

Optical Link Design, Amplifiers, Dispersion Compensation, and Solitons

Optical Link Design Preview

- **Data coding effects**
- **Link design**
 - **Power budget**
 - » **Dynamic range effects**
 - **Timing analysis**
 - » **Dispersion-limited distance**
 - » **Attenuation-limited distance**
- **Optical amplifiers**
 - **Fiber amplifiers**
- **Dispersion compensation techniques**
- **Solitons**

Optical Link Design

- Have presented building blocks of fiber link...
- Need design procedure to meet specifications
- Iterative design procedure
 - Assumptions made and design carried out...
 - » Design *not* finished, however...
 - » Verify design meets objectives and...
 - » Represents economical, as well as technical, solution
 - » If not, another pass
 - In particular, inspect assumptions to determine if changes might provide...
 - Simpler or...
 - Cheaper alternative

Fiber Links: Data Coding

- **Clock encoding**
 - Data recovery sometimes requires sampling circuit operate at system clock rate
 - Low-rate links use free-running clocks
 - » Requires periodic resynchronization for long-term operation
 - Most high-rate links encode clock into data stream for recovery at receiver
- Encode for error-checking, system overhead, maintaining constant dc level, etc.
- Requires increased bit rates in fiber
 - Differentiate “bit rate” and “data rate”
- Standard techniques have evolved for data encoding

Coding: NRZ Coding

- **Nonreturn-to-zero (NRZ) code:**
 - Signal *not* required to return to 0 during bit period
 - Average (DC) output varies with signal content (string of 1s will keep output at 1 level for duration of data string)
 - Simple to generate and decode
 - No clock-encoding or error detection/correction capabilities
 - Requires minimum bit rate
 - » Code rate equals data rate

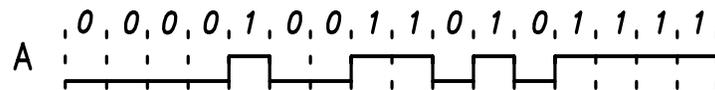


Fig. 7.1(Top),
p. 248

Coding: RZ Coding

- **Return-to-zero (RZ) code**

- Output level changes in each bit period
- Several variations...

- **Curve B**

- First half of bit period represents bit
- Second half always 0
 - » Problem: DC level depends on message
 - String of 1s has different average value than string of 0s)
 - » No clocking information transmitted

- **Curve C (“Manchester code”)**

- Transition at center of bit period
 - » Downward for 0; upward for 1
- Average of each bit period is constant
 - » DC level independent of data
- Clock encoded by transition
- Code rate twice data rate

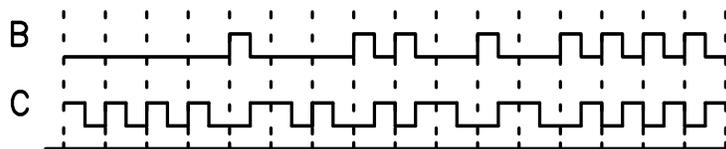


Fig. 7.1b & c,
p. 248

Coding (cont.)

- Many fiber optic encoding/decoding transmitter/receiver modules commercially available
 - ICs available to encode and decode
 - » Primarily error detection and correction
 - » Also encryption
- Increased fiber bandwidth allows increased freedom to incorporate coding
 - **Coding** inserts redundant bits into data stream (increasing required channel capacity)
 - Techniques frequently use *block codes*
 - » *Ex., mBnB code*
 - Encodes m data bits into n coded bits ($n > m$)
 - Bit rate (encoded): $n/m \times$ data rate

Link Design: Source Selection

- **Starting point: choice of...**
 - λ
 - **Laser vs. LED**
 - **SM vs. MM fiber**
- **Know desired data rate and approximate distance**
- **Estimate fiber/source/ λ**
 - **Decision tentatively made**

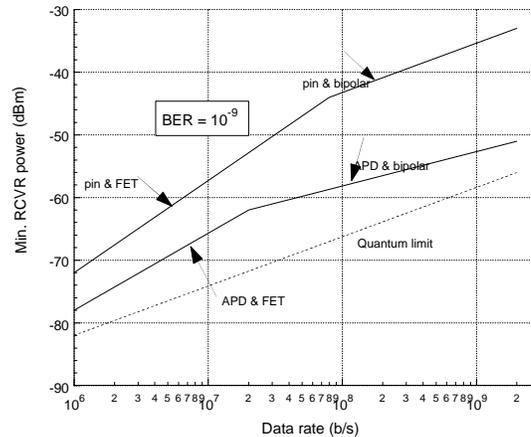
MM fiber & short- λ LED	$\leq 150 \text{ Mb}\cdot\text{s}^{-1}\cdot\text{km}$
MM fiber & short- λ laser	$\leq 2500 \text{ Mb}\cdot\text{s}^{-1}\cdot\text{km}$
MM fiber & long- λ LED	$\leq 1500 \text{ Mb}\cdot\text{s}^{-1}\cdot\text{km}$
SM fiber & long- λ laser	$> 25 \text{ Gb}\cdot\text{s}^{-1}\cdot\text{km}$

Link Design: Fiber Selection

- **Fiber choices:**
 - **SM or MM?** (GI or SI?)
 - **Depends on...**
 - » **Allowable dispersion** *and*
 - » **Power coupling into fiber**
- **If LED source...**
 - **Obvious fiber choice is MM**
 - **Long-wavelength LEDs sometimes used for short-distance links** (e.g., FDDI)
- **If laser source...**
 - **Either MM or SM fiber can be used** (depends on data rate and distance)
 - **Losses in both fiber types quite low**

Link Design: Power Budget

- With tentative choice of source/fiber/ λ ,
 - Compute power levels required at various link locations
- From desired data rate and BER...
 - Assume pin diode or APD
 - Find required detector power from sensitivity curves or specs



- Usually assume pin detector (lower cost, simpler operation)

Link Design: Power Budget (cont.)

- **Choice of preamp** (low-impedance, integrating front-end, or transimpedance receiver) **depends on...**
 - **Data rate and...**
 - **Amplifier noise**
- **From this analysis, obtain required receiver power P_R to achieve required performance**
- **System margin...**

$$L_M = P_T \text{ (dBm)} - P_R \text{ (dBm)} - \sum \text{losses (dB)}$$

- **Positive margin \Rightarrow successful link operation**
- **Negative margin \Rightarrow insufficient power at receiver to meet BER**
- **Losses can be allocated in any desired fashion by system designer**

Link Design: Power Budget (cont.)

- Possible losses

1. Source-to-fiber coupling loss at transmitter: L_T (dB)
2. Connector insertion loss for each *pair* of connectors: L_C
3. Splice insertion loss: L_S
 - n connectors or splices have total losses of nL_C (or nL_S), assuming all losses are equal
4. Fiber-to-receiver loss: L_R , (usually negligible)
5. Allowance for device aging effects: L_A
 - » For reduction in laser power over time and
 - » Future splicing requirements
6. Fiber losses: αl
7. Other losses (couplers, isolators, etc.)

Power Budget: Design Example

- **Example** (pp. 239-240)
- **Transmitter:** $P_T = 2 \text{ mW} \Leftrightarrow 3 \text{ dBm}$
 - Diameter: **225 μm**
- **Receiver**
 - From Fig. 6.24 (p. 239), $P_R[\text{dBm}]$ @ 100 Mb/s for BER = $10^{-9} \Rightarrow$
–40 dBm
- **Difference: 43 dB**
- **Fiber**
 - Graded-index ($g \approx 2$)
 - Core diameter: **50 μm**
 - Fiber diameter: **125 μm**
 - Loss: **5 dB/km**

Power Budget: Design Example (cont.)

Losses

– **Coupling loss:** $L_{\text{coupling}} = [\text{NA}(0)]^2 \left(\frac{a}{r_s}\right)^2 \left(\frac{g}{g+2}\right) = [0.25]^2 \left(\frac{25}{112.5}\right)^2$
 $= 0.0001543 = 0.01543\% \Leftrightarrow 28.1 \text{ dB} \text{ !!!!}$

– **Receiver losses**

» **Area mismatch (0 dB)**

» **Reflection losses (2 ea @ 0.1 dB = 0.2 dB)**

– **Aging allowance: 6 dB**

– **Joint loss: 0 dB (initially)**

– **Fiber loss: 5l**

Total loss: $L_{\text{total}} = L_{\text{coupling}} + L_{\text{RCVR}} + L_{\text{aging}} + L_{\text{joints}} + L_{\text{fiber}}$
 $= 28.1 + 0.2 + 6 + 0 + 5l = 34.3 + 5l$

Fiber length: $l = \frac{43 - 34.3}{5} = 1.74 \text{ km}$

Power Budget: Design Example (cont.)

- Repeat with 3 splices...
 - Fiber available in 1-km lengths
- Splice loss: 3 ea @ 0.1 dB
- Total loss:

$$\begin{aligned}L_{\text{total}} &= L_{\text{coupling}} + L_{\text{RCVR}} + L_{\text{aging}} + L_{\text{joints}} + L_{\text{fiber}} \\ &= 28.1 + 0.2 + 6 + 0.3 + 5l = 34.6 + 5l\end{aligned}$$

- Fiber length: $l = \frac{43 - 34.6}{5} = 1.68 \text{ km}$

Power Budget: Design Example IV

- Repeat with 3 connector pairs...
 - Fiber available in 1-km lengths

- Splice loss: 3 ea @ 1.0 dB

- Total loss:
$$L_{\text{total}} = L_{\text{coupling}} + L_{\text{RCVR}} + L_{\text{aging}} + L_{\text{joints}} + L_{\text{fiber}}$$
$$= 28.1 + 0.2 + 6 + 3.0 + 5l = 37.3 + 5l$$

- Fiber length:

$$l = (43 - 37.3) / 5 = 0.94 \text{ km}$$

- Only two connector pairs required; repeat calculation...

$$L_{\text{total}} = L_{\text{coupling}} + L_{\text{RCVR}} + L_{\text{aging}} + L_{\text{joints}} + L_{\text{fiber}} \quad l = (43 - 36.3) / 5 = 1.34 \text{ km}$$
$$= 28.1 + 0.2 + 6 + 2.0 + 5l = 36.3 + 5l$$

- Needs three connector pairs (conundrum)
- Conclusion: 1 km link with connectors

Fiber Links: Dynamic Range

- Adequate system margin built into link, but...
 - Too much margin can cause problems with system dynamic range
- Keep receiver power above minimum detectable power *and* below maximum-rated detector power
 - Too much power saturates receiver (cannot maintain rise-time and fall-time specs)
- Calculation of system dynamic range
 - Write system margin:
$$L_M = 10\log(P_T/P_R) - L_{\text{system}}$$
$$L_{\text{system}} = \alpha l + L_T + nL_s + mL_c + L_R + L_A$$
- Transmitter power is linear function of drive current
 - For specified drive current
 - » Power has device-to-device variation
- Similar variations in fiber losses

Fiber Links: Dynamic Range (cont.)

- **Dynamic range of system**

- First, compute margin for **best-case** link...

- » Maximum transmitter power

- » Minimum required receiver power

- » Minimum system losses: $L_{M \max} = 10 \log(P_{T \max} / P_{R \min}) - L_{\text{system min}}$

- » Second, calculate margin for **worst-case** link...

- » Minimum transmitter power

- » Maximum required receiver power

- » Maximum system losses: $L_{M \min} = 10 \log(P_{T \min} / P_{R \max}) - L_{\text{system max}}$

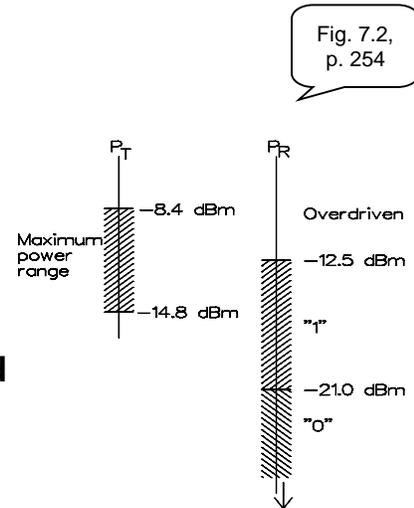
- **Dynamic range:** $DR \text{ (dB)} = L_{M \max} - L_{M \min}$

- Receiver must have equivalent dynamic range for system to work properly

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Fiber Links: Dynamic Range Example

- Example (p. 242)...
- HP HFBR-1501 transmitter specs...
 - Max power in 0.5-m pigtail at 60-mA max current: 8.4 dBm
 - Min power at same current: -14.8 dBm
- HP's HFBR-3500 fiber optic cable..
 - Maximum loss @ 665 nm: 0.63 dB/m
 - Minimum loss: 0.3 dB/m
- HFBR-2500 receiver...
 - Power level below -21.0 dBm for "0"
 - Power level between...
 - » Minimum of $P_R(1)_{min} = -21.0$ dBm and
 - » Maximum of $P_R(1)_{max} = -12.5$ dBm



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Fiber Links: Dynamic Range Example

- **Assume**

- Only cable losses
- No connectors
- No receiver losses
- No allowance for aging

- **Link length is $L-0.5$**

- **Maximum/minimum are...**

$$P_{R \max} = P_{T \max} - \alpha_{\min} (L-0.5) \leq P_R(1)_{\max}$$

$$P_{R \min} = P_{T \min} - \alpha_{\max} (L-0.5) \geq P_R(1)_{\min}$$

- First equation avoids overloading receiver
- Second equation ensures minimum required power at receiver

- **Consider 2-m link using HP devices**

- **Best case (“1” transmitted)...**

$$\begin{aligned} P_{T \max} &= P_{R \max} + \alpha_{\min} (L-0.5) \\ &= -12.5 + (0.3)(2-0.5) \\ &= -12.05 \text{ dBm} \Rightarrow 62.3 \mu\text{W} \end{aligned}$$

- **Worst case (“1” transmitted)...**

$$\begin{aligned} P_{T \min} &= P_{R \min} + \alpha_{\max} (L-0.5) \\ &= -21.0 + (0.63)(2-0.5) \\ &= -20.1 \text{ dBm} \Rightarrow 9.77 \mu\text{W} \end{aligned}$$

Fiber Links: Dynamic Range Example (cont.)

- Same calculations for six-meter spacing: $P_{T \max} = -10.85$ dBm;
 - $P_{T \min} = -17.35$ dBm
- As link distance increases, values approach each other until difference goes to zero...
 - Link cannot operate at longer distances
 - Maximum length limited by receiver dynamic range and properties of transmitter and fiber

- **Dynamic-range-limited** is where $P_{T \max} = P_{T \min}$...

$$P_R(\mathbf{1})_{\max} + \alpha_{\min}(L_{\max} - 0.5) = P_R(\mathbf{1})_{\min} + \alpha_{\max}(L_{\max} - 0.5)$$

$$L_{\max} - 0.5 = \frac{P_R(\mathbf{1})_{\max} - P_R(\mathbf{1})_{\min}}{\alpha_{\max} - \alpha_{\min}} = \frac{-12.5 - (-21)}{0.63 - 0.30} = 25.7 \text{ m}$$

- Increase distance by...
 - Increasing receiver dynamic range (i.e., $P_{R(1)\max} - P_{R(1)\min}$)
 - Using fiber with tighter tolerance on loss ($\alpha_{\max} - \alpha_{\min}$)

Fiber Links: Timing Analysis

- Need to analyze speed of link components to ensure that data rate can be met

- **System rise-time:**

$$\Delta t_{\text{sys}} = \sqrt{\sum_{i=1}^N \Delta t_i^2} = \sqrt{\Delta t_S^2 + \Delta t_R^2 + \Delta t_{\text{GVD}}^2 + \Delta t_{\text{modal}}^2}$$

- **Source rise-time, Δt_S**

- » Spec sheet or measure with pulsed input/fast detector

- **Receiver rise-time, Δt_R**

- » Spec sheet or...

- » Measure with pulsed optical signal, or...

- » Calculate from receiver bandwidth $B_{3\text{dB}}$ (measured in frequency domain)

$$\Delta t_R = 0.35/B_{3\text{-dB}}$$

Fiber Links: Timing Analysis

- **Group velocity dispersion time, Δt_{GVD} :**

$$\Delta t_{GVD} = \Delta t_{\text{mat}} + \Delta t_{\text{WG}} = -\frac{L}{c} \frac{\Delta\lambda}{\lambda} \left(\lambda^2 \frac{d^2 n}{d\lambda^2} \right) - \frac{n_2 L \Delta}{c} \frac{\Delta\lambda}{\lambda} \left(V \frac{d^2 (Vb)}{dV^2} \right)$$

- **Modal-dispersion time, Δt_{modal} :**

– Depends on many variables: excitation conditions, fiber construction, fiber length, and splice effects

– SI fiber: $\Delta t_{\text{modal}} = L(n_1 - n_2)/c$

– GI fiber:

» More complicated expression

» Delay time function of g and often g is optimized

- Parabolic ($g=2$) GI fiber: $\Delta t_{\text{modal}} = L[\text{NA}^2(0)]/8n_1^2 c$

Maximum Bit-Rate Condition

- Depends on coding...

$$\text{NRZ coding: } \Delta t_{\text{system}} \leq 0.7T_B = \frac{0.7}{B_R}$$

$$\text{RZ coding: } \Delta t_{\text{system}} \leq 0.35T_B = \frac{0.35}{B_R}$$

Timing Analysis: Example

- P. 245
- Consider 100 Mb·s⁻¹ link of prior design example
- LED source has rise-time of 8 ns (from specification sheet)
- *pin* diode has typical rise-time of 10 ns
- GVD dispersion
 - No waveguide dispersion at this wavelength
 - Material dispersion:
 - » LED has spectral width of 40 nm
 - » Silica fiber operating at 830 nm ($\lambda^2(d^2n/d\lambda^2) \approx 0.024$)
 - » For link distance of 1.74 km...

$$\begin{aligned}\Delta t_{\text{mat}} &= \frac{L}{c} \frac{\Delta\lambda}{\lambda} \left(\lambda^2 \frac{d^2n}{d\lambda^2} \right) = \left(\frac{1.74 \times 10^3}{3 \times 10^8} \right) \left(\frac{40}{830} \right) (0.024) \\ &= 6.71 \times 10^{-9} = 6.71 \text{ ns}\end{aligned}$$

Timing Analysis: Example (cont.)

- **Modal dispersion...**
 - Intermodal dispersion for T-200 GI fibers specified as 3.5 ns/km
 - For 1.74 km link, $\Delta t_{\text{modal}} = 6.09$ ns
- **System rise-time...**

$$\begin{aligned}\Delta t_{\text{sys}} &= \sqrt{\Delta t_S^2 + \Delta t_R^2 + \Delta t_{\text{mat}}^2 + \Delta t_{\text{modal}}^2} \\ &= \sqrt{8^2 + 10^2 + 6.71^2 + 6.09^2} \text{ ns} = 15.69 \text{ ns}\end{aligned}$$

Must compare system rise-time with required bit period T_B to achieve 100 Mb·s⁻¹ communications, ($T_B = 1/B_R$)

- **Requirement on system rise-time depends on data coding**

$$\Delta t_{\text{sys}} \leq \begin{cases} 0.70/B_R = 7.0 \times 10^{-9} \text{ s} & \text{(NRZ coding)} \\ 0.35/B_R = 3.55 \times 10^{-9} \text{ s} & \text{(RZ coding)} \end{cases}$$

Timing Analysis: Example (cont.)

- Our system rise-time was 18.3 ns; link cannot support data rate!
- Calculate data rates that system can support...
 - For NRZ coding

$$\Delta t_{\text{sys}} \leq 0.7T_B = 0.7/B_R$$
$$B_R \leq 0.7/\Delta t_{\text{sys}} = 0.7/18.3 \times 10^{-9} = 38.3 \text{ Mb/s}$$

- For RZ coding,

$$\Delta t_{\text{sys}} \leq 0.35T_B = 0.35/B_R$$
$$B_R \leq 0.35/\Delta t_{\text{sys}} = 0.35/18.3 \times 10^{-9} = 19.1 \text{ Mb/s}$$

- ***Neither coding can support 100 Mb·s⁻¹ data rate!***

Timing Analysis: Example (cont.)

- Possible solutions:
 - Each rise-time term must *individually* be smaller than desired system rise-time
 - » Source speed/receiver speed too large (faster source and receiver)
 - » Material dispersion too large
 - Reduce by reducing $\Delta\lambda$
 - Use LED with longer wavelength (while keeping $\Delta\lambda$ constant), or...
 - Use laser source (smaller $\Delta\lambda$)
 - » Modal dispersion too large
 - Reduce by finding fiber with lower modal dispersion spec
 - Use single-mode fiber
- Recalculate power budget and system rise-time

Timing Analysis: Dispersion-Limited Transmission

- Previous calculation illustrates important result
- Assuming system not limited by source or detector, can be limited
 - Either by losses (*“attenuation limited”*)...
 - Or by dispersion (*“dispersion limited”*)
- **Attenuation-limited transmission:**

$$L_{\max} = \frac{P_T(\text{dBm}) - P_R(\text{dBm})}{\alpha}$$

- Calculate **dispersion-limited transmission distances** by isolating each dispersion factor (modal dispersion or GVD dispersion)...

Dispersion-Limited Transmission (cont.): Material Dispersion-Limited Transmission

- Material dispersion in link using RZ coding...

$$\Delta t_{\text{mat}} = 0.35T_B$$
$$L_{\text{max}} = 0.35T_B c \left(\frac{\lambda}{\Delta\lambda} \right) \left(\frac{1}{\lambda^2 \frac{d^2 n}{d\lambda^2}} \right)$$

- Corresponding expression for NRZ coding...

$$\Delta t_{\text{mat}} = 0.7T_B$$
$$L_{\text{max}} = 0.7T_B c \left(\frac{\lambda}{\Delta\lambda} \right) \left(\frac{1}{\lambda^2 \frac{d^2 n}{d\lambda^2}} \right)$$

Dispersion-Limited Transmission (cont.): Modal-Dispersion-Limited Transmission

- SI fiber (RZ coding):

$$L_{\max} = \frac{0.35T_B c}{n_1 - n_2} = \frac{0.35c}{(n_1 - n_2)B_R}$$

- GI fiber (RZ coding):

$$L_{\max} = \frac{2.8T_B c n_1^2}{NA^2(0)} = \frac{2.8c n_1^2}{NA^2(0)B_R}$$

Dispersion-Limited Distance Example

- **Example (p. 248):**

- GI fiber: $n_1=1.45$, $\Delta = 1\%$, loss: 1 dB/km
- Source: $\lambda = 850$ nm, power in fiber: -10 dBm, linewidth of 60 nm
- Receiver: pin diode, requires...

$$P_R(\text{dBm}) = -65.0 + 20 \log (B'_R[\text{Mb}\cdot\text{s}^{-1}]) \quad (10^{-9} \text{ BER; RZ coding})$$

(a) Material-dispersion-limited:

$$L_{\max} = 0.35T_{BC} \left(\frac{\lambda}{\Delta\lambda} \right) \left(\frac{1}{\lambda^2 \frac{d^2n}{d\lambda^2}} \right); \quad \lambda^2 \frac{d^2n}{d\lambda^2} \approx 0.022 \quad (\text{Fig. 3.8, p. 48})$$
$$L_{\max} = 6.76 \times 10^{10} / B_R$$

Distance Limitations: Example (cont.)

- **Modal-dispersion-limited:**

$$\begin{aligned}L_{\max} &= \frac{5.6cn_1^3}{NA^4(0)B_R} = \frac{1.4cn_1^3}{n_1^4(2\Delta)^2B_R} \\ &= \frac{1.4c}{n_1\Delta^2B_R} = \frac{2.90 \times 10^{12}}{B_R}\end{aligned}$$

- **Attenuation-limited distance:**

$$\begin{aligned}L_{\max} &= \frac{P_T(\text{dBm}) - P_R(\text{dBm})}{\alpha} \\ &= \frac{-10 - (-65.0 + 20\log(B'_R))}{1.0} \\ &= 55.0 - 20\log\left(\frac{B_R}{1 \times 10^6}\right) \quad (B'_R \text{ in Mb/s})\end{aligned}$$

Distance Limitations: Example (cont.)

- **Results**

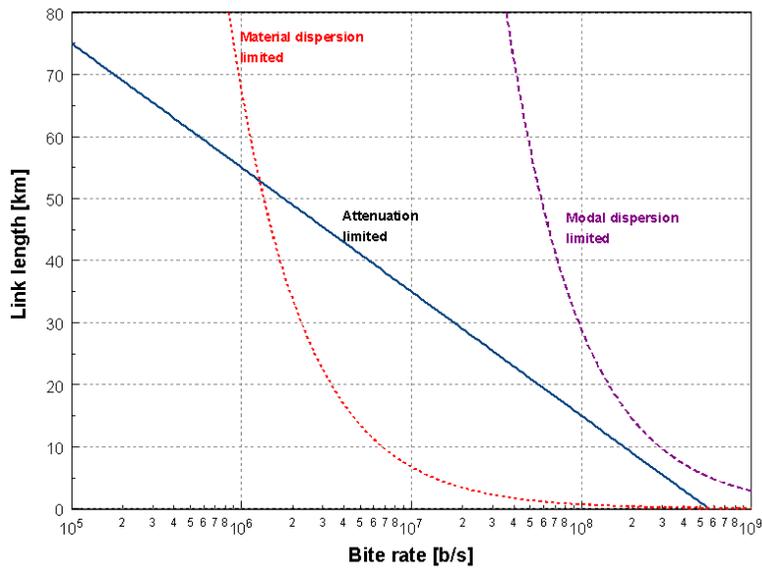


Fig. 7.3,
p. 262

- **Attenuation-limited: $<1.2 \text{ Mb}\cdot\text{s}^{-1}$**
- **Material-dispersion limited: $>1.2 \text{ Mb}\cdot\text{s}^{-1}$**
 - **Modal dispersion limit higher than material dispersion limit for this fiber**

Fiber Links: Commercial Modules

- **For moderate data rates and moderate distance transmission**
 - **Link design reduces to selection of commercial transmitter and receiver modules**
 - **Easily used**
 - **Provide proper signal levels (e.g., TTL in and TTL out)**
 - **User action...**
 - » **Selection of proper modules**
 - » **Design of electronic interface**
 - **Optical portion of design optimized by manufacturer**
- **Once link optical power reaches minimum detectable power, need to increase power...**
 - **Two techniques available...**
 - » **In-line repeaters**
 - » **Optical amplifiers**

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In-Line Repeater

- **Transforms signal into electrical form and regenerates optical signal at increased power**
 - » **Optical detector**
 - » **Signal-recovery circuits**
 - » **Optical source**
- **Pros: can be implemented**
- **Cons:**
 - » **Requires local power**
 - » **Full electronic recovery system at each repeater**
 - » **Costly electronics for high data rates**
 - » **Requires multiple repeaters for multi-wavelength link**

Link Power: Optical Amplifiers (cont.)

- **Optical amplifier**

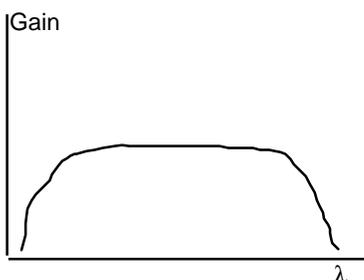
- Amplify *optical* signal without forming electronic equivalent
- Pros:
 - » Potential economic advantage
 - » Conceptually simple
 - » Can amplify multiple wavelengths
- Cons
 - » Requires local electrical power
 - » Adds noise
- Can also be used to...
 - » Preampify before receiver
 - » Overcome losses at splitters
- Both semiconductor amplifiers and fiber amplifiers

Ideal Optical Amplifier

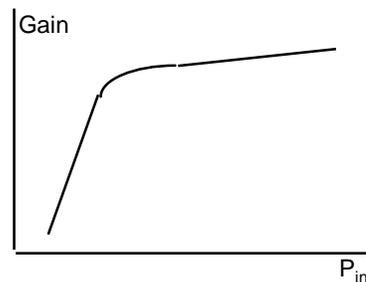
- Provide high gain: >30 dB
- Wide spectral bandwidth (10s nm)
- Uniform gain over amplifier spectral width
- Bi-directional operation
- Add minimum noise from amplifier
- No interference between multiple wavelengths
- Provide gain independent of signal polarization
- Low insertion loss
- Gain available over wide range of input power levels (i.e., gain does not saturate at high values of input power)
- Small, compact amplifier pump source
- Good conversion efficiency

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• Gain vs . wavelength



Gain vs. input power



Optical Amplifiers: Problems

- Optical amplifiers (with isolators) not bi-directional
- Amplifiers add noise to signal
 - Spontaneous emission light guided by amplifying fiber is further amplified
 - **Amplified spontaneous emission noise (ASE noise)**
 - » Spontaneous emitted light amplified in remaining length
 - Spectral width reduced by narrow optical filter centered on signal wavelength (increases amplifier insertion loss)

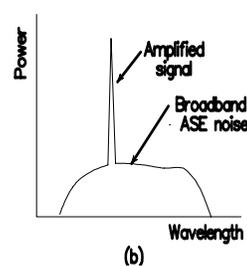
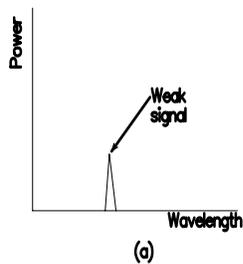


Fig. 7.4,
p. 264

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- Added noise of amplifier represented by noise figure

$$F = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}}$$

Optical Amplifiers: ASE Noise Effects

- ASE noise and gain saturation
 - Gain reduced by strong signals

$$g = \frac{g_0}{1 + (P_{in} / P_{sat})}$$

g_0 : unsaturated gain coefficient (determined by material and pump power)

P_{sat} : amplifier saturation power

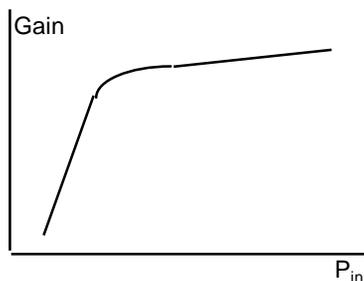
- » Overall amplifier power gain

$$G = G_0 e^{-\frac{(1-G)P_{in}}{P_{sat}}}$$

- G_0 : unsaturated gain of amplifier
- Once G_0 , P_{in} , and P_{sat} known, solve for G
- Noise effects
 - » ASE noise reduces amplifier gain and robs potential gain from signal

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- Gain saturation



Optical Amplifiers: ASE Noise Effects (cont.)

- **Amplifier spacing**
 - Noise leads to interesting tradeoff...
 - Noise is larger when gain is larger
 - » **Least ASE noise when...**
 - Optimum gain *just* compensates for fiber losses (gain=loss)
 - Amplification distributed uniformly over entire link
 - How to make long lengths of weakly amplifying fiber?
 - How to provide uniform pump power over entire length of fiber?
 - » **Second best solution**
 - Many small-gain amplifiers closely spaced (uneconomical)
 - » **Current practice**
 - Space amplifiers widely apart and accept noise penalty

Links-41

- **Optimum gain**
 - ☞ Gain coefficient equal to loss coefficient
 - ☞ I.e., make fiber transparent to signal

Erbium-Doped Fiber Amplifiers

- Popular optical amplifier
- Operates in 1530 to 1570 nm window
- Pumped by diode laser operating at 980 or 1,480 nm
- Gains: 30→40 dB
 - Lengths: 10s of meters
 - Output power levels of 1 mW
 - Pump power: few 10s of mW
 - Insertion loss: typically <1 dB

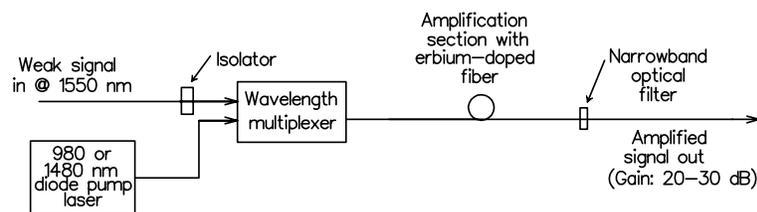


Fig. 7.6,
p. 266

Links-42

- Pump coupling
 - ☞ Co-propagating: propagates in signal direction
 - ☞ Counter-propagating: propagates against signal direction

Erbium-Doped Fiber Amplifiers (cont.)

- **Potential disadvantages**

- Limited to operation near 1550 nm
 - » Fiber-amplifier @ 1300 nm?
 - Praseodymium-doped fibers
 - Silica not good host; use fluoride-based glass
- Non-trivial pump power
 - » 40→50 mW at 980 & 1,480 nm
- Amplifier-fiber lengths > several meters
- Adds amplifier noise to signal

- **Models:**

- Interaction between...
 - » Signal beam
 - » Amplifying medium
 - » Pump beam
 - » Amplified spontaneous emission
- Simple analyses based on model results

Cascaded Amplifiers

- Typical in-line amplifier application

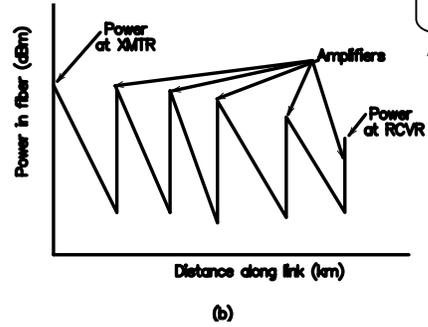
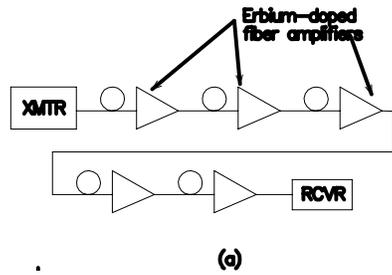
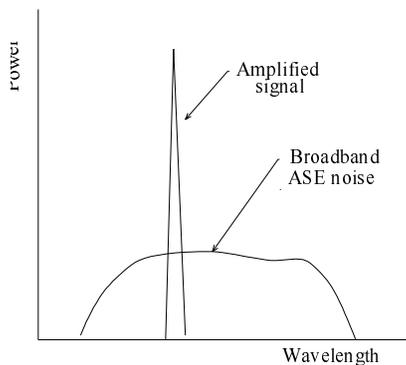


Fig. 7.7,
p. 268

- Amplifiers boost signal after attenuation
- Process *cannot* be carried out indefinitely
 - Amplifiers add noise to signal
 - Noise eventually overwhelms signal

Links-44

- Signal and noise spectra



Links-44

Cascaded Amplifiers (cont.)

- Consider string of N amplifiers...
 - Assume...
 - » Equal spacing (l)
 - » Equal loss between amplifiers (multiplicative loss, L)
 - Each amplifier has different gain G_i
 - » Amplifies
 - Signal
 - Noise from previous amplifiers
 - » Adds ASE power
 - » Assume output of each amplifier has optical filter of bandwidth, B_o
 - » At output of n -th amplifier, output signal power

$$P_{\text{signal},n,\text{out}} = G_i P_{\text{signal},n,\text{in}} = G_i L P_{\text{signal},n-1,\text{out}}$$

Links-45

- Loss, L , is multiplicative loss ($P_{\text{out}} = L P_{\text{in}}$)
- Size of gain is controlled by pump power and length of amplifying fiber
 - ☞ (For given fiber and pump strength, there is optimum fiber length
 - * Maximizes gain

Cascaded Amplifiers (cont.)

- **Forward-propagating ASE power (function of gain and n_{sp})**

$$P_{ASE,i} = 2n_{sp} h\nu \Delta\nu_{amp} (G_i - 1) \quad P_{ASE,i,out} = 2n_{sp} h\nu B_o (G_i - 1) = \frac{B_o}{\Delta\nu_{amp}} P_{ASE,i} = bP_{ASE,i}$$

$$b = B_o / \Delta\nu \text{ (}\Delta\nu\text{: amplifier spectral width)}$$

- **Total ASE power out of i -th amplifier:**

$$\begin{aligned} P_{ASE,i,out} &= G_i P_{ASE,i,in} + bP_{ASE,i,out} (G_i, n_{sp}) \\ &= G_i LP_{s,i-1,out} + bP_{ASE,i,out} (G_i, n_{sp}) \end{aligned}$$

- **Adding power contributions, total power out of i -th amplifier**

$$P_{Total,i,out} = P_{signal,i,out} + P_{ASE,i,out} = G_i LP_{Total,i-1,out} + \underbrace{2n_{sp} (G_i - 1) h\nu B_o}_{P_{ASE,i}}$$

- **Initial values:**

$$- P_{signal,0,out} = P_{in} \text{ (signal power in fiber at XMTR)}$$

Cascaded-Amplifier Example

- pp. 257-258
- **Assume: same total output power of each amplifier**

$$P_{total,n,out} = P_{in}$$

- **Typical parameters**
 - $\lambda = 1545 \text{ nm}$, $P_{in} = 9 \text{ mW}$, $G_0 = 35 \text{ dB}$ (3,182), $LG_0 = 3$ ($\Rightarrow L = 3/G_0 = 9.48 \times 10^{-4} \Rightarrow -30.2 \text{ dB loss}$), $n_{sp} = 1.3$, $\Delta\nu = 3.1 \times 10^{12}$ (25 nm)
- **Assume optical filter bandwidth: $B_o = 126 \times 10^9 \text{ Hz}$ (1 nm)**
- **Find G_n of each amplifier**

$$G_i = \frac{P_{in} + 2n_{sp}h\nu B_o}{LP_{in} + 2n_{sp}h\nu B_o}$$

- Noting that $2n_{sp}h\nu B_o \approx 4.2 \times 10^{-8} \text{ W}$, $P_{in} = 9 \times 10^{-3} \text{ W}$, $LP_{s,0} \approx 9 \times 10^{-6} \text{ W}$

$$G_i \approx 1/L = G = 1.054 \times 10^3 \Rightarrow 30.2 \text{ dB}$$

- » Gain balances attenuation
- **Distance between amplifiers if $\alpha = 0.5 \text{ dB/km}$: $l = 30.2/0.5 = 60.4 \text{ km}$**

Links-47

- **Equation for G_i is solution of**

$$P_{total,i,out} = P_{in} = LG_i \left(\underbrace{P_{signal,i-1,out} + P_{ASE,i-1,out}}_{P_{in}} \right) + 2n_{sp}h\nu B_o (G_i - 1)$$

$$G_i = \frac{P_{in} + 2n_{sp}h\nu B_o}{LP_{in} + 2n_{sp}h\nu B_o} \approx \frac{1}{L}$$

Cascaded Amplifiers Example (cont.)

- P_{sat} needed to achieve this gain...

$$P_{sat,i} = \frac{(1-L)P_{in}}{\ln LG_0} = 8.19 \text{ mW}$$

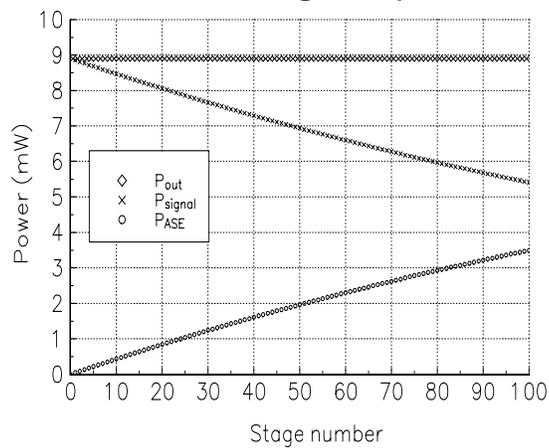
- Calculate and plot $P_{s,i,out}$, $P_{total,i,out}$ and $P_{ASE,i,out}$ for each of 100 stages...

– $P_{total,i,out}$ is easy: $P_{total,i,out} = P_{in} = 9 \text{ mW}$

Links-48

- Iterative approach

- Power plots (discussed in detail on following slide)



Links-48

Cascaded Amplifiers Example (cont.)

- Calculating total power and ASE power out of each amplifier...

Stage	$P_{\text{total, in}}$	$P_{\text{total, out}}$	$P_{\text{ASE, out}}$
1	LP_{in}	$GLP_{\text{in}} = P_{\text{in}}$	$1P_{\text{ASE}}$
2	LP_{in}	$GLP_{\text{in}} = P_{\text{in}}$	$G(L 1P_{\text{ASE}}) + 1P_{\text{ASE}} = 2P_{\text{ASE}}$
3	LP_{in}	$GLP_{\text{in}} = P_{\text{in}}$	$G(L 2P_{\text{ASE}}) + 1P_{\text{ASE}} = 3P_{\text{ASE}}$
...
i	LP_{in}	$GLP_{\text{in}} = P_{\text{in}}$	$G(L ([i-1]P_{\text{ASE}})) + 1P_{\text{ASE}} = iP_{\text{ASE}}$

$$P_{\text{ASE, i, out}} = iP_{\text{ASE}} = i(2n_{sp} h\nu B_o (G-1))$$

– Find $P_{\text{signal, i, out}}$ from...

$$P_{\text{signal, i, out}} = P_{\text{total, i, out}} - P_{\text{ASE, i, out}} = P_{\text{in}} - 2in_{sp} h\nu B_o (G-1)$$

Cascaded Amplifiers Example (cont.)

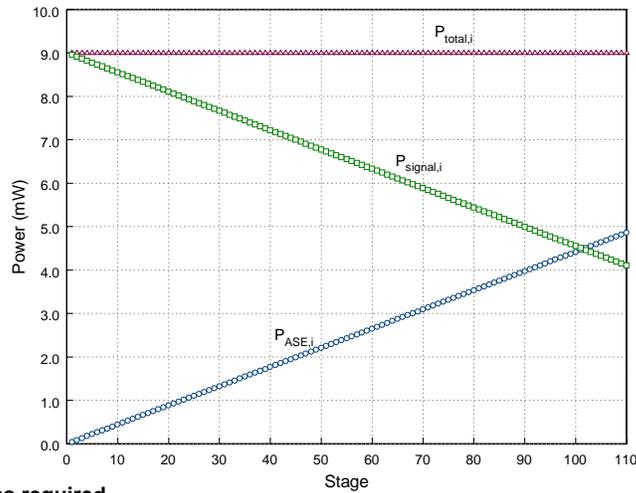


Fig. 7.8,
p. 271

- $P_{total,i,out}$ is flat, as required
- After first amplifier, ASE power begins to grow linearly with i ...
 - Subsequent amplification of attenuated ASE power from prior amplifier(s) and...
 - Addition of ASE power by each amplifier
- Signal power steadily falls
 - Increasing ASE power uses increasing portion of gain
 - But, signal decreases much slower than it would without amplifiers
 - Eventually, signal lost in noise

Links-50

Cascaded Amplifiers: Receiver SNR

- **Noise sources...**
 1. **Shot noise due to signal**
 2. **Thermal noise associated with detector load**
 3. **Noise due to mixing (or "beating") of signal and ASE**
 - » **Produces frequencies within receiver electronic bandwidth**
 4. **Noise due to mixing of different ASE components**
 - » **Produces frequencies within receiver bandwidth**
- **Noise sources 3 and 4:**
 - **New noise introduced by ASE light**

Cascaded Amplifiers: Receiver SNR (cont.)

- Mean-square noise currents associated with latter noise sources

$$\left\langle I_{\text{sig-ASE}}^2 \right\rangle = 2I_{\text{ASE}} I_{\text{sig}} B_e / B_o \quad \left\langle I_{\text{ASE-ASE}}^2 \right\rangle = I_{\text{ASE}}^2 B_e / B_o$$

$$I_{\text{ASE}} = \mathfrak{R}_0 P_{\text{ASE}} \quad I_{\text{sig}} = \mathfrak{R}_0 P_{\text{sig}}$$

\mathfrak{R}_0 : detector responsivity and B_e : receiver electrical bandwidth ($=B_R/2$)

- Define $R_B = B_o / B_e$ and $R_{\text{ASE}} = P_{\text{ASE}} / P_{\text{sig}}$
- Assuming Gaussian noise and that only ASE-signal and ASE-ASE beat noises are important, the Q for given BER must satisfy...

$$Q \geq \frac{2\sqrt{R_B}}{R_{\text{ASE}} + \sqrt{4R_{\text{ASE}} + R_{\text{ASE}}^2}}$$

- Let's illustrate application of this formula...

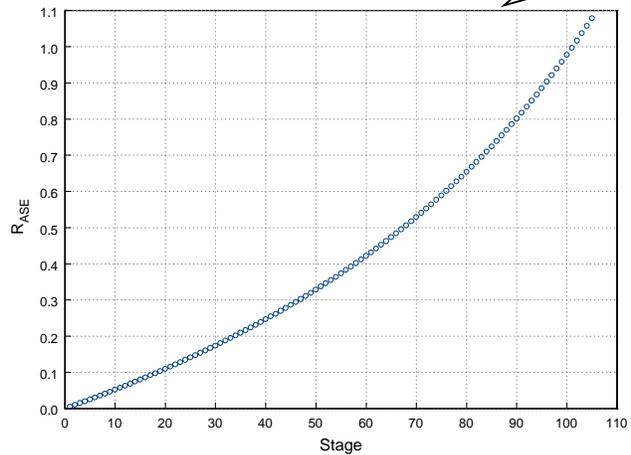
Cascaded Amplifiers: RCVR SNR Example

- Same link as prior example (see notes)
- B_R : 2.5 Gb·s⁻¹; BER: 10⁻⁹ (⇒ Q = 6.0)
- Enough SNR to achieve BER after 100 amplifiers and fiber between them?
- Electrical bandwidth $B_e \approx B_R/2 = 1.25 \times 10^9$
- $R_B = B_o/B_e = 100.8$
- So...

$$Q = 6.0 \geq \frac{2\sqrt{R_B}}{R_{ASE} + \sqrt{4R_{ASE} + R_{ASE}^2}}$$

$$R_{ASE} (= P_{ASE}/P_{signal}) \leq 1.046 = 104.6\%$$

Note: 103 stages at ~60 km/stage = ~6,180 km!



Links-53

• Amplifier and link properties

- ☞ $P_{sat} = 8$ mW
- ☞ $P_{s,0} = 9$ mW
- ☞ $G_0 = 35$ dB
- ☞ $LG_0 = 3$
- ☞ $n_{sp} = 1.3$
- ☞ $B_o = 126 \times 10^9$ Hz
- ☞ $\Delta v_{amp} = 3.10 \times 10^{12}$
- ☞ $\lambda = 1545$ nm

Cascaded Amplifiers: Other Effects

- N cascaded amplifiers have decreased spectral bandwidth
 - Optical filter spectral response...

$$f(\lambda) = \frac{1}{1 + \left(\frac{\lambda - \lambda_c}{B_o}\right)^6}; \quad f_{\text{total}} = f(\lambda)^N = \frac{1}{\left[1 + \left(\frac{\lambda - \lambda_c}{B_o}\right)^6\right]^N}$$

λ_c : center wavelength of passband

B_o : 3-dB spectral width of the filter

- Cascade of N filters: $f_{\text{total}}(\lambda) = f(\lambda)^N$
 - » 3-dB bandwidth of N stages: $B' = B_o(\ln(2)/N)^{1/6}$
- Net effect: B_o replaced by effective bandwidth of cascaded units
 - Effective bandwidth reduces noise contributions from ASE noise of previous stages
 - Last amplifiers in chain contribute most noise at receiver

Links-54

Cascaded Amplifiers: Other Effects (cont)

- **Nonuniform spectral response**
 - **Problem with WDM (multiwavelength)**
 - **Complicates spectrum of ASE noise**
 - **Some parts attenuated more than others**
 - **Numerical modeling required**
- **Large amplifier gains**
 - **Use optical isolators after amplifiers**
 - » **Keep reflections from being amplified and upsetting data link**
 - » **Does not allow bi-directional links (e.g., OTDRs)**

L-band Optical Amplifiers

- **Current commercial EDFAs**

- **C-band** (“conventional band”)
- 1530–1570 nm
- Nominal “1550-nm amplifier”

- **New EDFAs**

- **L-band** (“long-wavelength band”)
- 1570–1605 nm
- Added bandwidth for more WDM channels
- Longer lengths for 30-dB gain
- Lower gain ripple (~1/10x)
- More pump power required (less pump efficiency)
- Avoids zero-dispersion wavelengths for dispersion-shifted fibers (hence, reduces 4-wave mixing in WDM systems)

Semiconductor Optical Amplifiers (SOAs)

- **Semiconductor diode amplifiers also amplify light**
 - **Laser diode devices**
 - **Pumped below oscillation**
 - **Introduce external signal into Fabry-Perot resonator**
 - **Pros:**
 - » **High gain (~30 dB) in small package**
 - **Cons:**
 - » **High insertion loss (6 dB or more)**
 - » **Amplitude light modulation in one channel affects gain characteristics for other channels (causing crosstalk)**
 - » **Nonlinearities in gain medium affect amplification process**
- **Few applications, due to popularity of erbium-doped fiber amplifiers**

Semiconductor Optical Amplifiers

- Operate laser chip (with no added mirrors; anti-reflection coated surfaces) below threshold
- Operates as amplifier
- Pros:
 - Small device
- Cons:
 - Narrow $\Delta\lambda$ (not good for WDM)
 - High insertion loss (>6 dB)
 - Net gain reduced (~20 dB)

Optical Amplifiers: Status

- Widely deployed in high capacity links
- Caused change in wavelength from 1300 nm to 1550 nm
- Work in progress...
 - Multistage amplifiers
 - Wide $\Delta\nu$ amplifiers
 - Flattened gain curve, $G(\lambda)$
 - » Precompensating spectral filter or power variation
 - » Bragg grating filter between amplifier stages
 - » Limiting $\Delta\lambda$ to flat region of gain
 - » Working in L-band (naturally flat gain)

Dispersion Compensation

- Many 1300-nm systems now being operated at 1550 nm
 - Non-dispersion-shifted legacy fiber system
 - » 1300 nm: $D \sim 2 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1}$
 - » 1550 nm: $D \sim 20 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1}$
- How to counter increased dispersion?
- Dispersion compensation...
 - Alternating fiber lengths with opposite dispersion
 - Dispersion-compensating devices
 - » High anomalous dispersion
 - » e.g., fiber mode converters, fiber grating devices
 - Special fiber amplifiers
 - Optical phase conjugation
 - Electronic processing
 - » Signal predistortion
 - » Post-detection pulse processing

Dispersion-Compensating Fiber

- Alternate positive dispersion fiber with negative-dispersion fiber

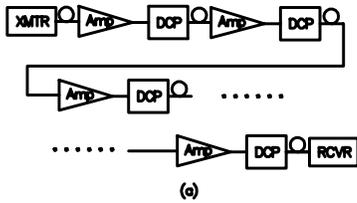
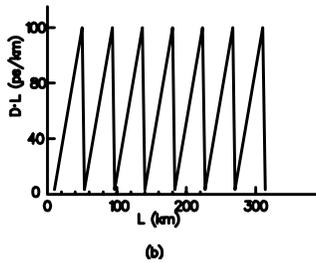


Fig. 7.11, p. 279



- Located at amplifier locations and

$$D_1 L_1 = D_2 L_2$$

- Want short length so that losses are not too severe
- Design high dispersion fiber
 - $D \sim 100 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1} \dots$
 - ...but losses also high
 - Figure of merit: $\text{FOM} = D/\alpha$

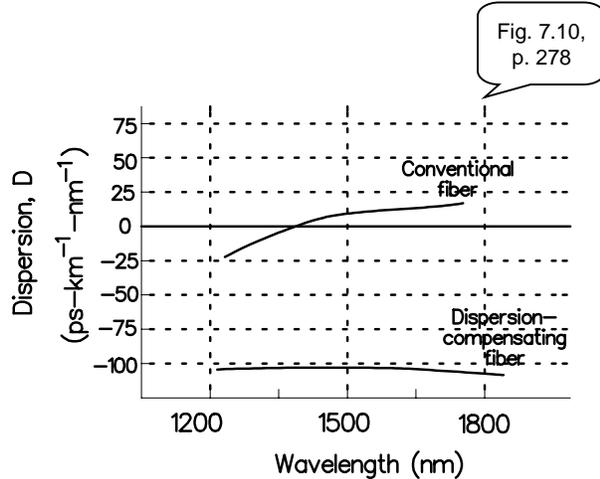


Fig. 7.10, p. 278

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- Figure of merit has been suggested to incorporate nonlinearities as well...

$$\text{FOM}_{\text{NL}} = \frac{A'_{\text{eff}}}{A_{\text{eff}}} \frac{\alpha'}{\alpha} \frac{(e^{\alpha_p L} - 1)^2}{e^{\alpha_p L}} \frac{e^{\alpha'_p L'}}{(e^{\alpha'_p L'} - 1)^2} \frac{D}{D'}$$

Solitons

- Soliton transmission demonstrations
 - **Solitons**: pulses of moderate power that induce self-phase modulation (SPM) in SM fiber to counter GVD dispersion
 - Multi-gigabit/sec signals sent through millions of kilometers of fiber
 - Dispersion is non-factor (first time that channel does not limit practical bandwidths or distances)
- Amplifier spacing
 - Amplifiers need to keep nonlinear interaction
 - Space ~30 km apart (closer than conventional links)
- Desired pulse shape: $\text{sech}^2(t)$
- Pulse jitter can limit data rate-distance
 - Use optical filters with slightly offset center frequencies (“sliding” filters)

Fiber Links: Summary

- **Data/clock encoding** increases B_R required
- Methodology used in **fiber-link design**
 - Meet performance requirements: data rate, BER, distance
 - Link can be **attenuation-limited** or **dispersion-limited**
 - » Requires calculation of
 - **Power budget** and
 - **System rise-time**
- **Optical amplifiers** (especially erbium-doped fiber amplifiers) allow all-optical signal amplification
 - **ASE noise** generated in amplifier and amplified by following amplifiers
 - SNR gradually decreases until BER cannot be met
 - Amplifier techniques increasingly popular in long-haul high-data-rate systems
- **Dispersion compensation** can increase data rate-distance
- **Solitons** offer superb performance
 - SPM cancels GVD dispersion
 - No pulse spread