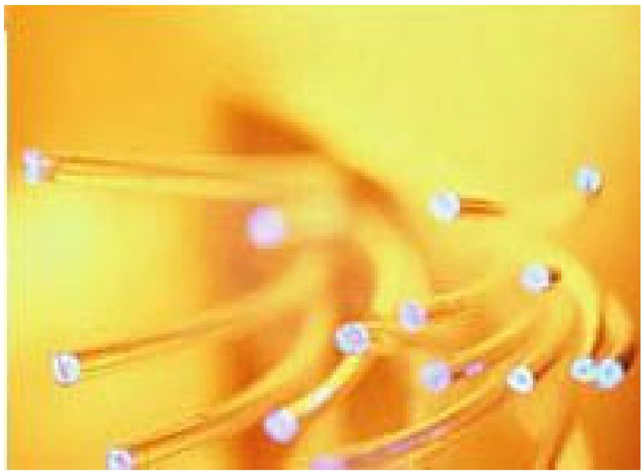
Properties of Optical Fibers



Fiber Properties Preview

- Optical attenuation
  - Power loss in fiber
    - » Causes...
      - Absorption and scattering in glass
      - Glass impurities, fiber imperfections, bends
    - » Minimum loss at 1550 nm
- Fiber dispersion
  - Pulse spreading limits maximum data rate
  - Causes
    - » Fiber modes
    - » *n* is function of wavelength
    - » Waveguide effects
  - Zero dispersion near 1300 nm
- Nonlinear effects
  - Accumulate over long distances
  - Limit maximum power that can be put into a fiber

Fiber Loss: Attenuation Factor

- **Optical power decreases exponentially as light travels through fiber**

$$P(z) = P(0)e^{-\alpha_p z}$$

- ***Attenuation factor*** α **(dB/km)**
  - **Expressed as dB/km loss**

$$\alpha = \frac{-10\log\left(P(z)/P(0)\right)}{z}$$

  - **Typical values: few tenths $\rightarrow$ few dB/km**
  - **Wavelength-dependent :**

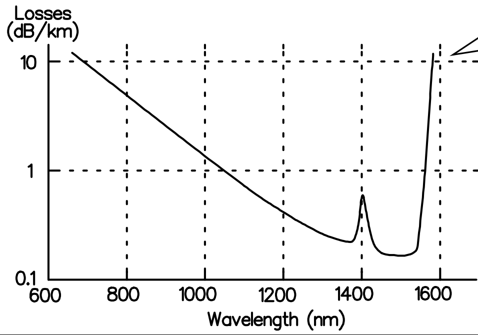


Fig. 3.1 p. 34

Props-3

Fiber Loss: Numerical Example p. 35

- Optical fiber losses: 0.6 dB/km at 1300 nm
- If 100 μW of power at transmitter, how much power at 22 km?

- Use dBm (or dBμ)

- See classroom discussion

Props-4

Fiber Loss: Attenuation (cont.)

- **Factors:**
  - **Material absorptions**
  - **Impurity absorptions**
  - **Scattering effects**
  - **Interface inhomogeneities**
  - **Radiation at bends**

Props-5

- Material absorptions: Silica (SiO_2) absorption
- Impurity absorptions
  - ☞ Impurity metals
  - ☞ H_2O vapor
- Scattering effects
  - ☞ Molecular scattering (~□-1/4); long-wavelength limit
  - ☞ Mie scattering
  - ☞ Nonlinear scattering
- Interface inhomogeneities
  - ☞ Particles
  - ☞ Geometry defects
- Bend losses
  - ☞ MM fiber: geometry changes light couples out of core
  - ☞ SM fiber: light tries to accelerate beyond c/n; radiates power
  - ☞ Negligible below critical turn radius of ~ 1 cm

Fiber Loss: 1. Material Absorption

Absorption – materials absorb light at certain wavelengths

1. Molecules of basic fiber material (silica = SiO_2)
   - Fundamental loss limit at high λs
     - » Change materials to lower loss ("Ultralow-loss" fiber)
2. Material impurities
   - Metallic ions
     - » Iron, cobalt, copper, chromium
     - » Remove by purification
       - ppb (parts per billion) concen-trations
   - OH^- water ion (peak at 1400 nm)
     - » Remove by chlorine drying
3. Hydrogen effects
   - Increased losses at 1.2 and 1.6 μm
   - Produced by...
     - » Corrosion or ...
     - » Bacteria
   - Increases loss by interaction with glass
   - Solution:
     - » Eliminate H_2 sources or...
     - » Add impermeable coating to fiber

Props-6

Fiber Loss: 2. Scattering Loss

- **Wave interacts with "particle" or molecules and transfers power to other directions**

  ***a. Linear scattering*:**

  » **Scattered power proportional to incident power**

  » **No change in frequency of scattered light**

  ***1. Rayleigh scattering*:**

  » **Particles << λ**

  - **Molecules, changes in *n* (change in composition), changes in density**

  » **Scattering strength ~1/λ^4**

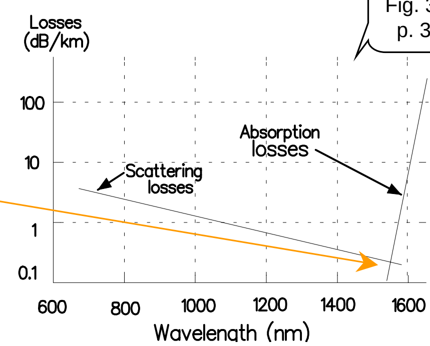
  » **Fundamental loss at low wavelengths**

  - **Minimum loss at 1550 nm!! in silica (SiO_2)**

  "Magic wavelength #1"

  - **Theoretical minimum ~0.15 dB/km**

Fig. 3.2
p. 38



Props-7

Fiber Loss: 2. Scattering Loss (cont.)

a. Linear scattering **(cont)**

2. Mie scattering

- » **Particles ~λ**
  - **Inhomogeneities**
    - **Core-cladding refractive index variations**
    - **Core-cladding interface impurities**
    - **Diameter fluctuations**
  - **Strains in fiber**
  - **Bubbles in fiber**
- » **Solution:**
  - **Remove imperfections**

Props-8

Fiber Loss: 2. Scattering Loss (cont)

b. Nonlinear Scattering

- **Cause: high *E* field (V/m)** **(i.e., combination of power, area, and distance)**
- **Power scattered forward, backward, or side directions,** **depending on interaction**

***A. Brillouin scattering*:**

» **Photon undergoes nonlinear interaction to produce...**

- **Vibrational energy ("phonons") and**
- **Scattered light ("photons")**

» **Upward and downward frequency shifts**

- **Strength of scattering varies with scattering angle**
  - **Maximum in backward direction; minimum of zero in forward direction**

» **Solution: keep power level below threshold**

- **Nonlinear scattering imposes "ceiling" on source power**
- **Brillouin-scattering threshold power level...**

$$P_B\,[\mathrm{W}] = \left(17.6\times10^{-3}\right) a'^2\,[\mu\mathrm{m}]\,\lambda'^2\,[\mu\mathrm{m}]\,\alpha\ \Delta\upsilon'[\mathrm{GHz}]$$

$$(\text{typically } \le 1 \text{ W in SM fiber})$$

Props-9

- Ex., 8/125 SM fiber with 0.8 dB/km loss at 1300 nm; source $\Delta\lambda$ of 0.013 nm,

  $\Rightarrow P_B$ = 0.879 W.

Fiber Loss: 2. Scattering Loss (cont.)

b. Nonlinear Scattering (cont)

***B. Raman scattering*:**

» **Nonlinear interaction produces….**

- **High-frequency phonon (instead low-frequency phonon of Brillouin scattering)**
- **Scattered photons**

» **Scattering predominantly in *forward* direction (power not lost)**

» **Raman-scattering threshold power:**

$$P_{\text{Raman}} = \left(23.6\times10^{-2}\right)a'^{2}\,[\mu\text{m}]\,\lambda'\,[\mu\text{m}]\,\alpha \qquad \text{(typically few W)}$$

» **Solution: keep power level below threshold**

- **Single channel fiber**
  - **Brillouin threshold lower than Raman and determines power "ceiling"**

Props-10

- Ex., 8/125 SM fiber with 0.8 dB/km loss at 1300 nm; source $\Delta\lambda$ of 0.013 nm,
  $\Rightarrow P_R = 3.93$ W

Fiber Loss: 3. Interface Inhomogeneities

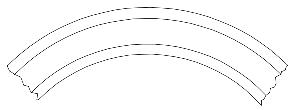
- **Some typical inhomogeneities**
  - **Impurities trapped at core-cladding interface**
  - **Impurities in fiber buffering**
  - **Geometrical changes in core shape and/or size**
- **SM fibers more susceptible**
- **Solution: Remove source of problem**
  - **Manufacturing quality control**

Props-11

Fiber Loss: 4. Bend Losses

A. Macrobends

- Large bends of cable and fiber

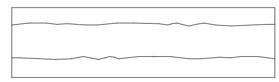


- At bend, core/cladding angle of incidence changes and power lost
- Lost power depends on bend radius
  - » Negligible losses until bend radius reaches critical size (typically < 1 cm)
  - » Solution:
    - Limit bend radius (e.g., add cable stiffener)

***B. Microbends*:**

- Small-scale bends in core-cladding interface

Fig. 3.3
p. 41



- Develop during fiber deployment or local mechanical stresses
- Develop due to cabling, spooling, or wrapping fiber on bobbin
  - » ***Cabling loss*** **and** ***spooling loss***
  - » Typical added loss:
    - ✠ 1 to 2 dB/km
  - » Solution (partial) : careful winding

- Expression for critical bend radius:

$$r_{\text{critical}} \approx 3n_2\lambda / 4\pi\,\text{NA}^3$$

Props-12

Fiber Loss: 4. Single-Mode Fiber Bend Loss

- Bend loss particularly important in SM fiber
- Dramatic loss increase above critical wavelength if fiber bent or perturbed
  - Appreciably high @ 1550 nm in 1300-nm designed fibers
  - Susceptibility depends on MFD and λ_{cutoff}
  - Worst-case is fiber with...
    - » Large MFD and low λ_{cutoff}
    - » Avoid this combination!
- Minimize bend losses by...
  - Choosing small ratio of core to fiber diameter
  - Having large Δ and/or...
  - Jacketing with compressible material

Props-13

Loss Summary

- Loss in fiber due to…
  - Absorption
  - Scattering (linear and nonlinear)
  - Fiber inhomogeneities
  - Bends
    - » Macrobends
    - » Microbends
- *Intrinsic losses* due to
  - Absorption
  - Scattering
- Minimum loss at 1.55 μm
- Theoretical minimum loss (~0.15 dB/km) almost achieved in practice

Props-14

Loss Measurements

- Insertion loss measurement
  - Uses optical source and optical power meter
  - Measure loss of piece of fiber
  - Add fiber to be tested
  - Extra loss is loss of fiber (plus connector/splice losses)
- Cutback method
  - Uses optical source and optical power meter
  - Measure loss of fiber under test
  - Delete some length of the fiber
  - Reduction of loss is loss of fiber
- Optical Time Domain Reflectometer (OTDR)
  - See following discussion...

Props-15

OTDR

- OTDR - Optical Time-Domain Reflectometer
- Ubiquitous fiber optic instrument
- Requires access to only one end of fiber
- Can measure...
  - Fiber length
  - Distance to fiber breaks, connections, splices
  - Fiber loss (dB/km)
  - Connector and splice loss

Props-16

OTDR Operation

- **Consists of pulsed laser, detector, electronic processing**
- **Weak backscatter from glass molecules**
- **Pulsed source, time-gated receive**
- **Received power level stored in memory**

Fig. 3.4
p. 44

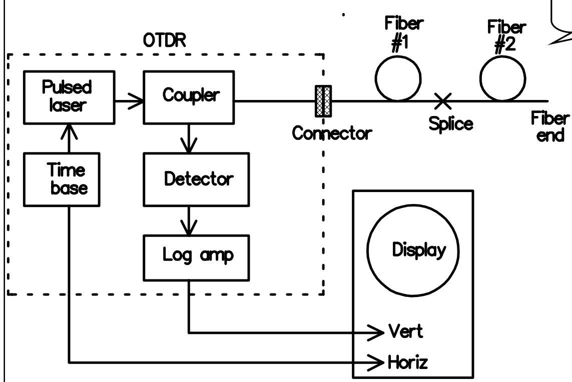
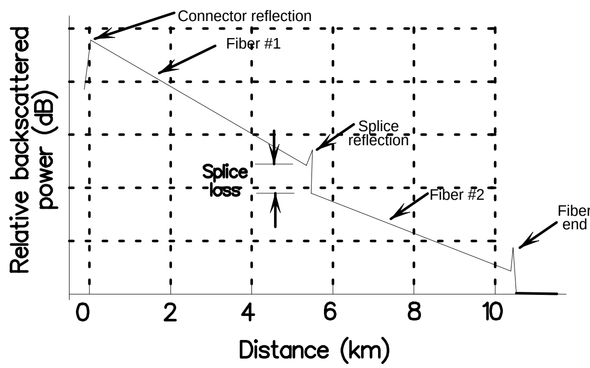


Fig. 3.5
p. 45



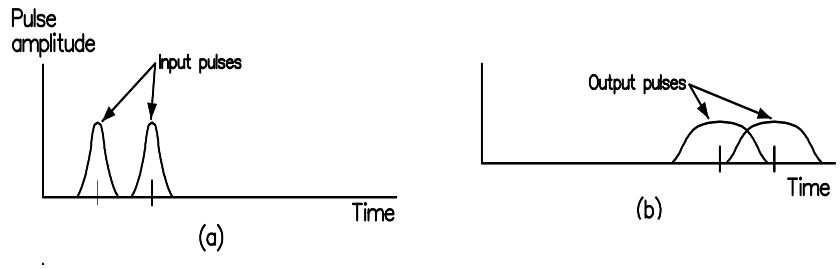
Props-17

- See problems 4, 5, 6, and 8 for details.

Dispersion in Optical Fibers

- Pulse spreads as it propagates; overlapping causes intersymbol interference

Fig. 3.6
p. 46



- Amount of spreading
  - Limits how close (in time) two adjacent output pulses can be
  - Limits maximum data rate
- Primary sources of spreading in fibers:
  - *Group velocity dispersion*
    - » *Material dispersion*
    - » *Waveguide dispersion*
  - *Modal dispersion*

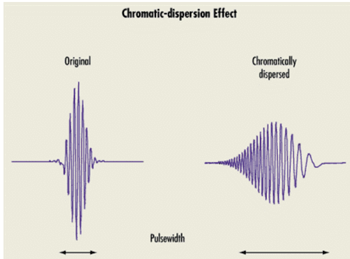


Figure 1. Chromatic dispersion results in the broadening of light pulses. Too much dispersion can create transmission errors.

Props-18

Group Velocity Dispersion

- GVD - Group velocity dispersion
- Consists of...
  - Material dispersion
  - Waveguide dispersion

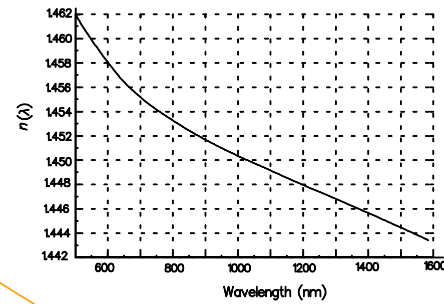
- We consider each separately and add effects together

Props-19

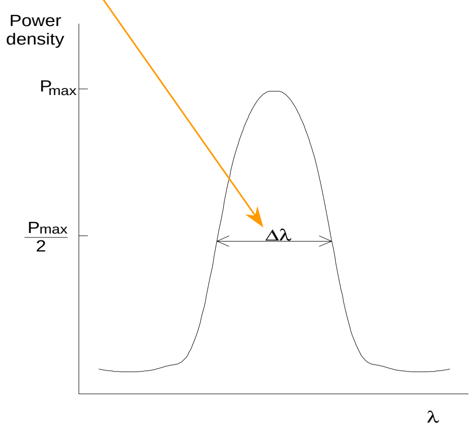
Fiber Dispersion: A. Material Dispersion

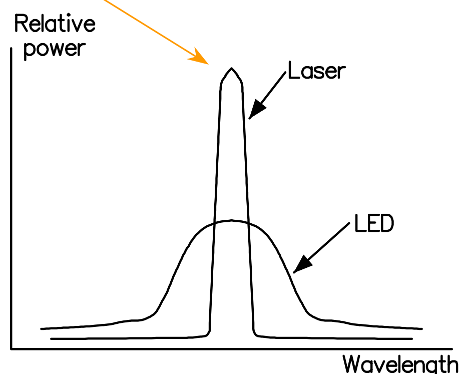
Fig. 3.7
p. 47

- **Velocity of light in SiO_2 is weak function of wavelength, *$n(\lambda)$***



- **All light sources have *spectral width* $\Delta\lambda$**
  - **Lasers narrower spectrum than LEDs**
- **Longer λs arrive at RCVR before shorter λs**





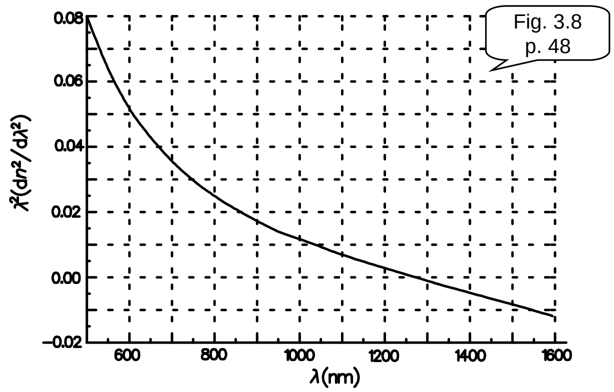
- Ex.: material dispersion in a 62.5/125 fiber with n1 = 1.48 and □ = 1.5% is86.3 ps□km1 □nm1 at 850 nm and is +35.6 ps□km1□nm1 at 1500 nm

Material Dispersion (cont.)

- **Pulse spread due to material dispersion**

$$\Delta\tau_{\text{mat}} = -\frac{L}{c}\frac{\Delta\lambda}{\lambda}\underbrace{\left(\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right)}_{\text{Figure 3.8, p. 48}}$$

- **Frequently normalized:** $D_{mat}=\Delta\tau_{mat}/(L\Delta\lambda)$ **[ps·km⁻¹·nm⁻¹]**

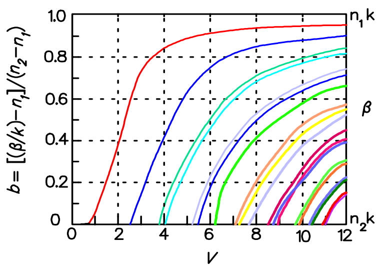


Props-21

Fiber Dispersion: B. Waveguide Dispersion

- **In region from 1,000 nm to 1600 nm in SM fibers...**
  - ***Waveguide dispersion* becomes important**
  - **Negligible in MM fibers and in SM fibers operated below 1,000 nm and above 1,600 nm**
- **Cause: velocity of mode is function of *a/λ***
- **Pulse spread due to waveguide dispersion**
- **$D_{WG} = \Delta\tau_{WG}/L\ \Delta\lambda$ [ps·km^{-1}·nm^{-1}]**

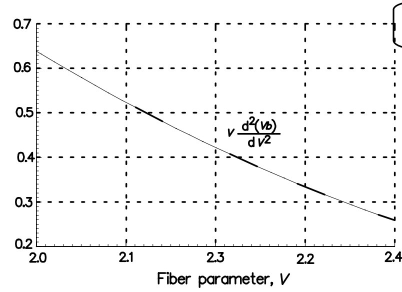
$$\Delta\tau_{wg} = -\left(\frac{n_2 L\Delta}{c}\right)\left(\frac{\Delta\lambda}{\lambda}\right)\underbrace{\left(V\frac{d^2(Vb)}{dV^2}\right)}_{\text{Figure 3.10, p. 52}}$$



Velocity of mode

$V = 2\pi a n_1$ sqrt{2Δ}/λ

Fig. 3.10 p. 52



Props-22

- Ex.: At 1300 nm, 9/125 single-mode fiber with n_1 = 1.48 and Δ = 0.22%

  ⇒ D_{WG} = –4.00 ps·km^{-1}·nm^{-1}

Fiber Dispersion: Zero-Dispersion SM Fiber

- **SM fiber:**
  - ***Total dispersion* = GVD = material + waveguide dispersions**
- **Small positive material dispersion can cancel small negative waveguide dispersion**
  - **Result: zero dispersion (at single λ)**
  - ***Zero-dispersion point in SM fiber occurs near "1300" nm***

"Magic" wavelength #2

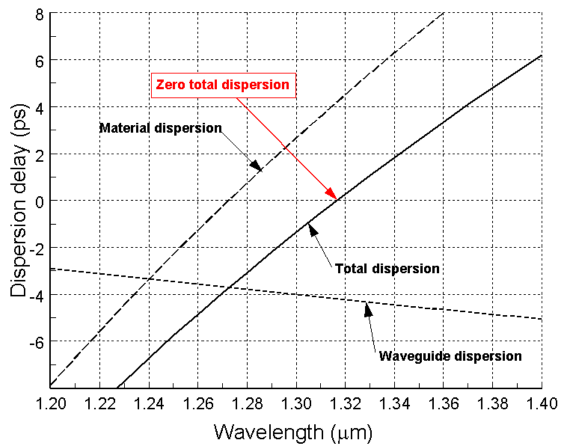


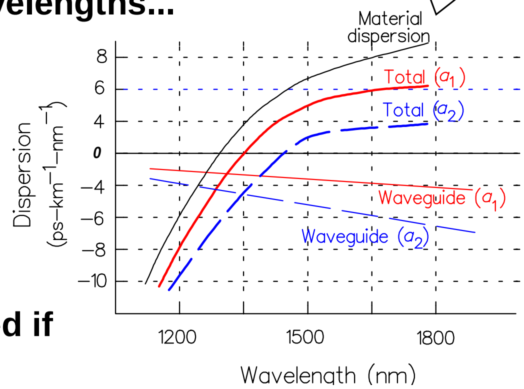
Fig. 3.11
p. 53

Props-23

Fiber Dispersion: Dispersion-Adjusted SM Fibers

- **Waveguide dispersion sensitive to...**
  - **Doping levels, *a*, λ, *n(r)***
- **Achieve zero dispersion at other wavelengths...**
  - **Anywhere from 1300 to 1700 nm**
  - **Ex., at 1550 nm, combine...**
    - **Minimum losses**
    - **Zero dispersion**
  - **Called *"dispersion-shifted" fiber***
- **Problem: Nonlinear effects maximized if dispersion is zero**
  - **Solution: "nonzero dispersion-shifted fiber"**
    - **Achieves low but nonzero dispersion**

Fig. 3.12
p. 54



Props-24

Dispersion-Shifted Fibers

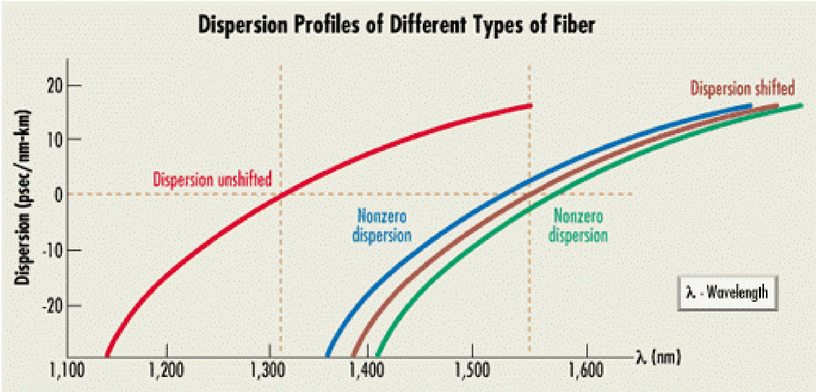
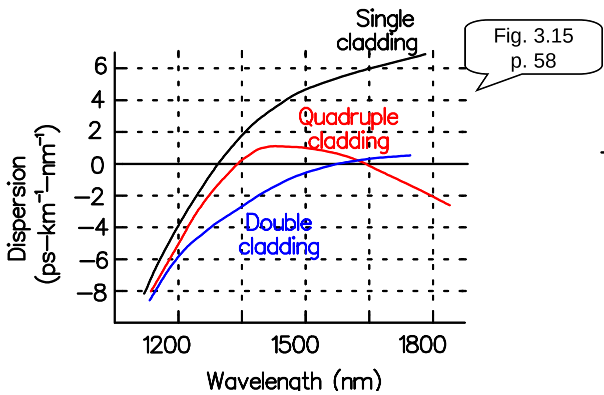


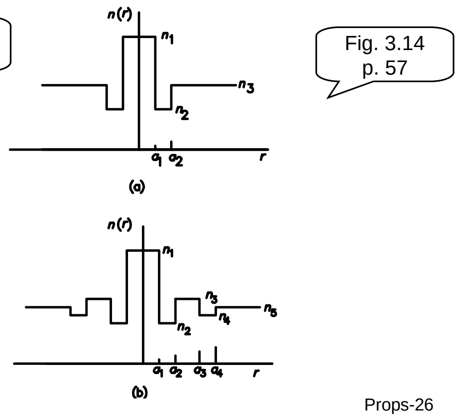
Figure 6. The dispersion profiles of different types of fiber.

Props-25

Fiber Dispersion: Dispersion-Flattened Fibers

- **Alternative approach:**
  - **Reduce dispersion to nonzero minimum between 1300 and 1500 nm**
  - **Allows use of both 1300 & 1500 nm sources**
    - » **Reasonable loss and dispersion**
- **Called *“dispersion flattened” fiber***
- **Multiple-cladding fibers successfully used**

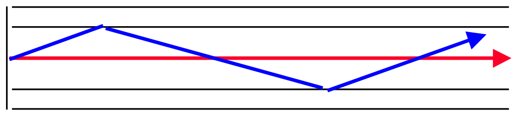




Props-26

Fiber Dispersion: C. Modal Dispersion

- ***Only*** **in multimode fibers!!**
- **Cause:**
  - **Each mode has slightly different path to receiver**



- **Time delay between fastest and slowest is modal pulse delay distortion and *in SI fiber* is...**

$$\Delta\tau_{\text{SI modal}} = \left(\frac{L\left(n_1 - n_2\right)}{c}\right)\left(1 - \frac{\pi}{V}\right) \approx \frac{L\left(n_1 - n_2\right)}{c} = \frac{L n_1 \Delta}{c}$$

  - $D_{SI\ modal} = \Delta\tau_{modal}/L$ **[ps·km^{-1}]**

Props-27

- Ex.: 50/125 step-index fiber with $n_1 = 1.47$ and $\Delta = 1.5\% \Rightarrow \Delta\tau_{modal}/L \approx 73.5$ ns·km^{-1}

Modal dispersion II: Graded-Index Fibers

- **GI fiber**
  - **Variable light velocity**
  - **Sinusoidal paths**
- **High-order modes have longer path lengths *but* also have higher average velocity ..**
  - **Longer path length approximately canceled by higher velocity**
- **Delay time of *m*-th mode….**

$$\tau_{\text{GI modal}} = \frac{LN_{g1}}{c}\left(1+\frac{g-2-\varepsilon}{g+2}\Delta\left(\frac{m}{N}\right)^{\frac{g}{g+2}} + \frac{\Delta^2}{2}\frac{3g-2-2\varepsilon}{g+2}\left(\frac{m}{N}\right)^{\frac{2g}{g+2}} + \text{other terms of } \Delta^3,\ \Delta^4,\ \text{etc}\right)$$

Eq. 3.38
p. 59

$$\varepsilon = -\frac{2n_1}{N_{g1}}\frac{\lambda}{\Delta}\frac{d\Delta}{d\lambda},\quad N_{g1} = n_1 - \lambda\frac{dn_1}{d\lambda},\ \text{and}\quad N = a^2\Delta k^2 n_1^2 \frac{g}{g+2}.$$

- **Minimize by zeroing 2nd term (set $g=2+\varepsilon$)**

Props-28

Modal Dispersion II: GI Fibers (cont.)

- **Linear term in Δ can be eliminated if...**

$$g = g_{\text{opt}} = 2 - \frac{2n_1}{N_{g1}} \frac{d\Delta}{d\lambda}$$

  - **Usable approximation is...**

$$g_{\text{opt}} \approx 2 - (12\Delta/5)$$

- **Net delay is...**

$$\Delta\tau_{\text{GI modal}} \approx \begin{cases} n_1\Delta \dfrac{g - g_{\text{opt}}}{(g+2)c} & g \neq g_{\text{opt}} \\ \dfrac{n_1\Delta^2 L}{2c} & g = g_{\text{opt}} \end{cases}$$

  - **$\Delta\tau_{\text{GI modal}}$ can be positive or negative**

- **GI modal dispersion factor of ~Δ smaller than SI**
  - **Max bit-rate of GI is ≥100x max bit-rate of SI!!**

Props-29

Fiber Dispersion: Dispersion Units

- Modal dispersion:
  - Dominates in MM fibers
    - Less in GI fibers than SI fibers
  - Depends on *L*
  - Independent of $\Delta\lambda$
    - Normalized units of [ns·km^{-1}]
    - Can be given as analog bandwidth-distance product: [GHz·km]
- Material dispersion and waveguide dispersion:
  - Dependent on $\Delta\lambda$ and *L*
  - Normalized units of [ns·km^{-1}·nm^{-1}]

Props-30

Bit-Rate and Dispersion

- **Maximum bit rate**

$$B_{R\max} \approx \frac{1}{4\Delta\tau_{\text{total}}}$$

where

$$\Delta\tau_{\text{total}} = \sqrt{\Delta\tau^2_{\text{modal}} + \Delta\tau^2_{\text{GVD}}}$$

and

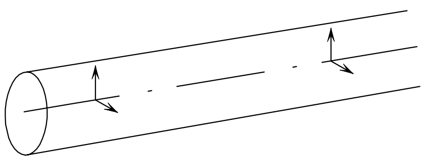
$$\Delta\tau_{\text{GVD}} = \Delta\tau_{\text{material}} + \Delta\tau_{\text{waveguide}}$$

- **Note that $B_{R\,max} \sim 1/L$**
- **(bit-rate)-distance product is constant for a given fiber**

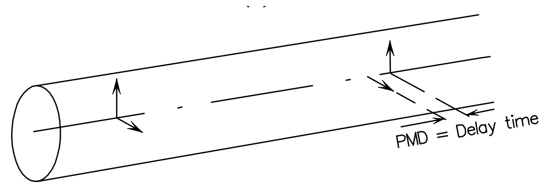
Props-31

Polarization Mode Dispersion (PMD)

- **Mode in singlemode fiber has two orthogonal polarizations** **(polarization: direction of E-field orientation)**
- **Perfect fiber...**
  - **Perfect circular core**
  - **No internal stresses** **(usually due to cabling stresses and environment stress)**
  - **Both polarizations propagate with exact same velocity**
  - **No relative delay**
- **Imperfect fiber...**
  - **Orthogonal polarizations have slightly different velocities** **(birefringence)**
  - **Arrive slightly apart**
- **Causes input light pulse to spread**
- **Polarization mode dispersion**
- **Can only minimized; not removed**
- **Varies randomly along length and with temperature** **(spec average value over time)**



(a)



(b)

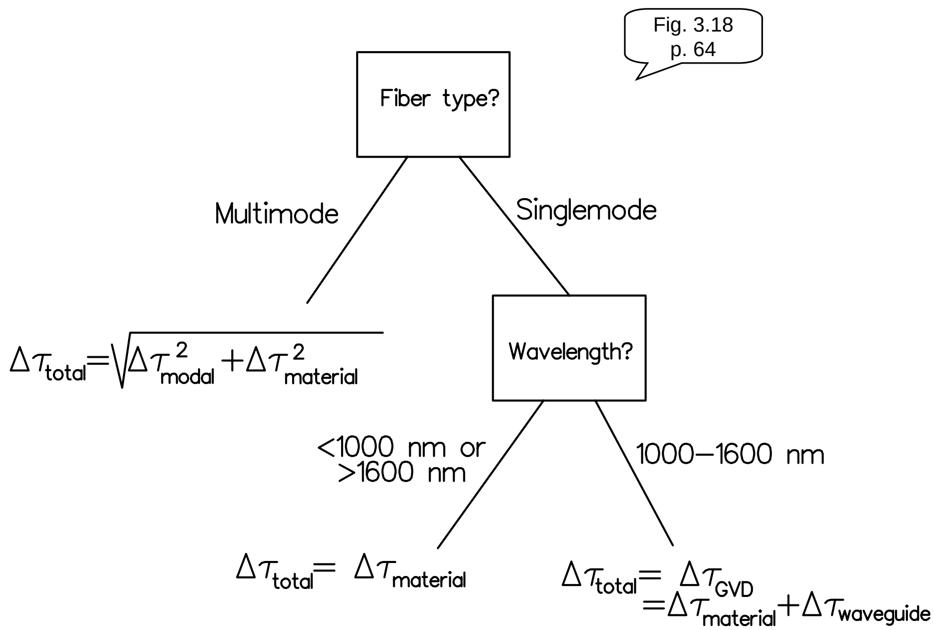
- Polarization:
  - ☞ Linear: E-field maintains orientation in a plane as light propagates
  - ☞ Circular: E-field rotates as wave propagates; tip of E-field stays constant distance from propagation axis
  - ☞ Elliptical: E-field rotates as wave propagates; tip of E-field changes distance from propagation axis
  - ☞ Random: E-field has random orientation and magnitude at any given location along propagation direction (also called “unpolarized”)
- Fibers
  - ☞ Usually don’t preserve polarization state as wave propagates
  - ☞ e.g., linear polarization is scrambled after a few meters of propagation in conventional fiber
  - ☞ Some special fibers preserve polarization
    - ✳ Called “polarization-maintaining” fiber (or “PM fiber”)
    - ✳ Costs $$$

Polarization Mode Dispersion (PMD) (cont)

- Varies with square-root of distance and environment (e.g., temperature, fiber movement)
  - Dimensions [$ps/\sqrt{km}$]
  - Controlled by fiber/cable makers
  - Typical 0.03 – 1.3 ps/sqrt{km}
- Currently important in singlemode applications operating with low dispersion and…
  - B_R > 2.5 Gb/s or...
  - Analog applications with wide bandwidths (e.g., high channel-count cable systems)
- Fiber's PMD can limit…
  - link distance (at 10 Gb/s or higher) or
  - link bit rate (or bandwidth)
- Alternative: fiber with smaller PMD; active compensators

Props-33

Dispersion Calculation Decision Tree



- **Note: account for PMD separately if SM fiber at 10 Gb/s or higher**

Props-34

Fiber Dispersion: Summary

- **Total dispersion:**
  - **Multimode fibers: modal dispersion and material dispersion**
  - **Single-mode fiber: material dispersion and waveguide dispersion (1000 nm to 1600 nm only)**
  - **Near 1300 nm, dispersions can cancel**
- **Dispersion ~*L***
  - **Max bit rate ~ $1/\Delta\tau$ ~ *1/L***
    - » **Max bit rate × *L* is constant**
- **Fibers specified by bit rate-distance product**

Fiber Type	(Bit-rate)•distance product
Single-mode	Many Gb/s•km
Step-index multimode	Few 10s Mb/s •km
Graded-index multimode	Several 100s Mb/s •km

Props-35

- Bit rate-distance trade-off
  - ☞ Longer distances require reduction of bit rate

Dispersion: RMS Pulse-Spreading Approach

- **Alternative approach to delay times**
- **Define RMS pulse width**

$$\sigma_s = \sqrt{\int_{-\infty}^{\infty} t^2 p(t)dt - \left(\int_{-\infty}^{\infty} tp(t)dt\right)^2} = \sqrt{\int_{-\infty}^{\infty} t^2 p(t)dt} \quad \text{(for symmetric wave)}$$

- **Relate input and output pulse widths...**

$$\sigma_{\text{out}}^2 = \sigma_{\text{in}}^2 + \sigma_{\text{fiber}}^2$$

where

$$\sigma_{\text{fiber}}^2 = \sigma_{\text{modal}}^2 + \sigma_{\text{GVD}}^2 = \sigma_{\text{modal}}^2 + \left(\sigma_{\text{material}} + \sigma_{\text{waveguide}}\right)^2$$

where

$$\sigma_{\text{modal}}(\text{SI}) \approx \frac{Ln_1\Delta}{c} = \frac{L(\text{NA})^2}{4\sqrt{3}\,n_1 c}$$

$$\sigma_{\text{mod}\,al}(\text{GI}) \approx \begin{cases} \dfrac{0.246 L N_{g1}\Delta\left|g - g_{opt}\right|}{c(g+2)} & 1 > \left|g - g_{opt}\right| >> \Delta \\[2ex] \dfrac{0.150 L N_{g1}\Delta^2}{c} \approx \dfrac{n_1 \Delta L}{2c\sqrt{3}} & g = g_{opt} \end{cases}$$

$$\sigma_{\text{material}} \approx \frac{L}{c}\left(\frac{\sigma_\lambda}{\lambda}\right)\left(\lambda^2 \frac{d^2 n_1}{d\lambda^2}\right) \quad \text{and} \quad \sigma_{\text{waveguide}} = -\frac{n_2 L\Delta}{c}\left(\frac{\sigma_\lambda}{\lambda}\right)\left(V\frac{d^2(Vb)}{dV^2}\right)$$

Props-36

Fiber Nonlinearities Revisited

- **Nonlinear effects used to be negligible for modest powers and distances**
- **Now cause problems because of power levels (and multiple signals) and long distances**

$$E(z+dz)=E(z)e^{\left(-\frac{\alpha_p}{2}+jk+\underbrace{\frac{\gamma P(z)}{2A_{eff}}}_{\text{nonlinear term}}\right)dz}$$

- **The nonlinear coefficient, γ, is small. Large power, small core area, and/or long distance make effects noticeable**
- **Nonlinear fiber parameters**

Effective area

$$A_{eff}=\frac{\left(\iint I(r,\theta)r\,dr\,d\theta\right)^2}{\iint I^2(r,\theta)r\,dr\,d\theta}\approx A_{\text{wave}}=\frac{\pi(\text{MFD})^2}{4}$$

Effective length

$$L_{eff}=\frac{1-e^{-\alpha_p L}}{\alpha_p}\approx\frac{1}{\alpha_p}\ \ (\text{for L>>}1/\alpha_\text{p})$$

Props-37

Fiber Nonlinearities (cont.)

- Nonlinear coefficient, γ, is small and can be…
  - – real (a gain or loss) or...
  - – imaginary (phase effect)
- Stimulated scattering
  - » Raman scattering
  - » Brillouin scattering
- Nonlinear index effects
  - » Single-signal
    - Self-phase modulation
  - » Multi-signal
    - Cross-phase modulation
    - Four-wave mixing

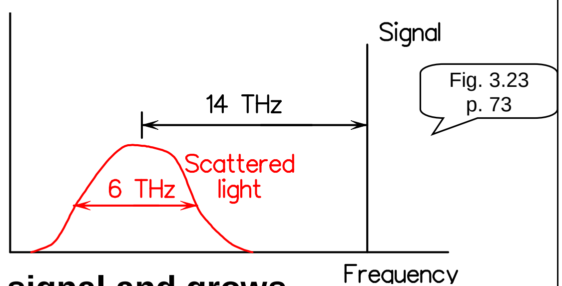
Props-38

Nonlinear Scattering

- Interaction of photon and phonon to produce ***frequency-shifted*** **photon**

$$\nu_{\text{scattered}} = \nu_{in} - \nu_{phonon}$$

- **Stimulated Raman scattering**
  - Input light causes generation of scattered light
  - Coherent scattered light coherent
  - Scattered light is broad (Δν ~ 6 THz) with center frequency 14 THz below input frequency



  - Scattered light takes energy from signal and grows exponentially

$$I_{\text{scatter}}(z) = I_{\text{scatter}}(0)e^{G_R I_{\text{signal}} z} \qquad (\text{for } I_{\text{scatter}} << I_{\text{signal}})$$

Props-39

Stimulated Raman Scattering (cont.)

- See sample problem on p. 74 of text (Fiber w MFD of 11 µm; effective area of $1\text{x}10^{-6}$ cm^2; laser with 100 mW in fiber @ 1,000 nm)

$$\nu_{\text{pump}} = \frac{c}{\lambda} = \frac{3\times10^{8}}{1\times10^{-6}} = 3\times10^{14}\ \text{Hz}; \qquad \nu_{\text{signal}} = \nu_{\text{pump}} - 14\times10^{12} = 286\times10^{12} \ \Rightarrow\ 1048\ \text{nm}$$

Raman gain at 1000 nm:

$$\text{G}_\text{R}[1.0\ \mu\text{m}]=\text{G}_\text{R}[0.694\ \mu\text{m}]\left(\frac{0.694}{1}\right)^{2} = 4.33\times10^{-14}\ \text{m}\bullet\text{W}^{-1}$$

Fiber gain in 1,000 m of fiber:

$$\frac{\text{I}_{\text{signal}}}{\text{I}_{\text{signal in}}} = \exp\left(G_R I_{pump} z\right) = \exp\left(\left(4.33\times10^{-14}\right)\left(1\times10^{9}\right)\left(1000\right)\right) = 1.044$$

- Threshold power for “significant” Raman scattering (scattered power equals signal power)

$$P_{\text{Raman}} \approx \frac{16A_{\text{eff}}}{G_R L_{eff}} \qquad \left(G_R = 0.9\times10^{-13}\ \text{at } 0.694\ \mu\text{m}\right)$$

Props-40

Stimulated Brillouin Scattering

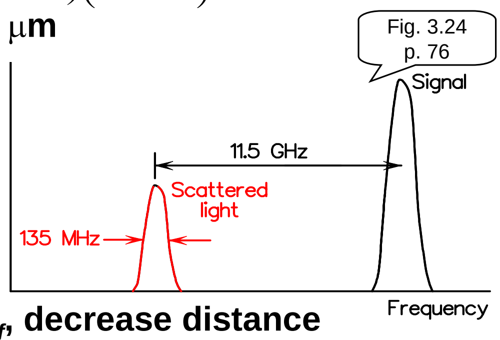
- Similar to stimulated Raman but phonon frequency is higher
- Linewidth, $\Delta\nu_B$, of scattered light is narrow (~135 MHz in silica glass) (and frequently narrower than signal)
- Signal ("pump") is frequently wider than $\Delta\nu_B$, so we need correction factor of $\Delta\nu_B / \Delta\nu_{pump}$ to gain coefficient...

$$G_B = G_{B0}\left(\frac{\Delta\nu_B}{\Delta\nu_{\text{pump}}}\right) = \left(\frac{2\pi n^7 p_{12}^2}{c\lambda^2 \rho V_s \Delta\lambda_B}\right)\left(\frac{\Delta\nu_B}{\Delta\nu_{\text{pump}}}\right)$$

- G_{B0} is ~$1/\lambda^2$ and is 4.5×10^{-9} cm/W at 1 μm
- Power threshold

$$P_{\text{Brillouin}} \approx \frac{21 A_{\text{eff}}}{G_B L_{eff}}$$

- Raman limit is more restrictive
- Solution: reduce power, increase A_{eff}, decrease distance



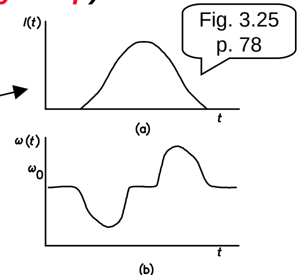
Props-41

Self-Phase Modulation (SPM)

- **Single channel *phase* effect**
- **Power in signal can change *n* in material** ($\Delta n = n_2 P/A_{eff}$)
- **Pulse train passing point in fiber is time-varying power, *P(t)***
- ***P*ower variations in time cause *n* to change in time which causes instantaneous frequency to change in time (*frequency chirp*)**

$$n = n_0 + \underbrace{n_2 P / A_{eff}}_{\text{index change}} \quad \text{and} \quad \phi = \omega_0 t - \frac{\omega_0 n z}{c}$$

$$\omega \equiv \frac{d\phi}{dt} = \omega_0 - \underbrace{\frac{\omega_0 n_2 z}{c A_{eff}} \frac{dP}{dt}}_{\text{Frequency "chirp"}}$$



- **Chirp broadens signal spectrum; increases dispersion effects; decreases max bit-rate of link**
- **Solution**
  - **Reduce power, increase A_{eff}, decrease distance**

Props-42

Cross-Phase Modulation (XPM)

- **Multichannel effect** (several wavelengths present in fiber, each carrying different data)
- **Power fluctuations in *other* channels cause *n* to change, causing signal frequency chirp**
- **Chirp…**
  - **Broadens spectrum of signal light,**
  - **Causes more dispersion, and…**
  - **Decreases max bit-rate**
- **Solution**
  - **Reduce power, increase A_{eff}, decrease distance**

Props-43

Four-Wave Mixing

- **Also called *four-photon mixing***
- **Multichannel effect**
- **Channels "mix" or "beat" due to nonlinearity and produce inter-modulation (IM) frequencies**

$$I = k\left|\sum_i \left(E_1 + E_2 + \ldots + E_i\right)\right|^2$$

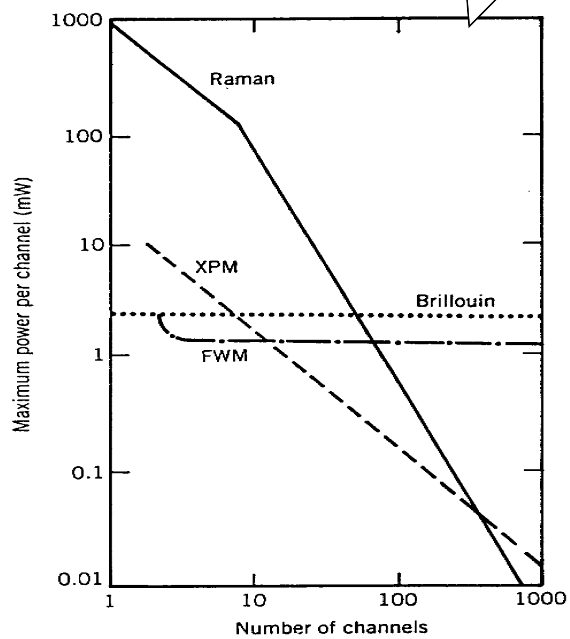
- **If *N* signals present, $N^2(N-1)/2$ IM frequencies result**
  - **e.g., 3 frequencies ⇒ 9 IM frequencies**
- **If frequencies evenly spaced, some IM frequencies fall on top of some signal frequencies and cause interference**
- **Aggravated by operating near zero dispersion wavelength**
- **Solution...**
  - **Reduce power, increase A_{eff}, decrease distance**
  - **Avoid zero-dispersion wavelength region (use nonzero dispersion-shifted fiber)**
  - **Space channels unequally**

Props-44

Summary of Nonlinear Effects

- **Single channel: Brillouin limit (several mW)**
- **Multichannel signals (see figure)**
  - **Up to 11 channels: 4-wave mixing (<2 mW/channel)**
  - **11 to several 100 channels: cross-phase modulation limit (1 mW down to ~70 μW/channel)**
  - **>several 100 channels: Raman scattering limit (10s μW/channel)**

Fig. 3.26
p. 82



From A.R. Chraplvy, *J. Lightwave Technology*, vol. 8, p. 1548, 1980.

Props-45

Cables

- **Goal:**
  - **Provide strength and protection (while minimizing cable volume and weight)**
- **Avoid adding appreciable optical loss**
- **May have power-carrying conductors**

- **Desirable cable properties:**
  - **Minimize stress-produced optical losses**
  - **High tensile strength**
  - **Immunity to water vapor penetration**
  - **Stability of characteristics in environment**
  - **Ease of handling and installation**
    - » **Compatibility with installation equipment**
  - **Low costs**
    - » **Acquisition**
    - » **Installation**
    - » **Maintenance**

Props-46

Cable Components

- Optical **fibers**: single or multiple fibers
- **Buffering** material: soft substance around fiber
  - – Isolate from radial compressions and localized stresses
- **Strength members**: high tensile-strength materials for longitudinal strength
  - – High-strength, low-weight materials (e.g., Kevlar)
- **Power conductors**: copper conductors or copper-coated high-strength wires
- **Filler yarns**: take up space between strength members and provide some buffering and block water
- **Jacket**: abrasion protection; waterproofing; protection from rodents, fish, etc.; resistance to chemicals; smokeproof; nonflammable; etc.
  - – Jacket determines installation properties

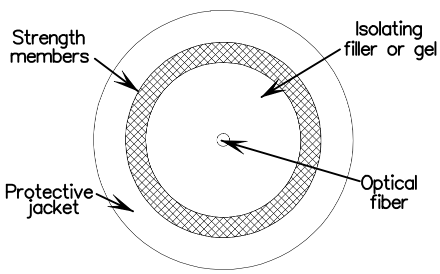
Props-47

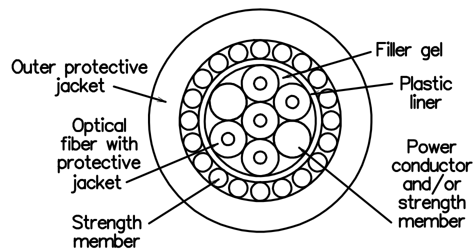
- Buffering
  - ☞ *Loose-buffered*: fiber movable in buffer
  - ☞ *Tight-buffered*: immovable fiber
- Tensile strength of fiber cable is sum of individual strengths
  - ❖ $T = \sum EiA_i$;
  - ☞ *T* is tensile load, *S* is maximum allowed strain or elongation (e.g., 1%), E_i is Young's modulus of i-th component, and A_i is cross-section area of i-th component
- Potential problems:
  - ☞ Elongation of cable
    - ✳ Typical fiber: ~1%
    - ✳ Typical stress member: ~20% before breaking
    - ✳ Solution: wind fiber in helix inside cable

Cables (cont.)

- Wide range of installation environments
  - Ducts
  - Aerial stringing from posts
  - Trenches
  - Underwater installation
  - Laying cable on ground
- Representative duct cable (left)
- Representative aerial cable (right)

Fig. 3.27 & 28
p. 84 & 85

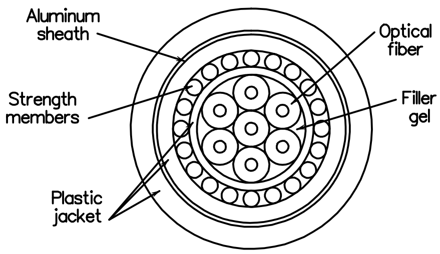


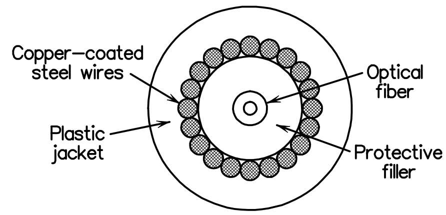


Cables (cont.)

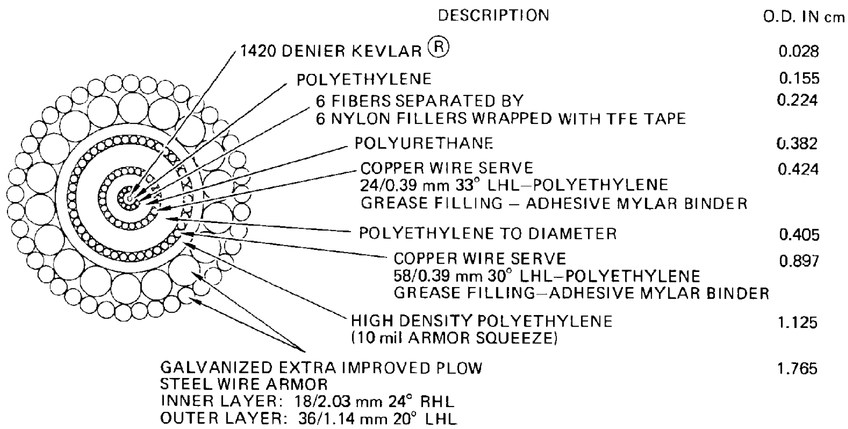
- **Representative cable for burial in trenches (left)**
  - **More outer protective layers**
- **Representative cable for short-distance, undersea transmission (right)**
  - **Copper-clad steel wires for power and cable-strength**
  - **Electric power in cable can provoke defensive behavior from sharks and other fish in certain areas; cable may need extra protective layers**

Fig. 3.29 & 30
p. 85



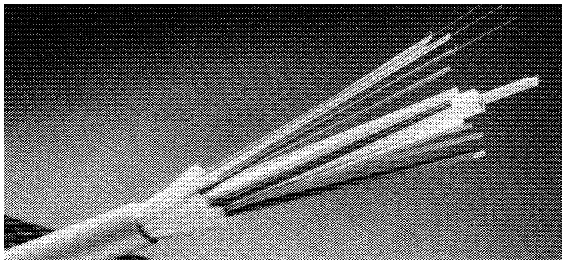


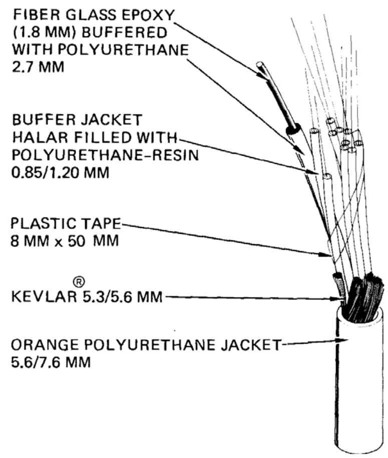
Cable for Navy Towed Array

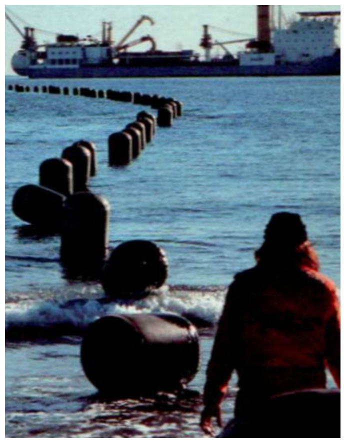


Props-50

Example of Fiber Cable & Cable Laying







Props-51

Fiber Properties Review

- Optical attenuation
  - Power loss in fiber (dB/km)
    - » Causes
      - Absorption and scattering in glass
      - Glass impurities, fiber imperfections, bends
    - » Minimum loss at 1550 nm

- Fiber dispersion
  - Pulse spreading limits maximum data rate
  - Causes
    - » Fiber modes
    - » *n* is function of wavelength
    - » Waveguide effects
  - Zero dispersion in SM near 1300 nm (and 1550 nm)

- Nonlinear effects
  - Accumulate over long distances
  - Limit maximum power that can be put into fiber

Props-52

Fiber Spec Sheets

- **See Website for sample data sheets…**

- **Corning fiber data sheets**
- **Lucent multimode fiber data sheets**