Lecture 1
Instructor and TA Info

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Discussion: TBD
Office Hours: TBD
Course Website:
  http://www.ece.ucsb.edu/courses/ECE162/162C_S10Blumenthal/default.html
Teaching Assistant: Wenzao Li <wli@ece.ucsb.edu>
TA Office Hours: TBD
Course Info

Catalog Description:

Course Prerequisites:
ECE 162A, 162B

Required Text: Course Notes

Recommended Reading:
Course Topics

1. **Electronic properties of semiconductor materials for optoelectronic devices:**
   Develop firm understanding of the theory and fundamental electrical characteristics of semiconductor materials relevant to optoelectronic devices.

2. **Optical properties of selected semiconductor materials:**
   Develop sound understanding of basic optical characteristics of some semiconductor materials.

3. **P-N junction – the basic structure for optoelectronic device realization**
   Gain sound understanding of the principles of operation of various junctions, including Schottky contacts and heterojunctions and their importance to optoelectronic device fabrication.

4. **Light Emitting Diodes (LEDs):**
   Develop good understanding of the principles of operation of LEDs, their structures and applications.

5. **Semiconductor Laser Diodes**
   Understand the principles of operation of semiconductor laser diodes and the role they play in modern fiber optic communication systems.

6. **Photodetectors**
   Understand the operation of different types of photodetectors: PIN, APD, Photoconductive and Bolometer.

7. **Optoelectronic modulators.**
   Understand the principles of the electro-optic effect, materials that exhibit the EO effect and how they can be fabricated into practical intensity or phase modulators.
Homework and Grading

Homework:
Will be assigned each week on Tuesday and due the following Tuesday at the start of class. Late homework up to 1 day late will receive 20% reduction in grade. Assignments handed in more than 1 day after due date will not be graded.

Grading:
Homework: 30%
Midterm Exam: 30%
Final Exam: 40%
Motivation: Internet Growth
Motivation: Bandwidth

- E-mail: 10 bit/s
- World Wide Web: 1 Mbit/s
- Internet videoconferencing: 10 Mbit/s
- Video on demand, HDTV: 100 Mbit/s to 1Gbps
Motivation: Bandwidth

- More users \times \text{Higher bandwidths} = \text{More transmission capacity.}
- Today: 100 \text{ million users} \times 50 \text{ kbit/s} = 5 \text{ Tbit/s worldwide}
- 2015: 5 \text{ billion users} \times 50 \text{ Mbit/s} = 250 \text{ Pbit/s} \quad (P \text{ stands for peta } = 10^{15})
Traffic doubles every year!
Data Transmission

- 2000: 0.1 Bit/s, Smoke Signals
- 300: 1 Bit/s, Alphabetic signaling (Greeks)
1840: 10 Bit/s, Telegraph (Morse)
1870: 100 Bit/s, Time Division Multiplexing (Baudot)
1930: 1 kBit/s, Teletype
1970: 50 Mbit/s, Microwave transmission
1979: 100 Mbit/s, LEDs/Fiber optic transmission
1985: 1 Gbit/s, Lasers/Single mode fiber
1996: 10 Gbit/s, WDM: Wavelength division multiplexing
Law of the Photon

Data rate doubles every 16 months

Data Rate (bits/sec)

Year

1800 1850 1900 1950 2000 2050

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Optical Fiber: Propagation Limits

- **Medium**
  - Max Bit Rate
  - Loss at 10 Gbit/s

- **Twisted pair:**
  - 100 kbit/s

- **Coaxial cable:**
  - 1 Gbit/s
  - 1 dB/m

- **Microwave waveguide:**
  - 1 Gbit/s
  - 0.1 dB/m

- **Optical fiber (0.82 µm):**
  - 1 Gbit/s
  - 0.001 dB/m

- **Optical fiber (1.55 µm):**
  - 100 Gbit/s
  - 0.0002 dB/m

The low loss window in optical fiber is from 1.3 to 1.6 µm is 50,000 GHz wide.
How to Achieve Higher Capacity?

- More cables
- More fibers/cables (600 fibers/cable common)
- Higher bit rates (10 Gbit/s now standard, 40Gbps being installed)
- Multiple wavelengths (WDM) (32-96 commercial)
Lightwave Trends

Channel Bit Rate

- 10 Mb/s
- 100 Mb/s
- 1 Gb/s
- 10 Gb/s
- 100 Gb/s
- 1 Tb/s

WDM Channels

- 128
- 64
- 32
- 16
- 8
- 4
- 2
- 1

- '80
- '83
- '85
- '86
- '87
- '89
- '91
- '96
- '97

Total Capacity
- 3 Tb/s

1 bit/Hz over erbium bandwidth

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## Evolution of Fiber-Optic Point-to-Point Transmission

<table>
<thead>
<tr>
<th>Multimode fiber-optic waveguides &gt;5dB/km attenuation</th>
<th>Low loss Single mode optical fibers 1 dB/km @ 1310 nm</th>
<th>Operation in the low loss window of 0.2 dB/km @ 1550 nm but high dispersion @ 1550 nm</th>
<th>Multichannel erbium doped fiber amplifiers (EDFAs) @ 1550 nm deployed.</th>
<th>AT&amp;T True Wave Fiber and Corning Large Optical Core Fiber reduce fiber FWM</th>
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</thead>
<tbody>
<tr>
<td>Early 70s</td>
<td>Multimode Fabry-Perot 1310 nm lasers</td>
<td>New dispersion shifted fiber yields Zero dispersion @ 1550 nm and 0.5 dB/km loss @ 1310 nm</td>
<td>Mid 90s</td>
<td>Mid 90s</td>
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<td>Room temperature</td>
<td>Development of single frequency DFB 1310 nm and 1550 nm lasers</td>
<td></td>
<td>Multichannel WDM @ 1550 nm. Number of channels and channel spacing limited by fiber four-wave mixing (FWM)</td>
<td>Optical Solitons, dispersion compensation</td>
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<tr>
<td>GaAs LEDs and multimode FP Lasers @ 830 nm</td>
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<td>Early 80s</td>
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<td>Multichannel WDM @ 830 nm</td>
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<td>Mid to Late 80s</td>
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<td>Multichannel WDM @ 1310 nm</td>
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<td>Late 80s to Early 90s</td>
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<td>Multichannel WDM @ 1550 nm</td>
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### Timeline:

- **1st Generation**
  - Early 70s
  - Room temperature
  - GaAs LEDs and multimode FP Lasers @ 830 nm

- **2nd Generation**
  - Multimode Fabry-Perot 1310 nm lasers

- **3rd Generation**
  - Development of single frequency DFB 1310 nm and 1550 nm lasers
  - New dispersion shifted fiber yields Zero dispersion @ 1550 nm and 0.5 dB/km loss @ 1310 nm

- **4th Generation**
  - Multichannel WDM @ 1550 nm. Number of channels and channel spacing limited by fiber four-wave mixing (FWM)

- **5th Generation**
  - AT&T True Wave Fiber and Corning Large Optical Core Fiber reduce fiber FWM
  - Optical Solitons, dispersion compensation
Transmission Bandwidth Evolution

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1st Generation

LED $T_x$ $\rightarrow$ MMF $10$ km $\rightarrow$ Regenerator $\rightarrow$ $R_x$ 50 to 100 Mbps

2nd Generation

1.31 µm MM Laser $T_x$ $\rightarrow$ SMF $50$ km $\rightarrow$ $R_x$ Few 100 Mbps to 1.7 Gbps

3rd Generation

1.55 µm SM Laser $T_x$ $\rightarrow$ SMF $100$ km $\rightarrow$ $R_x$ 2.5 Gbps to 10 Gbps

4th Generation

SM DFB Laser $T_x$ ($\lambda_1$) $\rightarrow$ SM DFB Laser $T_x$ ($\lambda_2$) $\rightarrow$ SM DFB Laser $T_x$ ($\lambda_3$) $\rightarrow$ MUX $\rightarrow$ SMF 100’s km $\rightarrow$ EDFA $\rightarrow$ DeMUX

2.5 Gbps to 10 Gbps per wavelength. 8 to 128 wavelengths

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Evolution of Fiber-Optic Networks

<table>
<thead>
<tr>
<th>1st Generation</th>
<th>2nd Generation</th>
<th>3rd Generation</th>
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</thead>
<tbody>
<tr>
<td><strong>Point-to-point fiber links connected to electronic switching equipment</strong></td>
<td><strong>High performance data communications. Serial HIPPI standard introduced, fiber at 1.2 Gbps. Fiber Channel standard introduced at 200, 400 and 800 Mbps.</strong></td>
<td><strong>Introduction of Optical Channel (OC) layer by the ITU. Routing in the optical layer.</strong></td>
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<td><strong>Late 80s</strong></td>
<td><strong>Mid to Late 90s</strong></td>
<td><strong>Late 00s</strong></td>
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<td><strong>Late 90s</strong></td>
<td><strong>Early to late 2000</strong></td>
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<tr>
<td>Fixed wavelength add/drop multiplexing. Protection and survivability in the optical layer.</td>
<td>Reconfigurable WDM add/drop multiplexers. Optical crossconnects</td>
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WDM Optical Network Evolution

- WDM Point-to-Point Links
- Fixed Wavelength Add/Drop with Electronic Switching
- WDM Photonic Crossconnects
- WDM OEO Crossconnects
- ROADMs
- Photonic Crossconnects/Wavelength Conv.


- Opaque Networks
- Transparent Networks
### High Volume: Fiber to the Home (FTTH)

<table>
<thead>
<tr>
<th></th>
<th>FTTH</th>
<th>FTTC</th>
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</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>Huge</td>
<td>Large</td>
</tr>
<tr>
<td>Cost</td>
<td>$1200</td>
<td>$800</td>
</tr>
<tr>
<td>Labor</td>
<td>23%</td>
<td>26%</td>
</tr>
<tr>
<td>Materials</td>
<td>19%</td>
<td>23%</td>
</tr>
<tr>
<td>Fiber</td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>Electronics</td>
<td>58%</td>
<td>51%</td>
</tr>
<tr>
<td>Optoelectronics</td>
<td>14%</td>
<td>2%</td>
</tr>
</tbody>
</table>

**FTTH Initiatives announced by Verizon, Bellsouth, SBC for 2004-2010**
What You Need to Know

- Modes in optical fibers (wave equation …)
- Modes in optical waveguides (lasers, modulators, …wave equation, birefringence)
- Lasers (gain, absorption, lasing,…)
- Modulators, Photodetectors, Amplifiers
- Multiplexers, Dispersion compensation
Optoelectronics

- **Photodetectors:**
  - Usually crystalline material (lower dark current, hence better sensitivity)
  - Bandgap smaller than required (but no more than necessary. Smaller bandgaps tend to have larger dark currents).

- **Lasers**
  - Always crystalline material
  - Bandgap equal to $\frac{hc}{\lambda}$
Growth

- MBE: Molecular beam epitaxy
- MOCVD: Metal organic chemical vapor deposition
- Substrate: Binary (otherwise every wafer is a little different)
- Epitaxy requires lattice constant equal to binary substrate.
- Correct lasing wavelength require correct bandgap.
- Hence, a quaternary layer is required (two degrees of freedom):
  - $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$
Ternary Materials

- Mix two binaries together. The bandgap is approximately the arithmetic average of the two (Vegard’s law) e.g. Ga$_x$Al$_{1-x}$As
- There are two types of sites: group III and group V. (II-VI compounds also possible).
- Ternaries cannot be grown on binary substrates in general because the lattice constants don’t line up and dislocations occur. Special case: Ga$_x$Al$_{1-x}$As because the lattice constants of GaAs and AlAs are almost equal.
Quaternary materials

- To match bandgap and lattice constant, two degrees of freedom are required.

- Example: $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$
  - $X$ is the fraction of group III sites occupied by Ga.
  - $Y$ is the fraction of group V sites occupied by As.

- In a bandgap chart, the dots are binaries, the lines are ternaries, and the regions bounded by 4 lines are quaternaries.
Epitaxial Layers

- Epitaxial layers of different compound semiconductors can be grown on top of each other.
- Small differences in lattice constants can be accommodated for thin layers (strained layers: Compressive or tensile).
- Too much accumulated strain results in dislocations.
Bandgap Heaven

- Offsets in blue #s
- Bandgaps in black
- Units are meV

\[ \Delta E_C [\text{InAs-AlSb}] = 1.35 \text{eV} \]

\[ m^* [\text{InAs}] = 0.023 \, m_e \]

InAs RT \( \mu > 30,000 \text{ cm}^2/\text{Vs} \)
Guidelines

- Figure out bandgaps. (draw horizontal where there is no depletion).
- Figure out conduction band and valence band discontinuity.
- Figure out Fermi level for each material.
- Draw flat band first, then flatten out the Fermi level.
- Keep the band separation constant for any region where the bandgap is not changing.