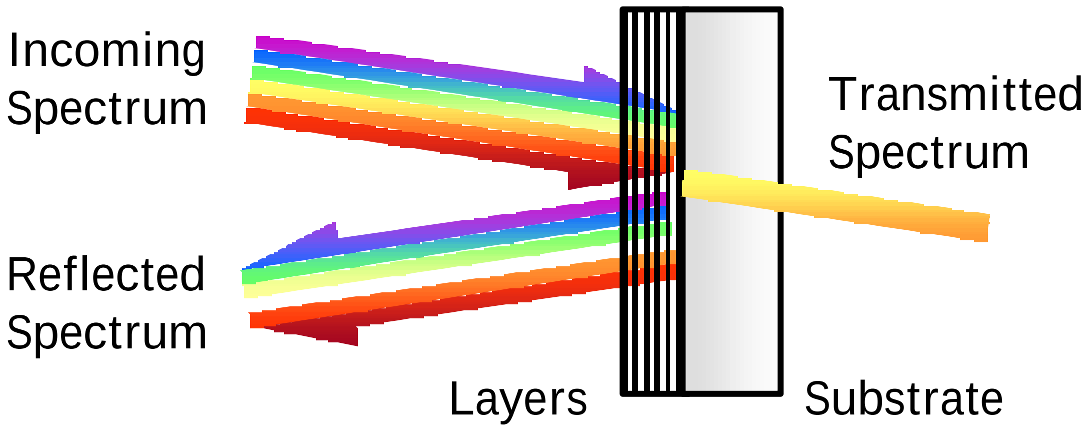
Filter Characteristics

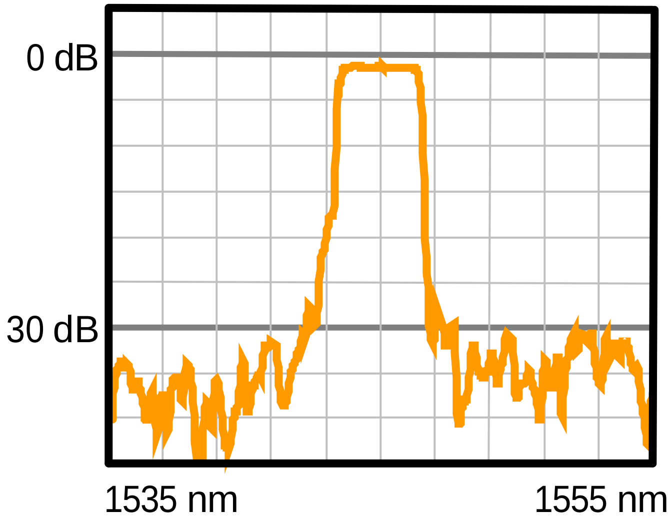
- Passband
  - Insertion loss
  - Ripple
  - Wavelengths (peak, center, edges)
  - Bandwidths (0.5 dB, 3 dB, ..)
  - Polarization dependence
- Stopband
  - Crosstalk rejection
  - Bandwidths (20 dB, 40 dB, ..)



Dielectric Filters

- Thin-film cavities
  - Alternating dielectric thin-film layers with different refractive index
  - Multiple reflections cause constructive & destructive interference
  - Variety of filter shapes and bandwidths (0.1 to 10 nm)
  - Insertion loss 0.2 to 2 dB, stopband rejection 30 to 50 dB

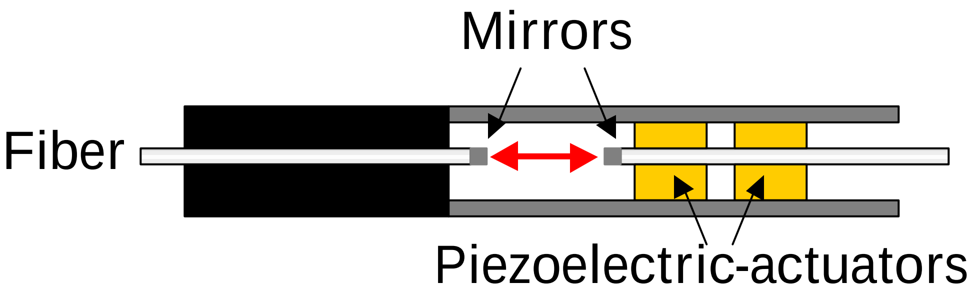


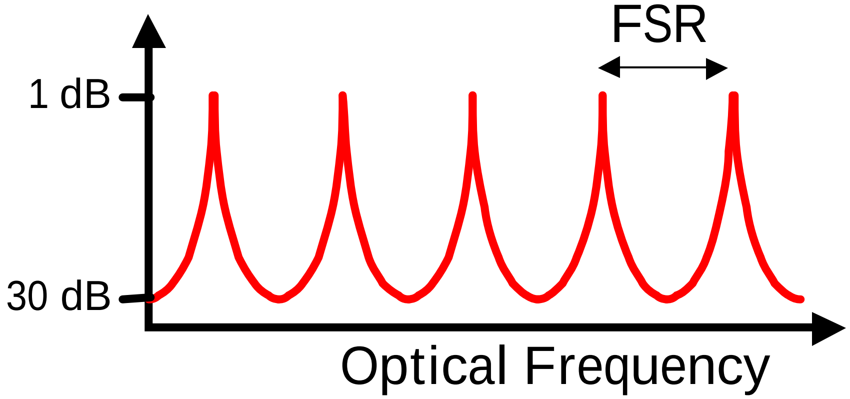


Tunable Fabry-Perot Filters

- Filter shape
  - Repetitive passband with Lorentzian shape
  - Free Spectral Range FSR = c / 2 • n • l (l: cavity length)
  - Finesss F = FSR / BW (BW: 3 dB bandwidth)

- Typical specifications for 1550 nm applications
  - FSR: 4 THz to 10 THz, F: 100 to 200, BW: 20 to 100 GHz
  - Insertion loss: 0.5 to 35 dB

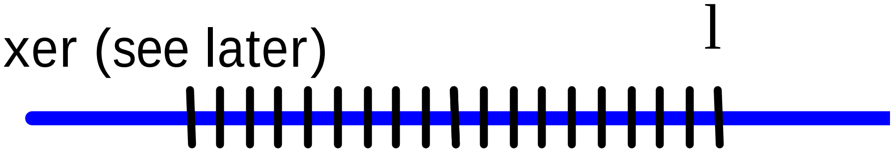




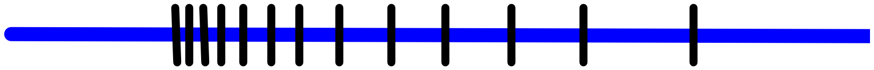
Fiber Bragg Gratings (FBG)

- Single-mode fiber with “modulated” refractive index
  - Refractive index changed using high power UV radiation

- Regular interval pattern: reflective at *one* wavelength
  - Notch filter, add / drop multiplexer (see later)



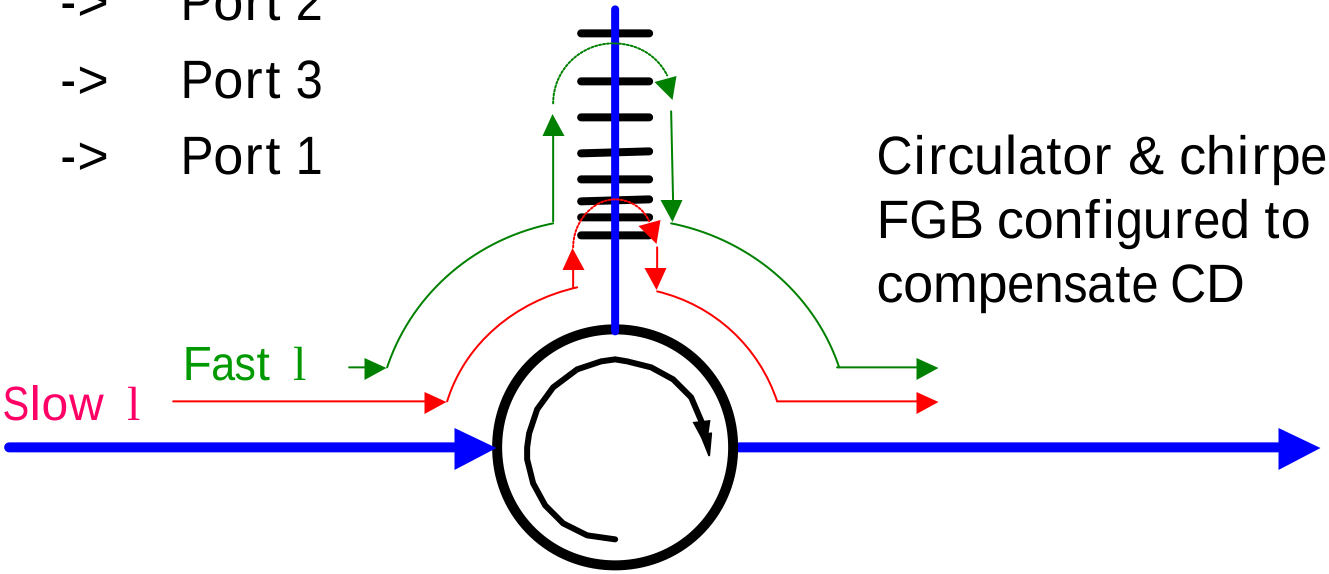
- Increasing intervals: “chirped” FBG
  - Compensation for chromatic dispersion



Circulators

- Optical crystal technology similar to isolators
  - Insertion loss 0.3 to 1.5 dB, isolation 20 to 40 dB

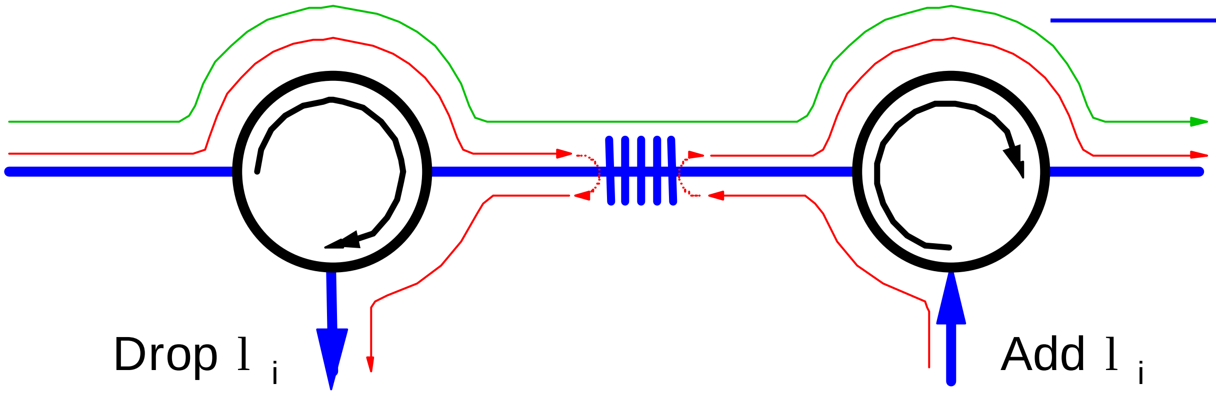
- Typical configuration: 3 port device
  - Port 1 -> Port 2
  - Port 2 -> Port 3
  - Port 3 -> Port 1



Circulator & chirped FGB configured to compensate CD

Add / Drop Nodes

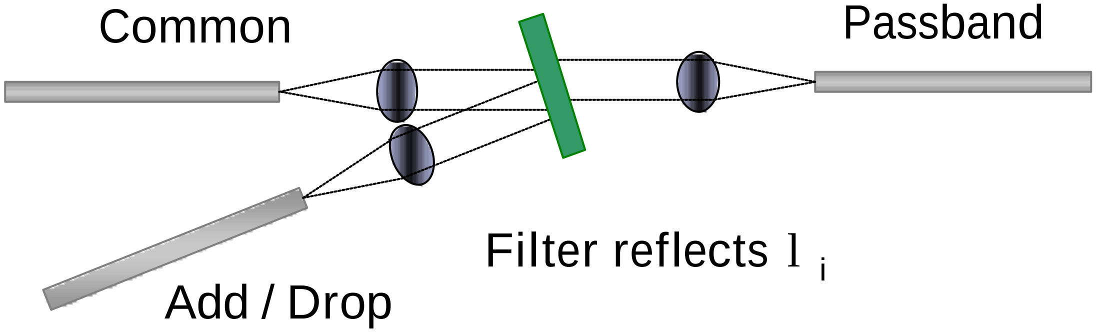
Circulator with FBG design



Drop l$_i$

Add l$_i$

Dielectric thin-film filter design



Common

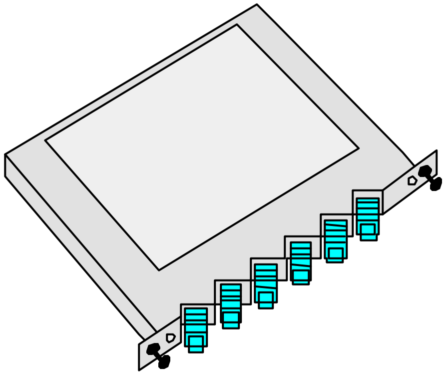
Passband

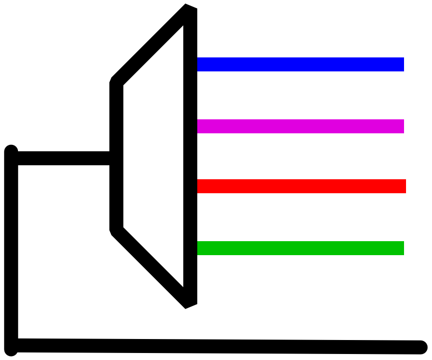
Filter reflects l$_i$

Add / Drop

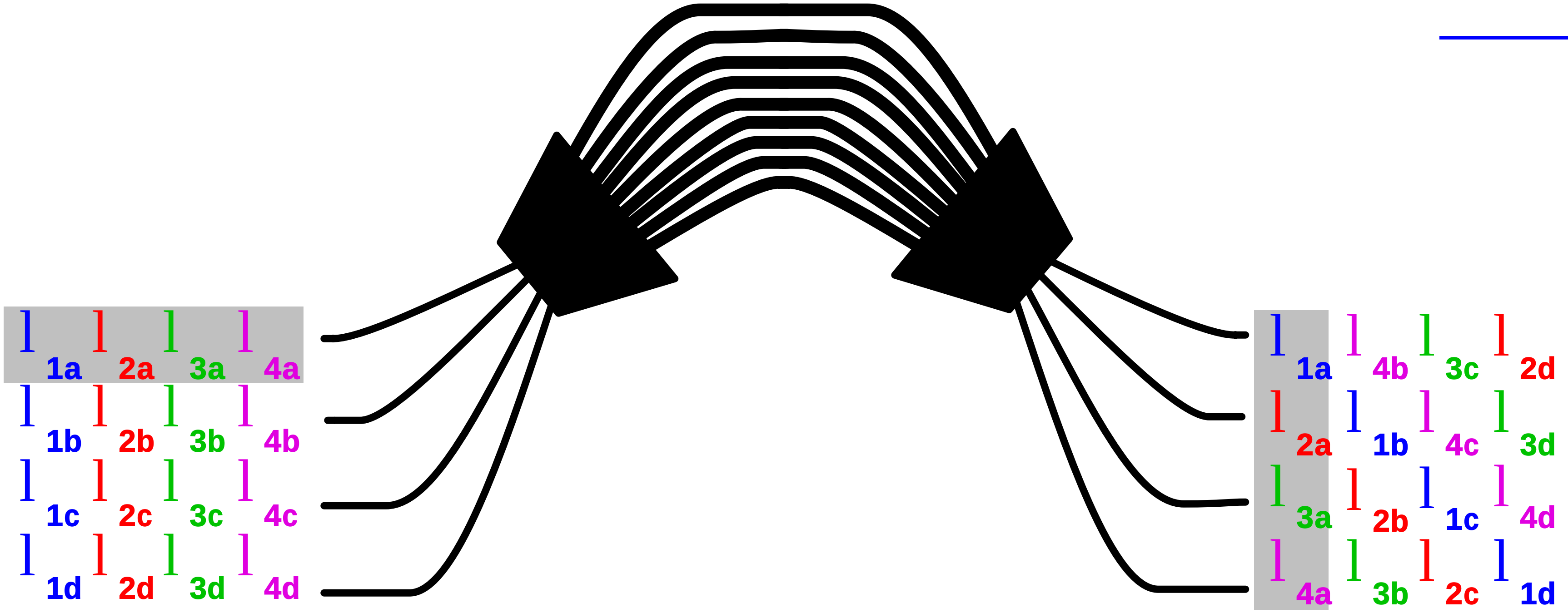
Multiplexers (MUX) / Demultiplexers (DEMUX)

- Key component of wavelength-division multiplexing technology (DWDM)
- Variety of technologies
  - Cascaded dielectric filters
  - Cascaded FBGs
  - Phased arrays (see later)
- High crosstalk suppression essential for demultiplexing





Array Waveguide Grating (AWG)



Rows .. .. translate into .. .. columns

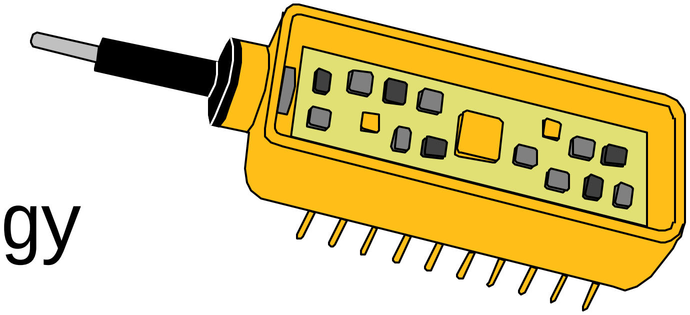
If only one input is used: wavelength demultiplexer!

Review Questions

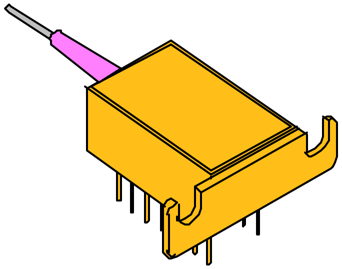
1. What is the difference between a WIC and a WDM?

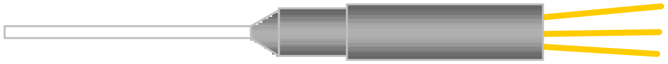
2. What are the losses of a 10% tap?

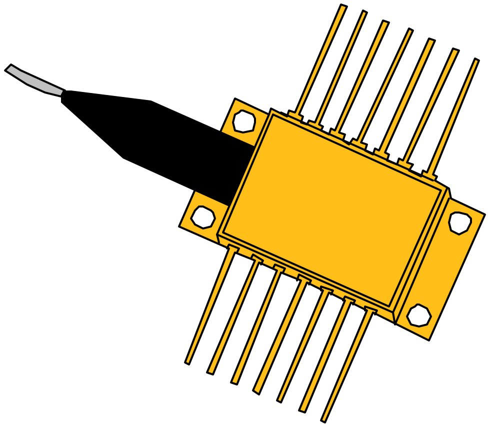
3. What does a demultiplexer do?



LW Technology





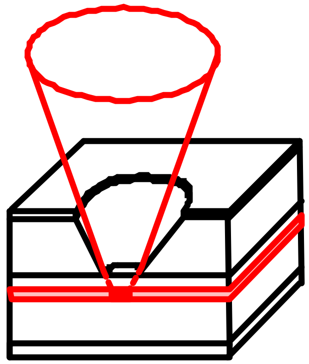


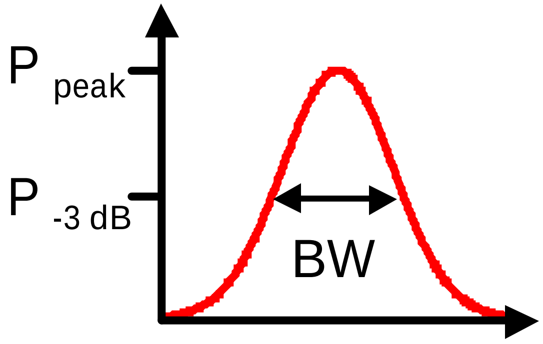
Transmitters & Receivers

Light-emitting Diode (LED)

- Datacom through air & multimode fiber
  - Very inexpensive (laptops, airplanes, lans)

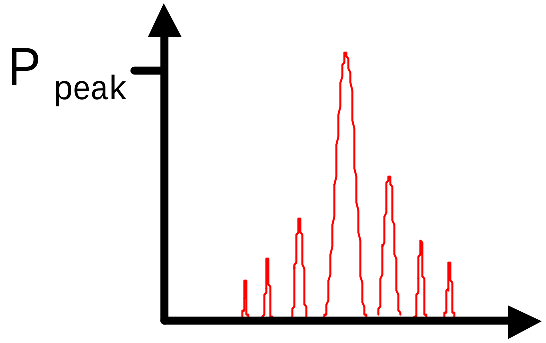
- Key characteristics
  - Most common for 780, 850, 1300 nm
  - Total power up to a few µW
  - Spectral width 30 to 100 nm
  - Coherence length 0.01 to 0.1 mm
  - Little or not polarized
  - Large NA (→ poor coupling into fiber)

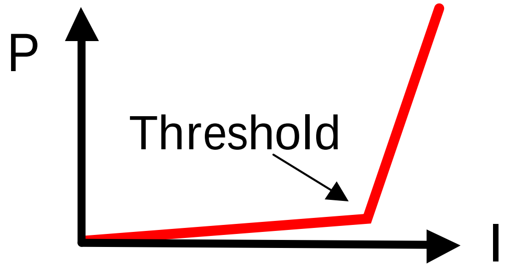


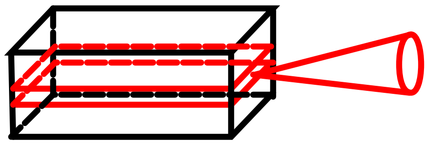


Fabry-Perot (FP) Laser

- Multiple longitudinal mode (MLM) spectrum
- “Classic” semiconductor laser
  - First fiberoptic links (850 or 1300 nm)
  - Today: short & medium range links
- Key characteristics
  - Most common for 850 or 1310 nm
  - Total power up to a few mw
  - Spectral width 3 to 20 nm
  - Mode spacing 0.7 to 2 nm
  - Highly polarized
  - Coherence length 1 to 100 mm
  - Small NA (→ good coupling into fiber)

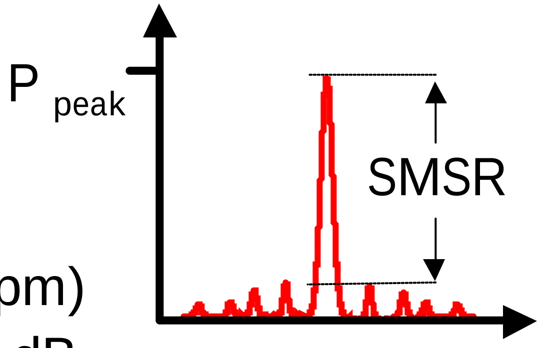


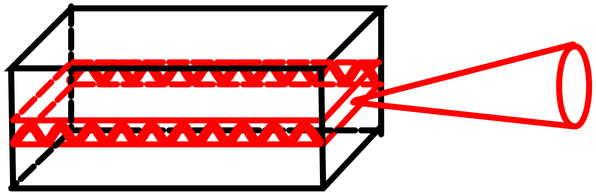




Distributed Feedback (DFB) Laser

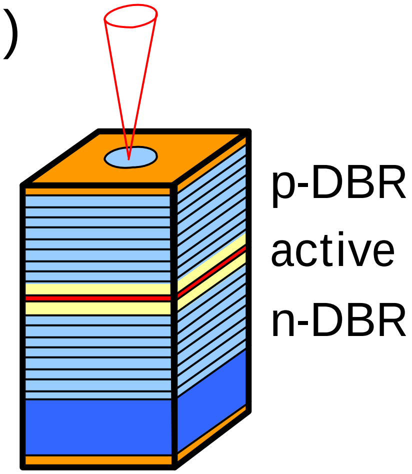
- Single longitudinal mode (SLM) spectrum
- High performance telecommunication laser
  - Most expensive (difficult to manufacture)
  - Long-haul links & DWDM systems
- Key characteristics
  - Mostly around 1550 nm
  - Total power 3 to 50 mw
  - Spectral width 10 to 100 MHz (0.08 to 0.8 pm)
  - Sidemode suppression ratio (SMSR): > 50 dB
  - Coherence length 1 to 100 m
  - Small NA (→ good coupling into fiber)



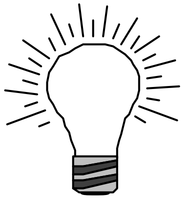


Vertical Cavity Surface Emitting Lasers (VCSEL)

- Distributed Bragg Reflector (DBR) Mirrors
  - Alternating layers of semiconductor material
  - 40 to 60 layers, each λ / 4 thick
  - Beam matches optical acceptance needs of fibers more closely
- Key properties
  - Wavelength range 780 to 980 nm (gigabit ethernet)
  - Spectral width: <1nm
  - Total power: >-10 dBm
  - Coherence length:10 cm to10 m
  - Numerical aperture: 0.2 to 0.3



Other Light Sources



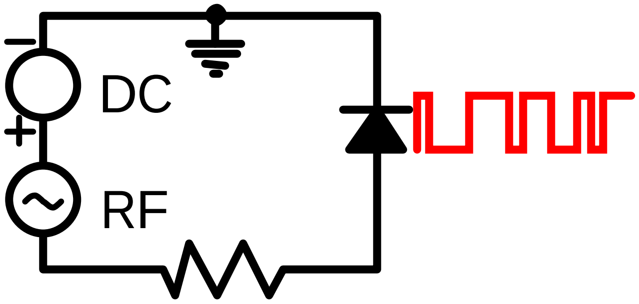
- White light source
  - Specialized tungsten light bulb
  - Wavelength range 900 to 1700 nm,
  - Power density 0.1 to 0.4 nw/nm (SM), 10 to 25 nw/nm (MM)
- Amplified spontaneous emission (ASE) source
  - “Noise” of an optical amplifier without input signal
  - Wavelength range 1525 to 1570 nm
  - Power density 10 to 100 µw/nm
- External cavity laser
  - Most common for 1550 nm band (some for 1310 nm)
  - Tunable over more than 100 nm, power up to 10 mw
  - Spectrum similar to DFB laser, bandwidth 10 kHz to 1 MHz

Basic Transmitter Design

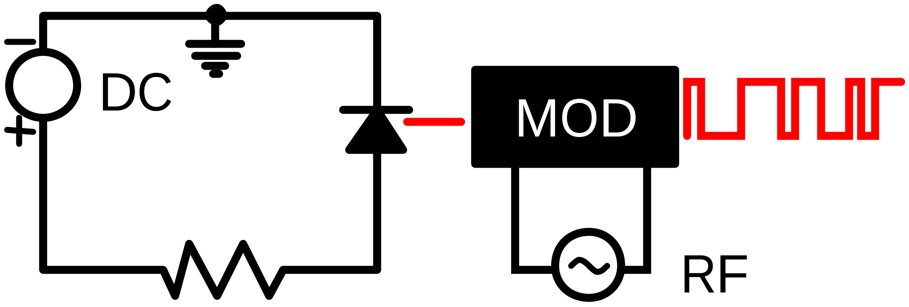
- Optimized for one particular bit rate & wavelength
- Often temperature stabilized laser
- Internal (direct) or external modulation
- Digital modulation
  - Extinction ratio: 9 to 15 dB
  - Forward error correction
  - Scrambling of bits to reduce long sequences of 1s or 0s (reduced DC and low frequency spectral content)
- Analog modulation
  - Modulation index typically 2 to 4%
  - Laser bias optimized for maximum linearity

Modulation Principles

- Direct (laser current)
  - Inexpensive
  - Can cause chirp up to 1 nm (wavelength variation caused by variation in electron densities in the lasing area)

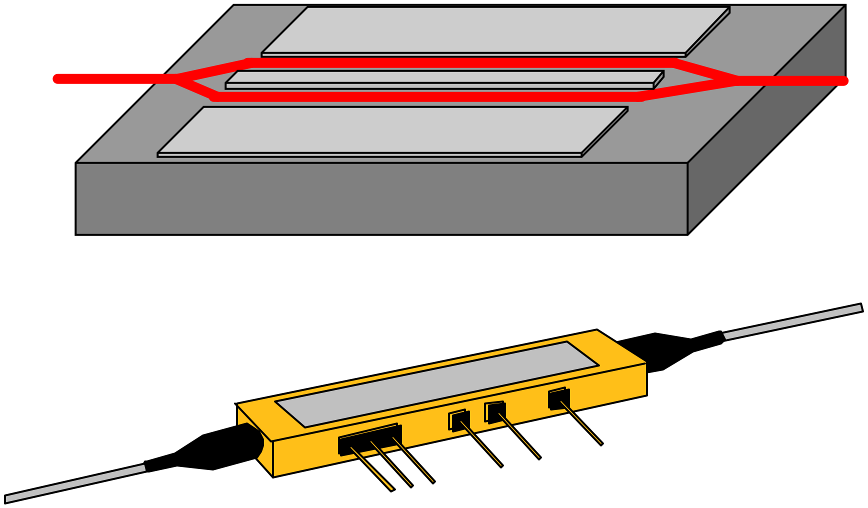


- External
  - 2.5 to 40 gb/s
  - AM sidebands (caused by modulation spectrum) dominate linewidth of optical signal

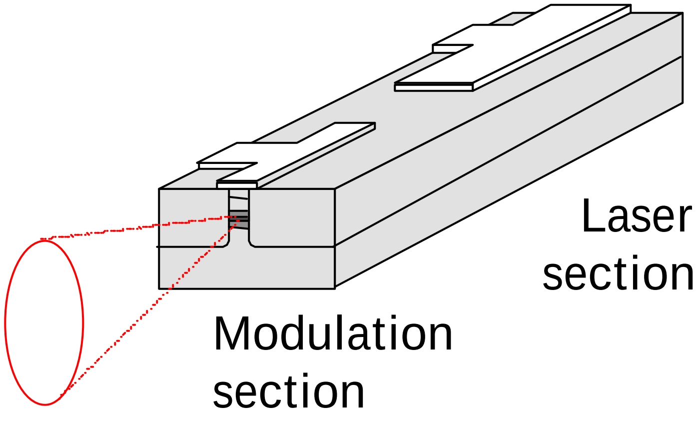


External Modulators

Mach-Zehnder Principle

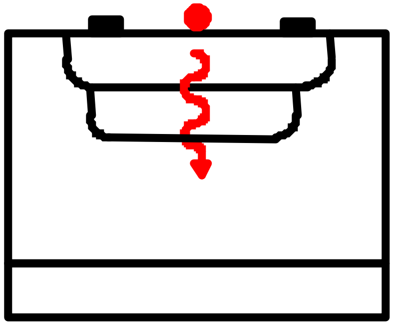


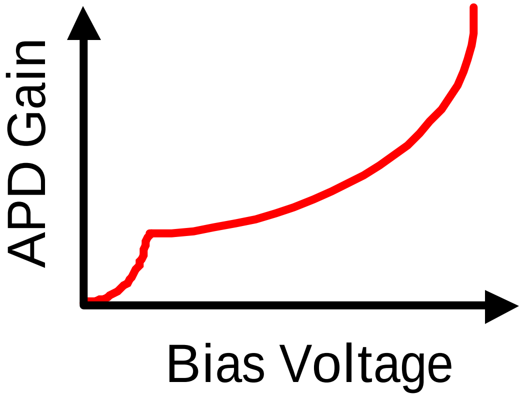
DFB laser with external on-chip modulator



Photodiodes

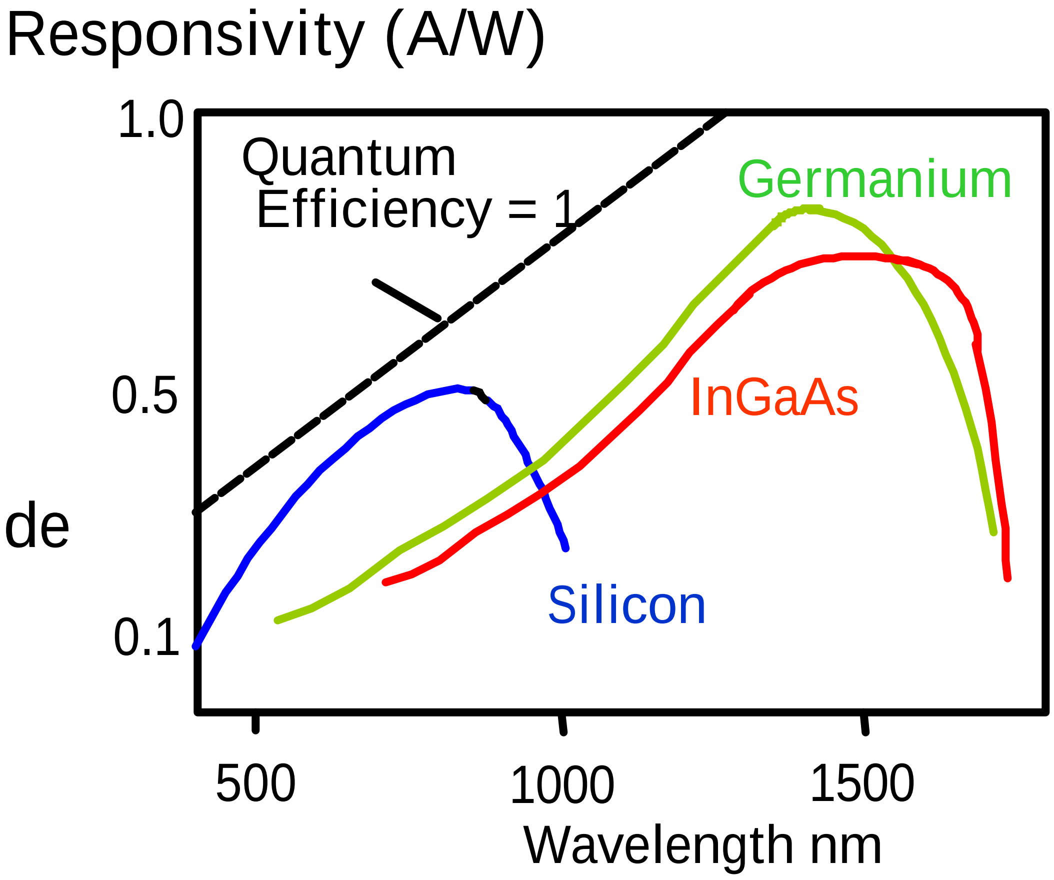
- PIN (p-layer, intrinsic layer, n-layer)
  - Highly linear, low dark current
- Avalanche photo diode (APD)
  - Gain up to x100 lifts detected optical signal above electrical noise of receiver
  - Best for high speed *and* highly sensitive receivers
  - Strong temperature dependence
- Main characteristics
  - Quantum efficiency (electrons/photon)
  - Dark current
  - Responsivity (current vs. L)





Material Aspects

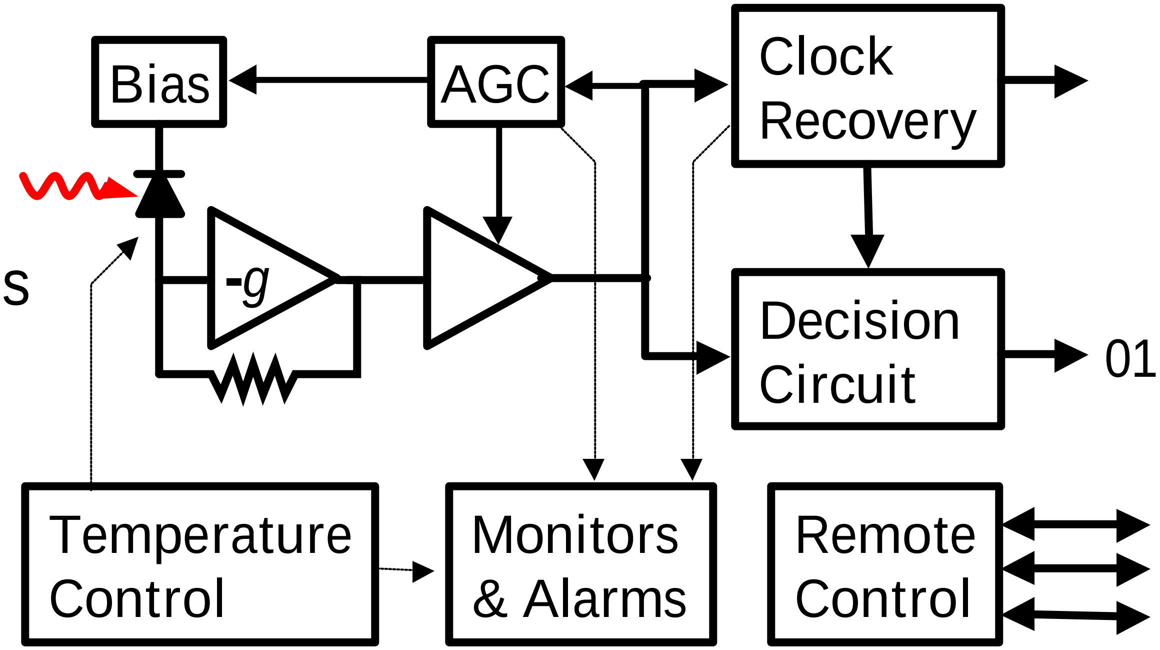
- Silicon (Si)
  - Least expensive
- Germanium (Ge)
  - “Classic” detector
- Indium gallium arsenide (InGaAs)
  - Highest speed



Basic Receiver Design

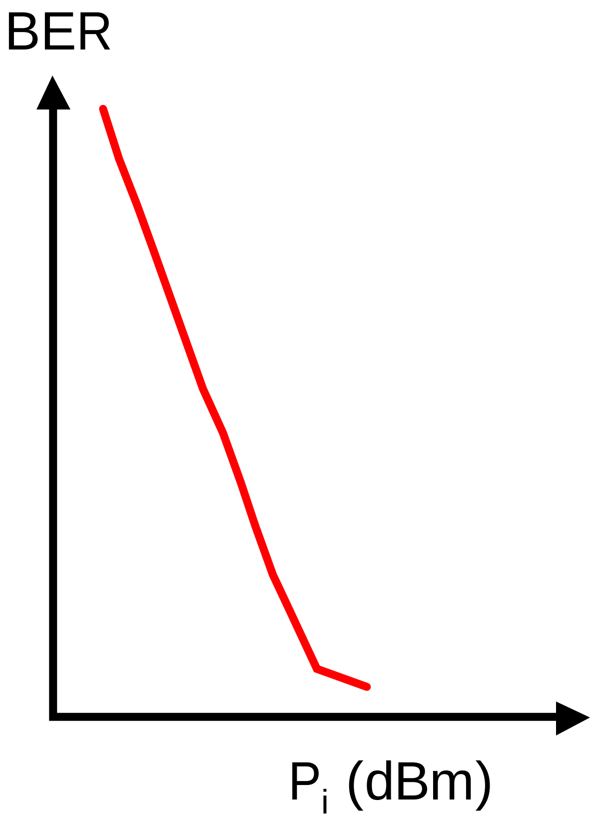
- Optimized for *one particular*
  - Sensitivity range
  - Wavelength
  - Bit rate

- Can include circuits for telemetry



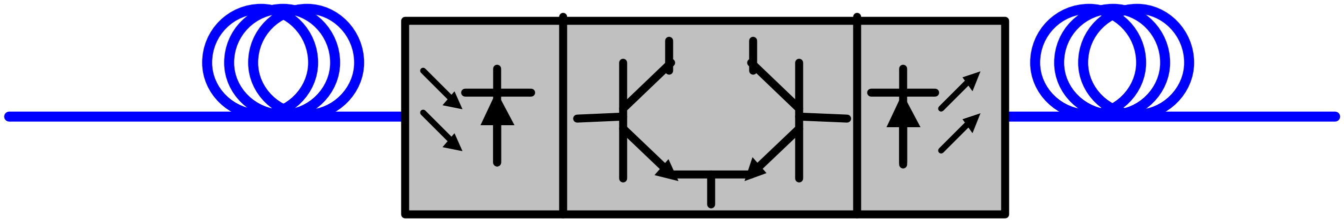
Receiver Sensitivity

- Bit error ratio (BER) versus input power (p_i)
  - Minimum input power depends on acceptable bit error rate
  - Power margins important to tolerate imperfections of link (dispersion, noise from optical amplifiers, etc.)
  - Theoretical curve well understood
  - Many receivers designed for 1E-12 or better BER

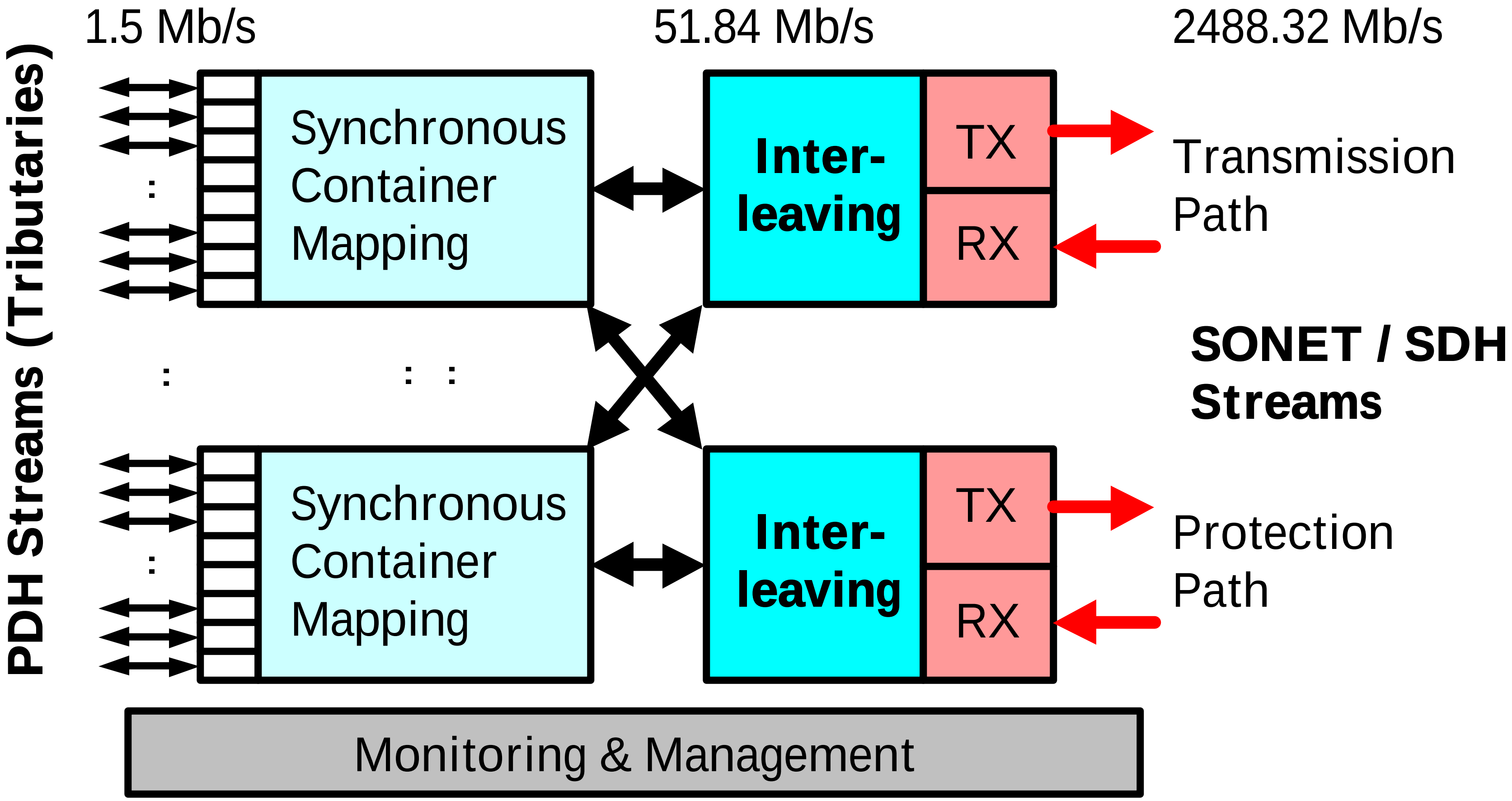


Regenerator

- Receiver followed by a transmitter
  - No add or drop of traffic
  - Designed for *one* bit rate & wavelength
- Signal regeneration
  - Reshaping & timing of data stream
  - Inserted every 30 to 80 km before optical amplifiers became commercially available
  - Today: reshaping necessary after about 600 km (at 2.5 Gb/s), often done by SONET/SDH add/drop multiplexers or digital cross-connects



Conceptual Terminal Diagram



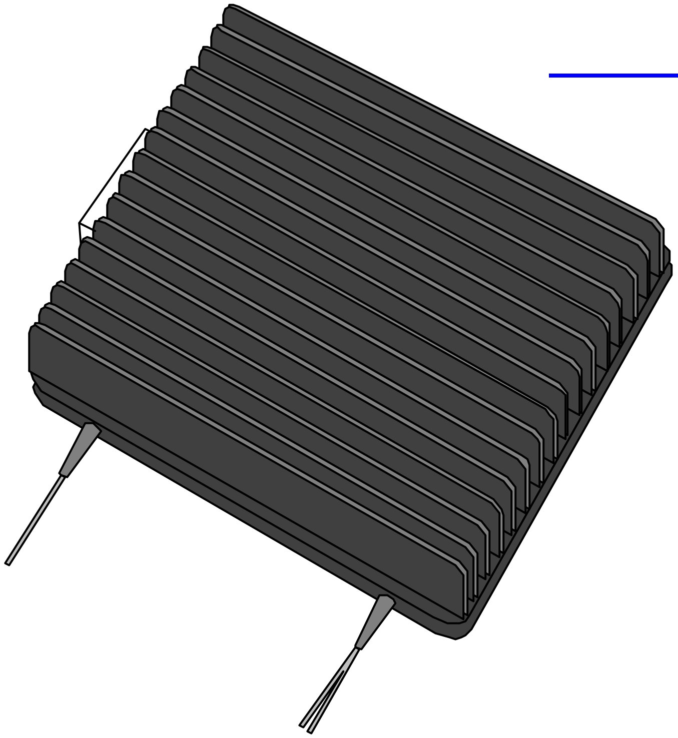
Review Questions

1. What are the differences between an LED, FP, and DFB lasers?

2. Which photodiode do you use for
   - Data communication?
   - Speed longhaul traffic?

3. How do you define receiver sensitivity?

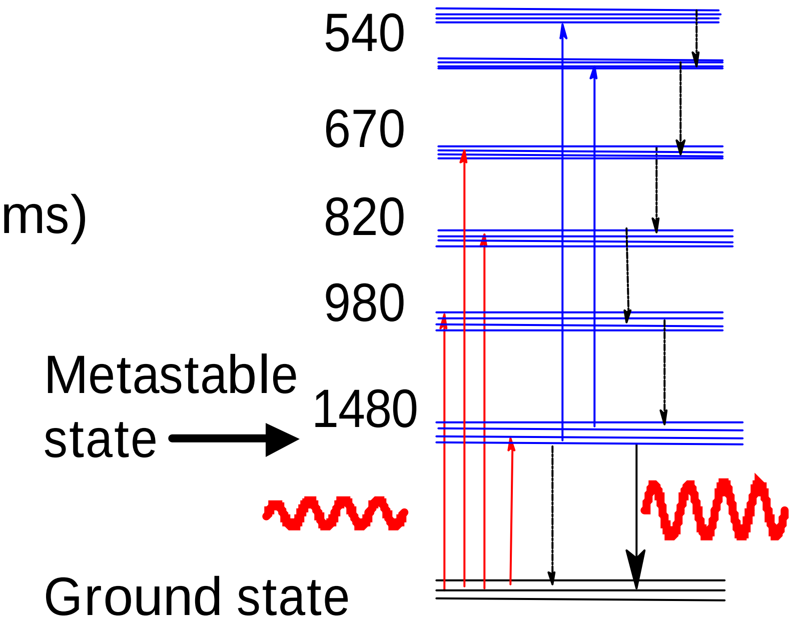
LW Technology



Optical Amplifiers

Erbium Properties

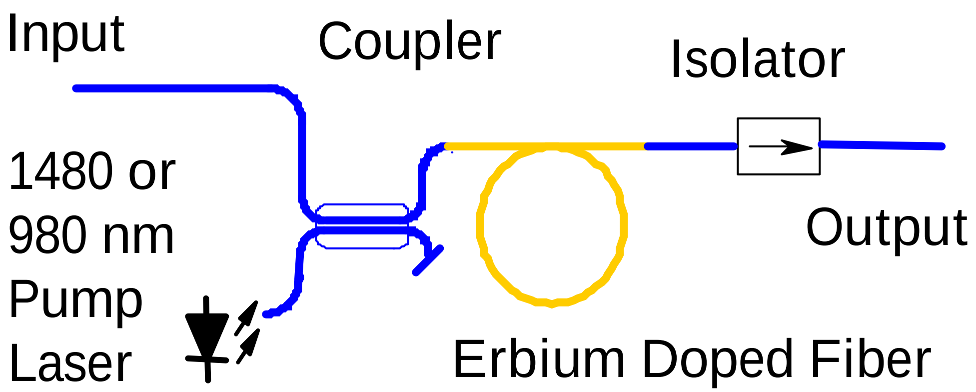
- Erbium: rare element with phosphorescent properties
  - Photons at 1480 or 980 nm activate electrons into a metastable state
  - Electrons falling back emit light in the 1550 nm range
- Spontaneous emission
  - Occurs randomly (time constant ~1 ms)
- Stimulated emission
  - By electromagnetic wave
  - Emitted wavelength & phase are identical to incident one



Basic EDF Amplifier Design

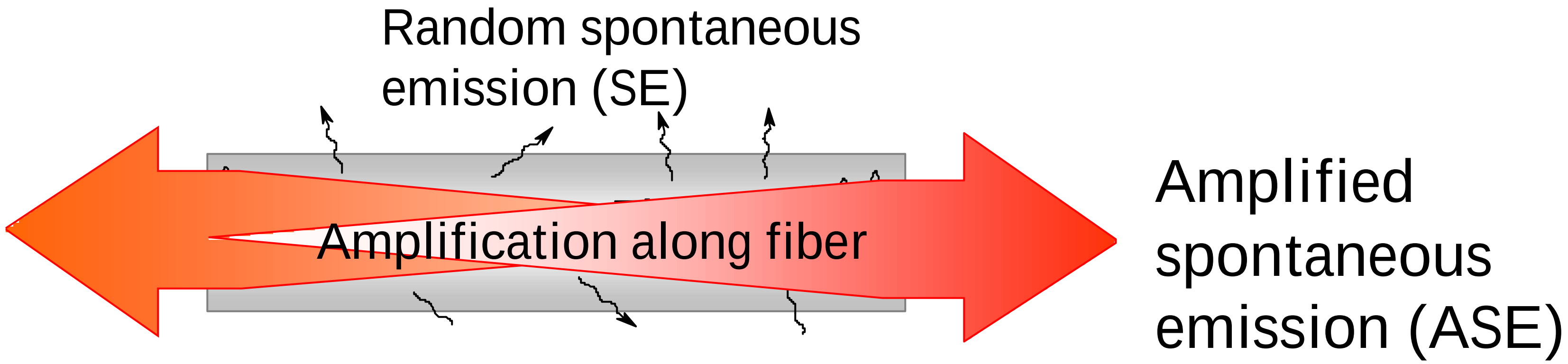
- Erbium-doped fiber amplifier (EDFA) most common
  - Commercially available since the early 1990's
  - Works best in the range 1530 to 1565 nm
  - Gain up to 30 dB (1000 photons out per photon in!)

- Optically transparent
  - "Unlimited" RF bandwidth
  - Wavelength transparent

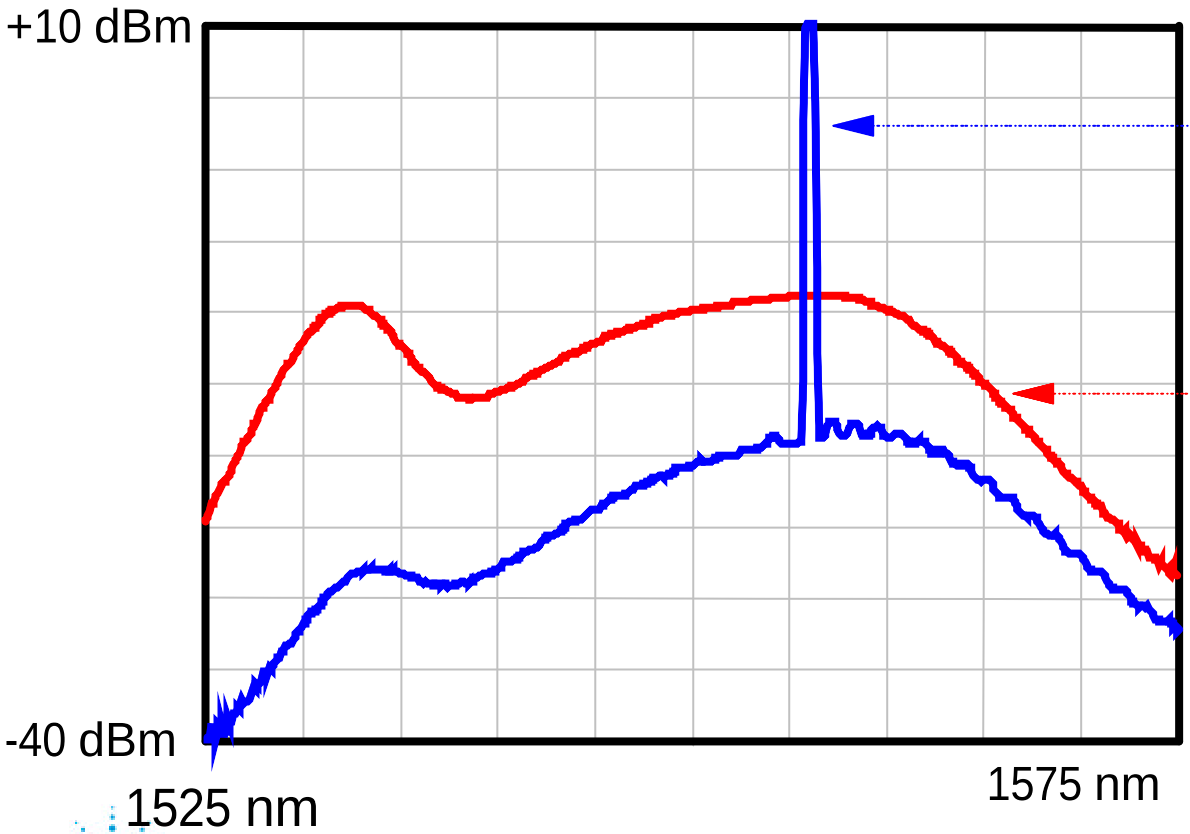


Amplified Spontaneous Emission

- Erbium randomly emits photons between 1520 and 1570 nm
  - Spontaneous emission (SE) is not polarized or coherent
  - Like any photon, SE stimulates emission of other photons
  - With no input signal, eventually all optical energy is consumed into amplified spontaneous emission
  - Input signal(s) consume metastable electrons → much less ASE



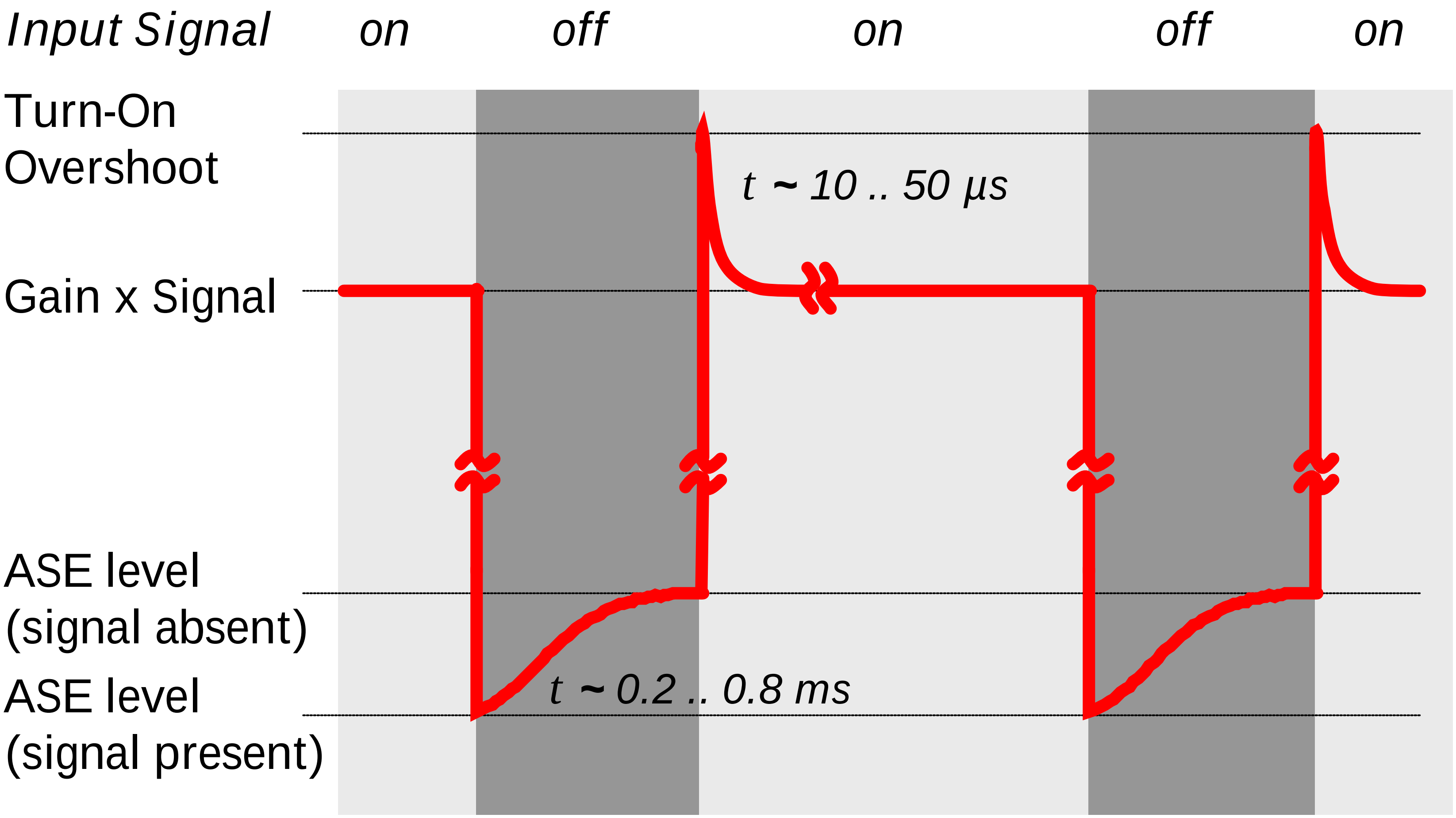
Output Spectra



Amplified signal spectrum (input signal *saturates* the optical amplifier)

ASE spectrum when ***no*** input signal is present

Time-Domain Properties

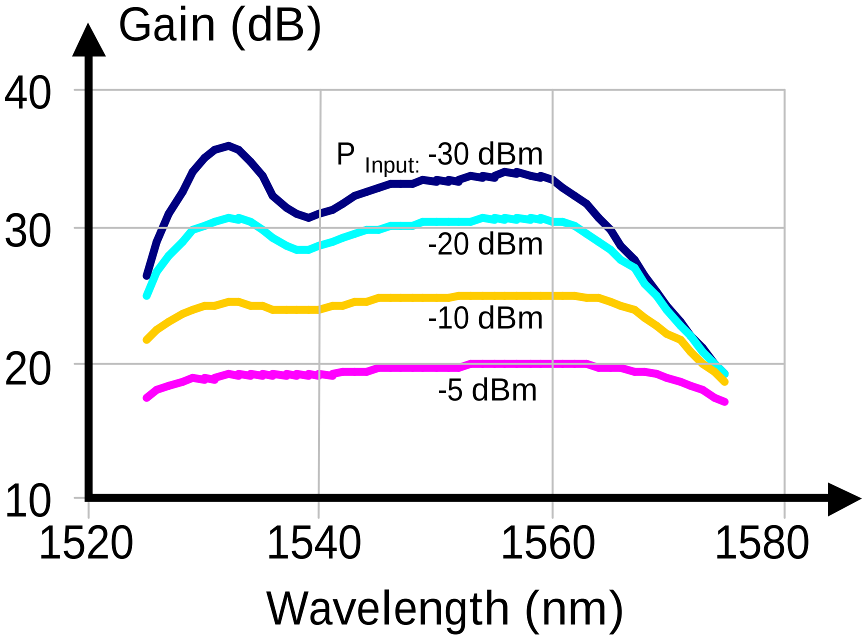


Optical Gain (G)

- **$G = S_{Output} / S_{Input}$**

  S_{Output}: output signal (without noise from amplifier)
  S_{Input}: input signal

- Input signal dependent
  - Operating point (saturation) of EDFA strongly depends on power and wavelength of incoming signal

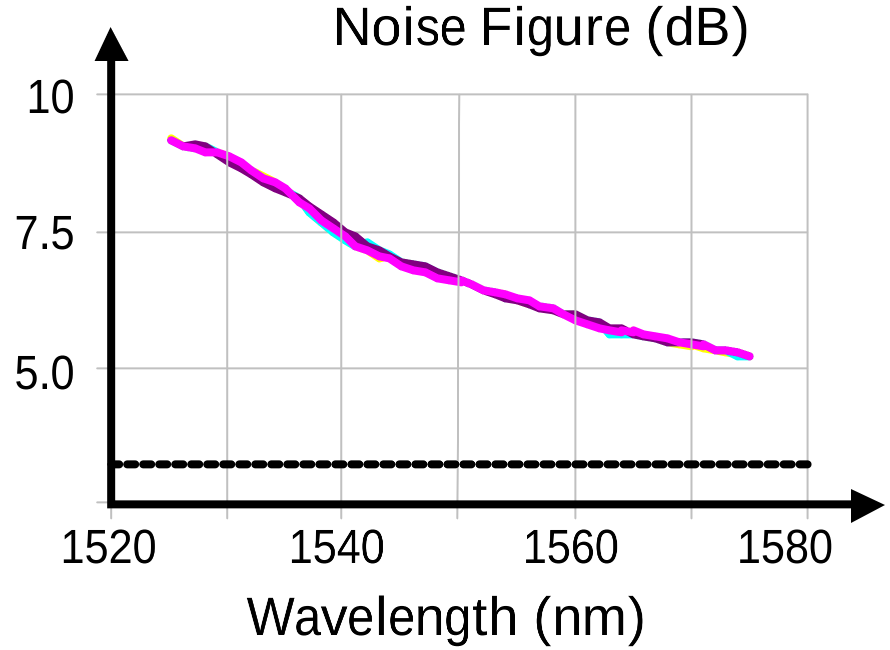


Noise Figure (NF)

- **$NF = P_{ASE} / (h \bullet n \bullet G \bullet B_{OSA})$**

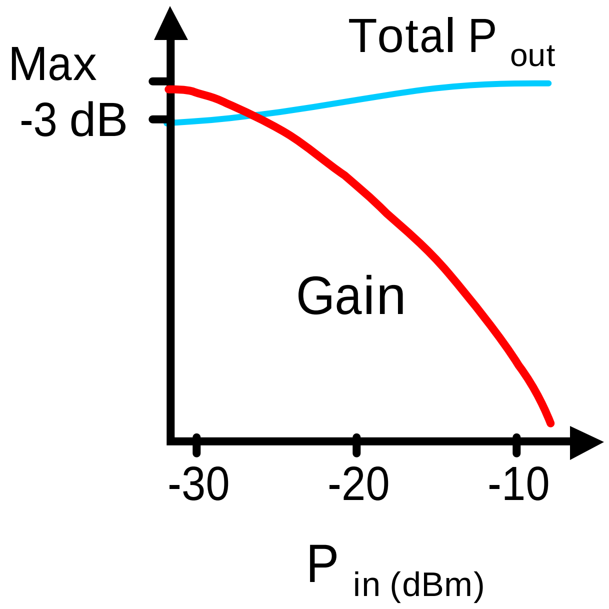
  P_{ASE}: ASE power measured by OSA
  h: Plank’s constant
  n: Optical frequency
  G: Gain of EDFA
  B_{OSA}: Optical bandwidth [Hz] of OSA

- Input signal dependent
  - In a saturated EDFA, the NF depends mostly on the wavelength of the signal
  - Physical limit: 3.0 dB



Gain Compression

- Total output power:
  Amplified signal + ASE
  - EDFA is in saturation if almost all Erbium ions are consumed for amplification
  - Total output power remains almost constant
  - Lowest noise figure
- Preferred operating point
  - Power levels in link stabilize automatically



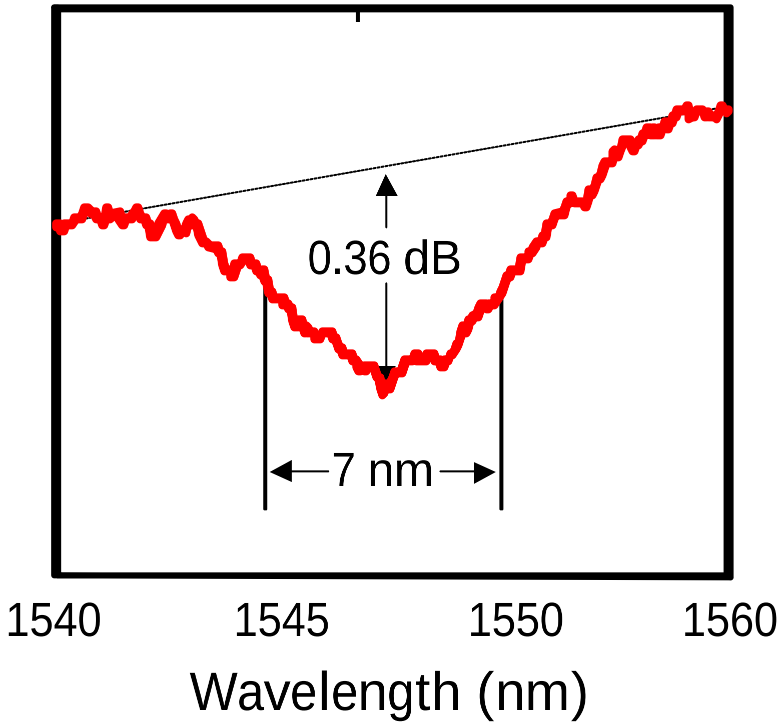
Polarization Hole Burning (PHB)

- Polarization Dependent Gain (PDG)
  - Gain of small signal polarized orthogonal to saturating signal 0.05 to 0.3 dB greater than the large signal gain
  - Effect independent of the state of polarization of the large signal
  - PDG recovery time constant relatively slow

- ASE power accumulation
  - ASE power is minimally polarized
  - ASE perpendicular to signal experiences higher gain
  - PHB effects can be reduced effectively by quickly scrambling the state of polarization (SOP) of the input signal

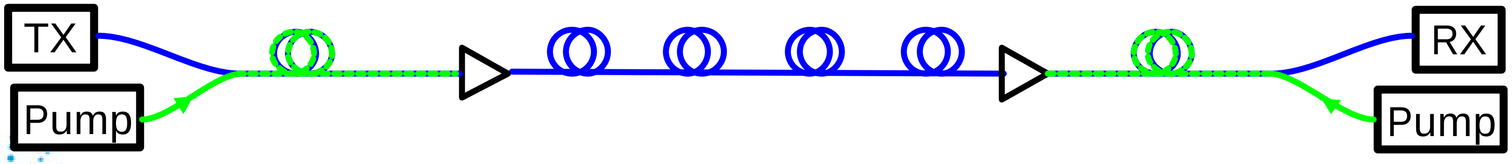
Spectral Hole Burning (SHB)

- Gain depression around saturating signal
  - Strong signals reduce average ion population
  - Hole width 3 to 10 nm
  - Hole depth 0.1 to 0.4 dB
  - 1530 nm region more sensitive to SHB than 1550 nm region
- Implications
  - Usually not an issue in transmission systems (single λ or DWDM)
  - Can affect accuracy of some lightwave measurements

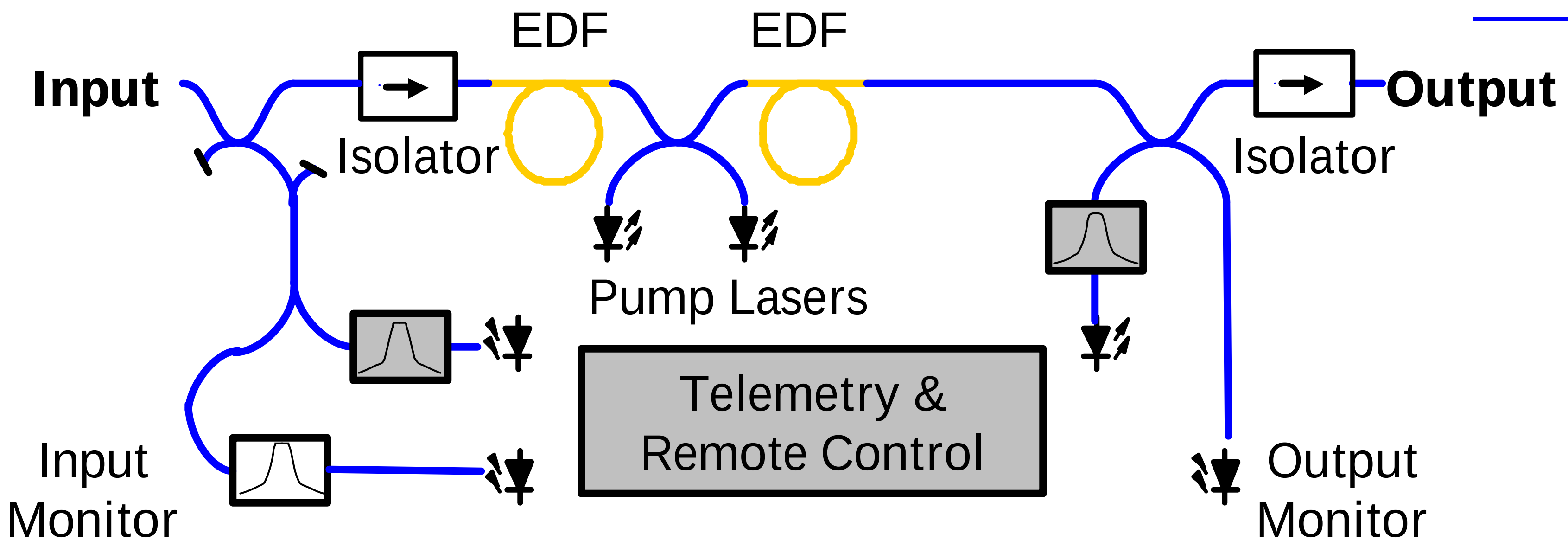


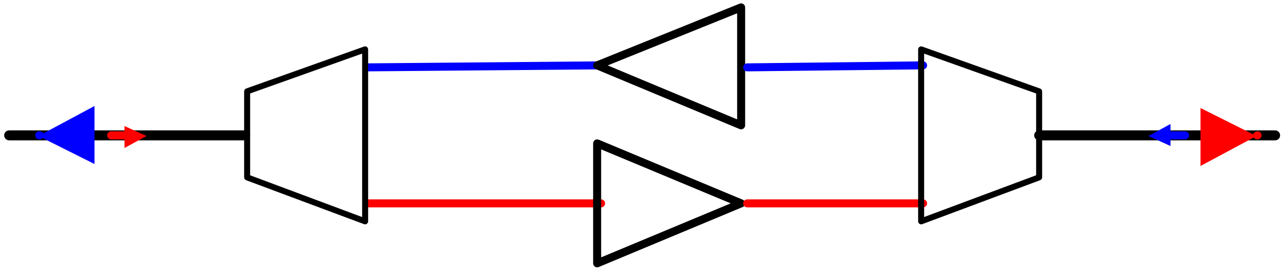
EDFA Categories

- In-line amplifiers
  - Installed every 30 to 70 km along a link
  - Good noise figure, medium output power
- Power boosters
  - Up to +17 dBm power, amplifies transmitter output
  - Also used in cable TV systems before a star coupler
- Pre-amplifiers
  - Low noise amplifier in front of receiver
- Remotely pumped
  - Electronic free extending links up to 200 km and more (often found in submarine applications)



Commercial Designs





Security Features

- Input power monitor
  - Turning on the input signal can cause high output power spikes that can damage the amplifier or following systems
  - Control electronics turn the pump laser(s) down if the input signal stays below a given threshold for more than about 2 to 20 µs
- Backreflection monitor
  - Open connector at the output can be a laser safety hazard
  - Straight connectors typically reflect 4% of the light back
  - Backreflection monitor shuts the amplifier down if backreflected light exceeds certain limits

Other Amplifier Types

- Semiconductor Optical Amplifier (SOA)
  - Basically a laser chip without any mirrors
  - Metastable state has nanoseconds lifetime (-> nonlinearity and crosstalk problems)
  - Potential for switches and wavelength converters

- Praseodymium-doped Fiber Amplifier (PDFA)
  - Similar to EDFAs but 1310 nm optical window
  - Deployed in CATV (limited situations)
  - Not cost efficient for 1310 telecomm applications
  - Fluoride based fiber needed (water soluble)
  - Much less efficient (1 W pump @ 1017 nm for 50 mW output)

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Future Developments

- Broadened gain spectrum
  - 2 EDFs with different co-dopants (phosphor, aluminum)
  - Can cover 1525 to 1610 nm
- Gain flattening
  - Erbium Fluoride designs (flatter gain profile)
  - Incorporation of Fiber Bragg Gratings (passive compensation)
- Increased complexity
  - Active add/drop, monitoring and other functions

Review Questions

1. What components do you need to build an EDFA?

2. What is ASE?

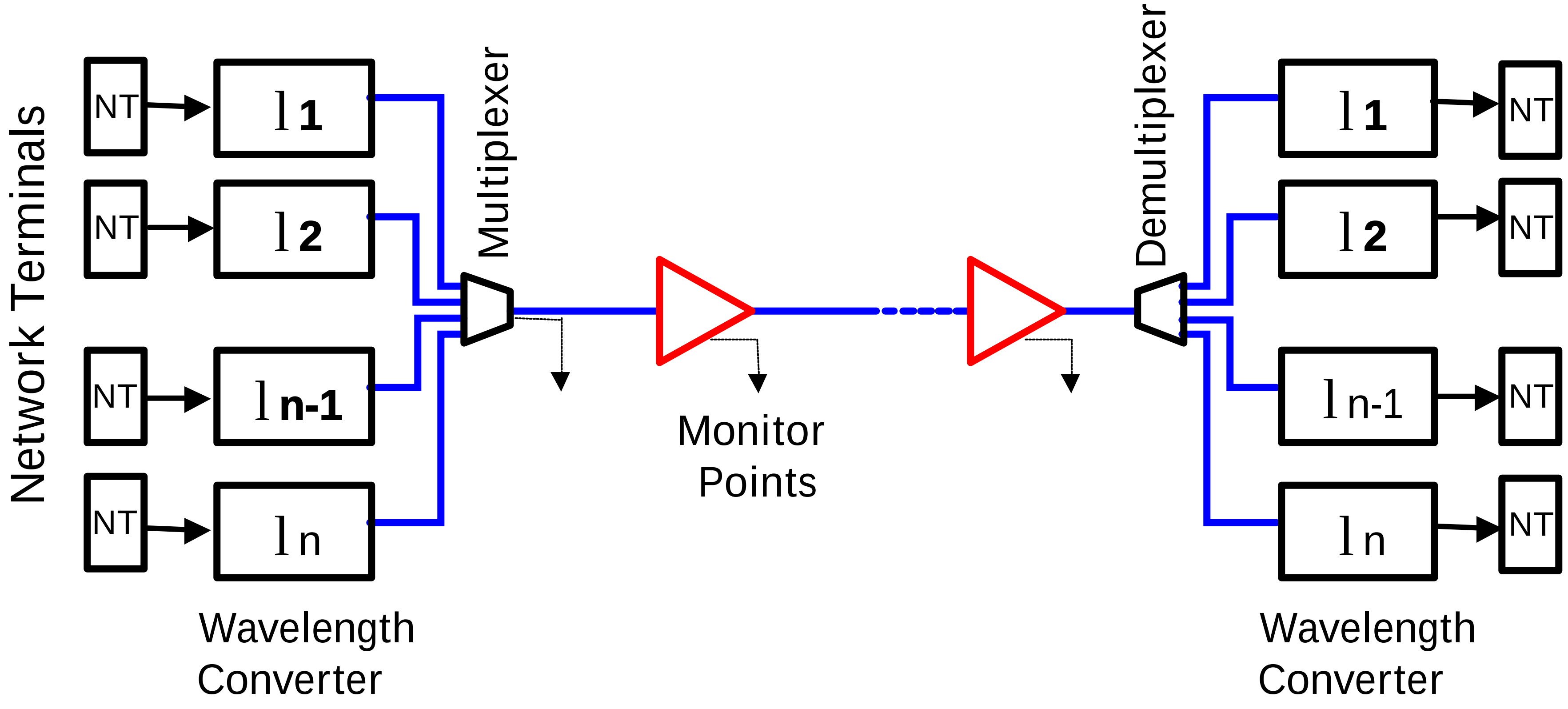
3. How do you saturate an amplifier?

LW Technology

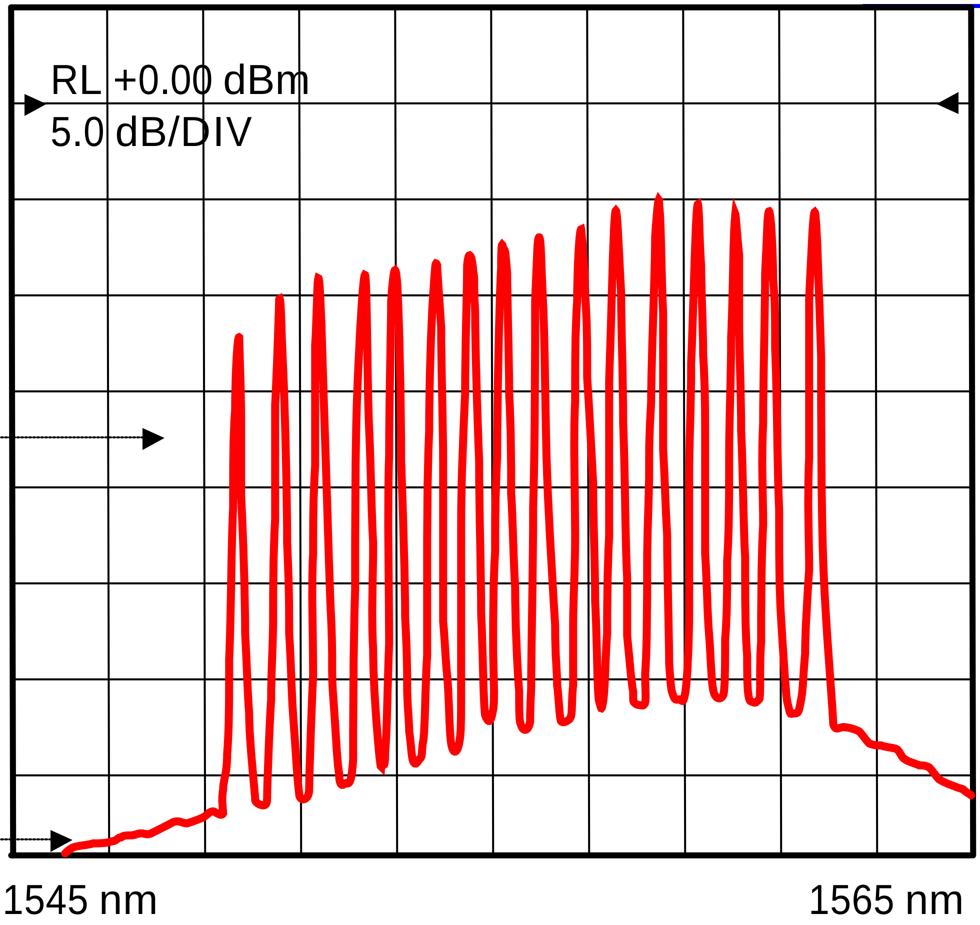
Wavelength-Division Multiplexing

Basic Design

(Dense Wavelength-Division Multiplexing)



DWDM Spectrum



Channels: 16
Spacing: 0.8 nm

Amplified Spontaneous Emission (ASE)

WDM Standards

- ITU-T draft Rec. G.mcs:
  “Optical Interfaces for Multichannel Systems
  with Optical Amplifiers”
  - Wavelength range 1532 to 1563 nm
  - 100 GHz (0.8 nm) channel spacing, 50 GHz proposed
  - 193.1 THz (1552.51 nm) reference
- ITU-T draft Rec. G.onp:
  “Physical Layer Aspects of Optical Networks”
  - General and functional requirements

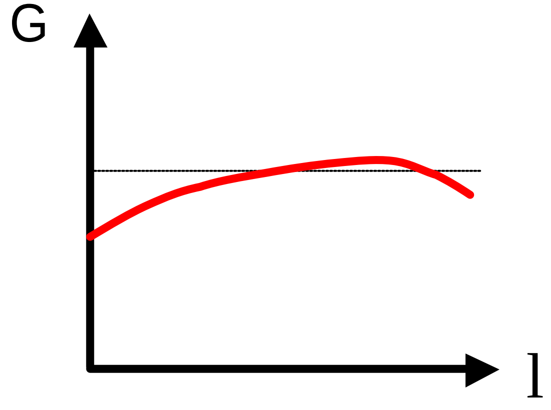
EDFAs In DWDM Systems

Optical amplifiers in DWDM systems require special considerations because of:

- Gain flatness (gain tilt) requirements
- Gain competition
- Nonlinear effects in fibers

Gain Flatness (Gain Tilt)

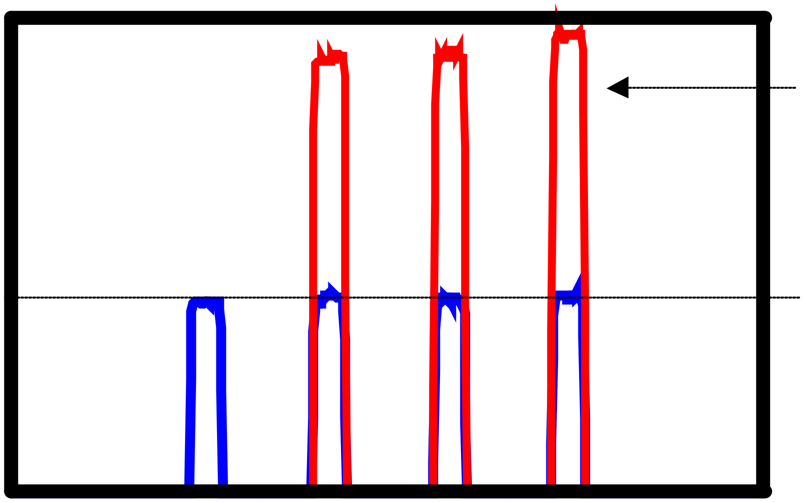
- Gain versus wavelength
  - The gain of optical amplifiers depends on wavelength
  - Signal-to-noise ratios can degrade below acceptable levels (long links with cascaded amplifiers)



- Compensation techniques
  - Signal pre-emphasis
  - Gain flattening filters
  - Additional doping of amplifier with Fluorides

Gain Competition

- *Total* output power of a standard EDFA remains almost constant even if input power fluctuates significantly
- If one channel fails (or is added) then the remaining ones increase (or decrease) their output power



Output power after channel one failed

Equal power of all four channels

Output Power Limitations

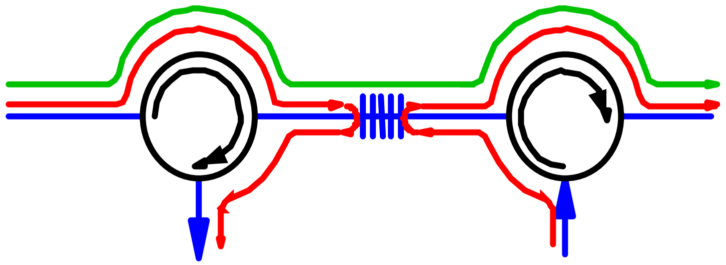
- High power densities in SM fiber can cause
  - Stimulated Brillouin scattering (SBS)
  - Stimulated Raman scattering (SRS)
  - Four wave mixing (FWM)
  - Self-phase and cross-phase modulation (SPM, CPM)
- Most designs limit total output power to +17 dBm
  - Available channel power: 50/N mW
    (N = number of channels)

DWDM Trends

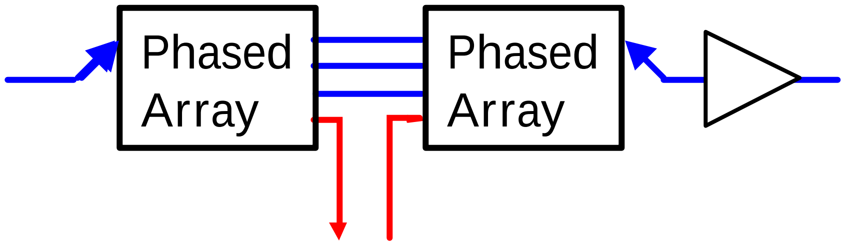
- Higher capacity
  - 120 channels for access network applications
  - 50 GHz channel spacing (25 GHz under investigation)
  - Wavelength range extended up to 1625 nm
- All optical network
  - Modulation & protocol transparency
  - Optical add/drop multiplexers
  - Optical cross-connects
  - Optical switch fabrics
  - Wavelength conversion

Add / Drop Points

- Fixed configurations
  - Simple and inexpensive
  - Inflexible



- Flexible configurations
  - Selective wavelength add/drop



Phased Array

Phased Array

- Future designs more sophisticated
  - High capacity & performance

Research Topics

- Optical cross-connects
  - Technology for large optical switches
- Network and traffic management
  - Digital versus optical routing
  - Traffic amount & network size
  - Virtual networks (private networks over public paths)
- Wavelength conversion
  - Wavelengths must be reused in large networks for optimal use of available capacity
  - Eventually has to include optical pulse regeneration (re-shaping, re-timing)

Review Questions

1. What technologies enable the use of DWDM?
2. What are the advantages of DWDM?
3. What are the disadvantages of DWDM?