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HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 4: Transmission System Engineering

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Lecture Outline

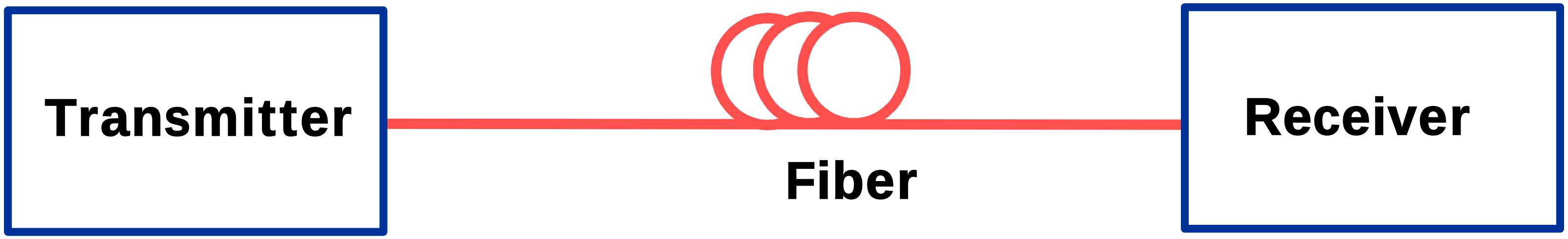
- Introduction
- Power penalty analysis
- Impairments
  - Crosstalk
  - Dispersion
  - Fiber Nonlinearities
- Design Considerations
- Conclusions

1. Introduction

- ❑ Aspects of optical transmission system engineering
  - Selection of the right fibers, transmitters, amplifiers etc.
  - Deals with various impairments or performance degradations
    - How to allocate margins (a preventive measure) for each impairment
    - How to reduce the effect of the impairments
  - Analyze tradeoffs between the different design parameters
- ❑ Target is to ensure reliable transport of information
  - Low BER, high Q-factor etc.

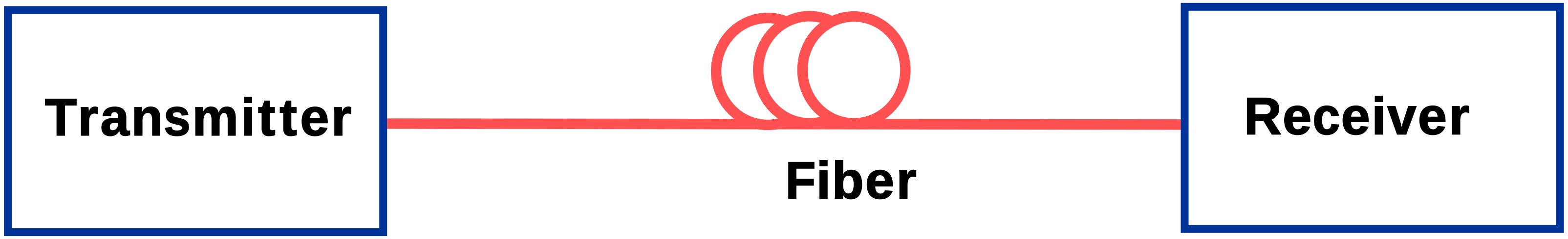
2. Link Design

- Simple fiber-optic communications link
  - Short distance
  - Low bit rate
  - Point-to-point



- Major concern is to ensure sufficient received optical signal power
  - Link power budget analysis

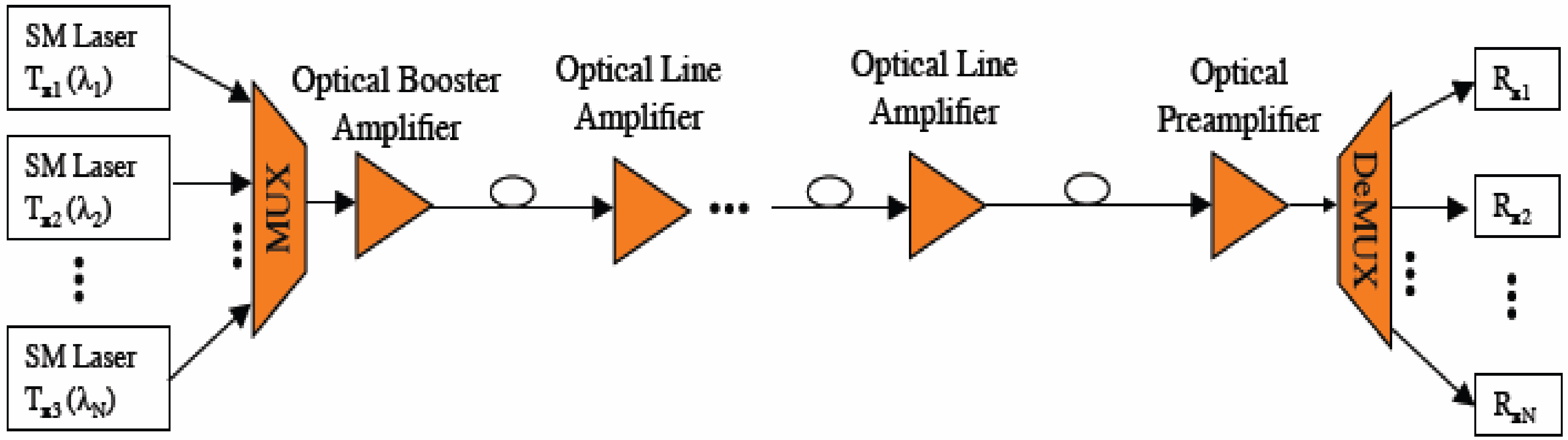
2.1 Link Power Budget



Item	Value	dB value
Transmitter: *1a) Average output power*	1.0 mW	0.0 dBm
Channel: *2a) Propagation losses* (10 km)	0.2 dB/km	-20.0 dB
Receiver: *3a) Signal power at receiver* *3b) Receiver sensitivity*		-20.0 dBm -30.0 dBm
Link Margin (Power Margin)	= (3a – 3b)	+10.0 dB

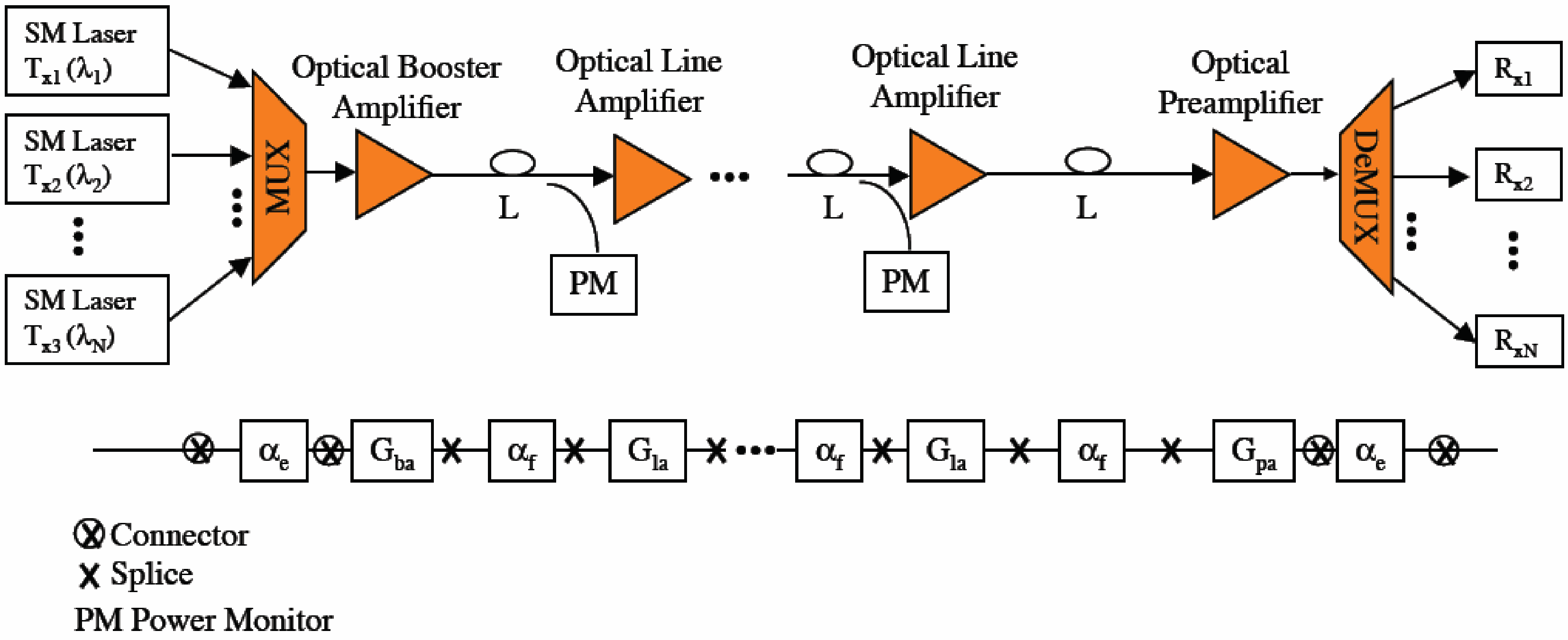
2.1 Link Power Budget

- A typical amplified WDM link includes:
  - Optical transmitters and receivers (1 each per wavelength)
  - Wavelength multiplexer and demultiplexers
  - Optical amplifiers
    - Boost amplifier: to increase the output power
    - Line amplifier: to compensate for fiber losses
    - Preamplifier: to improve receiver sensitivity



2.1 Link Power Budget

- ❑ A power budget for an amplified WDM link more detailed

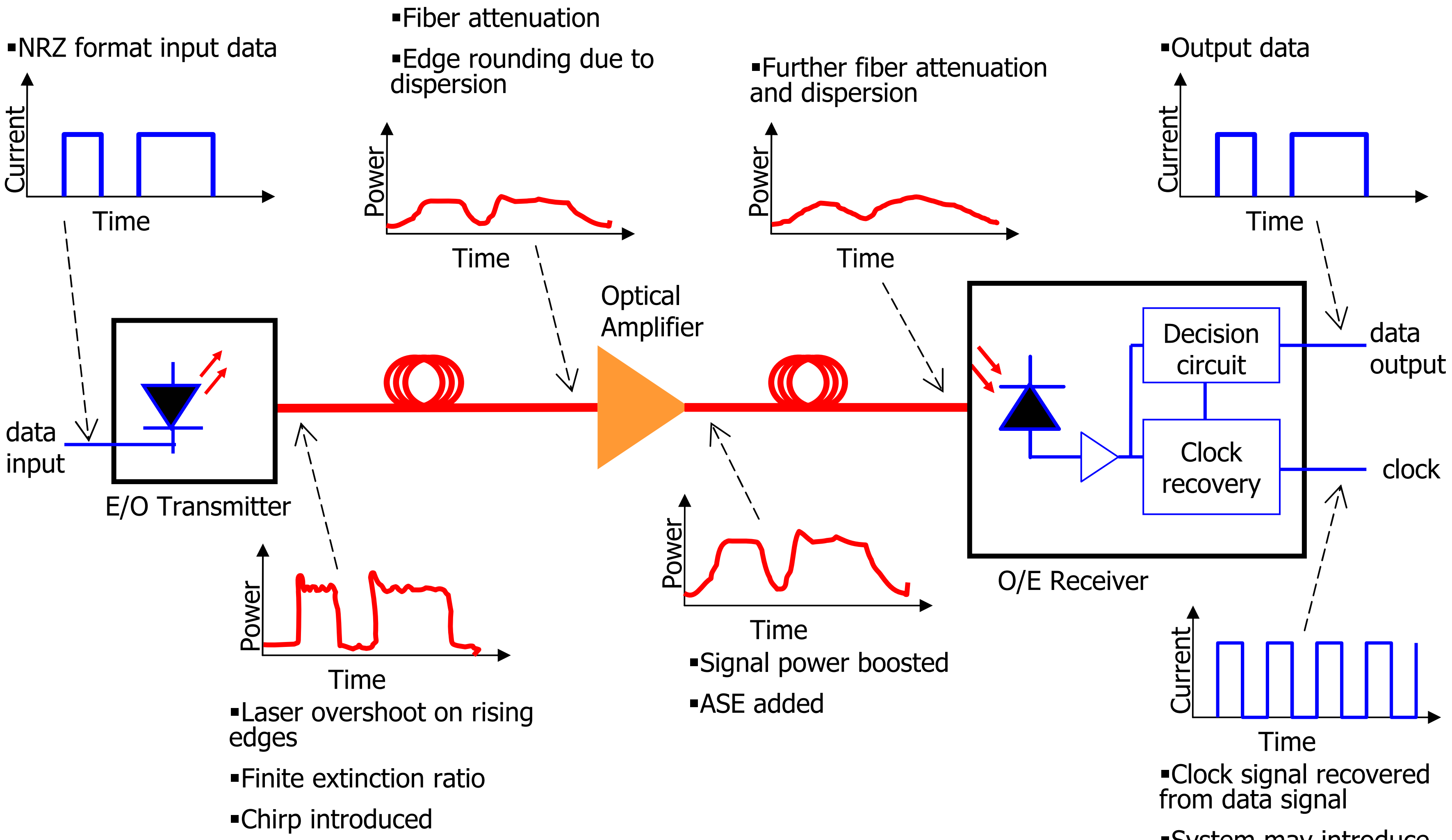


$$P_{rec} = P_{trans} - \alpha_{fiber} L_{total} - N_{conn}\alpha_{conn} - N_{splice}\alpha_{splice} - N_{PM}\alpha_{PM} - \sum \alpha_{excess} - \sum \alpha_{PDL} + \sum G_{OA} - \sum PP - M_{System}$$

2.2 Detailed Link Design

- ☐ In an amplified WDM link there is more to worry about than just the power budget
- ☐ Other signal impairment effects have to be considered

2.2 Detailed Link Design



- NRZ format input data

- Fiber attenuation
- Edge rounding due to dispersion

- Further fiber attenuation and dispersion

- Output data

- Laser overshoot on rising edges
- Finite extinction ratio
- Chirp introduced

- Signal power boosted
- ASE added

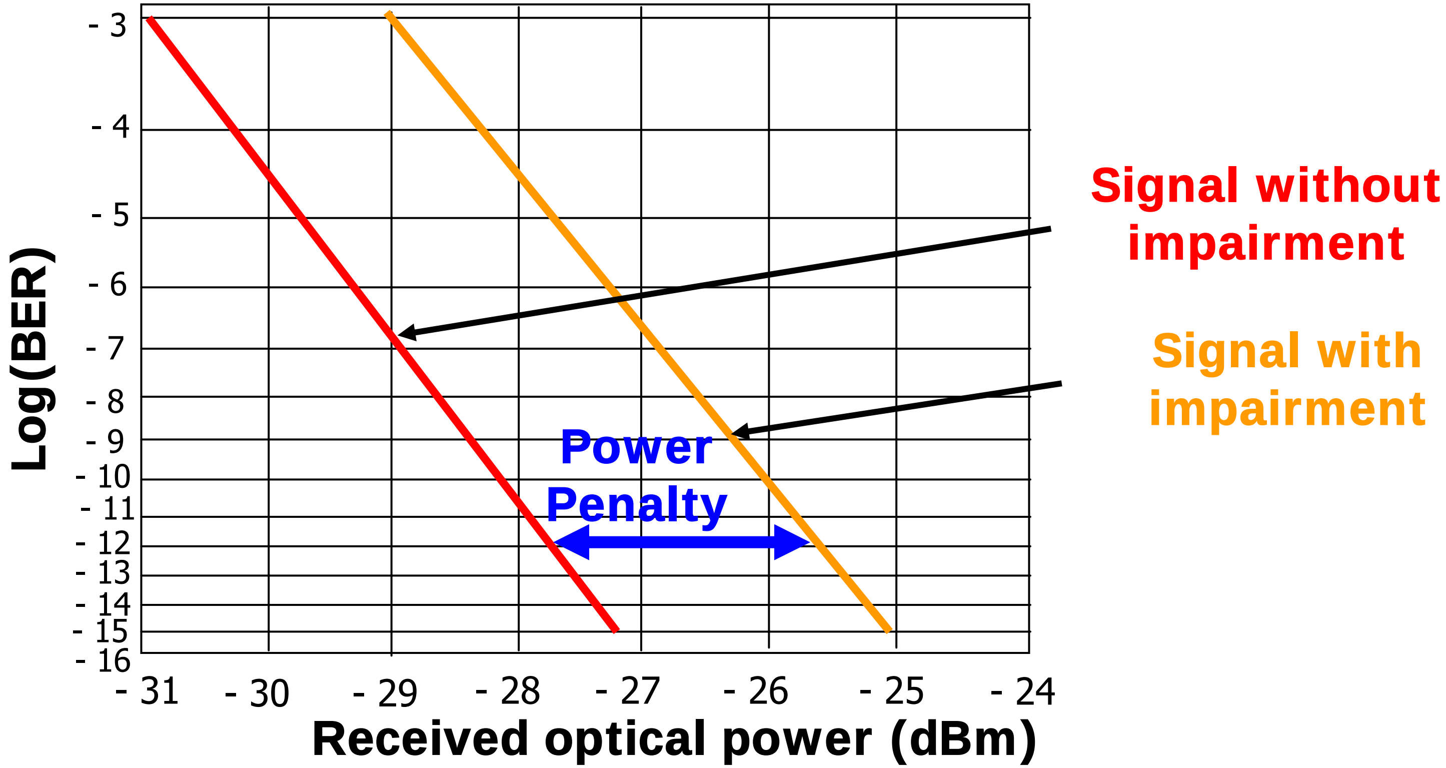
- Clock signal recovered from data signal
- System may introduce timing errors

Figure: Impairments in a simple digital fiber-optic communication link.

2.3 Power Penalty Analysis

- Each impairment results in a power penalty
  - The required increase in received signal power (in dB) to maintain a required BER performance in presence of an impairment
  - Reduction in electrical signal-to-noise ratio (Q-factor) attributed to a specific impairment
- Design of a link affected by multiple impairments requires a power penalty analysis

2.3 Power Penalty Analysis



2.3 Power Penalty Analysis

- ☐ Recall:

$$BER = Q\left(\frac{I_1 - I_0}{\sigma_1 + \sigma_0}\right)$$

$$= Q\left(\frac{R\left(P_1 - P_0\right)}{\sigma_1 + \sigma_0}\right)$$

2.3 Power Penalty Analysis

- Power penalty (PP) ⇒ ratio of the arguments of the $Q(\cdot)$ for the two cases (with and without impairments)

$$PP = -10\log\left[\frac{\left(\dfrac{R\left(P_1' - P_0'\right)}{\sigma_1' + \sigma_0'}\right)}{\left(\dfrac{R\left(P_1 - P_0\right)}{\sigma_1 + \sigma_0}\right)}\right]$$

with impairments

without impairments

2.3 Power Penalty Analysis

❑ Ideal transmission system

- No impairments
- Then example: BER = 10^{-12} ⇨ Q-factor=17 dB

❑ Practical transmission system

- Impairments exist (e.g. dispersion, imperfect devices) ⇒ cause power penalties
- Each penalty calculated assuming rest of system is ideal

2.3 Power Penalty Analysis

- ☐ Each impairment assigned its own PP
- ☐ This is an approximate design method because some impairments are related to each other

Impairment	Allocation (dB)
Ideal Q-factor	17
Transmitter	1
Crosstalk	1
Dispersion	2
Nonlinearities	1
Polarization dependent losses	3
Component ageing	3
System margin	3
Required Q-factor	31

3. Transmitter

- System design parameters related to transmitters include:
  - Output power (usually 1-10 mW)
  - Side-mode suppression ratio
  - Modulation type
  - Relative intensity noise (RIN)
  - Wavelength stability and accuracy
    - Example: DFB lasers have a 0.1 nm/°C temperature coefficient
    - Laser output wavelength may also drift due to ageing effects
    - Advanced lasers are packaged devices for monitoring and adjusting temperature and wavelength

3. Transmitters

- Extinction ratio *r*

$$r = \frac{P_1 \text{ Power to transmit “1”}}{P_0 \text{ Power to transmit “0”}}$$

  - Ideally it is assumed that $P_1 > 0$ and $P_0 = 0$ giving $r = \infty$
  - In practice *r* is between 10 and 20 (ITU recommends ≥ 12 dB)
  - Reducing extinction ratio reduces power difference between “1” and “0” levels
  - Produces a power penalty relative to ideal system ($r = \infty$)

3. Transmitters

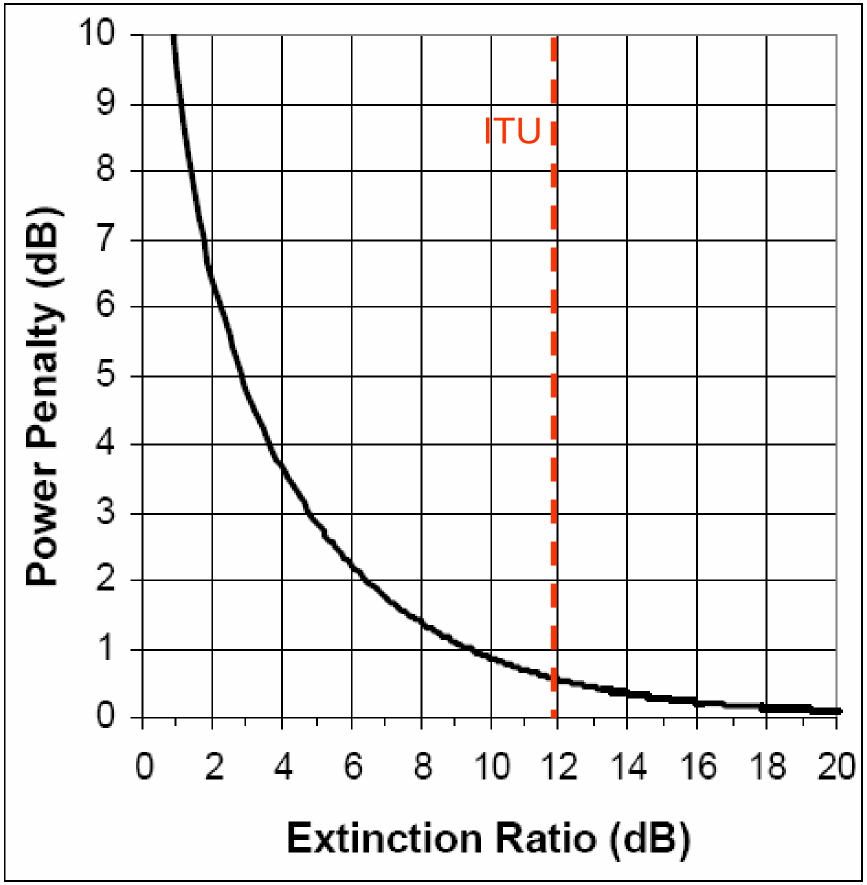


Figure 4. Power penalty vs. extinction ratio (dB ratios)

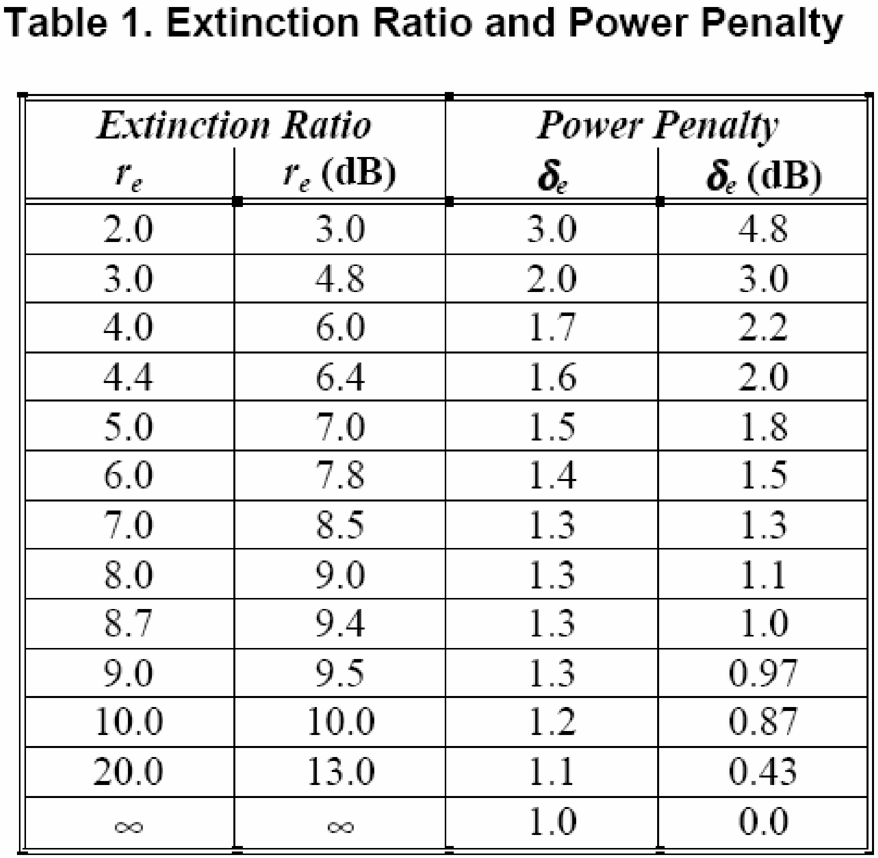


Table 1. Extinction Ratio and Power Penalty

Extinction Ratio		*Power Penalty*	
r_e	r_e (dB)	δ_e	δ_e (dB)
2.0	3.0	3.0	4.8
3.0	4.8	2.0	3.0
4.0	6.0	1.7	2.2
4.4	6.4	1.6	2.0
5.0	7.0	1.5	1.8
6.0	7.8	1.4	1.5
7.0	8.5	1.3	1.3
8.0	9.0	1.3	1.1
8.7	9.4	1.3	1.0
9.0	9.5	1.3	0.97
10.0	10.0	1.2	0.87
20.0	13.0	1.1	0.43
∞	∞	1.0	0.0

Source: MAXIM APPLICATION NOTE 596HFAN-02.2.0: “Extinction Ratio and Power Penalty,” 2001.

4. Receivers

- Key systems parameters associated with a receiver are:
    - Receiver sensitivity ⇒ required mean received optical power to achieve a certain BER
    - Overload parameter ⇒ maximum acceptable receiver input power

4. Receivers

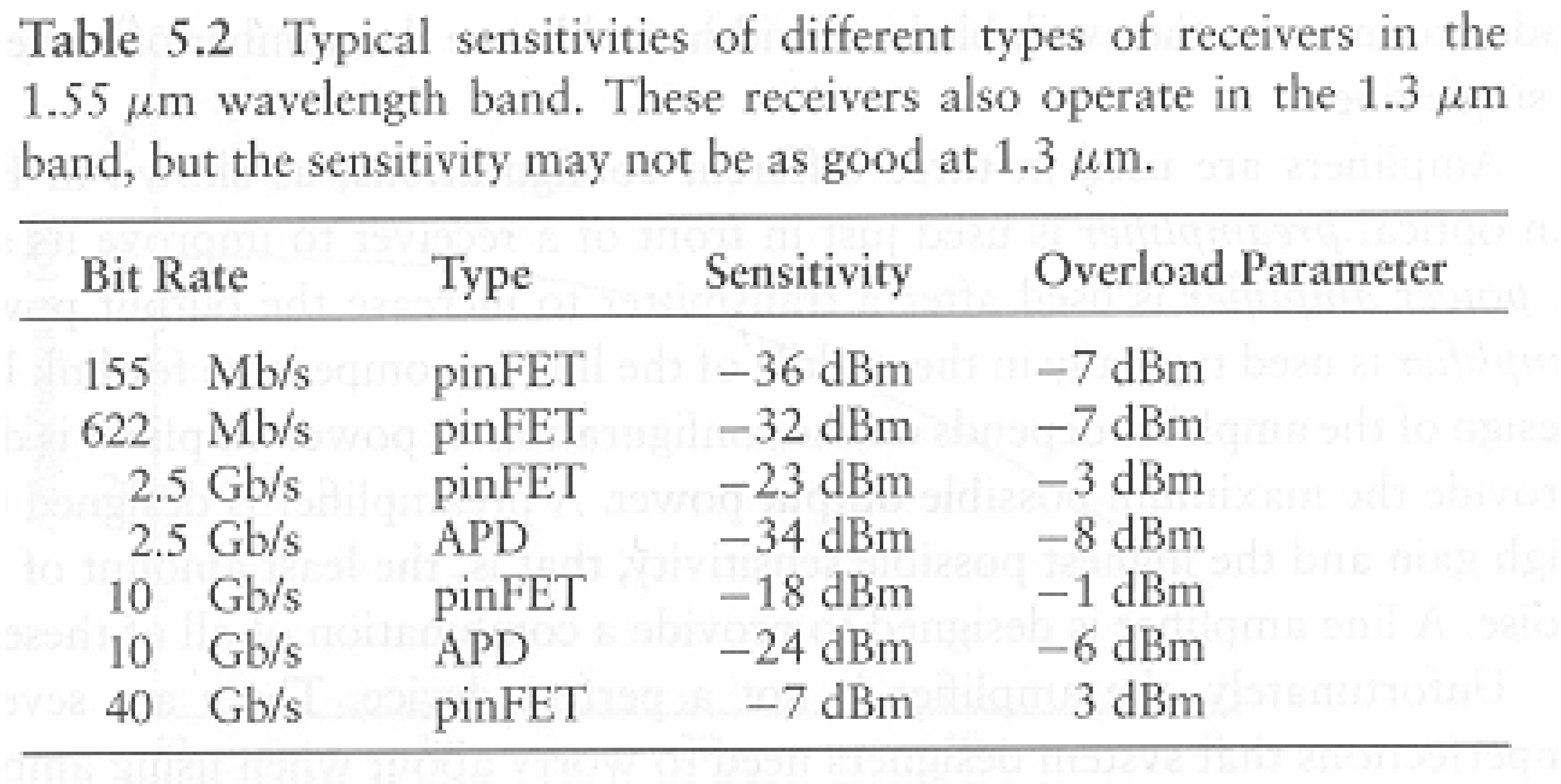
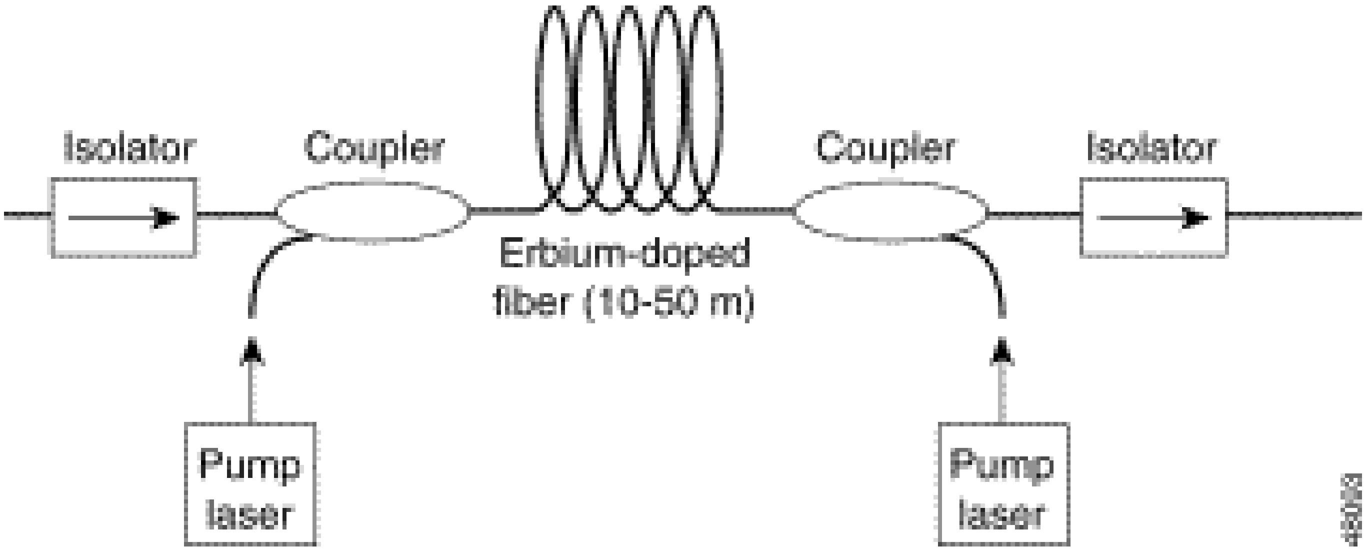


Table 5.2 Typical sensitivities of different types of receivers in the 1.55 μm wavelength band. These receivers also operate in the 1.3 μm band, but the sensitivity may not be as good at 1.3 μm.

Bit Rate	Type	Sensitivity	Overload Parameter
155 Mb/s	pinFET	−36 dBm	−7 dBm
622 Mb/s	pinFET	−32 dBm	−7 dBm
2.5 Gb/s	pinFET	−23 dBm	−3 dBm
2.5 Gb/s	APD	−34 dBm	−8 dBm
10 Gb/s	pinFET	−18 dBm	−1 dBm
10 Gb/s	APD	−24 dBm	−6 dBm
40 Gb/s	pinFET	−7 dBm	3 dBm

5. Optical Amplifiers

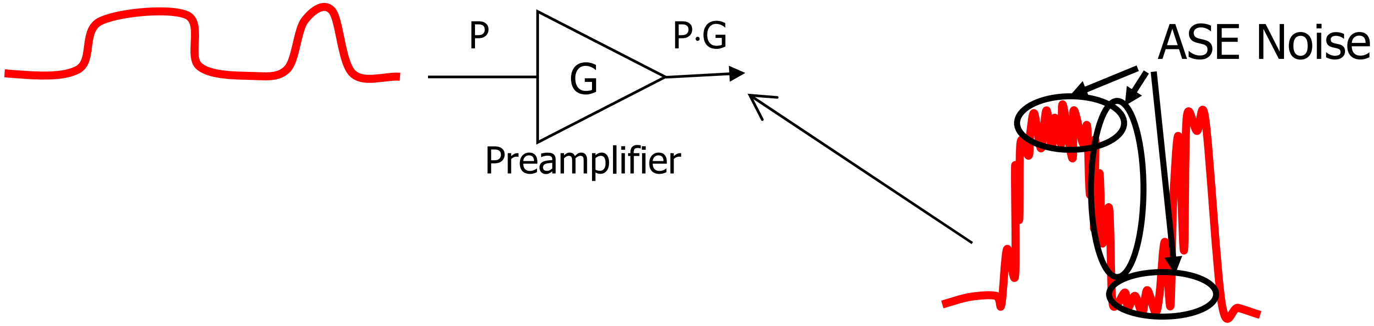
- Most common is erbium-doped fiber amplifier (EDFA) operating C-band (1530-1565 nm)
  - L-band EDFAs (1565-1625 nm) amplifiers used today to increase bandwidth
  - Raman amplifiers compliment EDFAs in long haul links



5. Optical Amplifiers

❑ EDFAs have several major imperfections:

- Produce ASE noise in addition to providing gain
- Gain not flat over entire transmission window
- Gain depends on the total input power



5.1 Gain Saturation

- There is a limit on the output power of an EDFA
  - Gain saturation ⇒ depends on pump power and amplifier design
  - EDFAs also operate in saturation but designer should be aware that gain is less

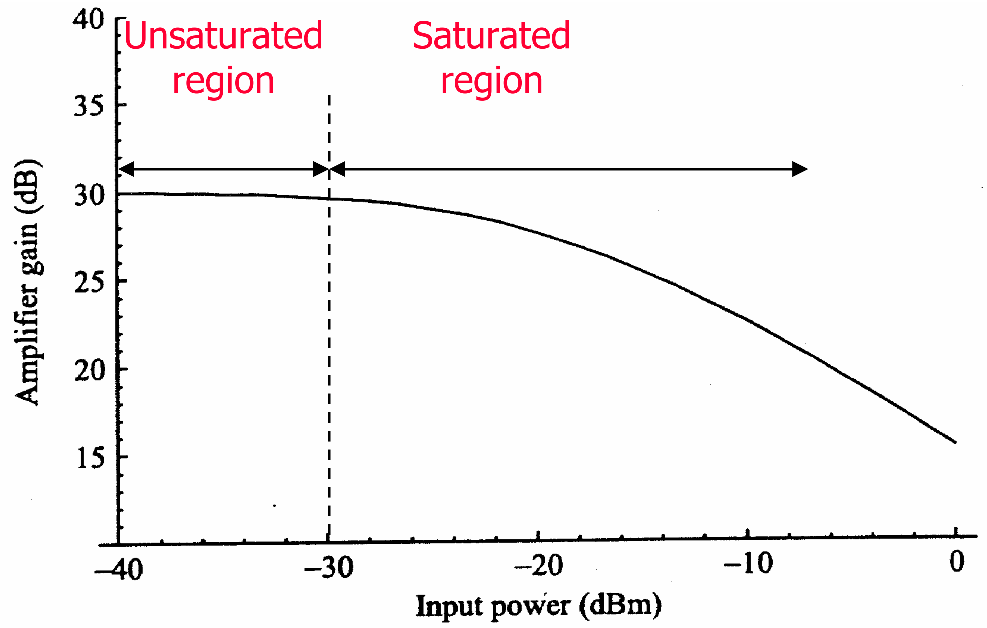


Fig: Gain characteristics of an EDFA with G_{max} = 30dB and P_{sat} = 10 dBm

5.2 Gain Equalization

- ❑ EDFA gain spectrum is not flat particularly in lower part of C-band window

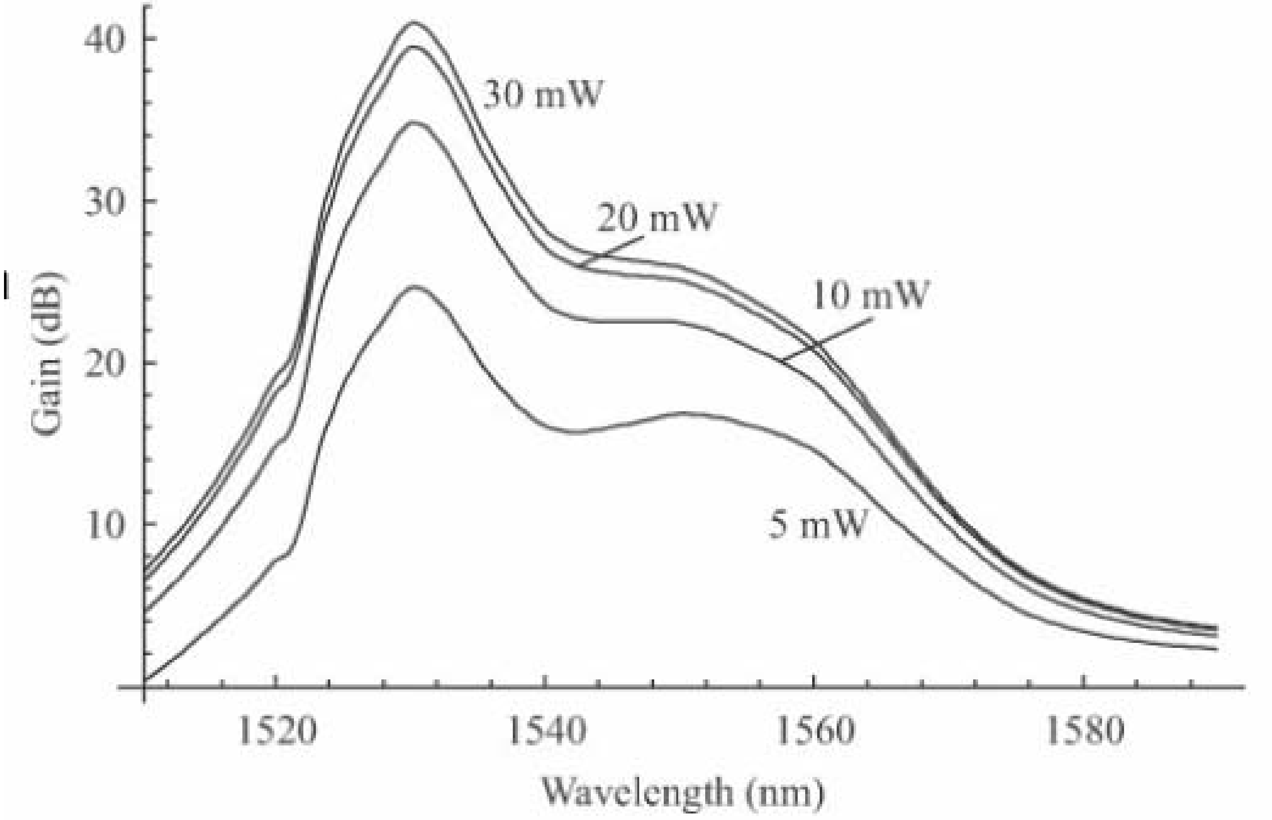


Figure: EDFA gain for different pump powers.

5.2 Gain Equalization

- Effects of non-flat gain spectrum become more significant for cascaded EDFAs

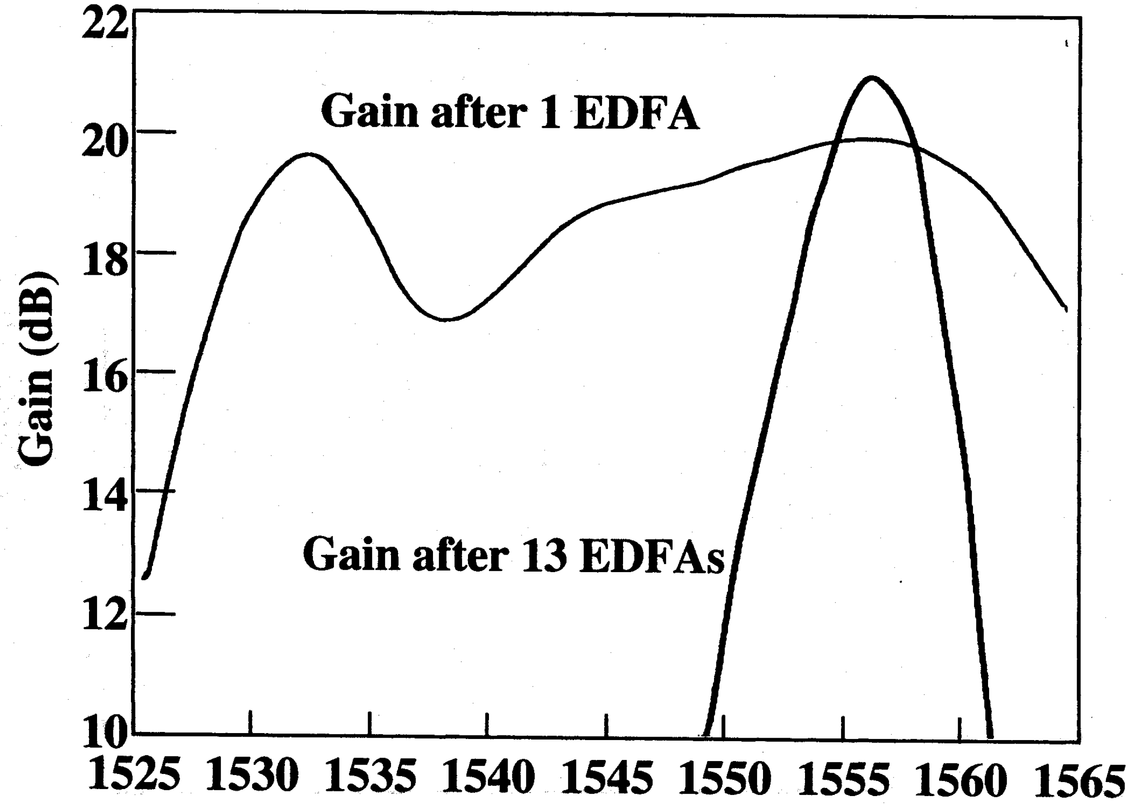


Figure: Gain windows for 1 EDFA and a cascade of 13 EDFAs.

5.2 Gain Equalization

- Other EDFA gain equalization methods
  - Pre-equalization or pre-emphasis
    - Channels that see lower gain are launched with higher power (see next slide)
    - Amount of equalization that can be done is limited
    - Only suitable for point-to-point links
  - Equalizers introduced after each amplifier stage (see next slide)
    1. Demultiplex and attenuate channels ⇒ Cumbersome, inflexible
    2. Tunable multichannel filters ⇒ Extra powering needed for control

5.2 Gain Equalization

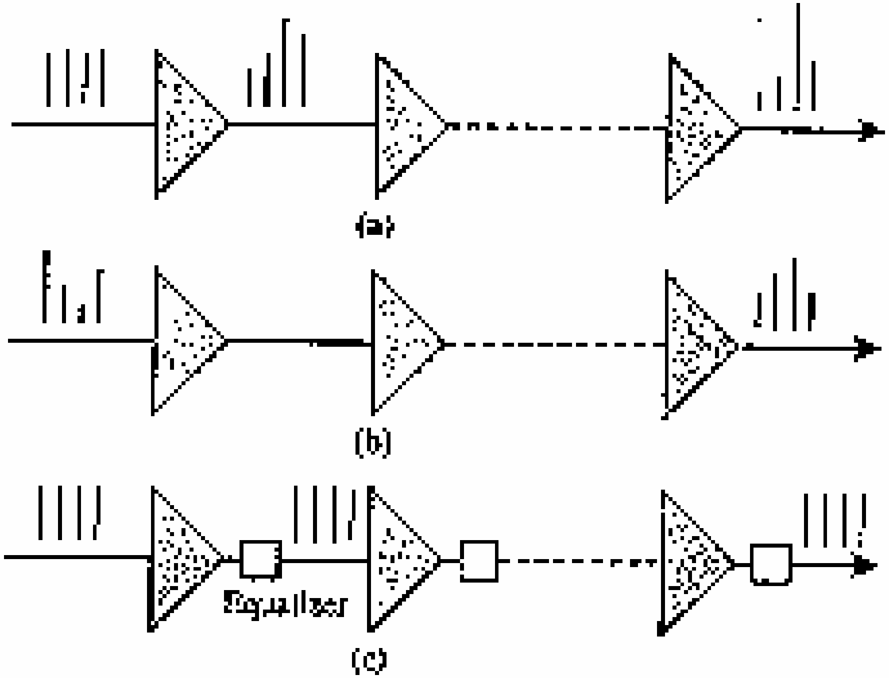


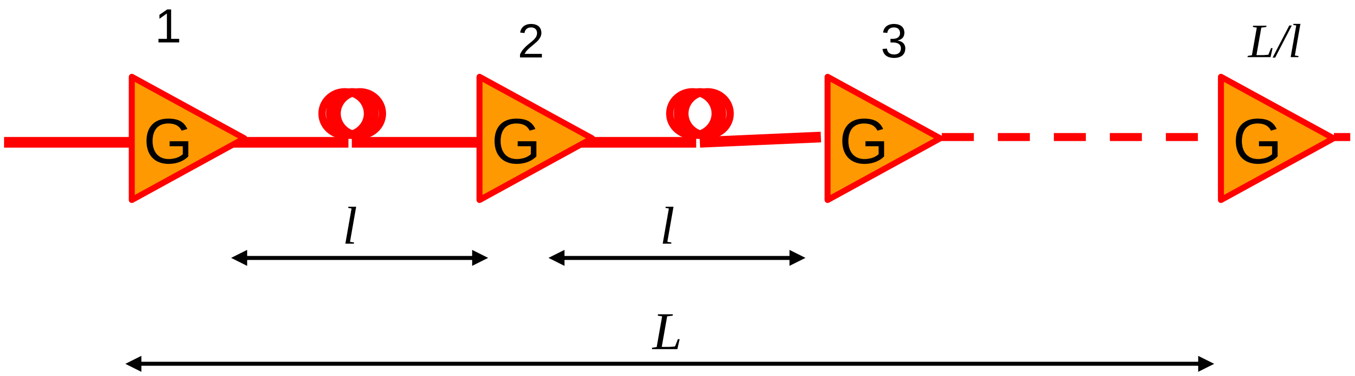
Figure 5.4 Effect of unequal amplifier gains at different wavelengths. (a) A set of channels with equal powers at the input to a cascaded system of amplifiers will have vastly different powers and signal-to-noise ratios at the output. (b) This effect can be reduced by preequalizing the channel powers. (c) Another way to reduce this effect is to introduce equalization at each amplifier stage. The equalization can be done using a filter inside the amplifier as well.

5.2 Gain Equalization

- ❑ Preferred EDFA gain equalization method ⇨ use shaping optical filter within the EDFA
  - Flatness over a wide wavelength range
  - Loss introduced by filter reduces power output and increased noise figure

5.3 Amplifier Cascades

❑ Longer fiber links would require several amplification stages to maintain signal power
  - Cascaded amplifiers
  - Gain of amplifier to compensate for loss of preceding fiber stage



5.3 Amplifier Cascades

- Optical signal to noise ratio (OSNR) a useful performance parameter
  - Accumulation of ASE noise ⇒ reduced OSNR

$$P_{\text{noise}}^{\text{tot}} = P_{ASE} \cdot L/l$$

$$\text{and OSNR} = P_{rec} \Big/ P_{\text{noise}}^{\text{tot}}$$

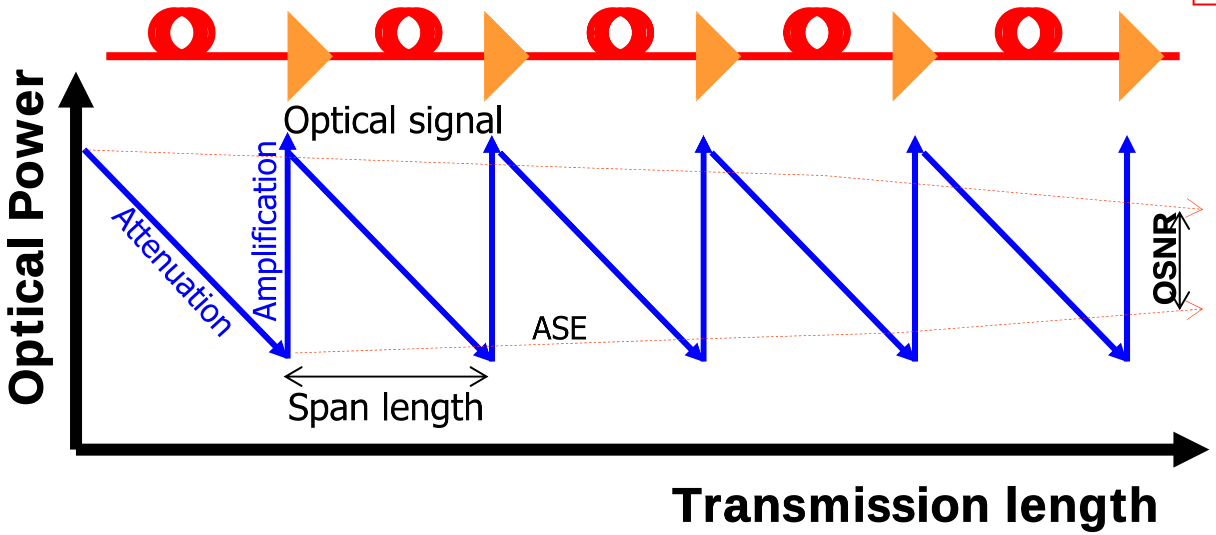


Figure : ASE accumulation and OSNR reduction in an amplified transmission system

5.4 Amplifier Spacing Penalty

- Ideally minimum ASE noise power when amplifier cascade has perfectly distributed gain ⇒ $G = 1$
  - Power penalty for using lumped amplifiers ($G > 1$) instead of ideal distributed gain amplifier

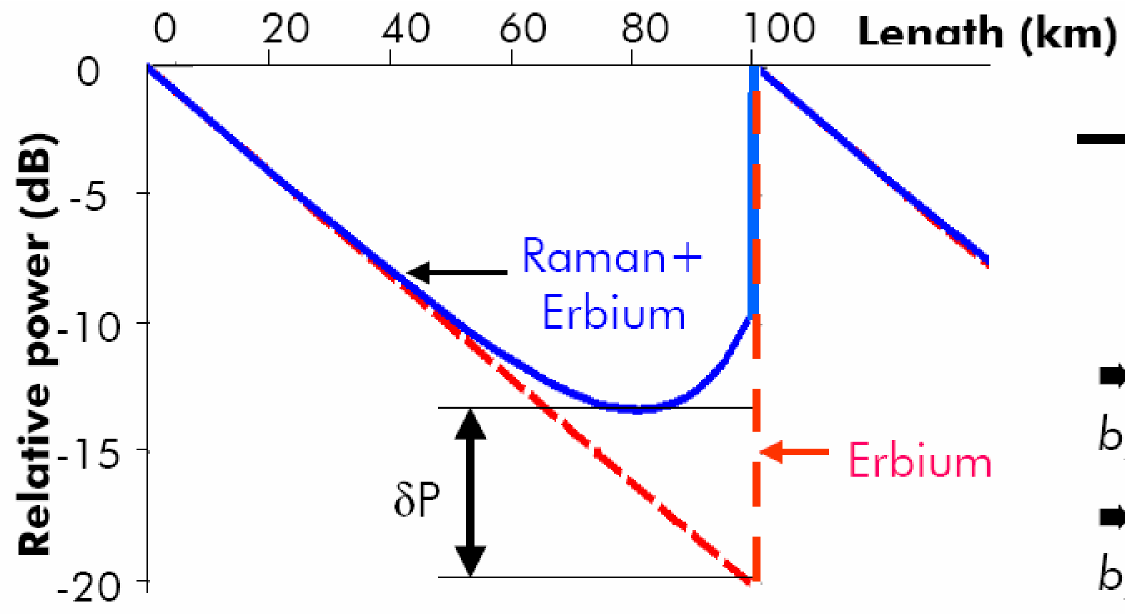
$$\boxed{PP_{\text{lumped}} = \frac{G-1}{\ln G}}$$

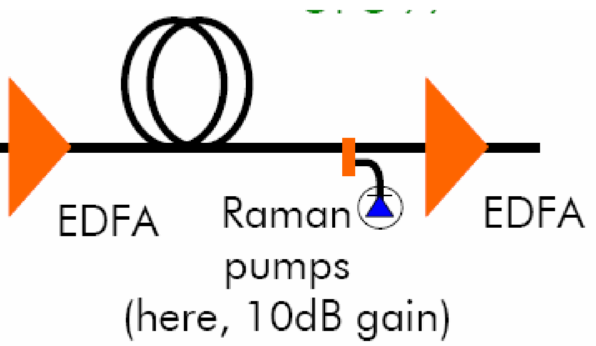
- Example: $PP_{\text{lumped}} = 0$ dB for $G = 1$
- Example: $PP_{\text{lumped}} = 13.3$ dB for $G = 20$ dB, $PP_{\text{lumped}} = 5.9$ dB for $G = 10$ dB

- Reducing gain (amplifier spacing) ⇨ reduces PP_{lumped}
  - But increases costs ⇒ More amplifiers huts required

5.4 Amplifier Spacing Penalty

- When distributed amplification is used
  - Continuous amplification as signal propagates along fiber
  - Reduces need to increase EDFAs and minimizes ASE
  - Example: EDFAs assisted by Raman amplification





➨ *Cumulated noise reduced by ~δP (e.g. 3-5dB)*

➨ *Margins improved by approx. the same amount.*

Multi-terabit/s optical transmission S. Bigo,
UTP/L/04/0070

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5.5 Power Transients and AGC

- Important to consider in WDM systems with EDFA cascades
  - If some channels fail or are OFF ⇒ Surviving channels see more gain and arrive with higher power at receiver
  - Setting up or taking down new channel(s) affect power levels on existing channels

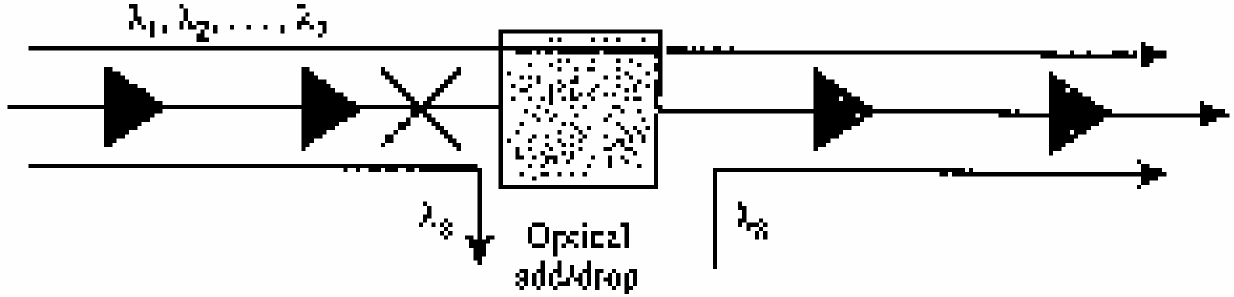


Figure 5.7 Illustrating the impact of failures in a network with optical amplifiers.

5.5 Power Transients and AGC

- ☐ Automatic gain control (AGC)
- ☐ Maintain EDFA output power
  - Tapping and monitoring input and/or output
  - Vary pump power

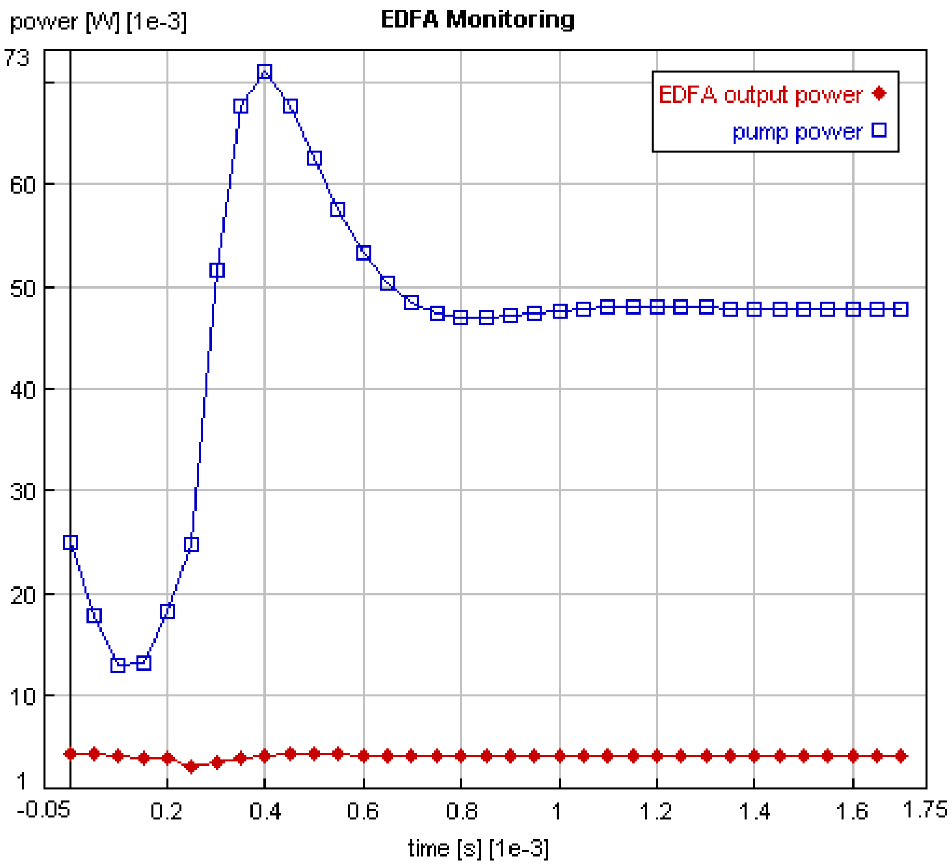


Figure: Power pump adjustment to maintain EDFA output power in a 4-channel WDM system

6. Crosstalk

❑ Interference between channels in WDM systems

- Introduced by signal leakages from various components
- Interchannel crosstalk ⇒ crosstalk and desired signal have different wavelengths

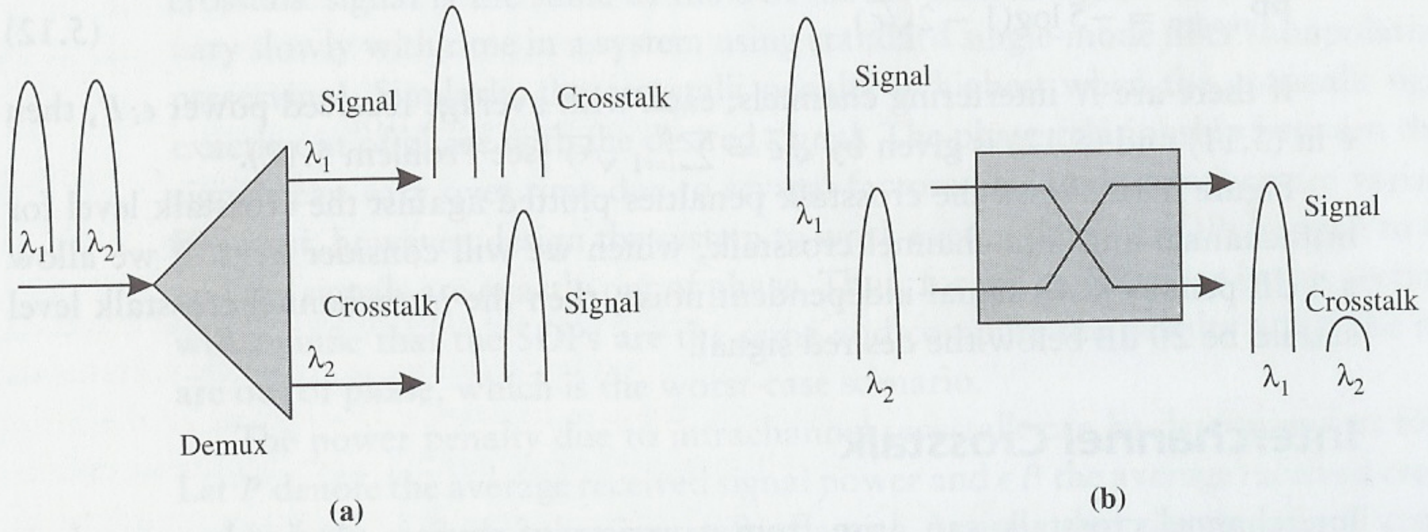


Figure 5.11 Sources of interchannel crosstalk. (a) An optical demultiplexer, and (b) an optical switch with inputs at different wavelengths.

6. Crosstalk

- Intrachannel crosstalk ⇒ crosstalk and desired signal have similar wavelengths

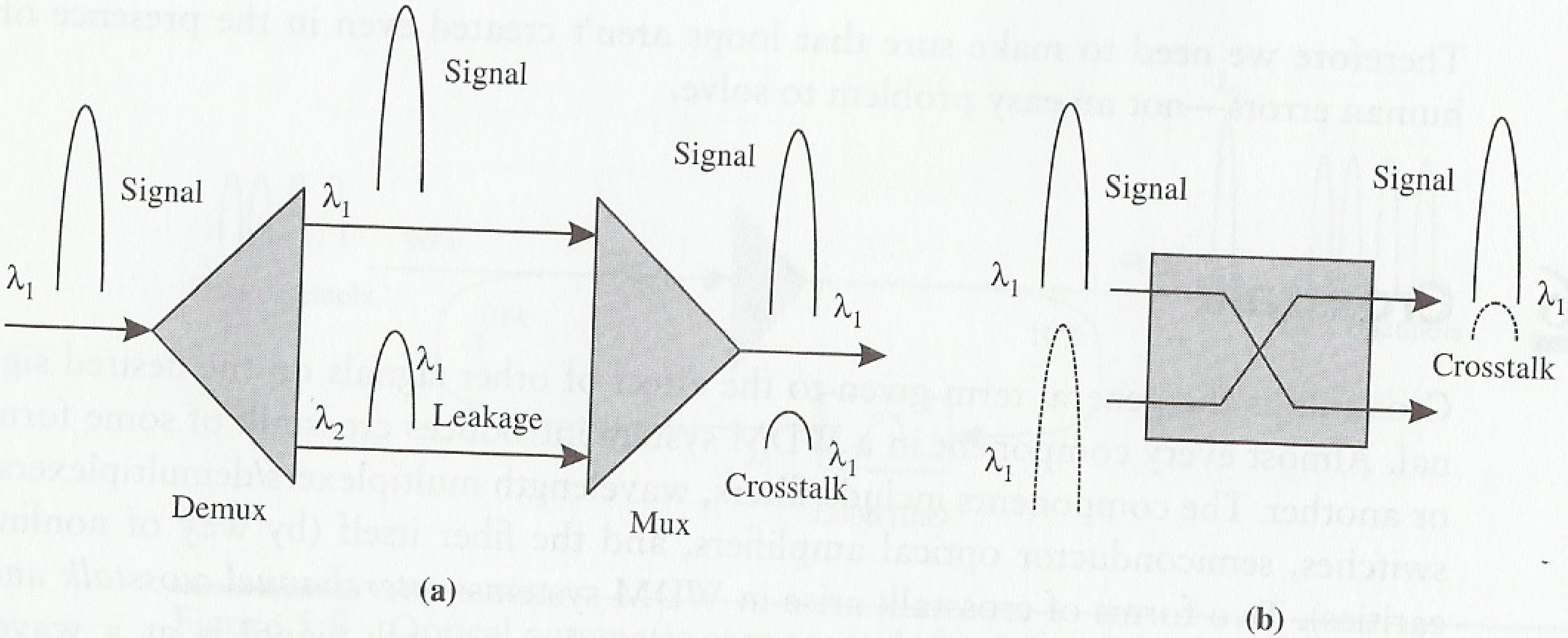
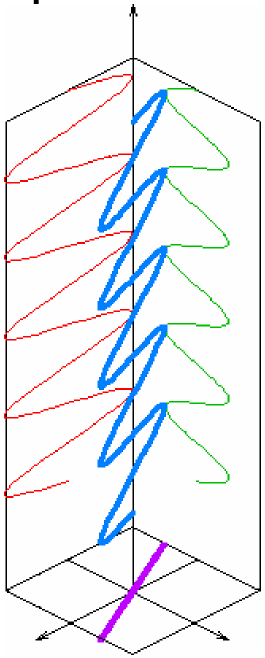


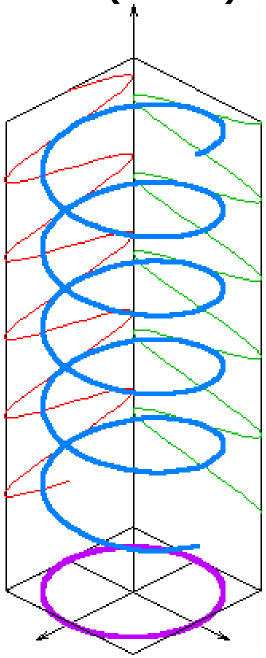
Figure 5.9 Sources of intrachannel crosstalk. (a) A cascaded wavelength demultiplexer and a multiplexer, and (b) an optical switch.

6.1 Worst Case Crosstalk

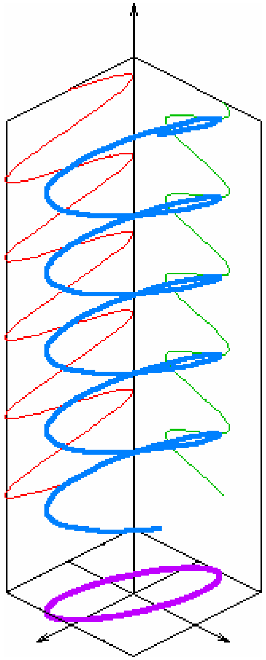
- Analysis of crosstalk PP dependant on polarization (orientation) and phase of interfering signals
  - Light waves in singlemode fibers are linearly polarized
  - Projected on to 2 equal orthogonal components (X and Y) or principal states of polarization (SOP)



Linear polarization



Circular polarization

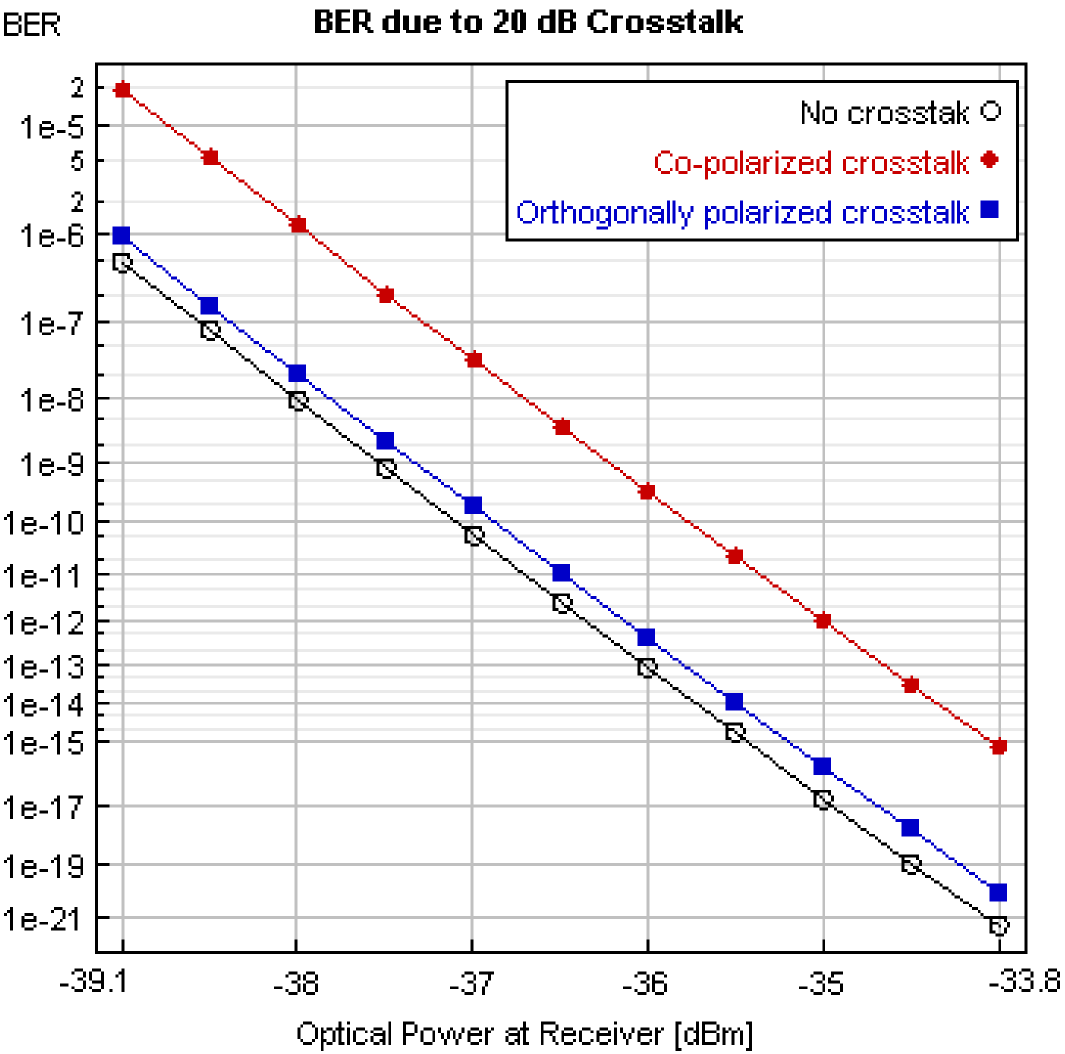


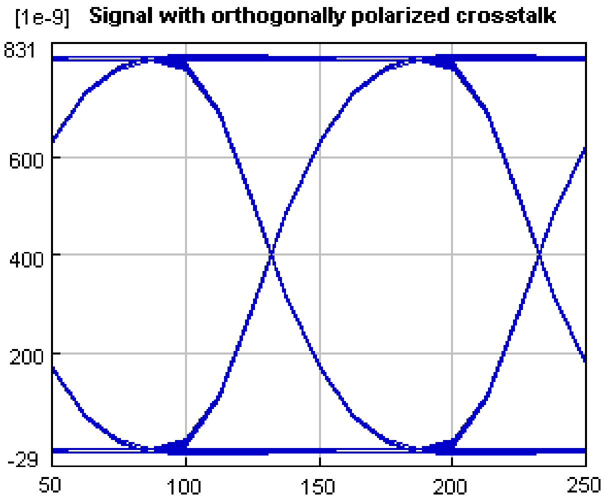
Elliptical polarization

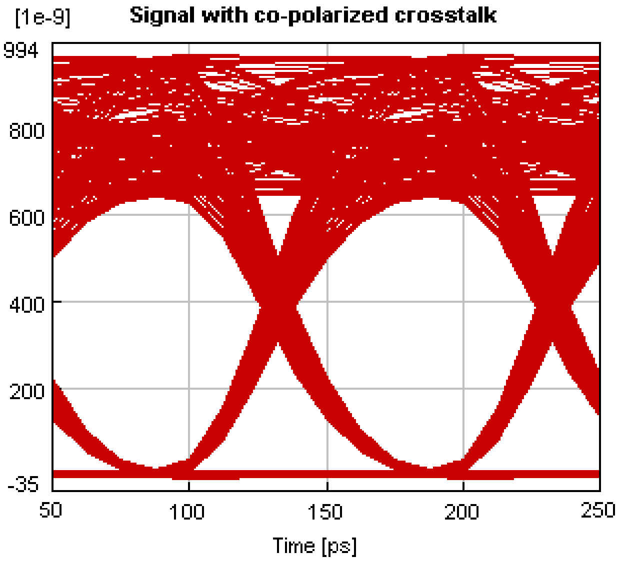
6.1 Worst Case Crosstalk

- Typical worst case analytical assumptions ⇒ give higher $PP_{crosstalk}$ than that experienced in practice
  - Interfering signals have equal SOP (co-polarized) and exactly out of phase
  - In practice SOP and phase relationships are not fixed and tend to vary with time e.g. due to temperature variations

6.1 Worst Case Crosstalk







6.2 Crosstalk PP

- ☐ $PP_{\text{crosstalk}}$ increases with the power ratio or crosstalk level ε

$$\varepsilon = \frac{\text{average crosstalk signal power}}{\text{average desired signal power}} \qquad 0 \le \varepsilon \le 1$$

- ☐ Aggregate ε increases with *N* the number of interfering signals

$$\boxed{\sqrt{\varepsilon} = \sum_{i=1}^{N} \sqrt{\varepsilon_i}}$$ Intrachannel crosstalk

$$\boxed{\varepsilon = \sum_{i=1}^{N} \varepsilon_i}$$ Interchannel crosstalk

6.2 Crosstalk PP

- ☐ PP due to intrachannel crosstalk more severe
  - Example: In plot below to ensure $PP_{crosstalk} \leq 1$ dB, for interchannel crosstalk $\varepsilon_{dB} \leq -10$ dB and for intrachannel crosstalk $\varepsilon_{dB} \leq -30$ dB
  - Devices with much high crosstalk isolation required for higher ε_{dB}

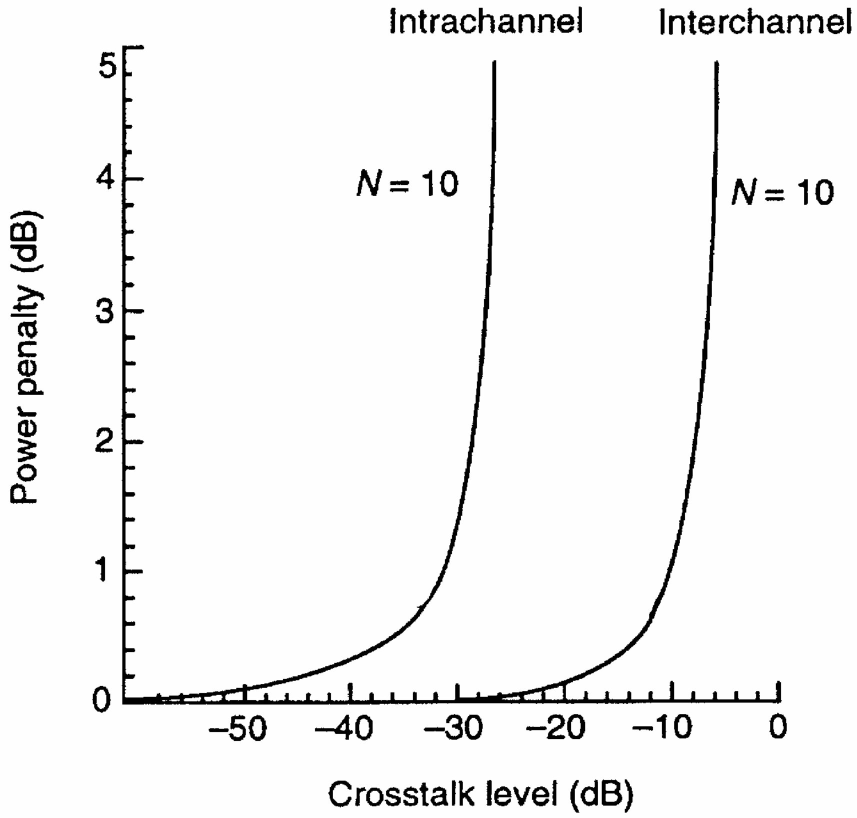


Figure. Estimated power penalty due to 10 interfering channels for both intra- and interchannel crosstalk cases

6.3 Crosstalk in Networks

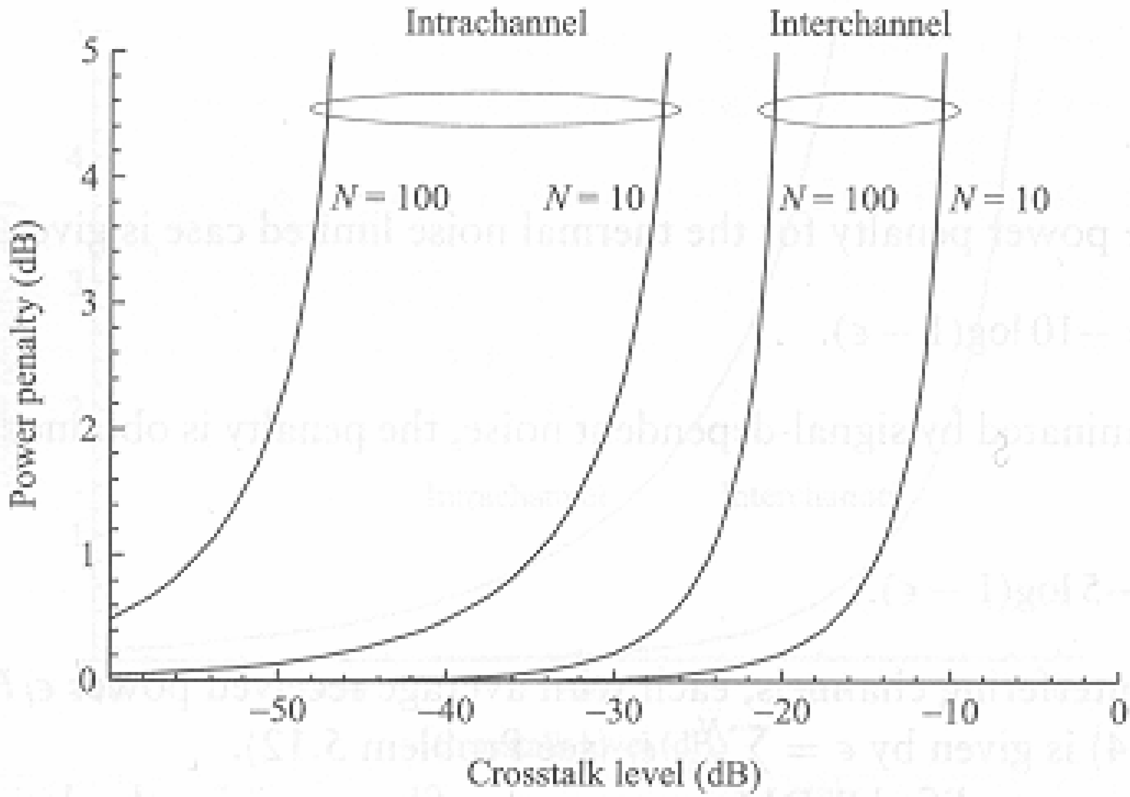
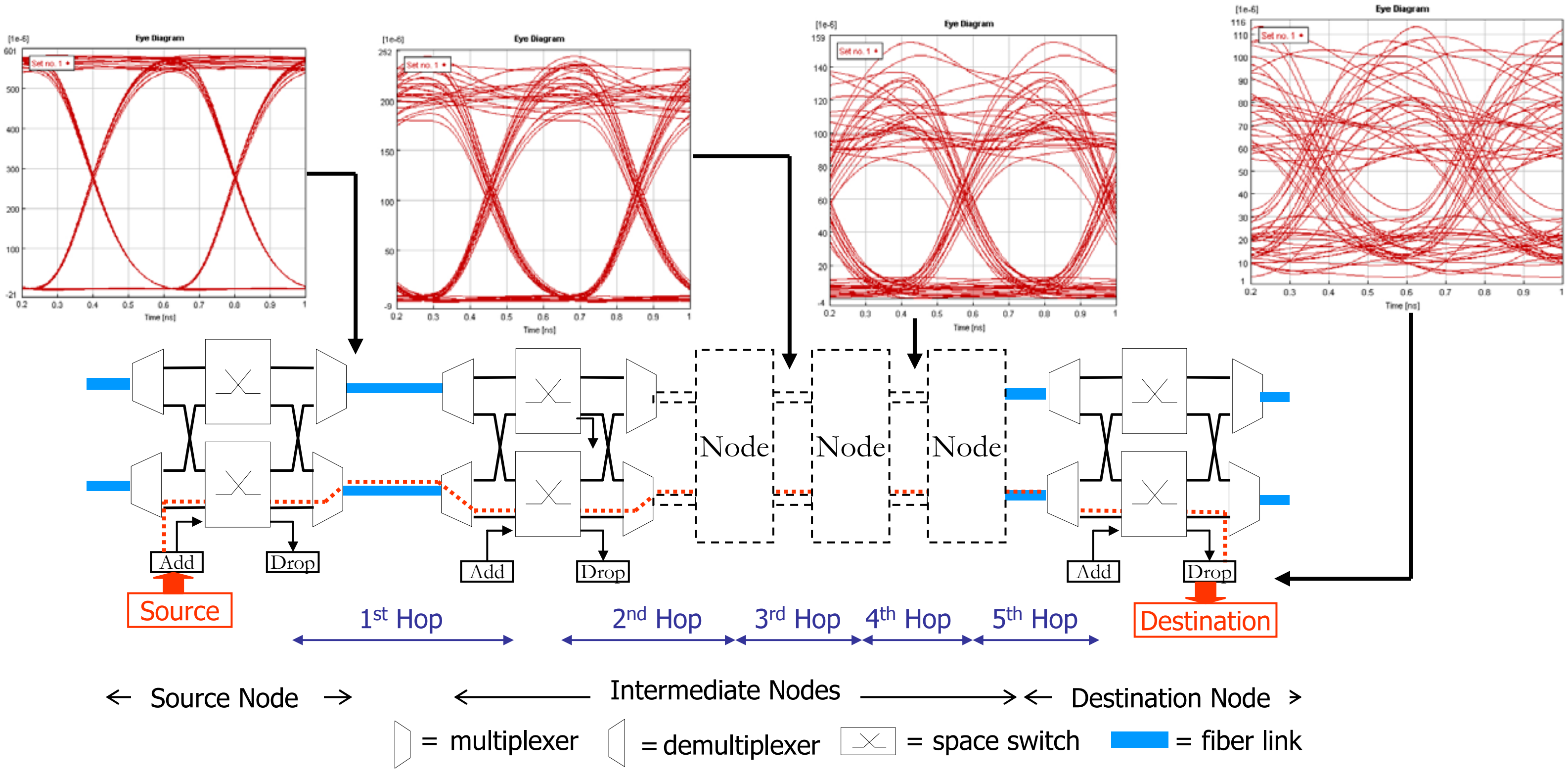


Figure 5.12 Signal-spontaneous noise limited intrachannel and interchannel crosstalk penalties as a function of crosstalk level $-10 \log \epsilon_s$ in a network. The parameter N denotes the number of crosstalk elements, all assumed to produce crosstalk at equal powers.

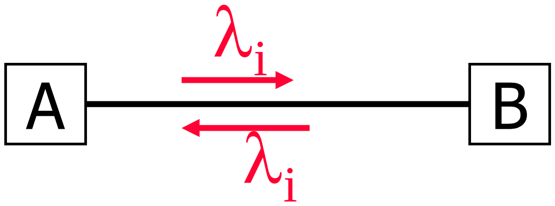
6.3 Crosstalk in Networks

- ❑ Signal propagates through multiple network nodes (hops)
  - Accumulates crosstalk from different devices in each node
  - Limits hop number before electrical regeneration becomes necessary

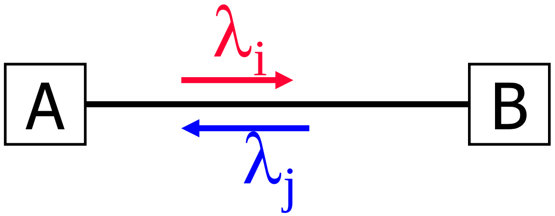


6.4 Bidirectional Systems

- Data transmitted in both directions over a common fiber
  - Physically this is possible



  - However, intrachannel crosstalk may arise due to back-reflections
  - Reflections from within end equipment can be carefully controlled
  - More difficult to restrict reflections from fiber link itself
- Therefore bidirectional systems always use different wavelengths in either direction ⇒ interchannel crosstalk



6.5 Crosstalk Reduction

❑ Improvement of crosstalk isolation devices
  - More careful designs producing devices with higher crosstalk isolation
  - Disadvantages: Lower yields and costly devices

6.5 Crosstalk Reduction

- Using architectural approaches to reduce crosstalk
  - Example: wavelength dilation by di-interleaving and interleaving doubles channel spacing

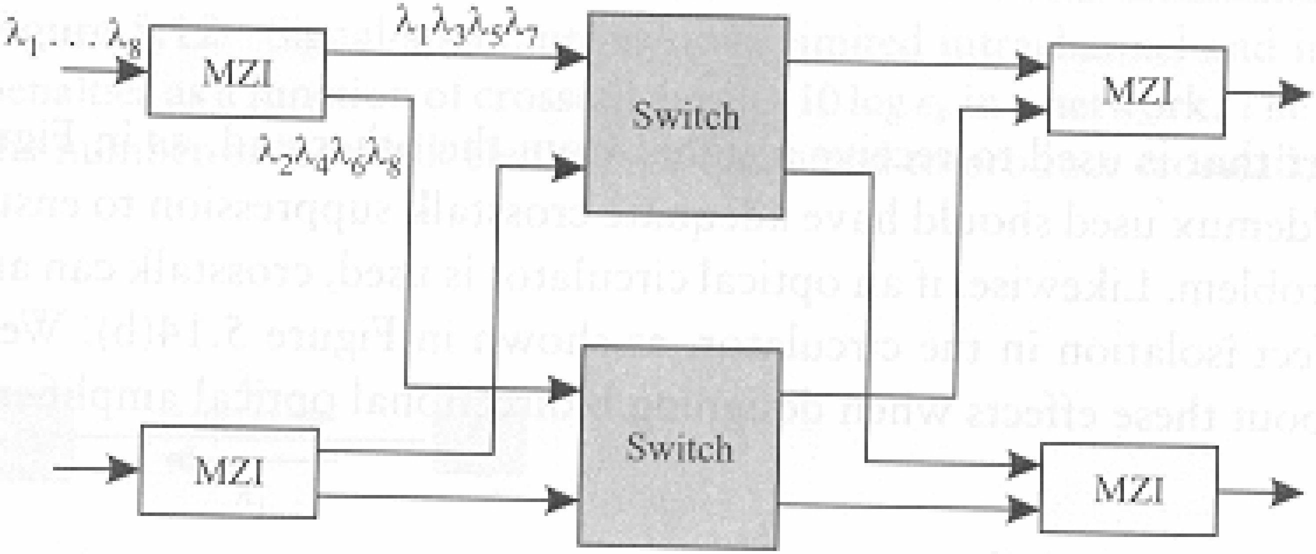


Figure 5.16 Using wavelength dilation to reduce switch crosstalk. MZI denotes a Mach-Zehnder interferometer that separates the channels into two groups or combines them.

6.6 Cascaded Filters

- ☐ Filter cascades
  - Passband gets narrower with increased cascaded components
  - Increased wavelength stability and accuracy requirements
- ☐ Center wavelength misalignments
  - Added signal loss
  - Increased interchannel crosstalk

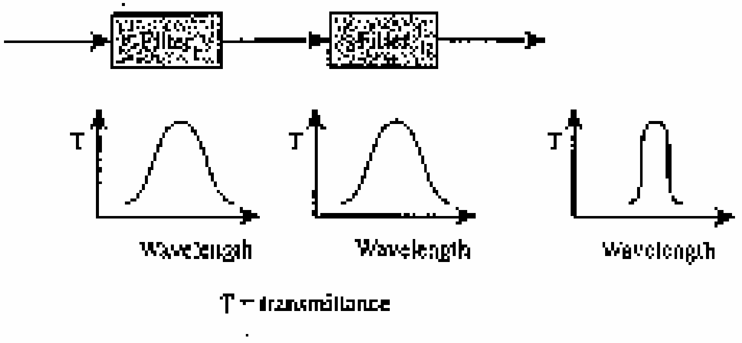


Figure 5.18 Bandwidth narrowing due to cascading of two filters.

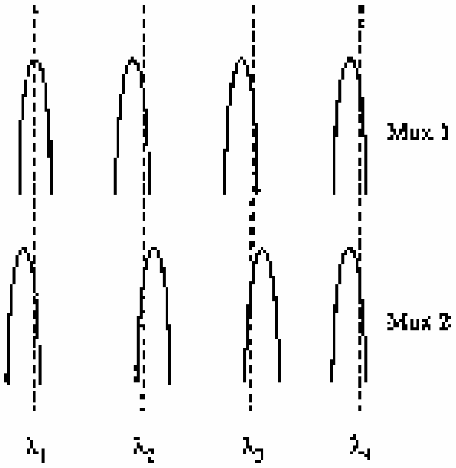
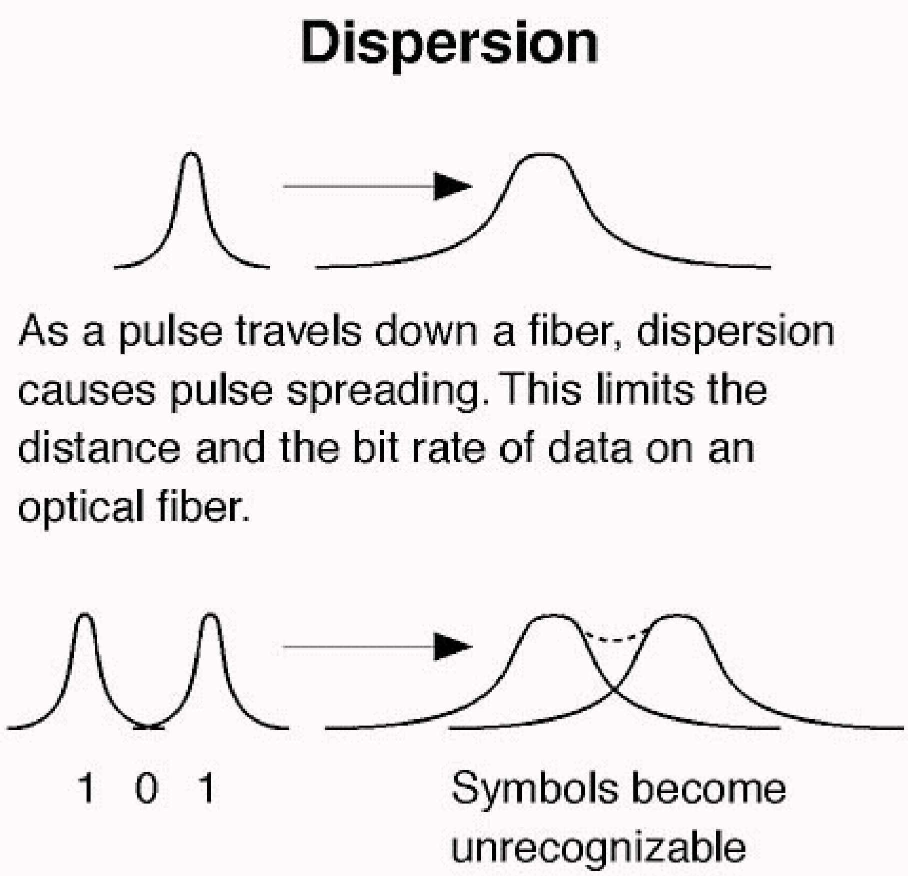


Figure 5.19 Wavelength misalignment between two mux/demuxes.

7. Dispersion

- ❑ Dispersion ⇨ different components of a common data signal travel with different velocities

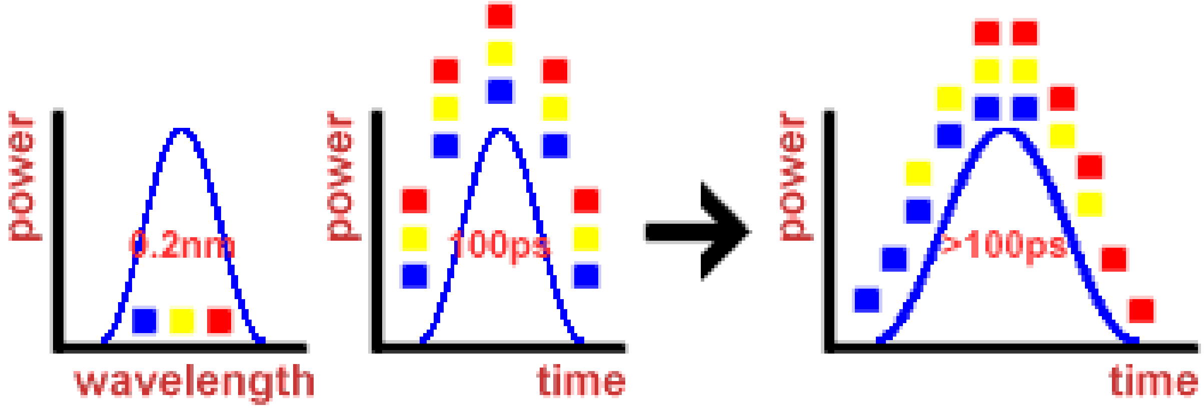


Dispersion

As a pulse travels down a fiber, dispersion causes pulse spreading. This limits the distance and the bit rate of data on an optical fiber.

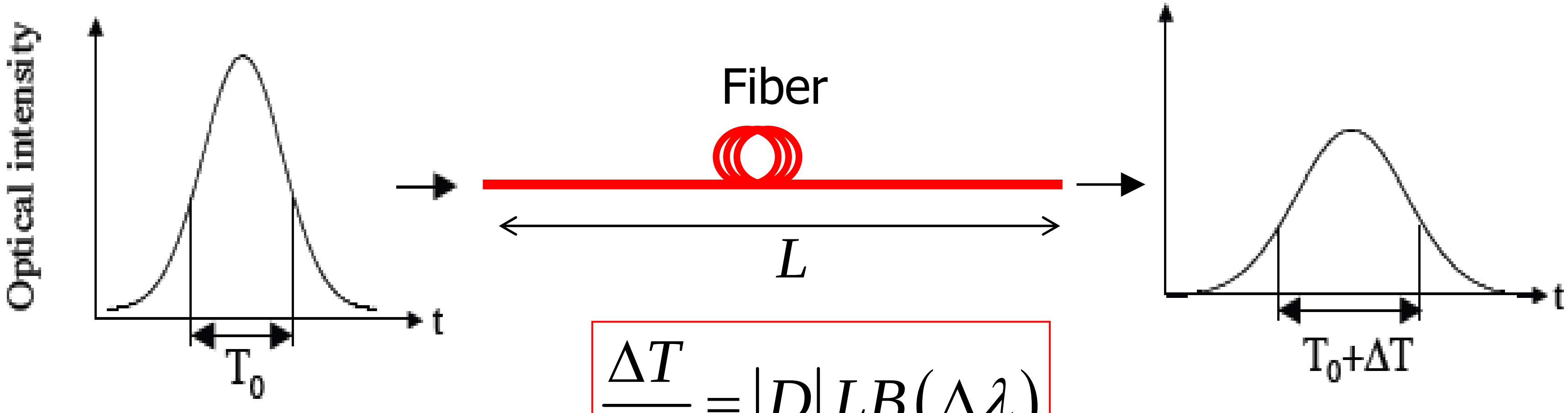
7.1 Chromatic Dispersion

- ☐ Most prominent dispersion is chromatic dispersion
  - Different frequency (wavelength) components of a signal travel with different velocities in fiber
  - Chromatic dispersion coefficient *D* in ps/nm-km
    - ps is the time spread of the pulse, nm is spectral width of the pulse andkm corresponds to link length
  - Typical D value for standard singlemode fiber (SMF) in C-band (1550 nm window) is D = 17 ps/nm-km and 1300 nm is D = 0 ps/nm-km



Chromatic Dispersion

7.2 Chromatic Dispersion Limitations



$$\boxed{\frac{\Delta T}{T_0} = |D| L B (\Delta\lambda)}$$

where *D* is dispersion coefficient, *L* is link length, *B* is the bit rate, $\Delta\lambda$ is the spectral width of pulse

- Recommendation for tolerable $\Delta T/T$ values specified by various standards (e.g. ITU-T G.957, Telcordia GR-253)
- Example 1: $PP_{chromatic} \leq 1$ dB $\Rightarrow$ $\Delta T/T=0.306$
- Example 2: $PP_{chromatic} \leq 2$ dB $\Rightarrow$ $\Delta T/T=0.491$

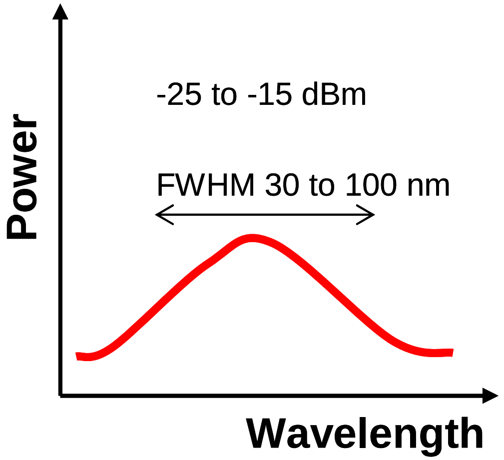
7.2 Chromatic Dispersion Limitations

- ❑ Assuming $\lambda = 1550$ nm, $\Delta\lambda = 1$ nm and D = 17 ps/nm–km
  - A $PP_{\text{chromatic}} < 2$ dB limit ($\Delta T/T = 0.491$) yields a condition $B \cdot L < 30$ (Gb/s)–km
    - If $B = 1$ Gb/s, $L \leq 30$ km
    - If $B = 10$ Gb/s, $L \leq 3$ km
    - If $B = 40$ Gb/s, $L \leq 750$ m

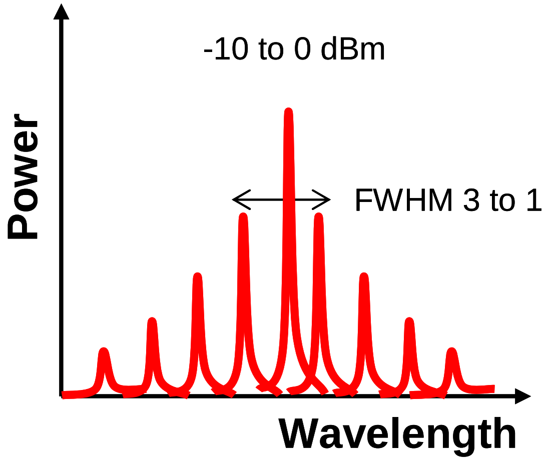
- ❑ There is a clear need for measures to reduce dispersion penalties!

7.2 Chromatic Dispersion Limitations

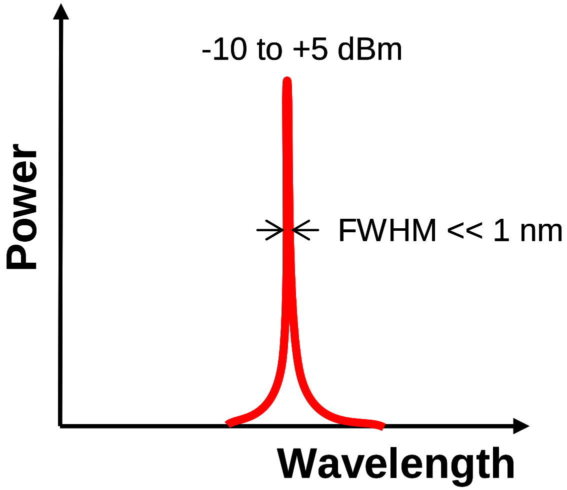
- ☐ Improve transmitter design to reduce dispersion penalties
  - Narrow spectral linewidth signal sources (e.g. SLM lasers)
  - External modulation to recude wavelength components introduced by chirping
- ☐ Dispersion compensation required if spectral linewidth still not narrow enough



LED spectrum



MLM laser spectrum



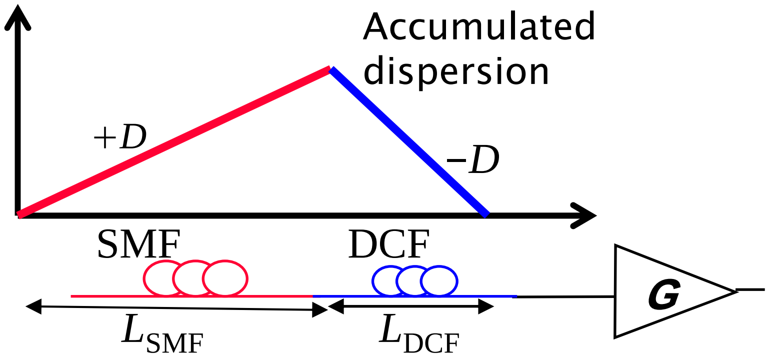
SLM laser spectrum

7.3 Chromatic Dispersion Compensation

- Electrical dispersion compensation or penalty reduction techniques
    - Equalizers or filters to remove ISI
    - Forward error correction
- Optical-based chromatic dispersion compensation
    - Dispersion compensating fibers
    - Chirped fiber Bragg gratings

7.3 Chromatic Dispersion Compensation

- Dispersion compensating fibers (DCF) provide negative dispersion (around -100 ps/nm-km) in the 1550 nm transmission window



$$L_{DCF} = \frac{L_{SMF}\cdot D_{SMF}}{\left|-D_{DCF}\right|}$$

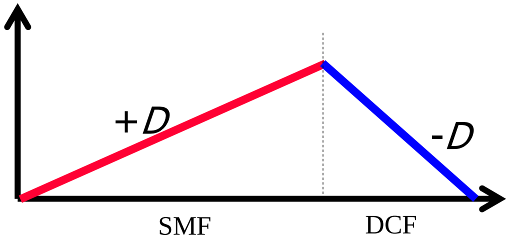
$$G = L_{SMF}\cdot\alpha_{SMF} + L_{DCF}\cdot\alpha_{DCF}$$

where D_{SMF} and D_{DCF} are the dispersion coefficient of the SMF and DCF fibres

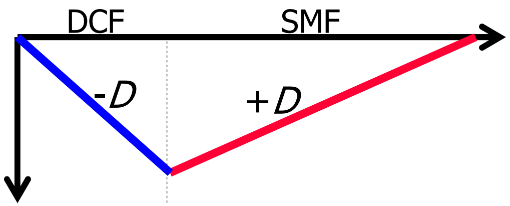
- DCF adds loss to the system power budget ⇒ need higher gain from amplifiers

7.3 Chromatic Dispersion Compensation

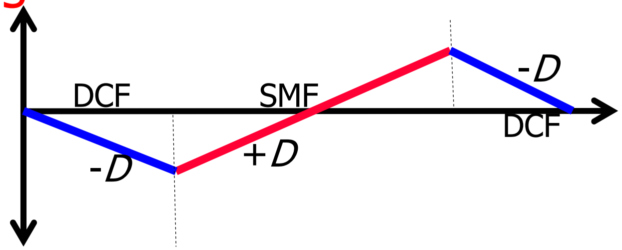
- ❑ DCFs could be deployed in different configurations



Post-compensated



Pre-compensated



Symmetrically compensated

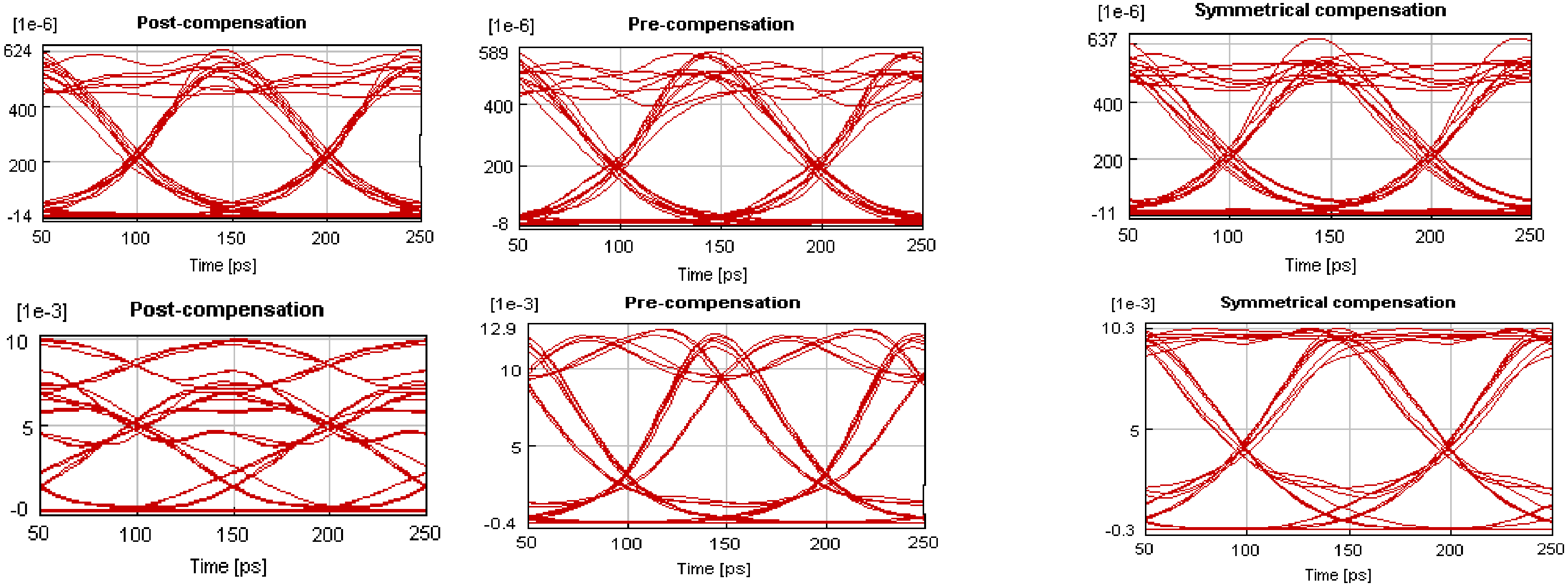


Figure: Eye diagrams for different compensation configurations for transmission of 10 Gb/s NRZ data signals over 240 km SMF link. Top for low fiber nonlinearity, bottom for excessive nonlinearities.

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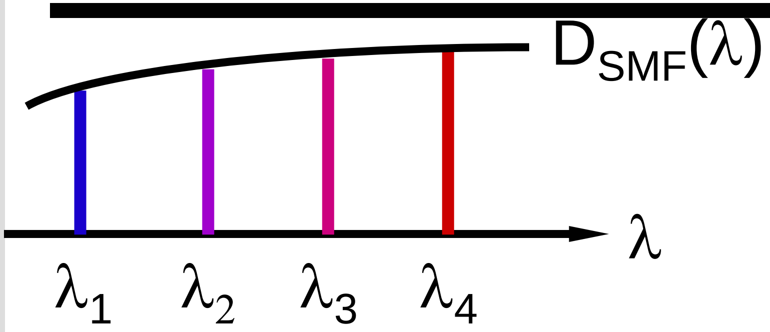
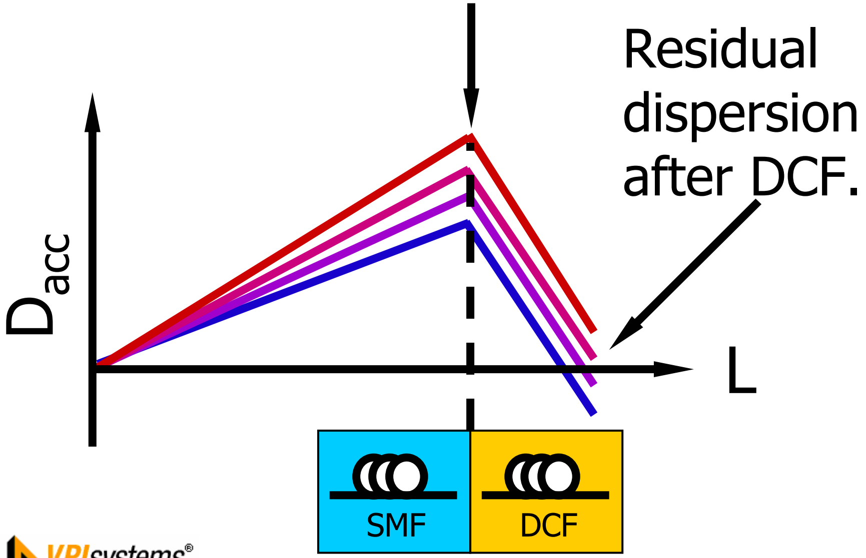
7.3 Chromatic Dispersion Compensation





Different accumulated dispersion.

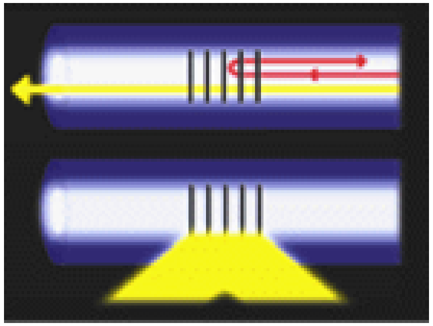
Residual dispersion after DCF.

- ❑ Dispersion slope
  - Dispersion varies with λ
  - Unequal compensation with uniform dispersion compensation
- ❑ Need for dispersion slope compensation
  - To compensate for residue dispersion
  - Critical ≥ 40 Gbit/s

7.3 Chromatic Dispersion Compensation

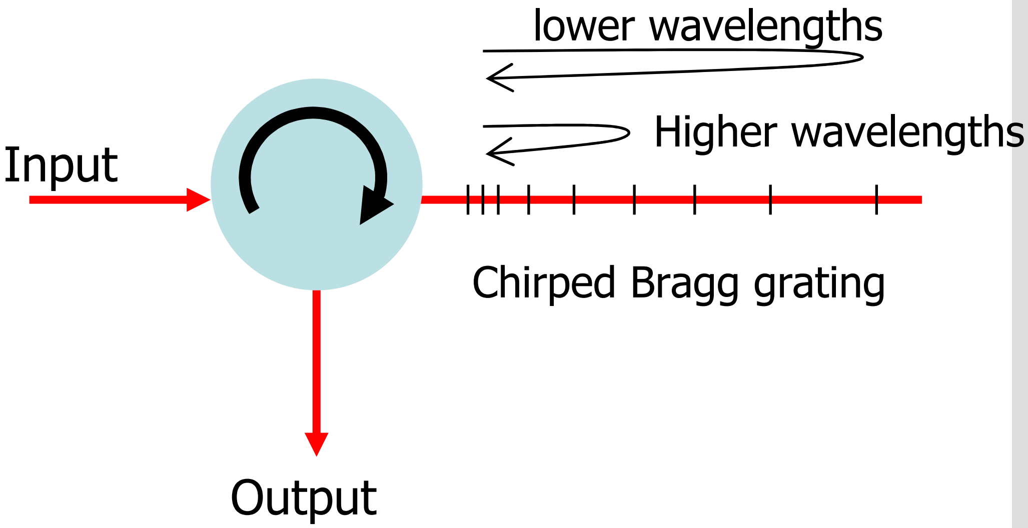
❑ Chirped fiber Bragg gratings

- Period of gratings varies linearly with position
- Reflects different wavelengths at different points along its length ⇒ different delays at different wavelengths



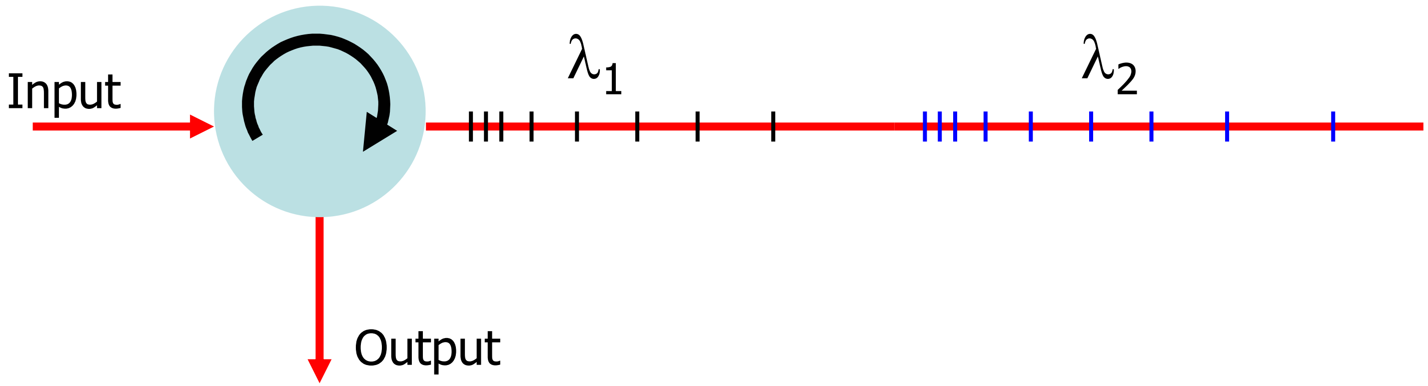
When the UV light passes through a phase mask, an interference pattern is produced creating a structural change in the core of the fiber resulting in a permanent and stable modification of its refractive index.

Uniform grating



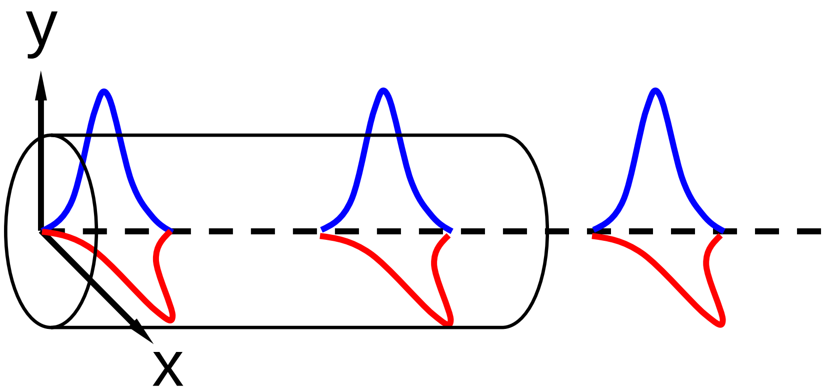
7.3 Chromatic Dispersion Compensation

- ☐ Different chirped fiber Bragg gratings necessary to simultaneously compensate dispersion for different wavelengths



7.4 Polarization Mode Dispersion

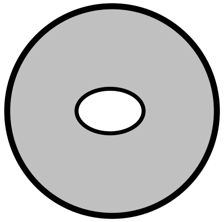
- ❑ If a singlemode fiber is perfectly cylindrical
  - A signals two orthogonal polarization components travel at same speed



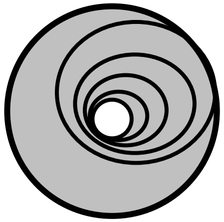
- ❑ In practice deployed fibers not perfectly cylindrical ⇒ leads to polarization mode dispersion (PMD)
  - Different polarization components travel with different velocities

7.4 Polarization Mode Dispersion

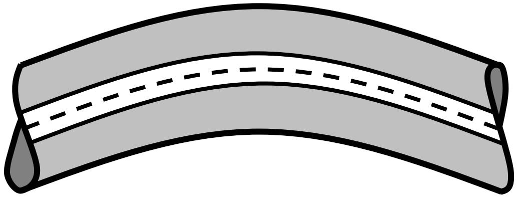
Noncircular core:



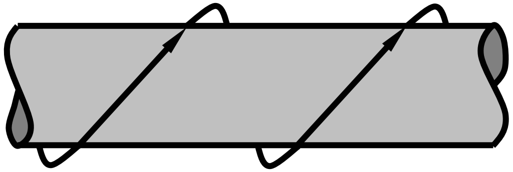
Mechanical stress:



Bending:



Torsion:

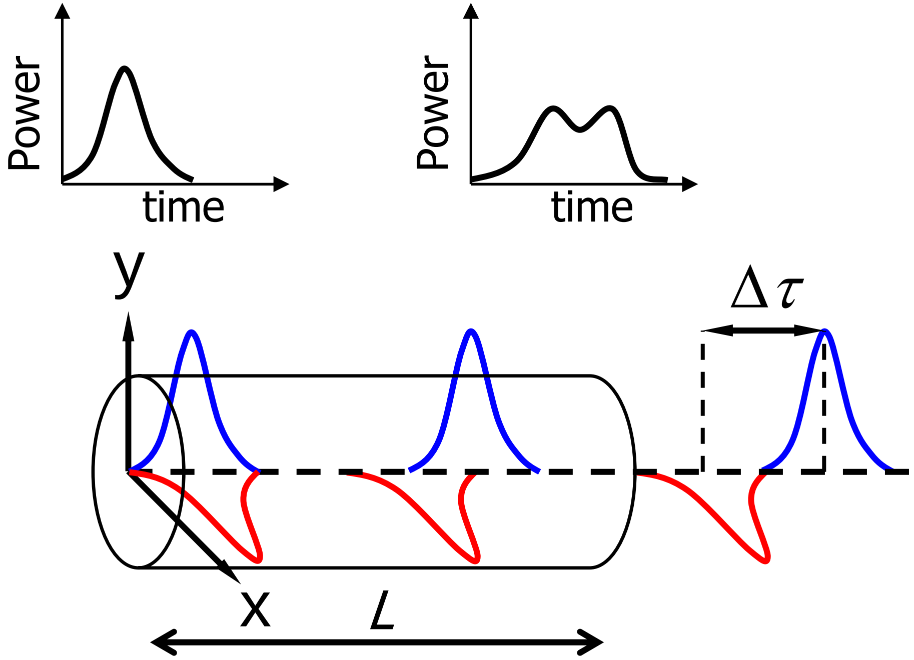


Possible causes:

- Fiber manufacturing process
- Laying the fiber into the ground
- Spooling fiber for shipping
- Indoor cabling
- Temperature variations
- Nearby vibrations

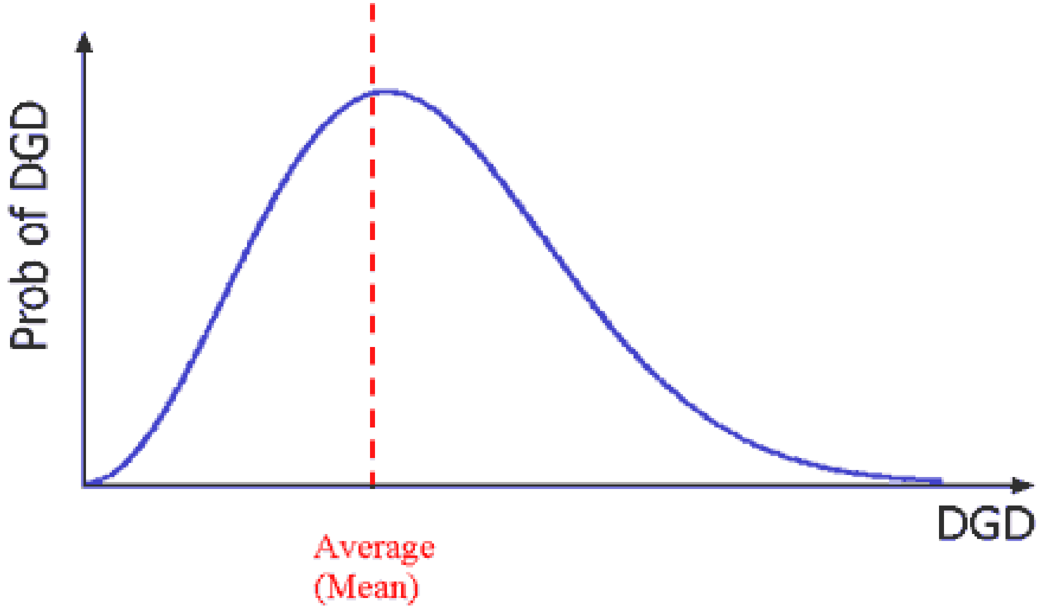
7.5 PMD Power Penalty

- Differential group delay (DGD) $\Delta\tau$ between the 2 polarization components due to PMD
  - Longer DGD ⇒ higher PMD power penalty (PP_{PMD})



7.5 PMD Power Penalty

- ❑ State of polarization varies slowly with time
  - DGD not constant ⇒ a Maxwellian random variable
  - PP_{PMD} also time varying



$$\langle \Delta\tau \rangle = D_{PMD}\sqrt{L}$$

where D_{PMD} is the fiber's PMD coefficient [in ps/(km)$^{0.5}$]

7.5 PMD Power Penalty

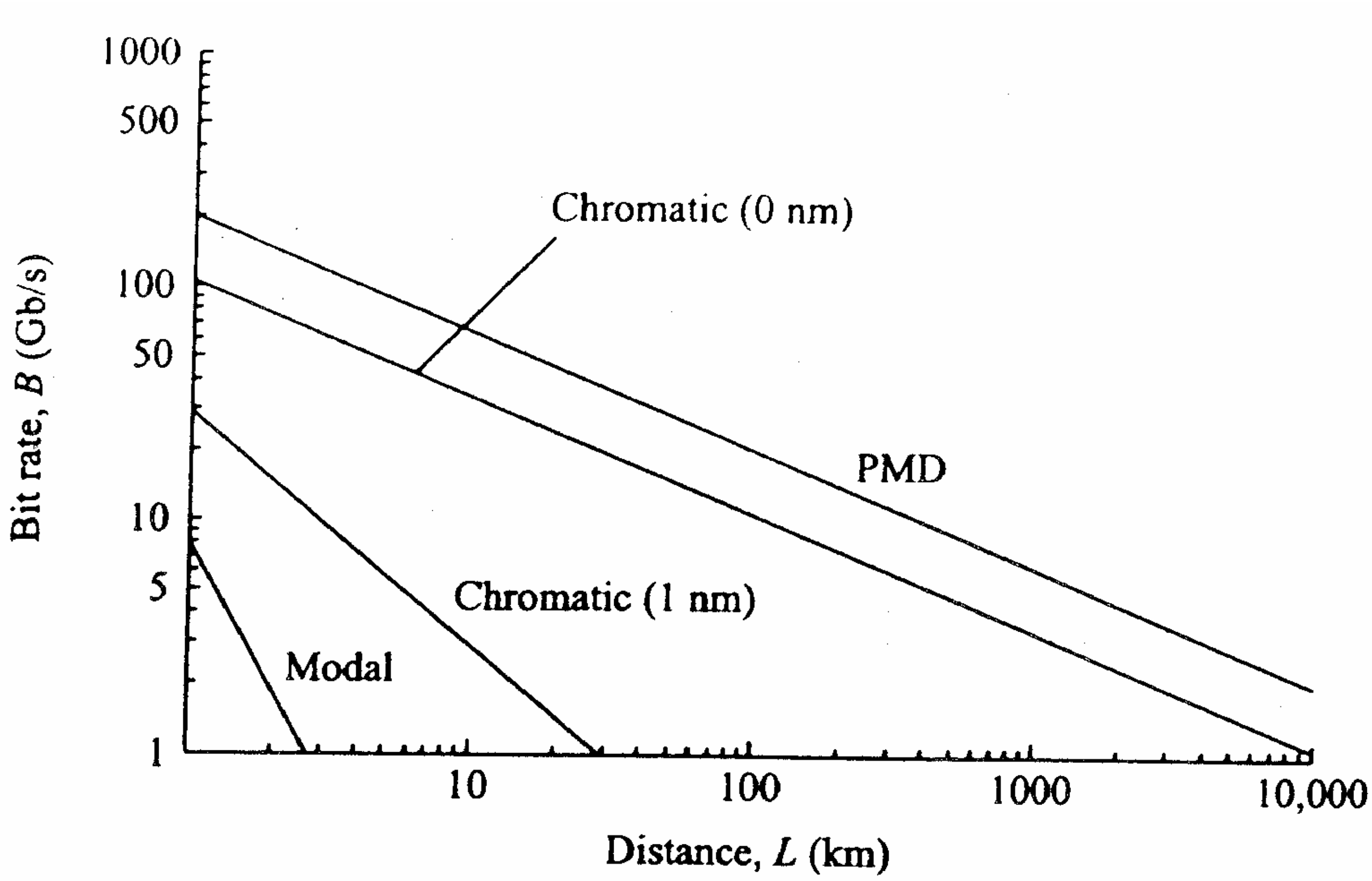


Figure: Distance and bit rate limits due to various dispersion mechanisms. D = 17 ps/nm-km and D_{PMD} = 0.5 ps/(km)$^{0.5}$

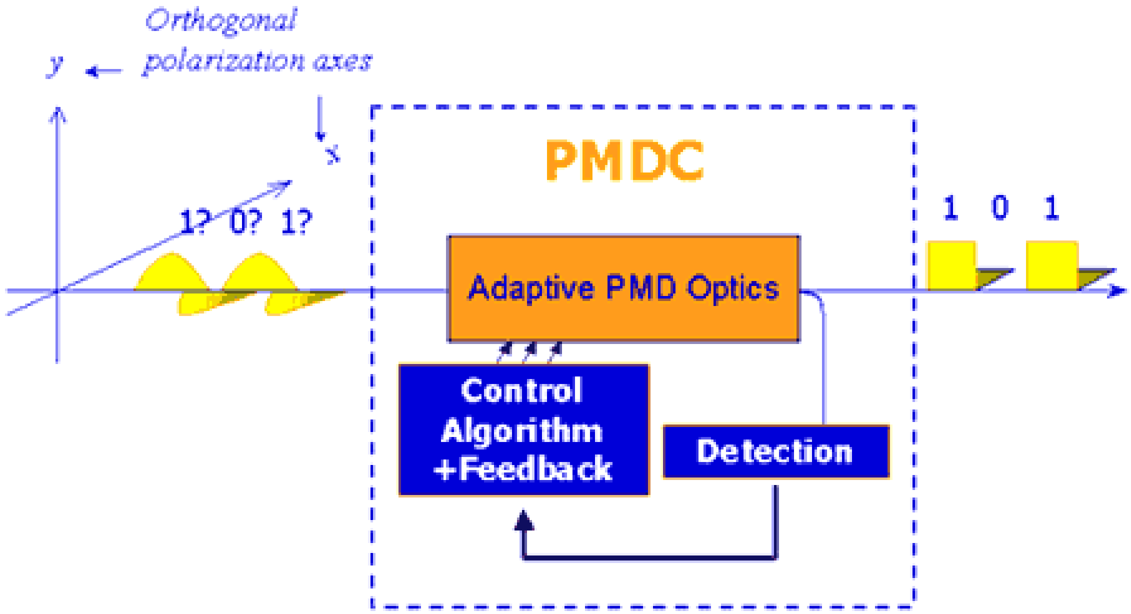
7.6 PMD Compensation

- ❑ ITU G.691 ⇒ when $<\Delta\tau>/T < 0.3$ then $PP_{PMD} \leq 1$ dB
  - Example distance limitation for different fibers shown below
  - Need for PMD compensation!

B (Gbit/s)	Distance (km) limit for new very low PMD fiber $D_{PMD} = 0.02$ ps/(km)$^{0.5}$	Distance (km) limit for legacy fiber $D_{PMD} = 1$ ps/(km)$^{0.5}$
2.5	4×10^6	1600
10	2.5×10^5	100
40	16,000	6.25

7.6 PMD Compensation

- PMD difficult to compensate due to its time-varying nature
  - Transmitted pulses separated into polarization components
  - The “fast” component is delayed to compensate for DGD
  - A feedback from detected signal is required to track PMD changes
  - One compensator needed for each wavelength channel since PMD also wavelength dependant



7.7 Polarization Dependant Losses

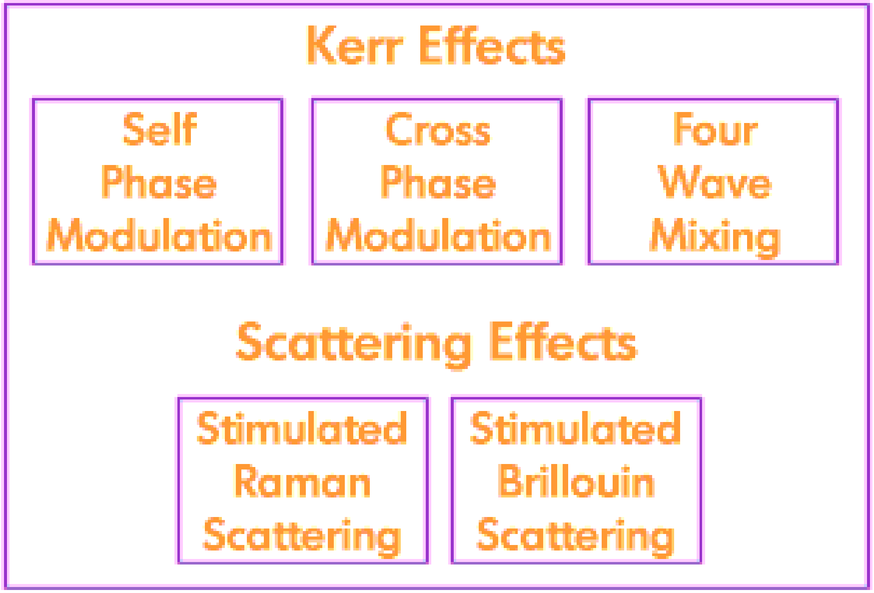
- Components may have a polarization dependent loss (PDL)
  - Signal experiences different insertion loss (e.g. through isolator) depending on its state of polarization
  - Many such components on transmission path ⇒ PDL adds up in an unpredictable way
  - PDL may also vary with wavelength!
  - Careful design to maintain acceptable power budget

8. Fiber Nonlinearities

- ❑ If optical signal power is low, fiber considered to be linear medium
  - Increase optical transmit power overcomes power penalties and BER improves
- ❑ But… if power increased beyond certain level
  - Fiber links exhibit nonlinear effects
  - Degrade signal by distortion and crosstalk
  - Longer the link length the more the nonlinear interactions
  - Nonlinear effects of fibers place serious limitations on system design

8. Fiber Nonlinearities

- ❑ Main causes of fiber nonlinearity
  - Scattering effects
  - Refractive index variation (Kerr effects)
- ❑ All effects except SPM and CPM provide gain to some channels at the expense of depleting power from some other channels
- ❑ SPM/CPM affects only phase & causes spectral broadening ⇨ dispersion



8.2 Stimulated Brillouin Scattering

- Stimulated Brillouin scattering (SBS)
  - Distorts signal by producing backwards gain towards source
  - A signal produced in opposite direction with backscattered power

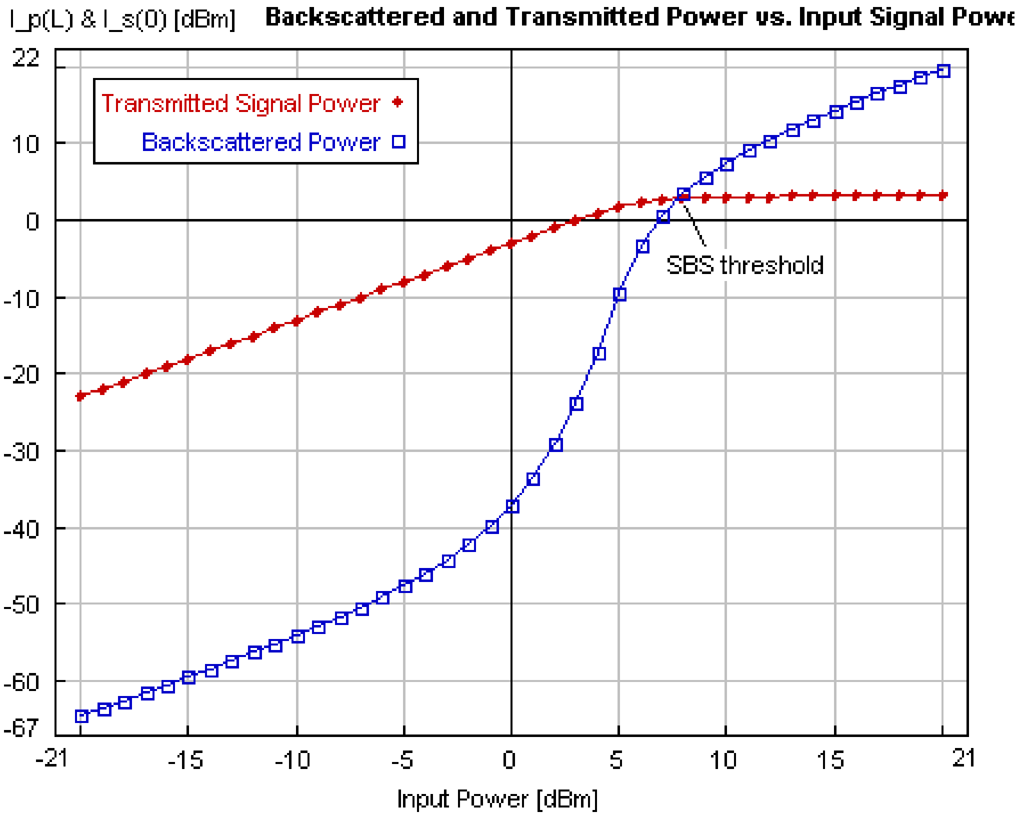


Figure. The dependence of transmitted and backscattered power on input signal power. Note that SBS threshold is when transmitted and backscattered powers are equal.

8.2 Stimulated Brillouin Scattering

❑ Possible SBS remedies

- Keep signal power below SBS threshold power ⇨ reduce amplifier spacing
- Interaction low if source spectral width < 20MHz SBS gain bandwidth
    - Increase spectral width of source (>20 MHz) but keep in mind chromatic dispersion!
- Use phase modulation schemes instead of amplitude or intensity modulation schemes

8.3 Stimulated Raman Scattering

- ☐ Stimulated Raman scattering (SRS)
  - Power transfer from lower to higher wavelength channels
  - Coupling occurs in both directions of propagation
  - Raman gain dependent on wavelength spacing ($\Delta\lambda$s)
  - Same effect used for fiber Raman amplifiers!

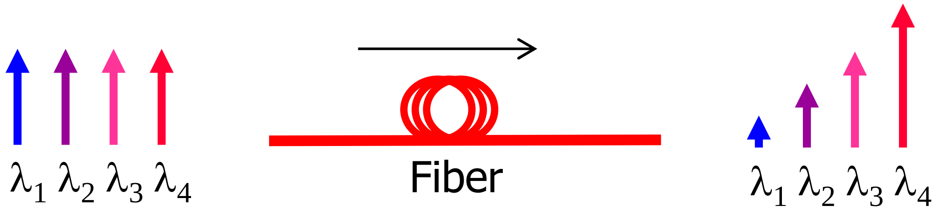


Figure: Signal distortion due to SRS

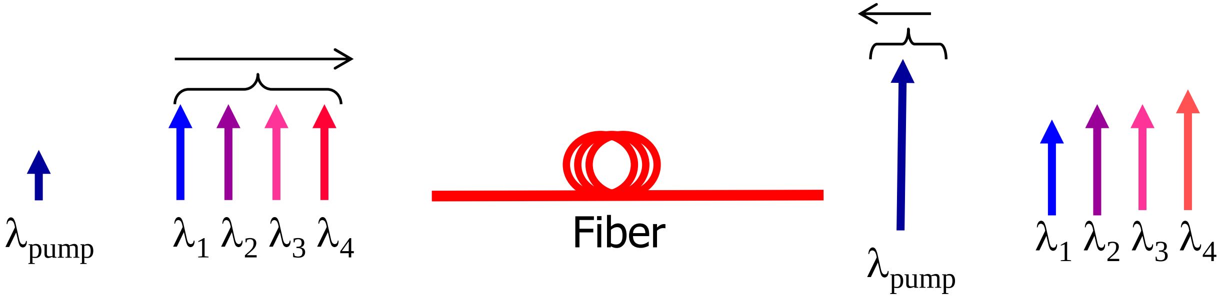


Figure: Fiber Raman amplification using SRS

8.3 Stimulated Raman Scattering

- ❑ Possible remedies
  - Keep channels spaced as far as possible
  - Keep signal power level below a certain SRS threshold

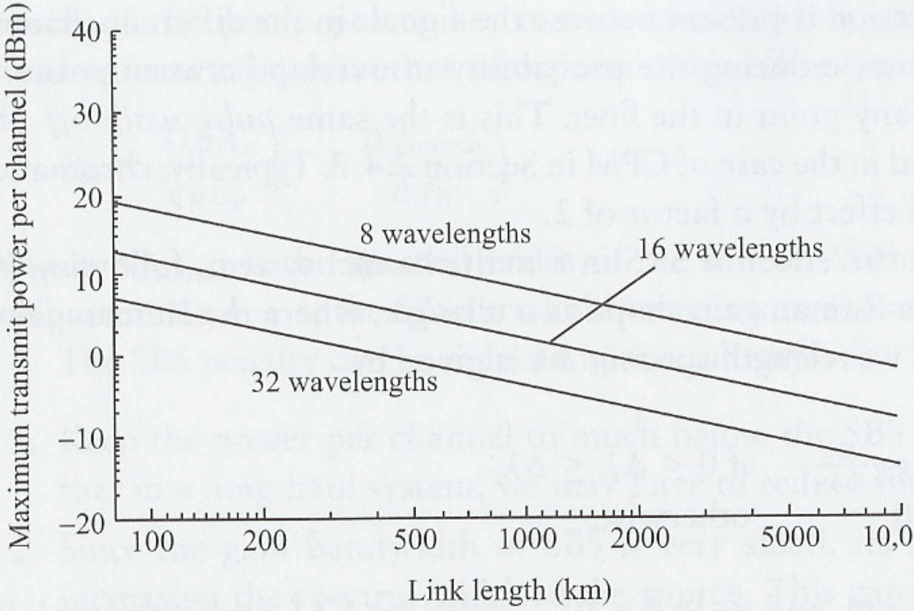
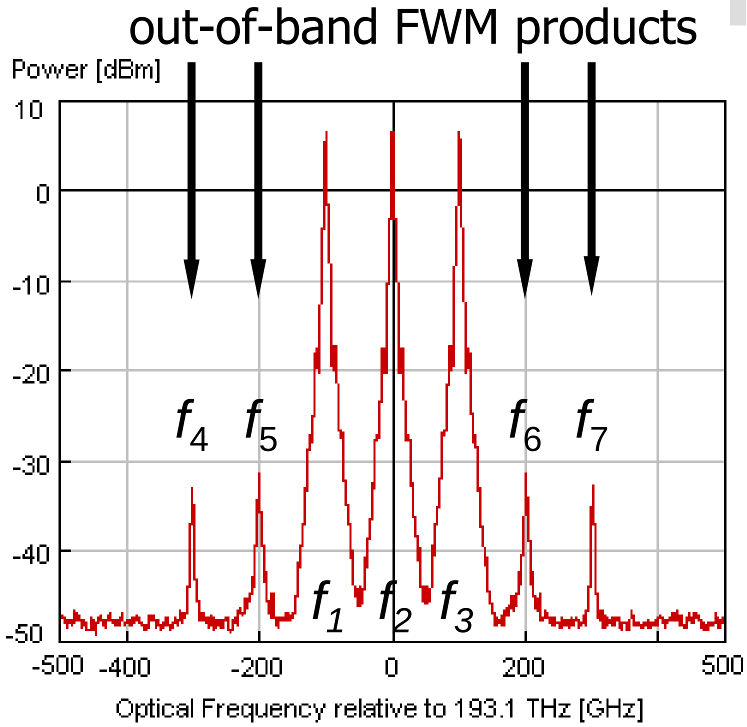


Figure 5.28 Limitation on the maximum transmit power per channel imposed by stimulated Raman scattering. The channel spacing is assumed to be 0.8 nm, and amplifiers are assumed to be spaced 80 km apart.

8.4 Four-Wave Mixing

- ☐ Four-wave mixing (FWM)
  - Signals at frequencies f_i , f_j and f_k interact
  - Produce crosstalk components or intermodulation products at frequency

$$\boxed{f_{ijk} = f_i + f_j - f_k,\ \text{where}\, i, j \neq k}$$



Example:

FWM products at f_5:

$$f_5 = f_1 + f_2 - f_3 \quad \text{and} \quad f_5 = 2f_1 - f_2$$

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8.4 Four-Wave Mixing

- FWM efficiency is enhanced when
  - Dispersion is very low ⇒ interacting signals have good phase relationship (worst case $PP_{\text{chromatic}}$)
  - Transmit power is high
  - Channel spacing is narrow

8.4 Four-Wave Mixing

- Worse for dispersion shifted fibers (DSF)
  - Have zero dispersion point in 1550 nm window

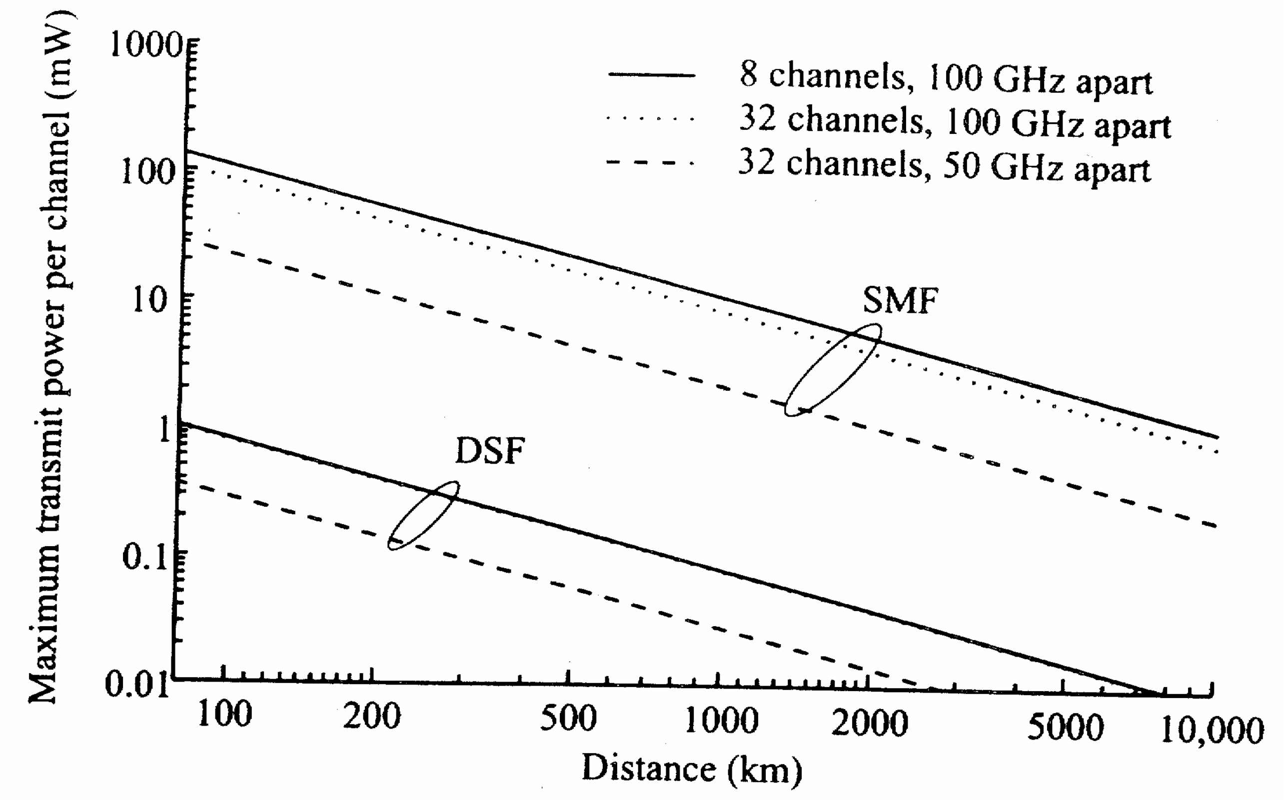
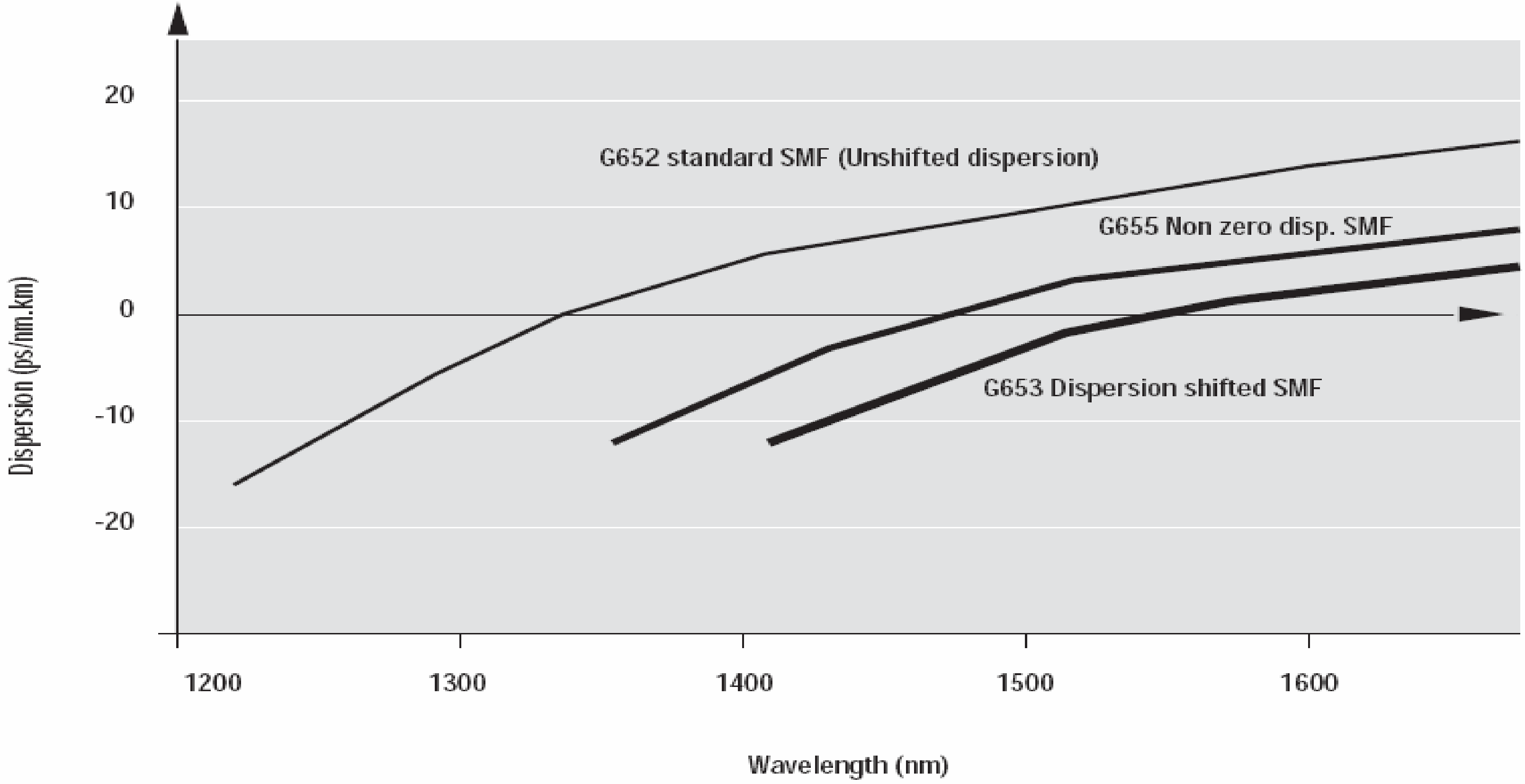


Fig. Limitation on the maximum power per channel due to FWM

8.4 Four-Wave Mixing

- Non-zero dispersion shifted fibres (NDF)
  - Low dispersion in 1550nm transmission window
  - Comprise solution between SMF (high $PP_{dispersion}$) and DSF (high PP_{FWM})



8.4 Four-Wave Mixing

❑ Other remedies for FWM it is too late or expense to install NDF

- Using DSF for wavelengths beyond 1560 nm (L-band)
- Reducing transmitter power ⇒ amplifier spacing
- Increase channel spacing
  - Increases phase mismatch between interacting signals
- Assign unequal channel spacing
  - Choose channels so that FWM terms do not overlap with data channels
  - Usually requires wider transmission windows
  - Might use channels not compliant with ITU-T wavelength grid

8.5 Self- and Cross-phase Modulation

- ❑ Due to intensity dependence of the refractive index
  - Power fluctuation lead to unwanted signal phase changes or modulations
  - Phase changes induces additional chirp (frequency variations)
- ❑ Self-phase modulation significant systems designed to operate at ≥10 Gb/s
  - Restricts maximum power per channel
- ❑ Cross-phase modulation considered for WDM systems with a channel spacing < 20 GHz

10. Overall Design Considerations

- ☐ What fiber type to deploy?

ITU-T Standard	Name	Typical CD value (C-band)	Applicability
G.652	standard Single Mode Fiber	17 ps/nm-km	OK for xWDM
G.652c	Low Water Peak SMF	17 ps/nm-km	Good for CWDM
G.653	Dispersion-Shifted Fiber	0 ps/nm-km	Bad for xWDM
G.654	Loss Minimized Fiber	20 ps/nm-km	Good for long-haul DWDM
G.655	Non-Zero Dispersion-Shifted Fiber	1-6 ps/nm-km	Good for DWDM
G.656	NDF for Wideband Optical Transport	2-14 ps/nm-km	Good for xWDM

10. Overall Design Considerations

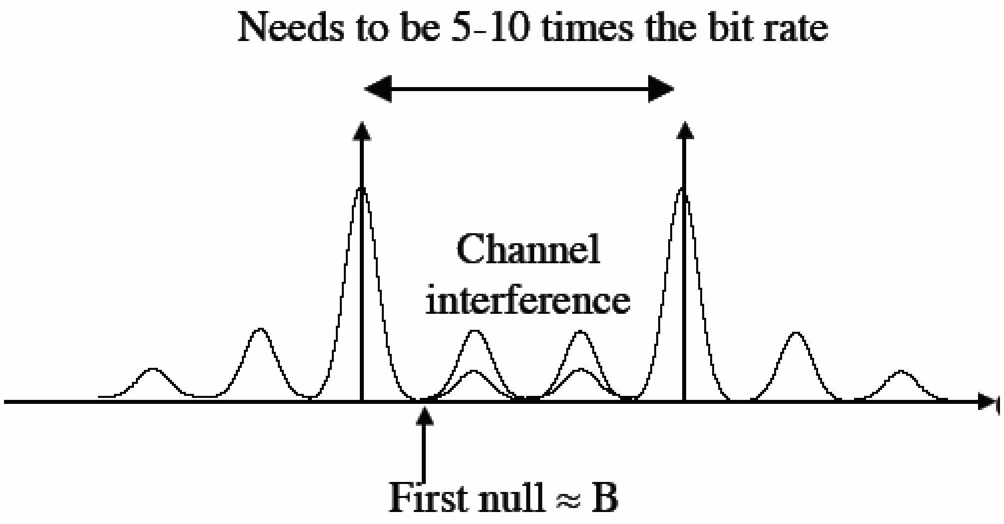
- ☐ What transmit power and amplifier spacing?
  - Points to consider include saturation power of EFDAs, effects of nonlinearities, safety requirements
  - From a cost point of view, amplifier spacing should be maximized

- ☐ What modulation type?
  - NRZ modulation currently most popular and least expensive
  - RZ modulation
    - Lower nonlinearity and dispersion penalties
    - For ultra-long-haul systems at 10 Gb/s and above
  - Phased-based modulation instead of intensity-based (OOK) modulation

10. Overall Design Considerations

❑ What wavelength channel spacing and channel number?

- Influencing actors ⇨ fiber type, component stability and crosstalk isolation
- Maximize possible channel number for future capacity upgrades
- A general rule of thumb ⇒ channel spacing needs to be at least 5-10 times the channel bit rate



11. Conclusions

- ❑ Studied the effects of various impairments on the design of new generation of optical systems and networks
  - Transmission system design requires careful attention to each impairment
  - System penalties ⇒ component specs ⇒ system cost

- ❑ Next lecture
  - Standards for first generation of commercially deployed optical systems/networks

Thank You!

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