Fundamentals of Optical Communications

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Overview

- Characteristics of Light
- Optical components
- Fibers
- Sources
- Receivers,
- Switches
Electromagnetic Spectrum

- Infrared light is used for optical communication.
Attenuation and Dispersion

- First Window
- Second Window
- Third Window
- Scattering
- OH Absorption

Attenuation in dB/km

Wavelength

Dispersion

800 1000 1200 1400 1600

850nm 1310nm 1550nm
Wavebands

First Window
Scattering
Second Window
OH Absorption
Third Window

Attenuation in dB/km

800 1000 1200 1400 1600

Wavelength

770 910 1260 1360 1460 1530 1625 1565 1675

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## Wavebands (Cont)

<table>
<thead>
<tr>
<th>Band</th>
<th>Descriptor</th>
<th>Range (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Original</td>
<td>770-910</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
<td>1260-1360</td>
</tr>
<tr>
<td>S</td>
<td>Short Wavelength</td>
<td>1360-1460</td>
</tr>
<tr>
<td>C</td>
<td>Conventional</td>
<td>1460-1530</td>
</tr>
<tr>
<td>L</td>
<td>Long</td>
<td>1530-1565</td>
</tr>
<tr>
<td>U</td>
<td>Ultralong</td>
<td>1565-1625</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1625-1675</td>
</tr>
</tbody>
</table>
Optical Components

- Fibers
- Sources/Transmitters
- Receivers/Detectors
- Amplifiers
- Optical Switches
Types of Fibers I

- Multimode Fiber: Core Diameter 50 or 62.5 μm
  Wide core ⇒ Several rays (mode) enter the fiber
  Each mode travels a different distance
- Single Mode Fiber: 10-μm core. Lower dispersion.

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Reducing Modal Dispersion

(a) Multimode Step-Index

(b) Multimode Graded-Index

(c) Single Mode

- Step Index: Index takes a step jump
- Graded Index: Core index decreases parabolically
Types of Fibers II

- **Dispersion-Shifted Fiber**: Zero dispersion at 1310nm. EDFAs/DWDM systems operate at 1550 nm. Special core profile ⇒ zero dispersion at 1550 nm.

- **Dispersion Flattened Fiber**: 3 ps/nm/km 1300-1700nm. Use 1300 nm now and 1550 in future. Low dispersion causes four-wave mixing ⇒ DSF/DFF not used in DWDM systems.
Non-zero dispersion shifted fiber (NZ-DSF):
⇒ 4 ps/nm/km near 1530-1570nm band
- Avoids four-way mixing

Dispersion Compensating Fiber:
- Standard fiber has 17 ps/nm/km. DCF -100 ps/nm/km
- 100 km of standard fiber followed by 17 km of DCF
⇒ zero dispersion
LOMMF

- Laser Optimized Multimode Fiber
- Supports 10 Gbps up to 300m with 850nm VCSEL
- Designed for central offices and storage area networks
- Easy upgrade from 10Mbps to 10Gbps
- 50 μm core diameter
- Limits Differential Mode Delay (DMD)
- Made by Lucent, Corning, Alcatel, New Focus, …
- Ref: NFOEC 2001, pp. 351-361
Plastic Fiber

- Original fiber (1955) was plastic (organic polymer core rather than glass)
- 980μ core of PolyMethylMethyelAcrylate (PMMA)
- Large Dia ⇒ Easy to connectorize, cheap installation
- Higher attenuation and Lower bandwidth than multimode fiber
- Can use 570-650 nm (visible light) LEDs and lasers (Laser pointers produce 650 nm)
- OK for short distance applications and home use
- Cheaper Devices: Plastic amplifiers, Plastic lasers
Hard Polymer Clad Silica Fiber

- 200 micron glass core ⇒ Easy to join
- Uses same wavelength (650nm) as plastic fiber
- Lower attenuation and lower dispersion than plastic fiber
- 155 Mbps ATM Forum PHY spec for plastic and HPCF up to 100m.
Polarization Mode Dispersion

- Two polarization modes may travel at different speeds
- Non-circular core may increase PMD
- High winds may induce time-varying PMD on above-ground cables
- Polarization Mode Dispersion (PMD) limits distances to square of the bit rate
  \[ \Rightarrow 6400 \text{ km at 2.5 Gbps, 400 km at 10 Gbps, 25 km at 40 Gbps} \]
Fiber Specifications

- Mode Field Diameter: 9.2 μm @1550nm
- Core Eccentricity: < 0.6μm
- Fiber Non-Circularity: <1%
- Attenuation at different wavelengths: 0.25 dB/km @1550, 1.5 dB/km @1383
- Dispersion at different wavelengths: 5.5 ps/nm-km @1530, 13.8 ps/nm-km @1620
- Attenuation uniformity: No discontinuity > 0.1 dB
- Cutoff Wavelength: < 1300 nm. Multimode below this.
- Zero Dispersion Wavelength: <1440 nm
- PMD < 0.1 ps/√km
- Effective Area: 65 μm²
- Zero Dispersion Slope: 0.058 ps/nm2km
Optical Sources

- Light Emitting Diodes (LEDs)
- Lasers (Light amplifier using stimulated emission of radiation):
  - Fabry-Perot Lasers
  - Distributed Feedback Lasers (DFBs): long distance
  - Vertical Cavity Surface Emitting Laser (VCSEL)
Light Emitting Diodes (LEDs)

- Wide spectral width = 60 nm ⇒ Low bit rates
- Low Power: 1 mW ⇒ Short distances
- Wide beam ⇒ Used with multimode fibers
- Rates up to 622 Mbps
## LEDs vs Laser Diodes

<table>
<thead>
<tr>
<th>Issue</th>
<th>LED</th>
<th>Laser Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias current</td>
<td>50-150 mA</td>
<td>100-500 mA</td>
</tr>
<tr>
<td>Power output</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>25-40 nm</td>
<td>2-5 nm</td>
</tr>
<tr>
<td>Rise/Fall Time</td>
<td>3-20 ns</td>
<td>0.5-2 ns</td>
</tr>
<tr>
<td>Bit Rate</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Coupling Efficiency</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Fiber Type</td>
<td>Multimode</td>
<td>Single-Mode (Generally)</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Safety</td>
<td>Safe</td>
<td>Unsafe if high power</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
External Mach-Zehnder (MZ) Modulators:
- Electro-optic material: Index changes with voltage
- Light split into two paths and then combined
- Index controlled ⇒ Phase at output is same or opposite
  ⇒ High or low amplitude

Integrated Electro-absorption:
- Absorption (loss) depends upon the voltage
- Integrated: The center frequency changes with level
  ⇒ “Chirp” ⇒ Wider line width ⇒ Cheaper
Optical Detectors

- Avalanche Photodetector (APD):
  - Electronic amplifier built in
  - Better sensitivity than PIN detector
  - Temperature sensitive
  - Data rates to 2.5 Gbps
- P-I-N Photodiode: Wideband 800 - 1600 nm
  - High data rate up to 100 Gbps
# PIN vs Avalanche Photodiodes

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PIN</th>
<th>APD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>0.5-0.7 μA/μW</td>
<td>30-80 μA/μW</td>
</tr>
<tr>
<td>Bias Voltage</td>
<td>10 V</td>
<td>100+ V</td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td>Availability</td>
<td>Easy</td>
<td>Mostly 850 nm</td>
</tr>
<tr>
<td>Cost</td>
<td>Less</td>
<td>More</td>
</tr>
</tbody>
</table>
Optical Amplifiers

- Operational principle similar to lasers
- Erbium Doped Fiber Amplifier (EDFA) - 95% market
- Raman Amplifiers
- Semiconductor Optical Amplifiers (SOA)
Erbium-Doped Fiber Amplifiers (EDFAs)

- Up to 30 dB amplification
- Flat response in 1535-1560 nm
  - Fiber loss is minimum in this region
  - Can be expanded to 40 nm width
Raman Amplifiers

- Stimulated Raman Scattering: pump photon gives up its energy to create another photon of reduced energy at a lower frequency.
- Less noise, more expensive, and less gain than EDFA
- Less noise $\Rightarrow$ Critical for ultra-high bit rate systems
- Wider band than EDFA using appropriate pump
Optical Switches

- Circuit
  - Electrical Fabric
  - Micro-Wave Fabric
  - Photonic Fabric

- Packet
  - Photonic Buffering
  - Elect. Buffering

- Electro-Mechanical
  - 2D MEMs
  - 3D MEMs

- Hologram
  - Bubbles
  - Polymer

- Thermo-Optic
  - Acousto-Optic

- Electro-Optic
  - Liquid Crystal
  - SOA
Optical Crossconnect Architectures

- DWDM O/E/O Switch Fabric O/E/O
- DWDM O/O/O Switch Fabric O/O/O
- DWDM O/O/O Switch Fabric O/O/O

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OEO vs OOO Switches

- **OEO:**
  - Requires knowing data rate and format, e.g., 10 Gbps SONET
  - Can multiplex lower rate signals
  - Cost/space/power increases linearly with data rate

- **OOO:**
  - Data rate and format independent
    - Data rate easily upgraded
  - Sub-wavelength mux/demux difficult
  - Cost/space/power relatively independent of rate
  - Can switch multiple ckts per port (waveband)
  - Issues: Wavelength conversion, monitoring
New Developments

1. Higher Speed: 40 Gbps
2. More Wavelengths per fiber
3. Longer Distances
Need all new optical and electronic components

Non-linearity's reduce distance by square of rate.

Deployment may be 2-3 years away

Development is underway. To avoid 10 Gbps mistake.

Cost goal: 2.5×10 Gbps
More Wavelengths

- C-Band (1535-1560nm), 1.6 nm (200 GHz) $\Rightarrow$ 16 $\lambda$’s
- Three ways to increase # of wavelengths:
  1. **Narrower Spacing**: 100, 50, 25, 12.5 GHz
     Spacing limited by data rate. Cross-talk (FWM)
     Tight frequency management: Wavelength monitors,
     lockers, adaptive filters
  2. **Multi-band**: C+L+S Band
  3. **Polarization Muxing**
More Wavelengths (Cont)

- More wavelengths ⇒ More Power
  ⇒ Fibers with large effective area
  ⇒ Tighter control of non-linearity's
  ⇒ Adaptive tracking and reduction of polarization mode dispersion (PMD)
Ultra-Long Haul Transmission

1. Strong out-of-band Forward Error Correction (FEC)
   Changes regeneration interval from 80 km to 300 km
   Increases bit rate from 40 to 43 Gbps

2. Dispersion Management: Adaptive compensation

3. More Power: Non-linearity's $\Rightarrow$ RZ coding
   Fiber with large effective area
   Adaptive PMD compensation

4. Distributed Raman Amplification:
   Less Noise than EDFA

5. Noise resistant coding: 3 Hz/bit by Optimight
Non-zero dispersion shifted fiber for DWDM

LED’s for low speed/short distance. Lasers for high speed and long distance.

DWDM systems use 1550 nm band due to EDFA

Raman Amplifiers for long distance applications

O/O/O switches are bit rate and data format independent
Homework 3

True or False?

T  F

- Optical communication uses infrared light
- C band is used commonly because of EDFAs.
- Graded index fiber has a lower modal dispersion than step index fiber
- Plastic fiber is cheaper than glass fibers
- Dispersion shifted fiber is used in DWDM systems
- If a signal can travel 1600 km at 10 Gbps, due to PMD it can travel 400 km at 40 Gbps
- Fiber becomes multimode above its cutoff wavelength
- Lasers are never used with multimode fibers
- Raman amplifiers are used in ultra-long haul systems
- O/O/O switches are commonly used in today’s networks
- Most DWDM systems currently use 12.5 nm spacing
- Ultra-long haul transmission requires precise dispersion management

Marks = Correct Answers _____ - Incorrect Answers_____ = _______