Optical Networking Components

- Reading: A review for routing and wavelength assignment approaches for wavelength routed optical WDM networks, Hui Zang et al
- Couplers, Splitters, Isolators, Circulators
- Filters, Gratings, Multiplexers
- Optical Amplifiers, Regenerators
- Light Sources, Tunable Lasers, Detectors
- Modulators
Couplers, Splitters

- Combines & splits signals
- Wavelength independent or selective
- Fabricated (a) fusing two fibers together in the middle; (b) using waveguides in integrated optics
- $\alpha = \text{coupling ratio}$
- $\text{Power}(\text{Output1}) = \alpha \text{Power}(\text{Input1})$
- $\text{Power}(\text{Output2}) = (1- \alpha) \text{Power}(\text{Input1})$
  - Power splitter if $\alpha=1/2$: 3-dB coupler
  - Tap if $\alpha$ close to 1
  - $\lambda$-selective if $\alpha$ depends upon $\lambda$ (used in EDFAs)
8-port Splitter Made by Cascading Y-Couplers

Figure 109. An 8-Port Splitter Made by Cascading Y-Couplers

8x8 Star Coupler

Power from all inputs equally split among outputs
Isolators and Circulators

- **Extension of coupler concept**
- **Non-reciprocal** => will not work the same way if inputs and outputs reversed
- **Isolator**: allow transmission in one direction, but block all transmission (e.g.: reflection) in the other
- **Circulator**: similar to isolator, but with multiple ports.

#### Multiplexers, Filters, Gratings

Wavelength selection technologies...

(a) Wavelength filter

(b) Wavelength multiplexer
Applications

- Wavelength (band) selection
- Static wavelength cross-connects (WXC), OADMs
- Equalization of gain
- Filtering of noise

Characteristics of Filters

- Low insertion (input-to-output) loss
- Loss independent of: geometry of waveguides
- Filter passband independent of temperature
- Flat passbands
- Sharp “skirts” on the passband & crosstalk rejection
- Cost: integrated optic waveguide manufacture
- Usually based upon interference or diffraction
Dynamic Wavelength Cross-connects

- Dynamic cross-connects!

High Channel Count Multiplexers

- Multi-stage Banded multiplexers
Multi-stage Interleaving

- Filters in the last stage can be much wider than each channel width

Amplifiers, Regenerators
Amplification

Optical Amplifiers vs Regenerators

Regenerator - 3R (Reamplify, Reshape and Retime)

EDFA - 1R (Reamplify)

EDFA amplifies all λs
OEO Regenerator

Figure 2.65 The model of a regenerator and the three major functions, optical receiver, electronic amplifier, and optical transmitter.

1R, 2R and 3R Regeneration
Regenerators vs O-Amplifiers

- Regenerators specific to bit rate and modulation format used; O-Amps are insensitive (i.e. transparent)
- A system with optical amplifiers can be more easily upgraded to higher bit rate w/o replacing the amplifiers
- Optical amplifiers have large gain bandwidths → key enabler of DWDM

**Issues:**
- Amplifiers introduce additional noise that accumulates
- Spectral shape of gain (flatness), output power, transient behavior need to be carefully designed

EDFA Enables DWDM!

- EDFAs amplify all λs in 1550 window simultaneously
- Key performance parameters include
  - Saturation output power, noise figure, gain flatness/passband
Optical Amplifier Varieties

Figure 1.66 Optical amplifiers are many, each suitable for a different spectral range.

Optical Amplifier Flat Gain Region

Figure 4.17 Optical amplifier flat gain region in C-band.
**Principles: Stimulated Emission**

- Transitions between discrete energy levels of atoms accompanied by *absorption* or *emission* of photons
- $E_2 \rightarrow E_1$ can be stimulated by an optical signal
- Resulting photon has *same energy, direction of propagation, phase, and polarization* (a.k.a *coherent*!)
- If stimulated emission dominates absorption, then we have *amplification* of signal
- Need to create a "*population inversion*" ($N_2 > N_1$) through a *pumping* process

**Spontaneous Emission**

- $E_2 \rightarrow E_1$, transitions can be spontaneous (i.e. *independent* of external radiation)
  - The photons are emitted in random directions, polarizations and phase (i.e. *incoherent*!)

- *Spontaneous emission rate* (or its inverse, *spontaneous emission lifetime*) is a characteristic of the system
  - Amplification of such incoherent radiation happens along with that of incident radiation
  - A.k.a. *amplified spontaneous emission (ASE)*: appears as noise
  - ASE could *saturate* the amplifier in certain cases!
Optical Amplification: mechanics

![Diagram of Optical Amplification](image)

**Figure 2.6b** For sustained amplification, the rate of excitation should be less or equal to the rate of stimulation + the rate of spontaneous emission.

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Erbium-Doped Fiber Amplifier (EDFA)

- Length of fiber: core doped with (rare earth) erbium ions $\text{Er}^{3+}$
- Fiber is pumped with a laser at 980 nm or 1480nm.
- Pump is coupled (in- and out-) using a $\lambda$-selective coupler
- An isolator is placed at the end to avoid reflections (else this will convert into a laser!)
EDFA success factors

- 1. Availability of compact and reliable high-power semiconductor pump lasers
- 2. EDFA is an all-fiber device → polarization-independent & easy to couple light in/out
- 3. Simplicity of device
- 4. No crosstalk introduced while amplifying!

EDFA: Operation

- When \text{Er}^{3+} \text{ ions introduced in silica, electrons disperse into an energy band around the lines } E_1, E_2, E_3 \text{ (Stark splitting)}
- Within each band, the ion distribution is non-uniform (thermalization)
- Due to these effects, a large \( \lambda \) range (50 nm) can be simultaneously amplified & luckily it is in the 1530nm range
**EDFA: Operation (Contd)**

- 980 nm or 1480nm pumps are used to create a population inversion between $E_2$ and $E_1$.
- 980 nm pump $\rightarrow E_1 \rightarrow E_3$ (absorption) & $E_3 \rightarrow E_2$ (spontaneous emission).
- 1480 nm pump $\rightarrow E_1 \rightarrow E_2$ (absorption, less efficient).

**Figure 115.** Energy Level States of Erbium. While the energy states are represented as horizontal lines, they are really “energy bands” centred around a specific energy state. This distribution of energy states is called a “Fermi-Dirac Distribution.”

**Towards Flat EDFA Gain**

- Long period fiber-grating used to add some “loss” in the peaks of the curve (see →).
Reducing EDFA Gain Ripples

Figure 4.14  Inverse filters reduce EDFAs gain ripple.

EDFA: Summary

Figure 2.71  An EDFA amplifier consists of an erbium-doped silica fiber, an optical pump, a coupler and isolators.

Figure 2.72  Pump absorption and signal emission spectra of EDFA.
Long-Haul All-optical Amplification

Figure 4.46  All optical amplification (EDFA + Raman) and dispersion compensation modules (DCM) enable the optical signal to reach ultra long distances (~4,000 km) between end terminals.

Light Sources: LEDs, Lasers, Tunable Lasers
Lasers: Key Target Characteristics

- Laser: an optical amplifier enclosed in a reflective cavity that causes it to oscillate via positive feedback
- High output power (1-10 mW normal, 100-200mW EDFA pumps, few Ws for Raman pumps)
- Narrow spectral width at specified $\lambda$.
  - Side-mode suppression ratio
  - Tunable laser: operating $\lambda$'s
- $\lambda$-stability: drift over lifetime needs to small relative to WDM channel spacing
- Modulated lasers: low (accumulated) chromatic dispersion

Recall: Energy Levels & Light Emission

![Energy Level Diagram]

*Figure 2.51* A four, three and multi-energy level system.
Spontaneous Emission, Meta-Stable States

Figure 63. Spontaneous Emission

Recall: Stimulated Emission

1. Atom in "ground" (low energy) state
2. Energy is supplied from outside and atom enters excited state
3. Photon arrives and interacts with excited atom.
4. Atom emits additional photon and returns to the ground state

Figure 62. Stimulated Emission
Laser vs LEDs

- **LED**: Forward-biased pn-junction
  - Spontaneous emission produces light
  - Broad spectrum
  - Low power: -20dBm
  - Low internal modulation rates: 100s of Mbps max
  - Useful in free space optical communication

- **Laser**:
  - Higher power output
  - Sharp spectrum (coherence): ↓ chromatic dispersion
  - Internal or External modulation: ↑ distance, ↑ bit rates
  - Multi-longitudinal mode (MLM): larger spectrum (10s of nm) with discrete lines (unlike LEDs)

Lasers vs Optical Amplifiers

- As reflectivity of the cavity boundaries (aka facets) ↑, the gain is high only for the resonant λ's of the cavity
  - All resonant λ's add in phase
  - Gain in general is a function of the λ and reflectivity

- If reflectivity (R) and gain is sufficiently high, the amplifier will “oscillate” i.e. produce light output even in the absence of an input signal!!!
  - This lasing threshold is where a laser is no longer a mere amplifier, but an oscillator
  - W/o input signal, stray spontaneous emissions are amplified and appear as light output

- Output is “coherent”: it is the result of stimulated emission
- LASER = “Light Amplification by Stimulated Emission of Radiation”
Longitudinal Modes: SLM and MLM

- $\lambda$: within the b/w of the gain medium inside the cavity
- Cavity length should be integral multiple of $\lambda/2$
  - Such $\lambda$s are called "longitudinal modes"
  - a multiple-longitudinal mode (MLM) laser (Large spectral width (10 nm or ~1.3 Thz!)
- Desired: single-longitudinal mode (SLM):
  - Add a filter to suppress other $\lambda$s by 30dB+

Lasing
Recall: History of SLM/MLM Usage

Tunable Lasers

- Tunable lasers: key enabler of re-configurable optical networks

  **Tunability characteristics:**
  - Rapid (< ms ranges)
  - Wide and continuous range of over 100 nm
  - Long lifetime and stable over lifetime
  - Easily controllable and manufacturable

- **Methods:**
  - **Electro-optical:** changing RI by injecting current or applying an E-field (approx 10-15 nm)
  - **Temperature tuning:** (1 nm range) may degrade lifetime of laser
  - **Mechanical tuning:** using MEMS (Micro Electro-Mechanical Systems) → compact
Photodetectors

Optical Receivers: Basic Ideas
Photoconductive Detector

- Application of external bias $\rightarrow$ absorbed photons lead to electron/hole pairs and a current (aka “photo-current”)
- Energy of incident photon at least the bandgap energy

Figure 97. Photoconductive Detector - Principle

Modulators
Electronic vs Photonic Regime

Cannot go negative in the photonic regime

Optical Modulation Methods

Figure 4.11 Optical modulation methods.
Issues in Optical Modulation

- On-Off keying (OOK) is the simplest
- Direct modulation vs External modulation
  - Extinction ratio: ratio of output power for bit=1 to output power for bit=0
  - Some lasers cannot be directly modulated
  - Direct modulation adds "chirp," i.e., time variation of frequency within the pulse!
    - Chirped pulses are more susceptible to chromatic dispersion
    - Combat chirp by increasing the power of bit=0, so that lasing threshold is not lost
    - Reduction of extinction ratio (down to 7dB)
- Solution: external modulation for higher speeds, longer distance/dispersion-limited regimes

External Modulation

- External modulation can be:
  - one-stage designs (if mode-locked lasers used) or
  - two stage designs
Switches

**Multiplexing: WDM**

- **TDM**: Time Division Multiplexing
  - 10Gb/s upper limit
- **WDM**: Wavelength Division Multiplexing
  - Use multiple carrier frequencies to transmit data simultaneously
Multiplexers, Filters, Routers

- **Filter** selects one wavelength and rejects all others
- **Multiplexer** combines different wavelengths
- **Router** exchanges wavelengths from one input to a different output

Switch Parameters

- **Extinction Ratio**: ratio of output power in ON state to the power in the OFF state
  - 10-25 dB in external modulators
- **Insertion loss**: fraction of power lost
  - Different losses to different outputs → larger dynamic range → may need to equalize (esp. for large switches)
- **Crosstalk**: ratio of power at desired vs undesired output
- Low polarization dependent loss (PDL)
- **Latching**: maintain switch state even if power turned off
- **Readout capability**: to monitor current state
- **Reliability**: measured by cycling the switch through its states a few million times
Switch Considerations

- **Number of switch elements**: complexity of switch
- **Loss uniformity**: different losses to different outputs (esp for large switches)
- **Number of crossovers**: waveguide crossovers introduce power loss and crosstalk (not a problem for free-space-switches)
- **Blocking characteristics**: any unused input port can be connected to any unused output port?
  - *Wide-sense non-blocking*: without requiring any existing connection to be re-routed → make sure future connections will not block
  - *Strict-sense non-blocking*: regardless of previous connections
  - *Re-arrangeably non-blocking*: connections may be re-routed to make them non-blocking

Crossbar Switch

Wide-sense non-blocking

Shortest path length = 1 vs longest = 2n-1

Fabricated w/o any crossovers
MEMS Mirror Switching Component

NxN Switching with MEMS Mirror Arrays
Analog Beam Steering Mirror

Planar Waveguide Switch

- Air bubble causes light to be reflected
- Trench filled with index matching fluid
- No air bubble implies light passes through
- Planar substrate
Planar Waveguide Switch