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**

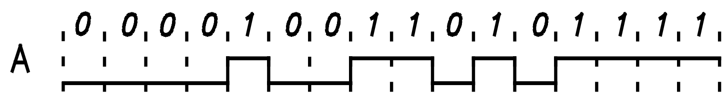
Fiber Links: Data Coding

- 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 fiber date rates
- Standard techniques have evolved for data encoding

Links-3

Coding: NRZ Coding

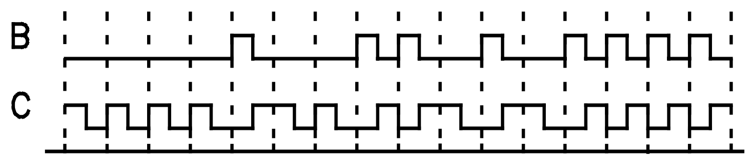
- *Nonreturn-to-zero (NRZ)* ***code***:
  - Signal *not* required to return to 0 during bit period
  - Average (DC) output varies with signal content (string of 1s will keep output at 1 level for duration of data string)
  - Simple to generate and decode
  - No clock-encoding or error detection/correction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



Links-4

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



Links-5

Coding (cont.)

- **Many fiber optic encoding/decoding transmitter/receiver modules commercially available**
- **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* bits into *n* bits (*n*>*m*)**
      - **Code rate: *n/m* × data rate**
  - **ICs available to encode and decode**
    - » **Primarily error detection and correction**

Links-6

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

Links-7

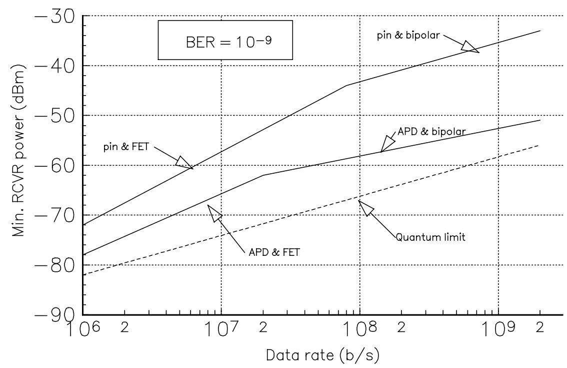
Link Design: Fiber Selection

- **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**

Links-8

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**



- **As an initial estimate, usually assume pin detector (lower cost, simpler operation)**

Links-9

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**

$$l_M = P_T(\mathrm{dBm}) - P_R(\mathrm{dBm}) - \mathrm{losses}(\mathrm{dB})$$

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

Links-10

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.)**

Links-11

Power Budget: Design Example

- Example (pp. 215-216, revised in errata)
- Transmitter: $P_T = 2\text{ mW} \Leftrightarrow 3\text{ dBm}$
  - Diameter: 225 μm
- Receiver
  - From Fig. 6.23 (p. 204) @ 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:** $l_{\text{coupling}} = \left[NA^2(0)\right]^2 \left(\frac{a}{r_s}\right)^2 \left(\frac{g}{g+2}\right) = [0.25]^2 \left(\frac{25}{112.5}\right)^2$

  $= 0.0001543 = 0.01543\% \Leftrightarrow 28.1 \text{ dB !!!!}$
- **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: 5*L***

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:** $l_{\text{total}} = l_{\text{coupling}} + l_{\text{RCVR}} + l_{\text{aging}} + l_{\text{joints}} + l_{\text{fiber}}$

$$= 28.1 + 0.2 + 6 + 0.3 + 5L = 34.6 + 5L$$

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

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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...**

$$l_{\text{total}} = l_{\text{coupling}} + l_{\text{RCVR}} + l_{\text{aging}} + l_{\text{joints}} + l_{\text{fiber}}$$
$$= 28.1 + 0.2 + 6 + 2.0 + 5L = 36.3 + 5L$$

$$L = (43 - 36.3)/5 = 1.34 \text{ km}$$

- **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:

$$l_M = 10\log\left(P_T / P_R\right) - l_{\text{system}}$$

$$l_{\text{system}} = \alpha L + l_T + nl_s + ml_c + l_R + l_A$$

- Transmitter power is linear function of drive current
  - For specified drive current
    - » Power has device-to-device variation
- Similar variations in fiber losses

Links-16

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:** $l_{M\ \max} = 10\log\left(P_{T\ \max} / P_{R\ \min}\right) - l_{\text{system min}}$
    - » **Second, calculate margin for *worst-case* link...**
    - » **Minimum transmitter power**
    - » **Maximum required receiver power**
    - » **Maximum system losses:** $l_{M\ \min} = 10\log\left(P_{T\ \min} / P_{R\ \max}\right) - l_{\text{system max}}$
  - **Dynamic range:** $\mathrm{DR}(\mathrm{dB}) = l_{M\ \max} - l_{M\ \min}$
- **Receiver must have equivalent dynamic range for system to work properly**

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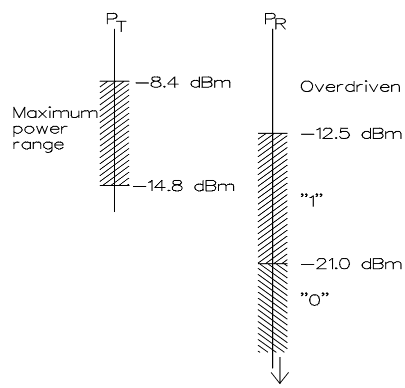
Fiber Links: Dynamic Range Example

- **Example...**
- **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**



Links-18

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...**

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

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

- **Consider 2-m link using HP devices**
- **Best case** **("1" transmitted)…**

$$\begin{aligned} P_{R\,\max} &= P_{T\,\max} - \alpha_{\min}\left(L-0.5\right) \\ &= -12.05 \text{ dBm} \Rightarrow 62.3\ \mu\text{W} \end{aligned}$$

- **Worst case** **("1" transmitted)...**

$$\begin{aligned} P_{R\,\min} &= P_{T\,\min} - \alpha_{\max}\left(L-0.5\right) \\ &= -20.1 \text{ dBm} \Rightarrow 9.77\ \mu\text{W} \end{aligned}$$

Fiber Links: Dynamic Range Example (cont.)

- **Same calculations for six-meter spacing: $P_{R\,max}$= –10.85 dBm;**
  - **$P_{R\,min}$= –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 $B_{3\,dB}$ (measured in frequency domain)**

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

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Fiber Links: Timing Analysis

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

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

- ***Modal-dispersion time, Δt_{modal}:***
  - **Depends on many variables: excitation conditions, fiber construction, fiber length, and splice effects**
  - **SI fiber:** $\Delta t_{\mathrm{modal}} = L(n_1 - n_2)/c$
  - **GI fiber:**
    - » **More complicated expression**
    - » **Delay time function of *g* and often *g* is optimized**
      - **Parabolic (*g*=2) GI fiber:** $\Delta t_{\mathrm{modal}} = L\left[\mathrm{NA}^2(0)\right]/8n_1^2 c$

Links-22

Maximum Bit-Rate Condition

- **Depends on coding...**

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

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

Links-23

Timing Analysis: Example

- **P. 219 (revised in errata)**
- **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 has $\lambda^2(d^2n/d\lambda^2) \approx 0.024$**
    - » **For link distance of 1.74 km...**

$$\Delta t_{\mathrm{mat}} = \frac{L}{c}\frac{\Delta\lambda}{\lambda}\left(\lambda^2\frac{\mathrm{d}^2 n}{\mathrm{d}\lambda^2}\right) = \left(\frac{1.74\times 10^3}{3\times 10^8}\right)\left(\frac{40}{830}\right)(0.024)$$

$$= 6.71\times 10^{-9} = 6.71\ \mathrm{ns}$$

Links-24

Timing Analysis: Example (cont.)

- **Modal dispersion...**
  - **Intermodal dispersion for T-200 GI fibers specified as 3.5 ns/km**
  - **For 2.5 km link, $\Delta t_{modal} = 8.8$ ns**
- **System rise-time...**

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

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**

$$\Delta t_{\text{sys}} \le \begin{cases} 0.70/B_R = 7.0\times10^{-9}\ \text{s} & \text{(NRZ coding)} \\ 0.35/B_R = 3.55\times10^{-9}\ \text{s} & \text{(RZ coding)} \end{cases}$$

Links-25

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**

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

  - **For RZ coding,**

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

- ***Neither*** **coding can support 100 Mb·s^{-1} data rate!**

Links-26

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**

Links-27

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:**

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

- **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...**

$$\Delta t_{mat} = 0.35T_B$$

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

- **Corresponding expression for NRZ coding...**

$$\Delta t_{mat} = 0.7T_B$$

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

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

- **SI fiber (RZ coding):**

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

- **GI fiber (RZ coding):**

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

Links-30

Dispersion-Limited Distance Example

- **Example (p. 222):**
  - **GI fiber: n_1=*1.45*, Δ = 1%, loss: 1 dB/km**
  - **Source: λ = 850 nm, power in fiber: –10 dBm, linewidth of 60 nm**
  - **Receiver: pin diode, requires**

    P_R(dBm) = –65.0 + 20 log (DR[Mb·s^{-1}])

    to maintain 10^{-9} BER with RZ coding

(a) Material-dispersion-limited:

$$L_{\max} = 0.35 T_B c \left(\frac{\lambda}{\Delta\lambda}\right)\left(\frac{1}{\lambda^2 \dfrac{d^2 n}{d\lambda^2}}\right); \qquad \lambda^2 \frac{d^2 n}{d\lambda^2} \approx 0.022 \ \text{(Fig. 3.8, p. 48)}$$

$$L_{\max} = 6.76 \times 10^{10} / B_R$$

Distance Limitations: Example (cont.)

- **Modal-dispersion-limited:**

$$L_{\max} = \frac{2.8 c n_1^2}{\mathrm{NA}^2(0)\mathrm{B}_R} = \frac{2.8 c n_1^2}{2 n_1 (n_2 - n_2)\mathrm{B}_R}$$

$$= \frac{1.4 c}{\Delta \mathrm{B}_R} = \frac{4.20 \times 10^{10}}{\mathrm{B}_R}$$

- **Attenuation-limited distance:**

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

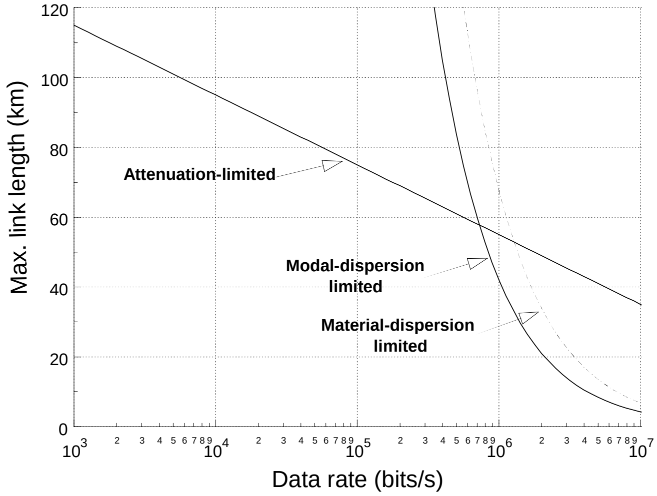
$$= \frac{-10 - \left(-65.0 + 20\log(B_R')\right)}{1.0}$$

$$= 55.0 - 20\log(B_R') \qquad (B_R' \text{ in Mb/s})$$

Distance Limitations: Example (cont.)

Fig. 7.3,
p. 223
revised

- **Results**



- **Attenuation-limited: <700 Mb·s^{-1}**
  - **Modal-dispersion limited: >700 Mb·s^{-1}**
  - **Material dispersion limit slightly higher than modal dispersion limit for this fiber**

Links-33

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

Links-34

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 power
    - » Adds noise
  - Can also be used to...
    - » Preamplify before receiver
    - » Overcome losses at splitters
  - Both semiconductor amplifiers and fiber amplifiers

Links-36

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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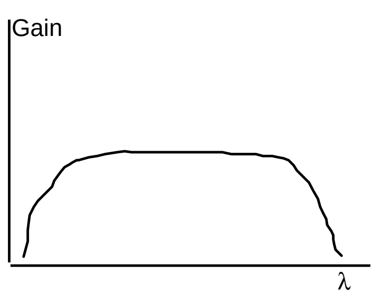
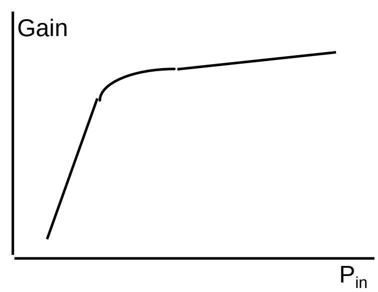
- **Gain vs . wavelength** **Gain vs. input power**





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)**

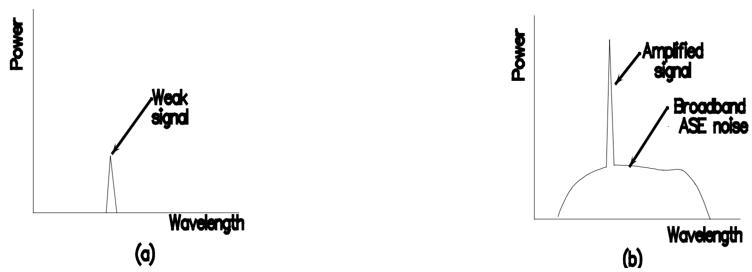


Fig. 7.4, p. 226

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- **Added noise of amplifier represented by noise figure**

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

Optical Amplifiers: ASE Noise Effects

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

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

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

P_{sat}: amplifier saturation power

» **Overall amplifier power gain**

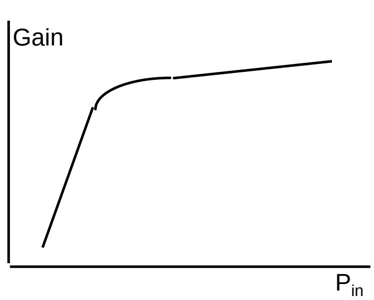
$$G = G_0 e^{\frac{(1-G)P_{in}}{P_{sat}}}$$

- **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**

- **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...**
      - **Optimum gain just compensates for fiber losses**
      - **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**

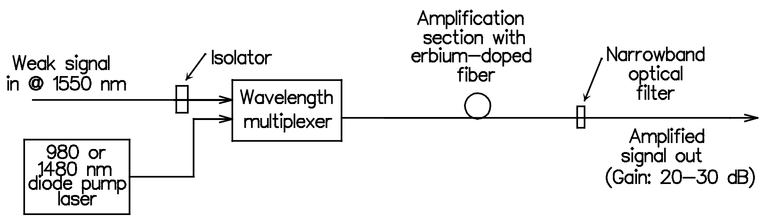
Links-40

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

Erbium-Doped Fiber Amplifiers

- Popular optical amplifier
- Operates in 1520 to 1550 nm window
- Pumped by diode laser operating at 950 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. 228



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- **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 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

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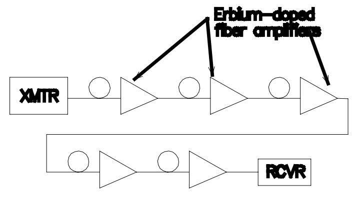
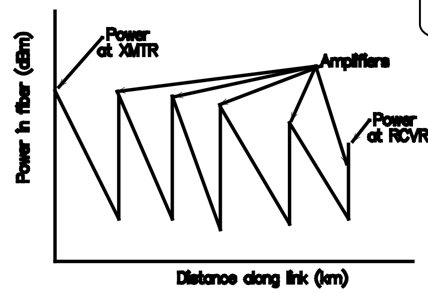
Cascaded Amplifiers

- **Typical in-line amplifier application**

Fig. 7.7, p. 229



(a)



(b)

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

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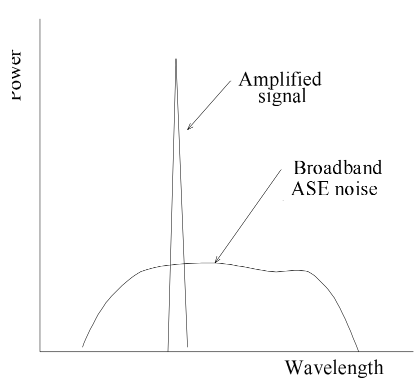
- **Signal and noise spectra**



Cascaded Amplifiers (cont.)

- Consider string of *N* amplifiers...
  - Assume...
    - » Equal spacing (*l*)
    - » Equal loss between amplifiers (*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 *i*-th amplifier, output signal power

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

Links-44

- Loss, L, is multiplicative loss (Pout = L Pin)
- 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})**

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

$b = B_o/\Delta\nu$ **($\Delta\nu$: amplifier spectral width)**

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

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

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

$$P_{\text{Total},i,\text{out}} = G_i L P_{\text{Total},i-1,\text{out}} + 2n_{sp}(G_i - 1) h\nu B_0$$

- **Initial values:**
  - $P_{signal,0,out} = P_{signal}$ **(signal power in fiber at XMTR)**

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Cascaded-Amplifier Example

- pp. 230—231, revised
- Assume: same total output power of each amplifier

$$P_{total,i,out} = P_{total,in} = P_{s,0}$$

- Typical parameters
  - λ = 1545 nm, $P_{s,0}$ = 9 mW, G_0 = 35 dB (3,182), LG_0 = 3 ($\Rightarrow L = 3/G_o$ = 9.48$\times 10^{-4}$ $\Rightarrow$ –30.2 dB loss), n_{sp} = 1.3, $\Delta\nu = 3.1\times10^{12}$ (25 nm)
- Assume optical filter bandwidth: $B_o = 126\times10^9$ Hz (1 nm)
- Find G_i of each amplifier

$$G_i = \frac{P_{s,0} + 2n_{sp}h\nu B_o}{2n_{sp}h\nu B_o + LP_{s,0}}$$

  - Noting that $2n_{sp}h\nu\ B_o \approx 4.2\text{x}10^{-8}$ W,

$$G_i \approx 1/L = 1.054\times10^3 \Rightarrow 30.2\ \text{dB}$$

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

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Cascaded Amplifiers Example (cont.)

- P_{sat} needed to achieve this gain

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

- 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: $P_{total,i,out} = P_{s,0,in} = 9 \text{ mW}$

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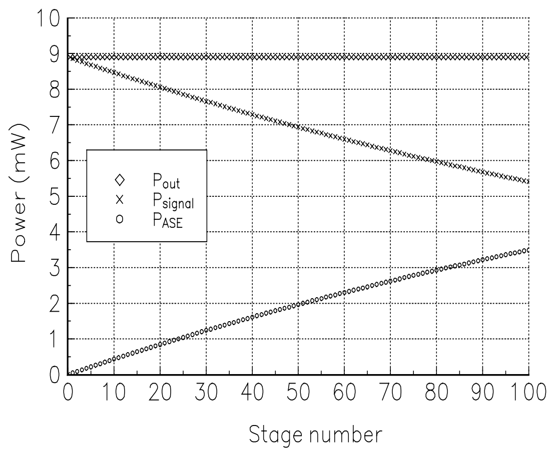
- Iterative approach

- Power plots (discussed in detail on following slide)



Cascaded Amplifiers Example (cont.)

- **Calculating signal power and ASE power out of each amplifier…**

Stage	$P_{total,\ in}$	$P_{signal,\ out}$	$P_{ASE,out}$
1	P_{signal}	$GP_{signal\ in}$	$1P_{amp\ ASE}$
2	$LP_{signal}+L(1P_{amp\ ASE})$	$GLP_{signal\ in}= P_{signal\ in}$	$G(L\ (1P_{amp\ ASE}))+ 1P_{amp\ ASE} =2P_{amp\ ASE}$
3	$LP_{signal}+L(2P_{amp\ ASE})$	$GLP_{signal\ in}= P_{signal\ in}$	$G(L\ (2P_{amp\ ASE}))+ 1P_{amp\ ASE} =3P_{amp\ ASE}$
…	…	…	…
n	$LP_{signal}+L([n-1]P_{amp\ ASE})$	$GLP_{signal\ in}= P_{signal\ in}$	$G(L\ ([n-1]P_{amp\ ASE}))+ 1P_{amp\ ASE} =nP_{amp\ ASE}$

$$P_{ASE,n,out} = nP_{amp\ ASE} = n\left(2n_{sp}\ h\nu B_o\left(G-1\right)\right)$$

- **Find $P_{signal,i,out}$ from...**

$$P_{\text{signal,n,out}} = P_{\text{total,i,out}} - P_{\text{ASE,i,out}} = P_{\text{signal},0} - 2nn_{sp}h\nu B_o\left(G-1\right)$$

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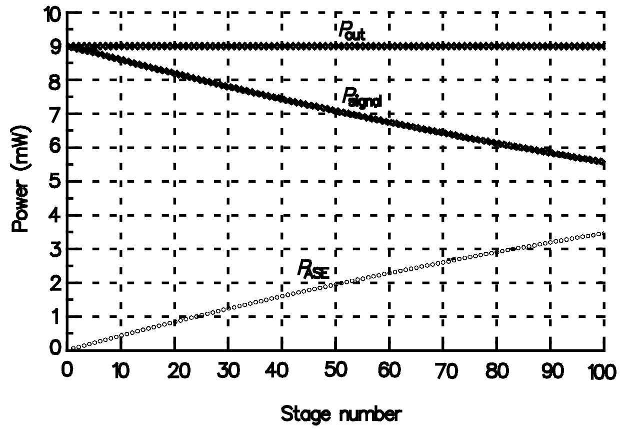
Cascaded Amplifiers Example (cont.)



- ***P**$_{total,i,out}$* **is flat, as required**
- **After first amplifier, ASE power begins to grow...**
  - **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**
  - **Signal decreases much slower than it would without amplifiers**
  - **Eventually, signal lost in noise**

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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

Links-50

Cascaded Amplifiers: Receiver SNR (cont.)

- **Mean-square noise currents associated with latter noise sources**

$$I^2_{\text{sig-ASE}} = 2I_{\text{ASE}} I_{\text{sig}} B_e / B_o \qquad I^2_{\text{ASE-ASE}} = 2I^2_{\text{ASE}} B_e / B_o$$

$$I_{\text{ASE}} = \Re P_{\text{ASE}} \qquad I_{\text{sig}} = \Re P_{\text{sig}}$$

$\Re_0$**: detector responsivity and** B_e**: receiver electrical bandwidth (**$=B_R/2$**)**

- **Define** $R_e = B_e / B_o$ 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 a given BER must satisfy…**

$$Q = \frac{2\sqrt{R_B}}{R_{\text{ASE}} + \sqrt{4R_{\text{ASE}} + R^2_{\text{ASE}}}}$$

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

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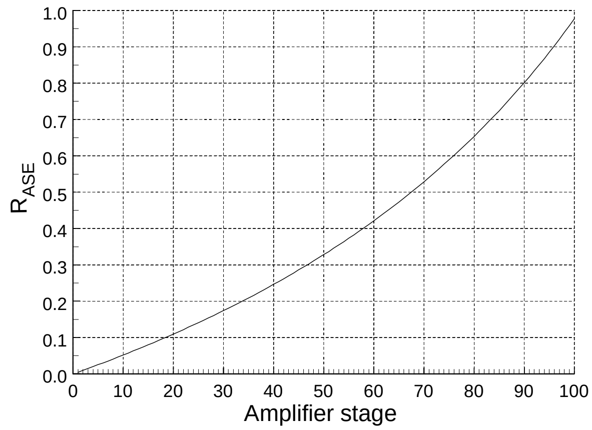
Cascaded Amplifiers: RCVR SNR Example

- **Same link as prior example (see notes)**
- **B_R: 2.5 Gb·s^{-1}; BER: 10^{-9} ($\Rightarrow Q = 6.0$)**
- **Enough SNR to achieve BER after 100 amplifiers and fiber between them?**
- **Electrical bandwidth $B_e \approx B_R/2 = 1.25\times10^9$**
- **$R_B = B_o/B_e = 100.8$**
- **So...**

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

$$R_{\mathrm{ASE}}\left(= P_{\mathrm{ASE}}/P_{\mathrm{signal}}\right) = 1.046 = 104.6\%$$



Note: 100 stages at ~60 km/stage = ~6,000 km!

- **Amplifier and link properties**
  - ☞ **Psat = 8 mW**
  - ☞ **Ps,0 = 9 mW**
  - ☞ **G0 = 35 dB**
  - ☞ **LG0 = 3**
  - ☞ **nsp = 1.3**
  - ☞ **Bo = 126[illegible]9 Hz**
  - ☞ **[illegible]amp = 3.10[illegible]12**
  - ☞ **● = 1545 nm**

Cascaded Amplifiers: Other Effects

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

$$f(\lambda) = \frac{1}{1 + \left(\frac{\lambda - \lambda_c}{B_1}\right)^6}$$

  λ_c: **center wavelength of passband**

  B_1: **3-dB spectral width of the filter**

  - **Cascade of N filters: $f_{total}(\lambda) = f(\lambda)^N$**
    - » **3-dB bandwidth of N stages reduced by factor of $(\ln(2)/N)^{1/6}$**
- **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**

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)**

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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**

Links-55

Optical Amplifiers: Status

- Widely deployed in high capacity links
- Caused change in wavelength from 1300 nm to 1550 nm
- Work in progress...
  - Wide $\Delta\nu$ amplifiers
  - Flattened gain curve

Dispersion Compensation

- Many 1300-nm systems now being operated at 1550 nm
  - Non-dispersion-shifted legacy fiber system
    - » 1300 nm: D~2 $ps \cdot nm^{-1} \cdot km^{-1}$
    - » 1550 nm: D~20 $ps \cdot nm^{-1} \cdot km^{-1}$
- 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

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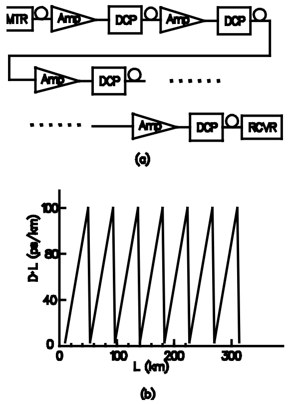
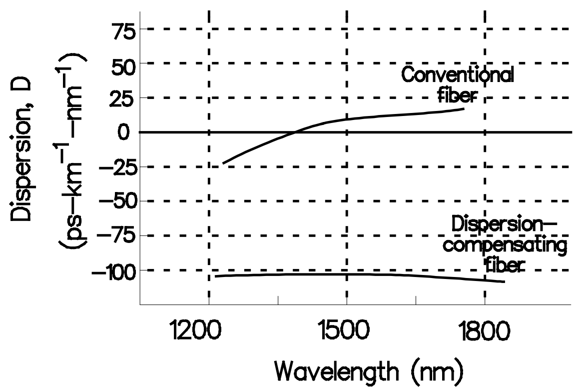
Dispersion-Compensating Fiber

- **Alternate positive dispersion fiber with negative-dispersion fiber**



- **Located at amplifier locations and**
  $D_1L_1 = D_2L_2$

- **Want short length so that losses are not too severe**
- **Design high dispersion fiber**
  - **D~100 ps·nm^{-1}·km^{-1}...**
  - **...but losses also high**
  - **Figure of merit: FOM = D/α**



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

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

Solitons

- Soliton transmission demonstrations
  - *Solitons*: pulses of moderate power that induce self-phase modulation in fiber to counter fiber 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: $sech^2(t)$
- 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 require-ments: 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

Links-60