Fiber-Optic Transmission

CME 451

Fiber Optic Communication

- Good medium for transmission
  - compared to UTP & coaxial
  - Low attenuation
  - High bandwidth
  - Noise immunity
- Disadvantages:
  - Conversion E-O-E adds complexity
  - Expensive to install

Propagation

- Propagation in fiber is complex
  - Solving Maxwell's equations.
- Total internal reflection as approximate model
  - Snell's law
  - Core: higher index of refraction
  - Cladding: lower index of refraction
  - Light travelling within a critical angle will be refracted towards the core.

Propagation

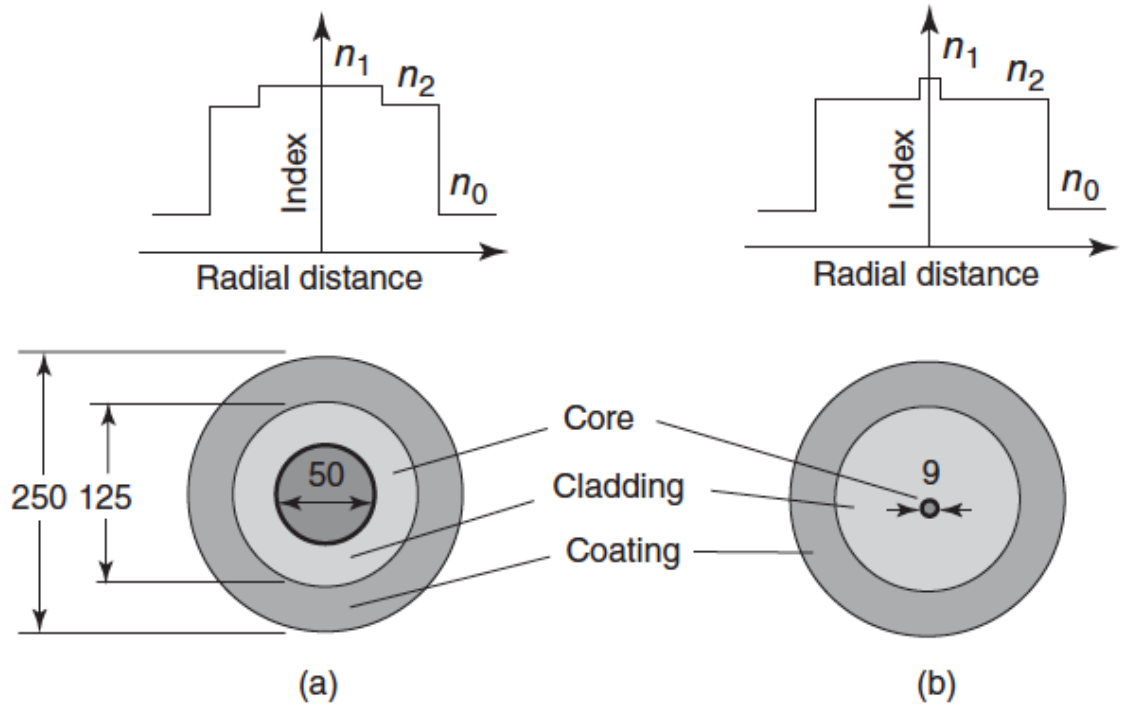

FIGURE 2.1 Refractive index profiles and cross sections for (a) multimode and (b) single-mode fiber. The coating, typically a polymer, protects the fiber without influencing the propagation characteristics.

Propagation

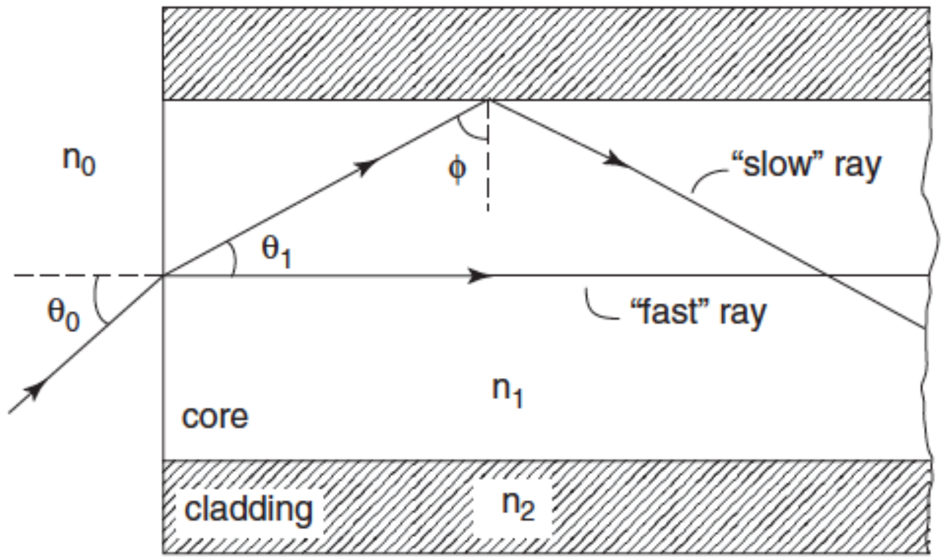

FIGURE 2.2 Ray propagation through a step-index multimode fiber. "Fast" and "slow" refer to the group velocities (i.e., the velocities of energy transport along the fiber axis).

$$\phi_{\text{critical}} = \sin^{-1}\frac{n_2}{n_1}$$

Propagation

- Mode: cross-section distribution of optical fields that travels unchanged along fiber.
- Depending on core size:
  - SMF: single-mode fiber (~ 9 μm)
  - MMF: multimode fiber (~ 60 μm)
- MMF: challenge of multimode dispersion.
- MMF for shorter distance and slower data rates.
- SMF for higher performance.

Propagation

- Fiber can be manufactured to minimize model dispersion
  - graded-index profile instead of step-index change.
  - refractive index varies smoothly: high in center to lower at perimeter
  - Parabolic profile: time taken to emerge at output is independent of ray angle.

Propagation

- Attenuation and dispersion properties are strongly wavelength dependent.
- Three windows:
  - First (850 nm): cheaper light source and detectors; higher loss
  - Second (1310nm, O-band): more expensive source and detector; moderate loss (note: water peak phenomenon 1380nm)
  - Third (1550nm, C-band): lowest loss of 0.2dB/km

Propagation

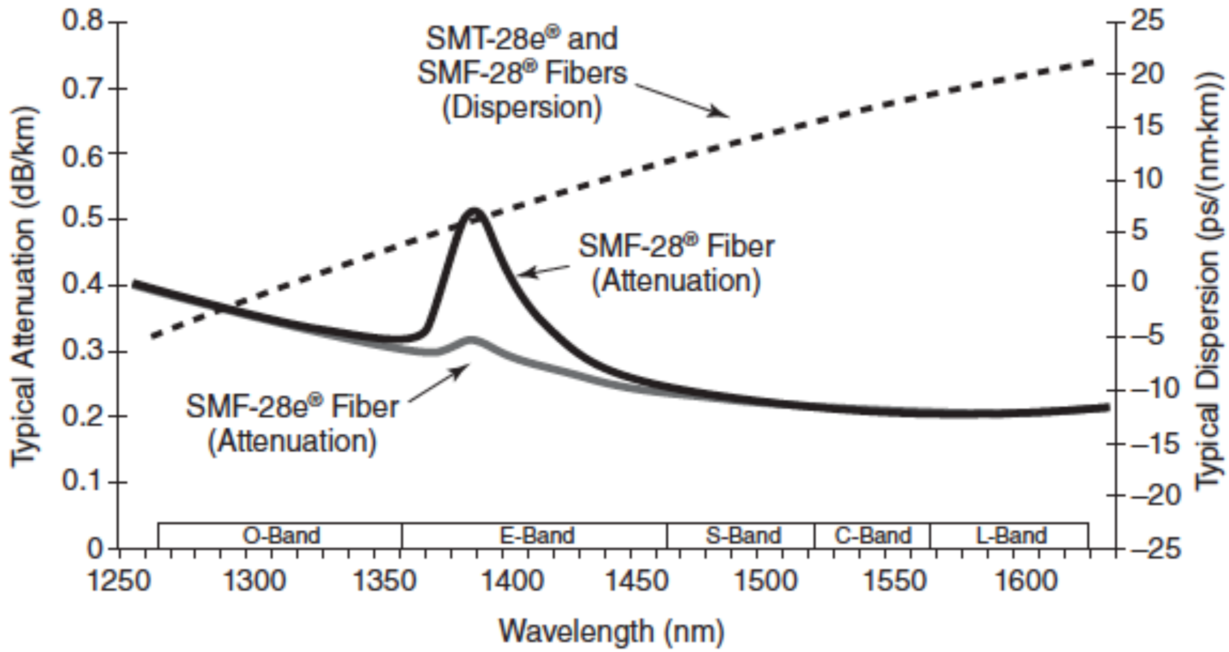

FIGURE 2.3 Attenuation spectrum of a typical single-mode fiber (SMF-28) and the reduced water peak fiber SMF-28e. Group velocity dispersion is also shown. (Courtesy of Corning Corporation.)

Light Sources

- Light-emitting diodes (LEDs)
  - inexpensive
  - Low output power & broad spectral width
- Laser diodes (LDs)
  - expensive
  - Higher power, narrower linewidth
- Spectral width: limiting factor in transmission speed and distance (due to group velocity dispersion)

LED

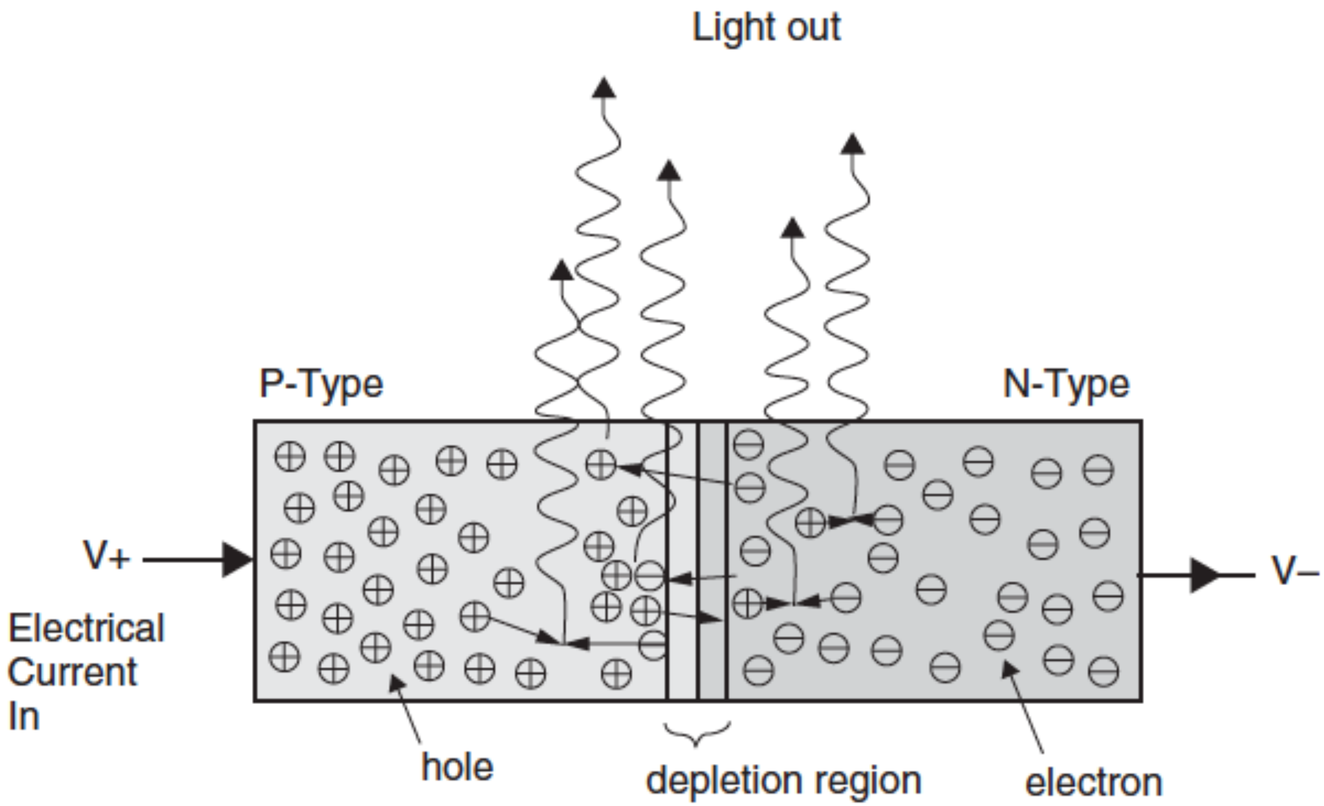

FIGURE 2.4 Basic operating principle of an LED. The radiation is omnidirectional but is shown to emit from one edge for illustrative clarity. The charge symbols represent free carriers; the fixed charges that keep the bulk p- and n-type regions charge neutral are not shown.

Laser Diode

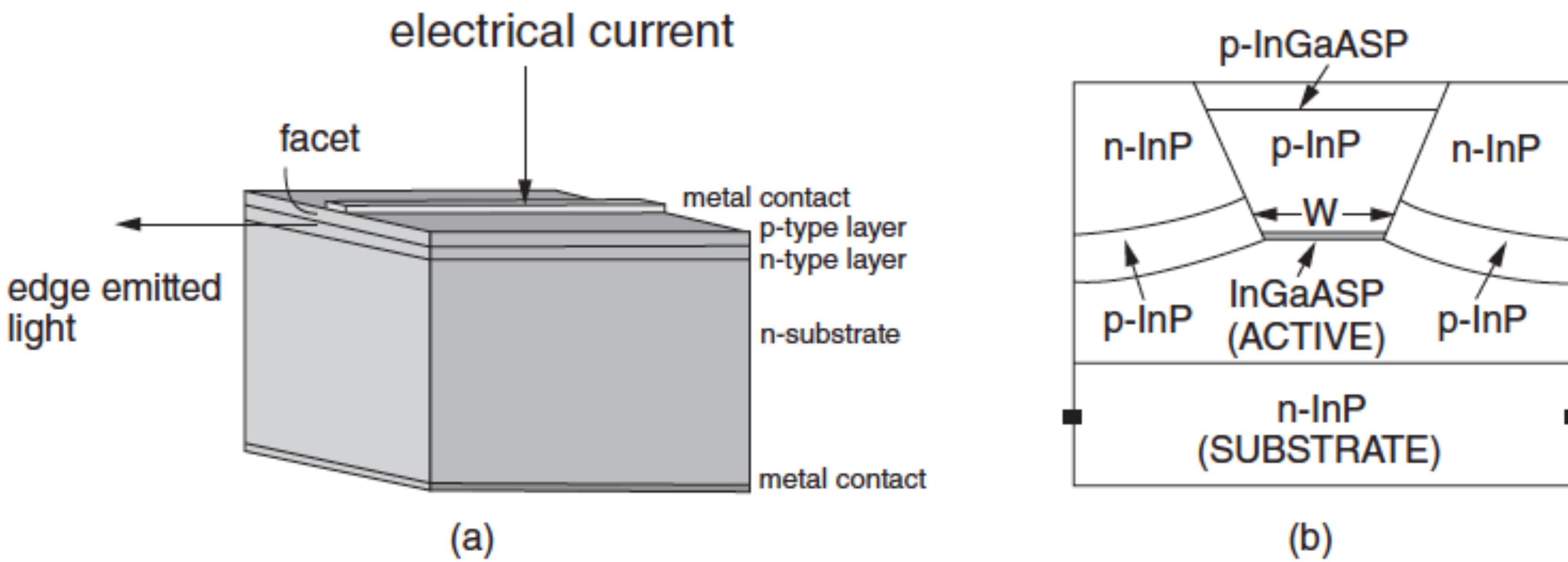

FIGURE 2.5 (a) Basic structure of an edge-emitting laser diode; (b) cross section of an etched mesa buried heterostructure laser. (From Agrawal and Datta, 1993.)

Laser

- Light amplification by stimulated emission of radiation
- Similar in structure to LED, with an active region between n- and p-type layers
- Types
  - Edge-emitting: Fabry-Perot (FP), distributed feedback (DFB)
  - Vertical-cavity surface-emitting laser (VCSEL)

LED and Laser

- LED has slower transient behavior
- Laser: optical feedback is introduced, by partially reflective facets, for amplification of photons.
- Active region of laser requires high doping & strong current injection, for population inversion
  - Gain in active region, through stimulated emission.
- At low forward bias current, spontaneous emission dominates (LED behavior)
- At sufficiently high bias current, for population inversion, stimulated emission leads to coherent light with narrow spectral width.

Photodetectors

- Used to convert optical signals into electrical signals, to recover transmitted information.
- Two types of diodes commonly used
  - p-type/intrinsic/n-type (PIN)
  - avalanche photodiode (APD)
- Both convert the envelope of the optical signal into an electrical baseband signal
  - current produced is proportional to low-pass version of the optical power
- 10 – 100 GHz bandwidth range: suitable only for envelope of ~200-THz optical carrier

Photodetectors

- PIN:
  - similar to pn junction
  - lightly doped or undoped (intrinsic) layer, to increase frequency response (by widening depletion region to allow light coupling)
  - used when low sensitivity is sufficient

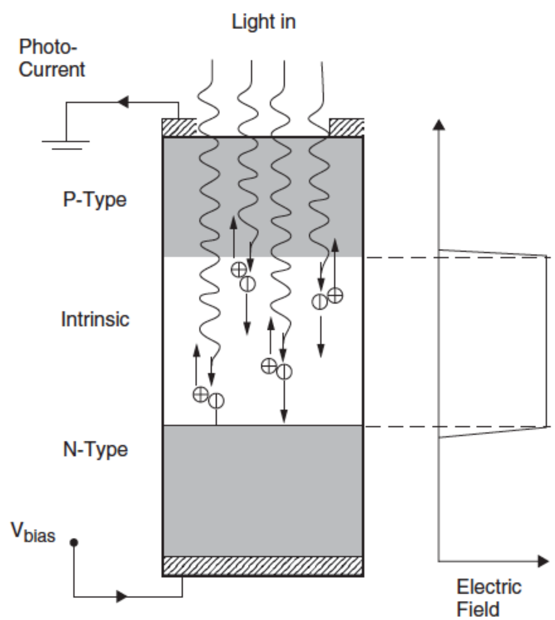

FIGURE 2.7 Basic structure and operating principle of a PIN diode (only newly generated carriers are illustrated, for clarity). The electric field distribution is shown at the right and is high in the depleted intrinsic layer.

Photodetectors

- APD:
  - Similar in structure to PIN diodes
  - additional doped multiplication layer, thus suitable when received powers are low
  - NB: shot noise is increased

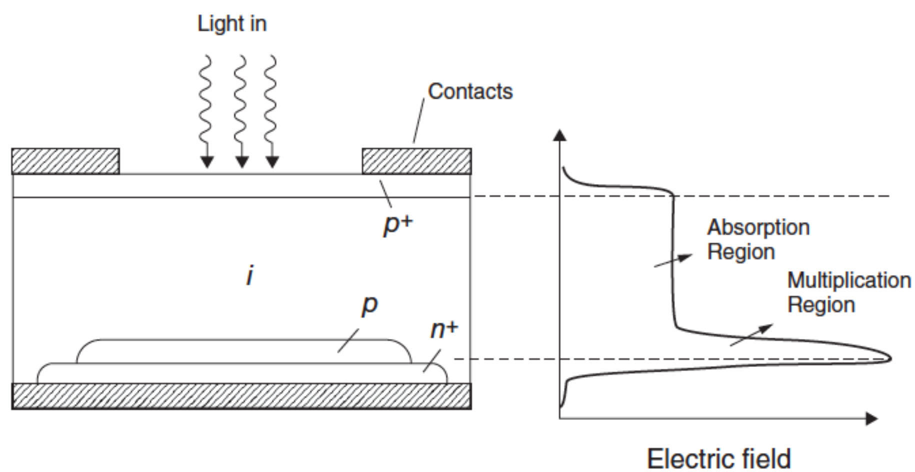

FIGURE 2.8 Basic structure of an avalanche photodiode and the electric field distribution through the absorption and multiplication regions.

Optical Modulation

- Candidate characteristics: phase, amplitude, polarization, frequency
- Two categories of modulation:
  - Direct: optical source itself modulated
  - External: source run in continuous-wave mode, and a modulator encodes information separately

Direct Modulation

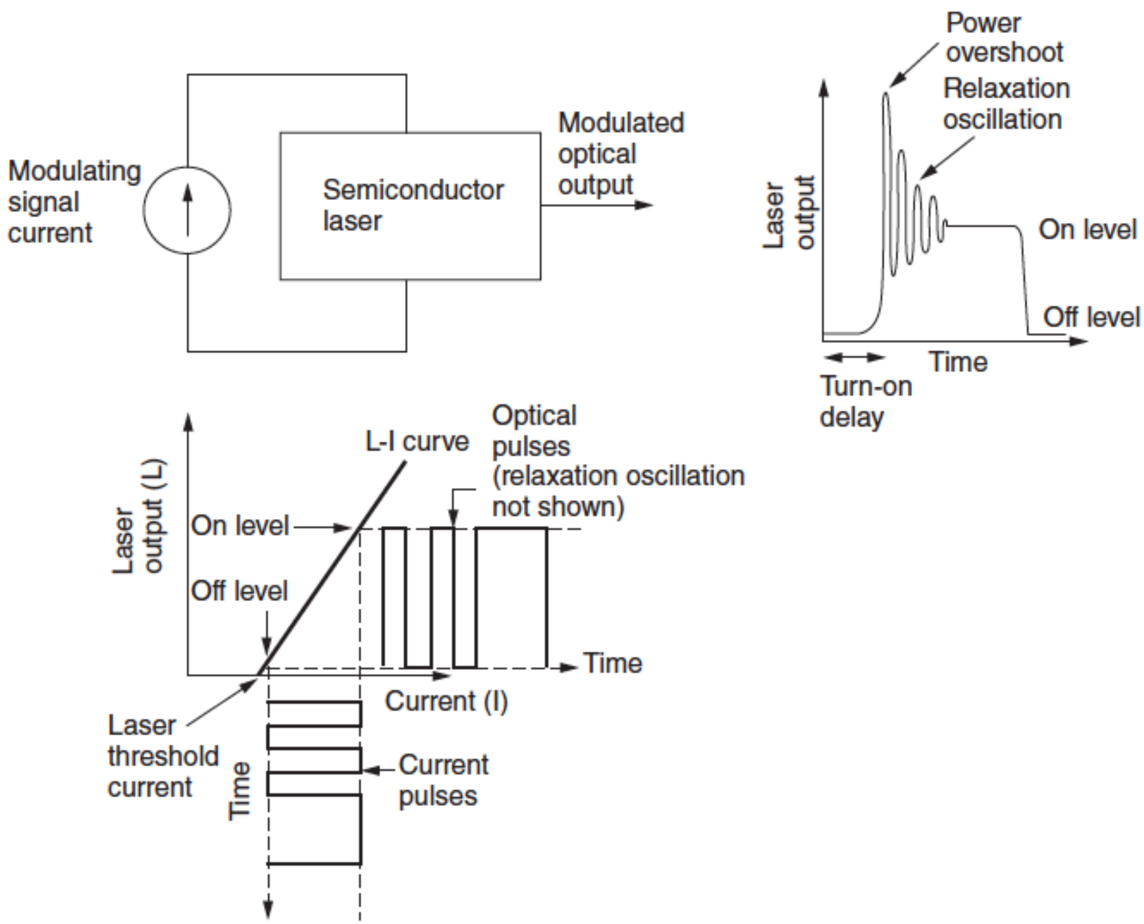

FIGURE 2.9 Direct modulation of a semiconductor laser.

External Modulation

- Used for high-bit-rate and long-distance links
- Better control of chirp
- Two main categories
  - Electroabsorption modulator (EAM): change absorption in semiconductor to modulate amplitude of light
  - Electrooptic modulator (EOM): change refractive index of material to modulate phase of light; translation to amplitude modulation with interferometer also possible.

External modulation

- EAM for short and intermediate applications
- EOM for long and ultralong-haul

TABLE 2.1 Typical Parameters for Electroabsorption and Electrooptic Modulation

Parameter	Electroabsorption	Electrooptic Modulation
Bandwidth	MHz to >40 GHz	MHz to >30 GHz
Drive voltage	<3 V	3–6 V
On/off extinction ratio at dc	<18 dB	>20 dB
Optical insertion loss	~8–10 dB	2–6 dB
Chirp parameter	Variable, depends on design and operating conditions	–0.7 or 0
Temperature stability	Requires active temperature control	Stable over at least ± 35 °C
Spectral range of operation	~2–10 nm	>60 nm
Length of active waveguide	<0.5 mm	10 to 40 mm

Optical amplification

- Recall 0.2 dB/km loss
  - 1120 dB for ~5600km from NY to London
- O-E-O possible but expensive
- Optical amplification necessary for long-distance applications
- Two types:
  - Erbium-doped fiber amplifier (EDFA)
  - Raman amplifier

Optical amplification

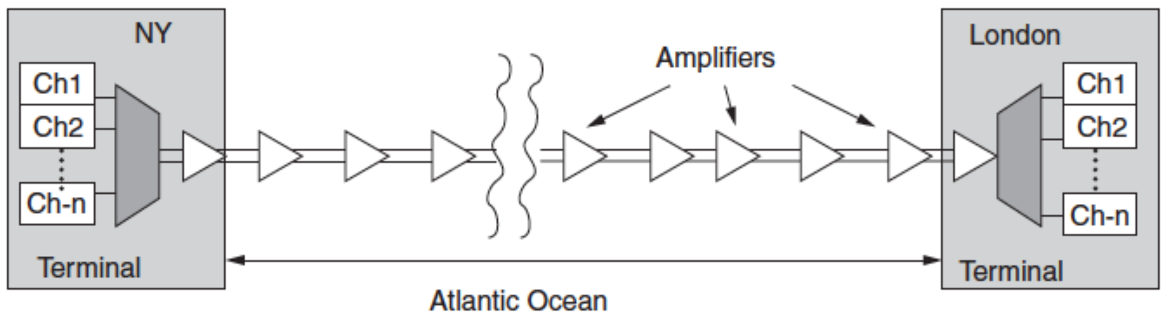

FIGURE 2.15 Multichannel long-haul link between New York and London using optical amplifiers.

Optical amplification

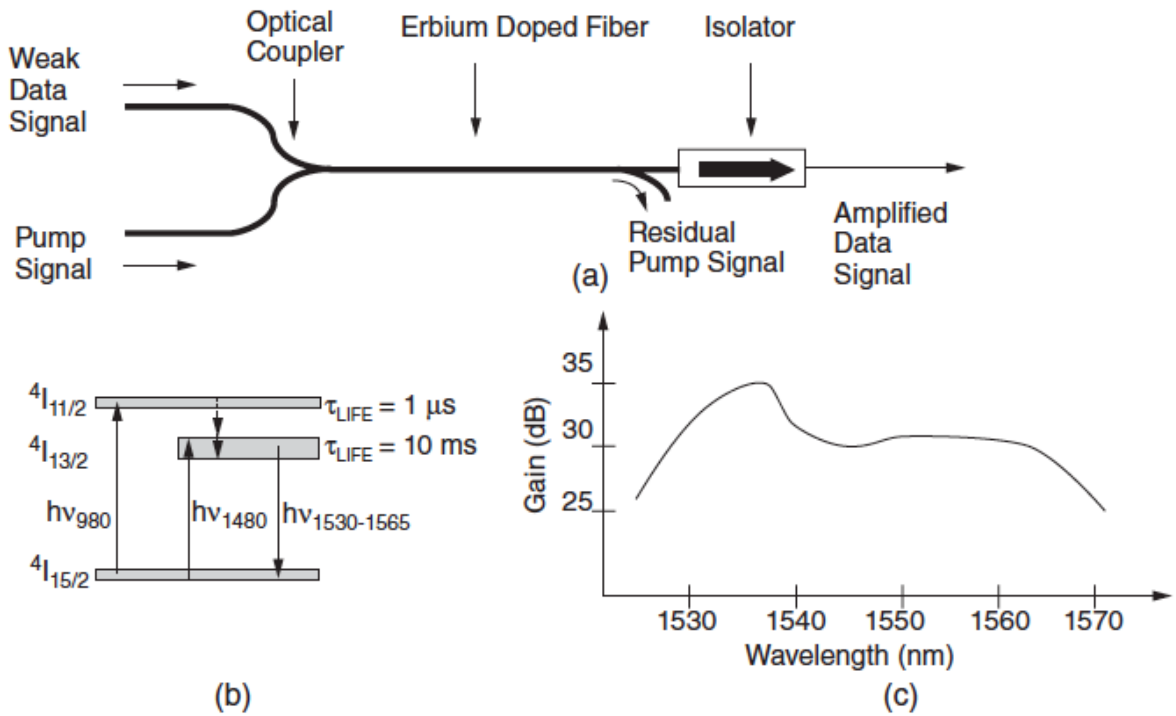

FIGURE 2.16 (a) Structure of an EDFA; (b) energy-level diagram; (c) an example of its optical spectrum.

Optical amplification

- EDFA amplifiers are more widely used; high gain across C and L bands.
- Raman amplifiers: based on stimulated Raman scattering (SRC, an inelastic process)
  - Require large pump powers (~1W)
  - Adjustable gain spectrum (1280 – 1530 nm not accessible with EDFA)
  - Distributed amplification: same fiber for transmission used as gain medium.

Distributed optical amplification

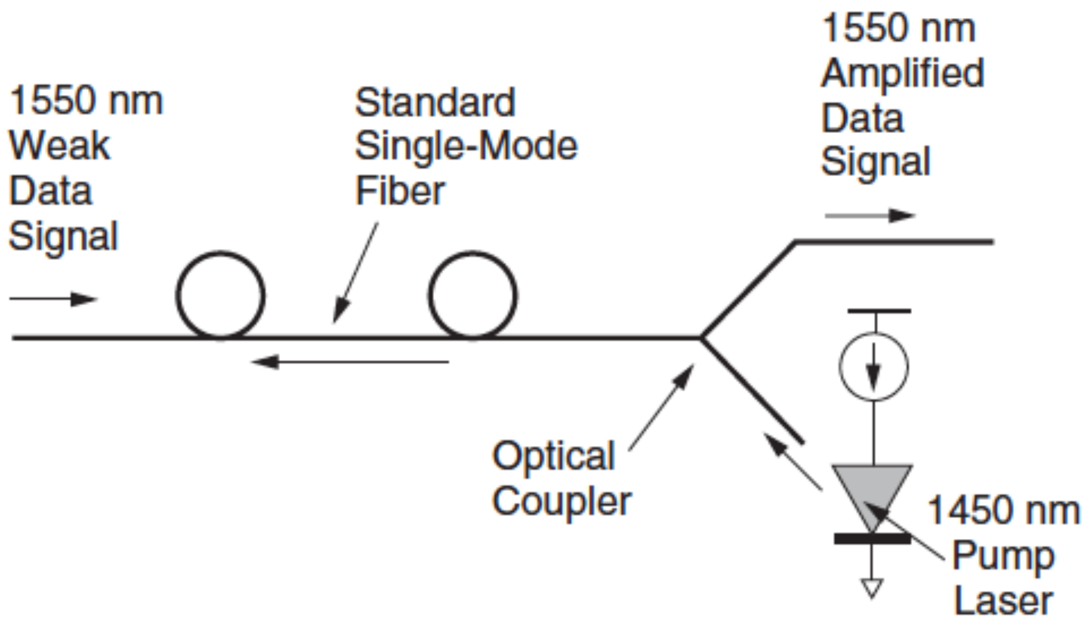

FIGURE 2.18 Distributed Raman amplifier with a counterpropagating pump.

Optical amplification

TABLE 2.2 Comparison Between EDFA and Raman Amplifiers

Feature	Erbium-Doped Fiber Amplification	Raman Amplification
Amplification band	1530 to 1610 nm	1280 to 1620 nm and beyond
Pump power	10 mW to 5+ W	500 mW to 5+ W
Pump wavelength	980 or 1480 nm	100 nm shorter than the signal wavelength
Gain[a]	20 to 30+ dB	10 to 30+ dB
Topology	Discrete	Discrete or distributed
Noise figure	3.5 to 6.5 dB	4 to 7+ dB (discrete) –3 to 1 dB (distributed)

[a]Because the gain of the distributed Raman amplifier is located inside an otherwise lossy fiber span, the gain is specified as on–off gain, representing the change in signal level at the output with the pump turned on as compared with the pump turned off. The actual gain from the input to the output of the Raman pumped fiber depends on the fiber loss and will be 0 dB if the amplifier cancels the loss perfectly.

Fiber Transmission Impairments

- Dispersive Effects
  - Multimode Dispersion
  - Chromatic Dispersion
  - Polarization Mode Dispersion
- Non-Linear Effects
  - Due to high power density in fiber (12.5 kW/cm^2)
  - Nonlinear phase modulation and stimulated scattering
    - Distortion in single channel systems and cross-talk in multichannel systems (stimulated Raman scattering).