Introduction to Integrated Photonic Devices

- Class: Integrated Photonic Devices
- Time: Wed. 1:10pm ~ 3:00pm.
  Fri. 10:10am ~ 11:00am
- Classroom: 資電106
- Lecturer: Prof. 李明昌 (Ming-Chang Lee)

Block Diagram of a Communication System

- **Transmitter**: A device converts the information into a suitable signal transmitting in channels.
- **Channel**: A medium bridges the distance between the transmitter and receiver. (EM wave → air, electronic signal → wire or cable, optical wave → fiber).
- **Receiver**: A device extracts weaken signal from the channel and amplifies it. The signal eventually is converted to its original information.
Three Milestones in Developing Optical Communication

- Laser (optical source) --- 1960s
  - From gas laser to semiconductor laser (diode laser, hetero-junction laser,...)

- Low-Loss optical fiber --- 1980s
  - 1000dB/km $\rightarrow$ 20dB/km $\rightarrow$ 0.2dB/km

- Semiconductor manufacturing --- 1990s ~
  - Silicon, III-V, II-VI, silica,...
  - Integrated optical devices

Advantage of Optical Interconnect

- Immunity from electromagnetic interference (EMI)
- Safety in combustible environments
- Security from monitoring
- Large bandwidth
- Low-loss transmission
- Small size, light weight
- Inexpensive
- Major disadvantage: difficult to use for electrical power transmission
What is the capacity of optical communication?

Suppose $\Delta \lambda$ is 0.05 $\mu$m, the bandwidth is 6.24 THz (much higher than electronic device).

Multiplexing Techniques

To fully utilize the bandwidth, two multiplexing techniques are developed.

OTDM: Optical Time Division Multiplexing

WDM: Wavelength Division Multiplexing

Rajiv Ramaswami, "Optical Networks"
A DWDM Point-to-Point Optical Link

- Laser diode, Receiver, Optical Mux/Demux, Optical amplifier, ...

Per-Fiber Capacity Trends
Optical Fiber vs. Twisted-Pair Cable

Twisted-Pair Cable

Optical Fiber

Optical Fiber vs. Coaxial Cable

Coaxial Cable

Optical Fiber
Benchmark between Optical Fibers and Twisted-Pair Cable

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Twisted Pair</th>
<th>Multi-Mode Fiber</th>
<th>Single Mode Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;100MHz</td>
<td>8GHz</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Power Transmission</th>
<th>Twisted Pair</th>
<th>Multi-Mode Fiber</th>
<th>Single Mode Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;0.01%</td>
<td>80-90%</td>
<td>&gt;99%</td>
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<thead>
<tr>
<th>Dispersion</th>
<th>Twisted Pair</th>
<th>Multi-Mode Fiber</th>
<th>Single Mode Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;&gt;1UI</td>
<td>~1UI</td>
<td>&lt;&lt;1UI</td>
</tr>
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</table>

- Singlemode fibers have unlimited capacity, low loss and low dispersion

Optical Signal Processing

- With the development of network communication, the transmitted signals need further processed such as switching, add-drop multiplexing, …

1. Processing in electronic domain

Switching, Add-drop Multiplexing
Wavelength Conversion, Signal Reshaping…
Optical Signal Processing

II. Processing in optical domain (discrete component)

De-multiplexer 2x2 switch

Attenuator Isolator

Thorlab Ltd.

Summary of Components in Optical Integrated Circuits

- Passive components --- linear optics
  - Waveguides/Couplers
  - Switches (optical interconnect, wavelength selective switches)
  - Filters (add-drop filters, MUX/DEMUX)
  - Dispersion compensators (chromatic dispersion, polarization dispersion)
  - Attenuator
  - Gain equalizer
  - Isolators/Circulators
Summary of Components in Optical Integrated Circuits

- Active components --- optoelectronics, nonlinear optics
  - Amplifiers
  - Lasers
  - LED
  - Modulators
  - Detectors
  - Wavelength converters

Passive vs. Active

**Passive Materials**
- Quartz (SiO$_2$)
- Lithium Niobate (LiNbO$_3$)
- Lithium Tantalate (LiTaO$_3$)
- Tantalum Pentoxide
- Niobium Pentoxide
- Silicon
- Polymers

**Active Materials (light source)**
- Gallium Arsenide (GaAs)
- Gallium Aluminum Arsenide (GaAlAs)
- Gallium Arsenide Phosphide (GaAsP)
- Gallium Indium Arsenide (GaNAs)
- Gallium Indium Arsenide (GaNAs)
- Other Compound III-V and II-VI
Monolithic Integrated Optical Communication System

- The signals are processed in optical domain
- All the optical components are integrated on a single chip

Evaluations of Optical Integrated Circuits

**Advantage**
- Compared with electrical ICs
  - Increased bandwidth
  - WDM
  - Could be low power consumption
  - Data transparent

**Disadvantage**
- High cost of developing new fabrication technology

**Compared with discrete optical components**
- Batch fabrication economy
- Smaller size
- Improved optical alignment
- Immunity to vibration
- Low power consumption
## Hybrid and Monolithic Integration

Hybrid: Combination of different OICs substrates (active and passive components/materials)

Monolithic Integration: Integration of different OICs on a single substrate

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>Well-developed Fabrication</td>
<td>Assembly or Packaging</td>
</tr>
<tr>
<td>Reliability of each component</td>
<td>Alignment</td>
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</table>

<table>
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<tr>
<th>Hybrid</th>
<th>Monolithic Integration</th>
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</thead>
<tbody>
<tr>
<td>Compactness</td>
<td>Challenging to fabrication</td>
</tr>
<tr>
<td>Self-alignment, Immunity to vibration</td>
<td></td>
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<tr>
<td>Cost reduction</td>
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### Roadmap of Optoelectronic Integrated Circuits

[Image of road map showing different levels of integration and components]
Process power will be divided into several processing units --- CPU, graphic processor, memory controller, math processor, etc.

Each processing unit requires large bandwidth for connection
- 1-Tflop CPU requires 1000Gb/s bandwidth
- 1 graphic processor requires 80Gb/s

Issue:
- Loss in copper wires
- Heat dissipation due to high speed clock

Integrated Photonics: Short-Distance Optical Interconnect

PC interconnect speed should keep with the number of transistors

Market Transition from Electrical to Optical

The upper limit of copper connection (electrical):
10-40 Gb/s for PC board material at < 1m distance
Intel Proposed Silicon Photonics

Moving Data With Light: The goal of silicon photonics is to integrate optical components—lasers, mirrors, modulators, and so on—onto ordinary silicon chips that can be manufactured using standard semiconductor equipment.

Commercialized CMOS Optical Transceivers --- Luxtera Inc.

Silicon 10G Modulators
- Driven with on-chip circuitry
- Highest quality signal
- Low loss, low power consumption

Flip-chip bonded lasers
- Wavelength 1550nm
- Passive alignment
- Non-modulated = low cost/available

Silicon Optical Filters - DWDM
- Electrically tunable
- Integrated w/ control circuitry
- Enables > 100Gb in single mode fiber

Complete 10G Receive Path
- Photon detectors
- Trans-impedance amplifiers
- Output driver circuitry

The Toolkit is Complete:
- 10Gb modulators and receivers
- Integration with CMOS electronics
- Cost-effective, reliable light source
- Standard packaging technology

Source: Luxtera Inc.
Fiber Structure

Cross section (not to scale)

Stamatios V. Kartalopoulos, "Introduction to DWDM Technology

Fiber Dimension

Multimode fiber:

Single-mode fiber:

Stamatios V. Kartalopoulos, "Introduction to DWDM Technology