Introduction to Photonic Integrated Circuits

Min-Hsiung Shih*(施閔雄)*

Research Center for Applied Sciences (RCAS)
&
Taiwan International Graduated Program (TIGP)
Academia Sinica, Taiwan

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Outlines

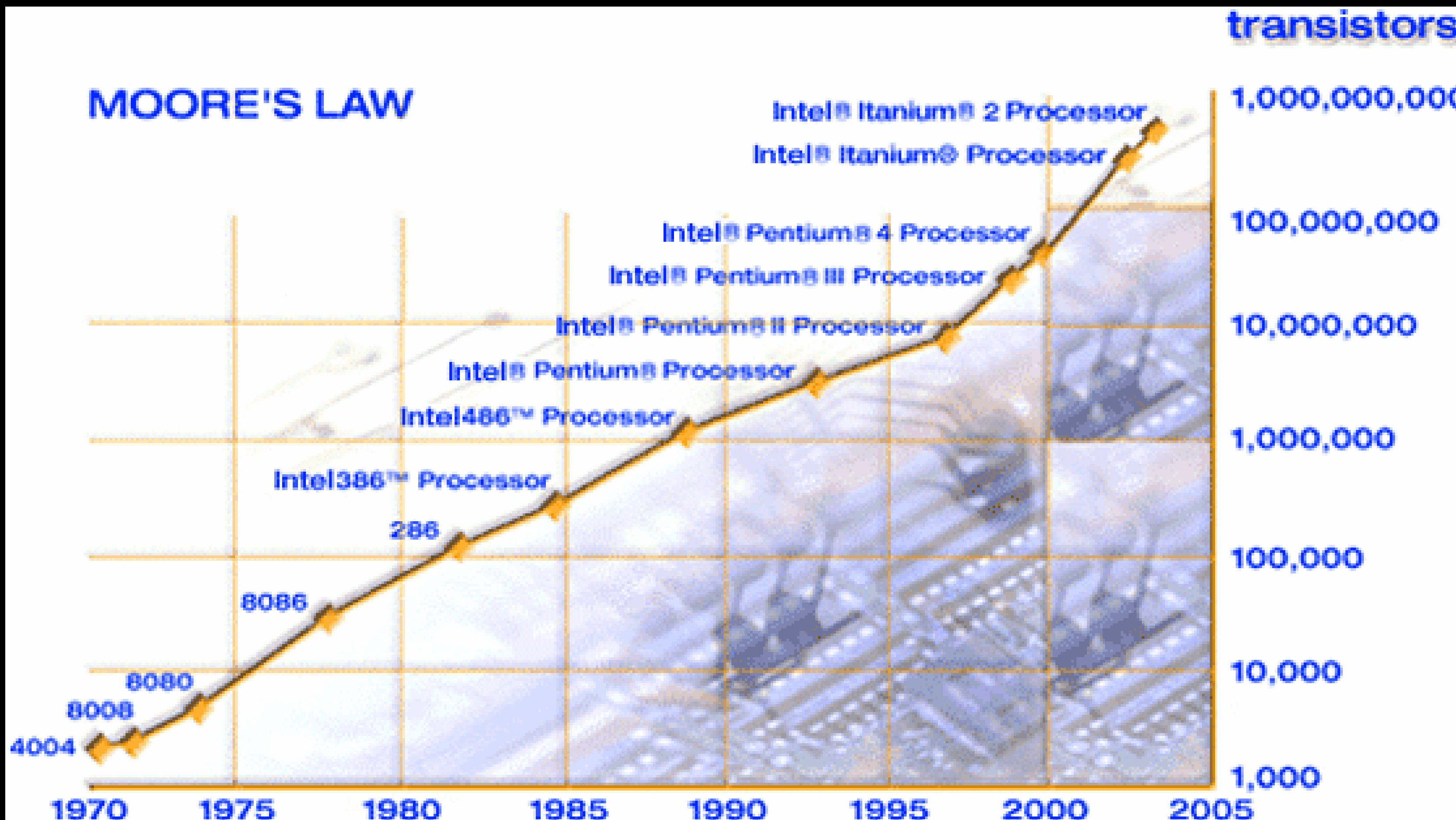
- **Optical communication and photonic integrated circuits**

- **Property of light**

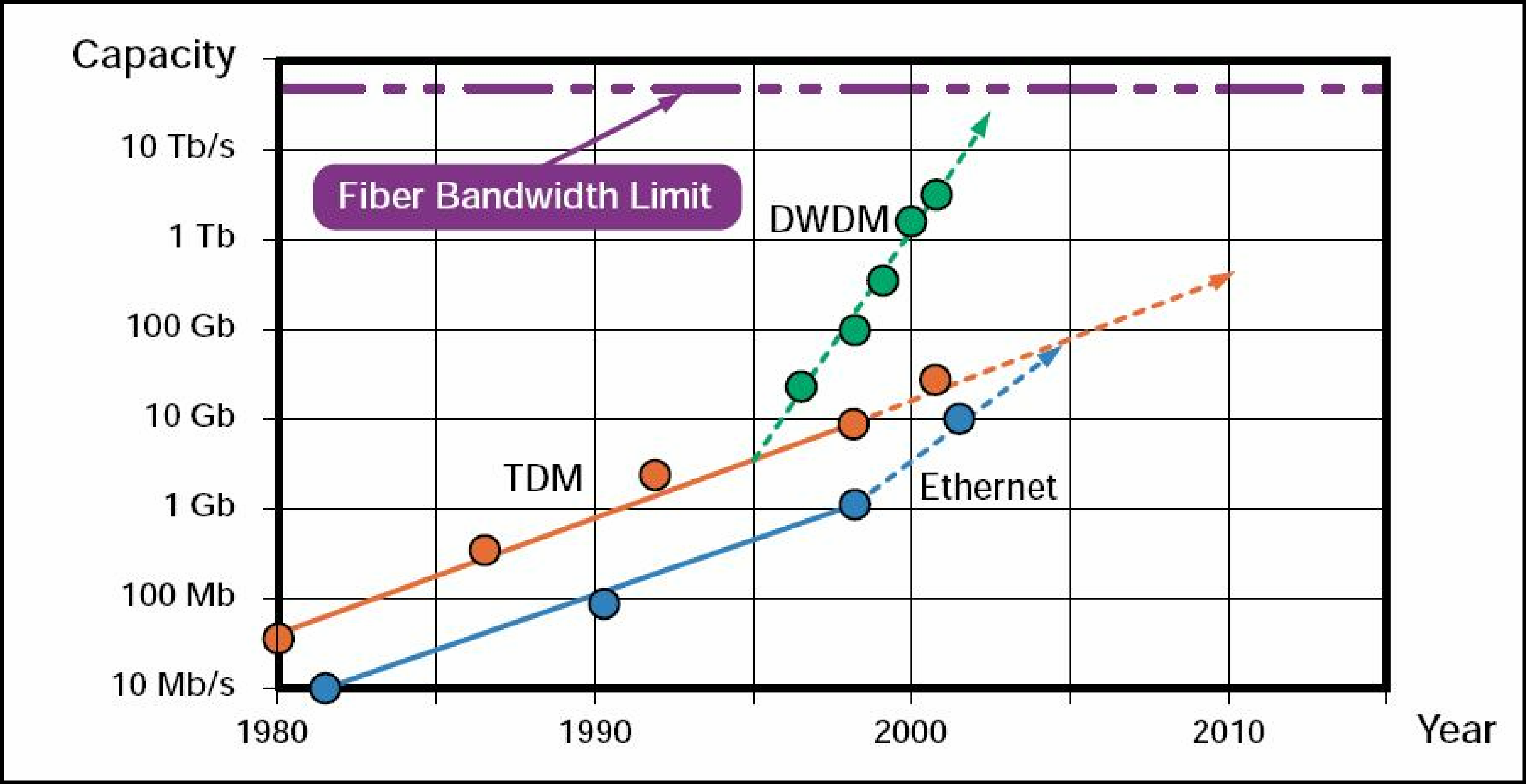
- **Elements for optical communication system**
  1) Lasers and amplifiers
  2) Waveguides and fibers
  3) Modulators
  4) Multiplexer and Demultiplexer elements
  5) Photodectors

- **Photonic crystal waveguide and bending structures**

Moore’s Law for ICs



Moore's Law and Communication Speed



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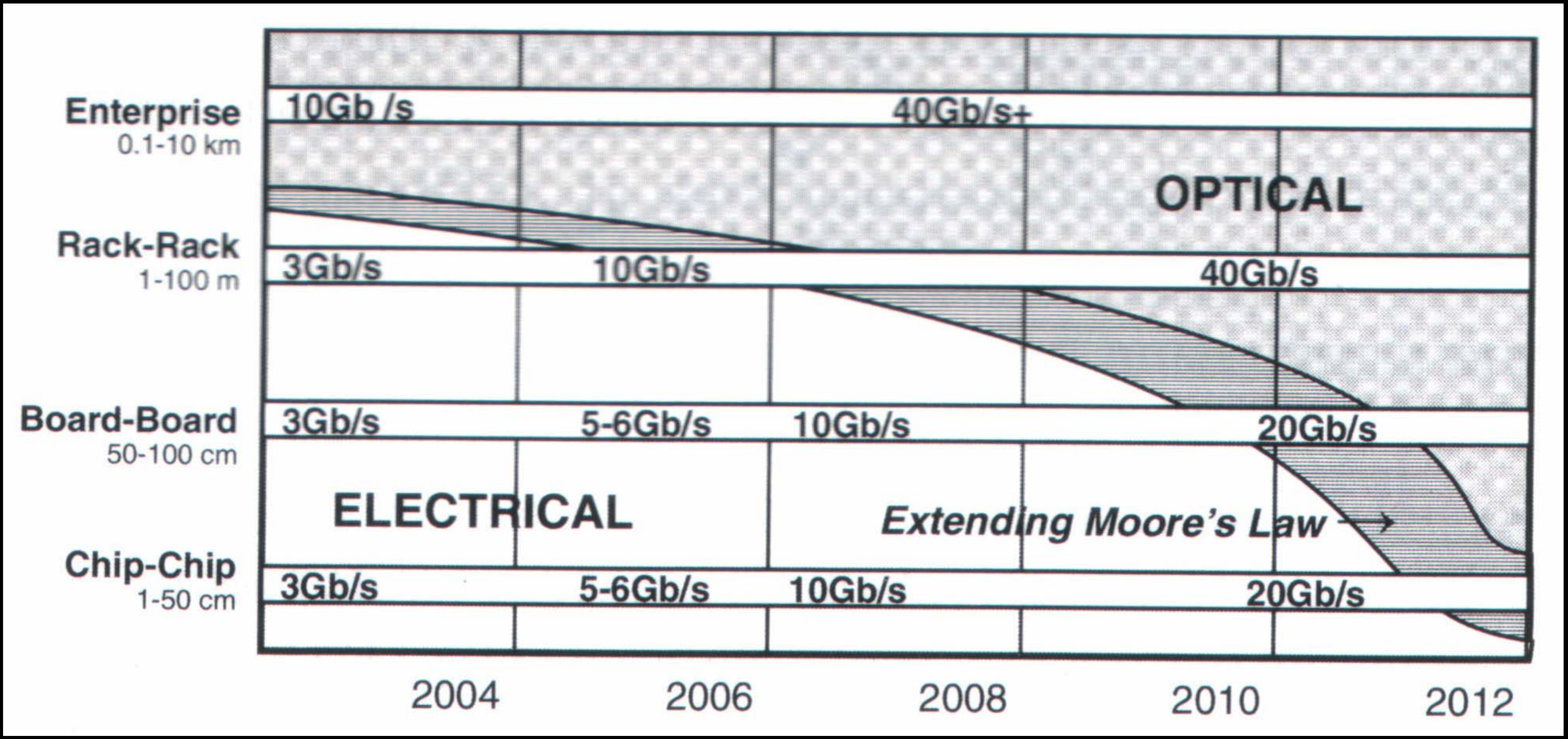
Speed Limitation of Electrical Communications



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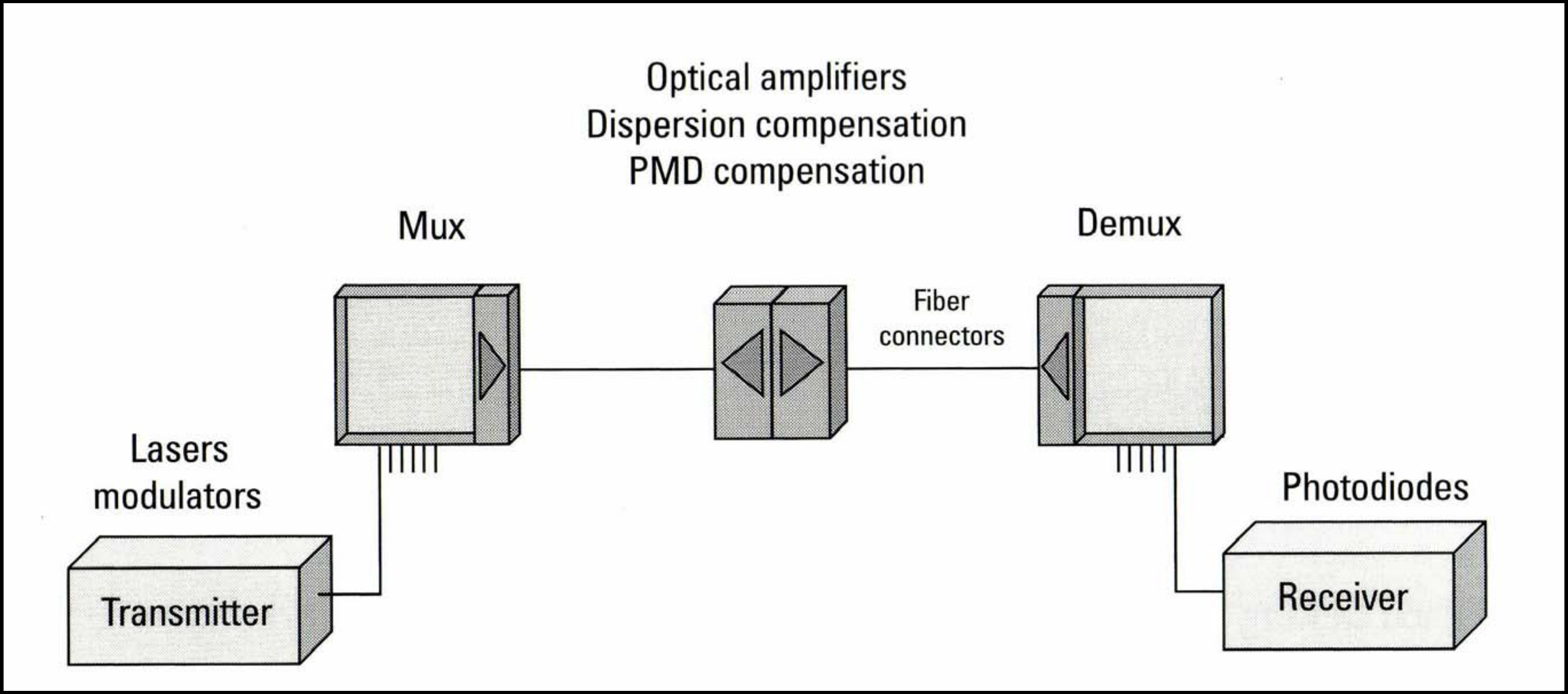
Optical Communication System



Typical DWDM (Dense Wavelength Division Multiplexing) system

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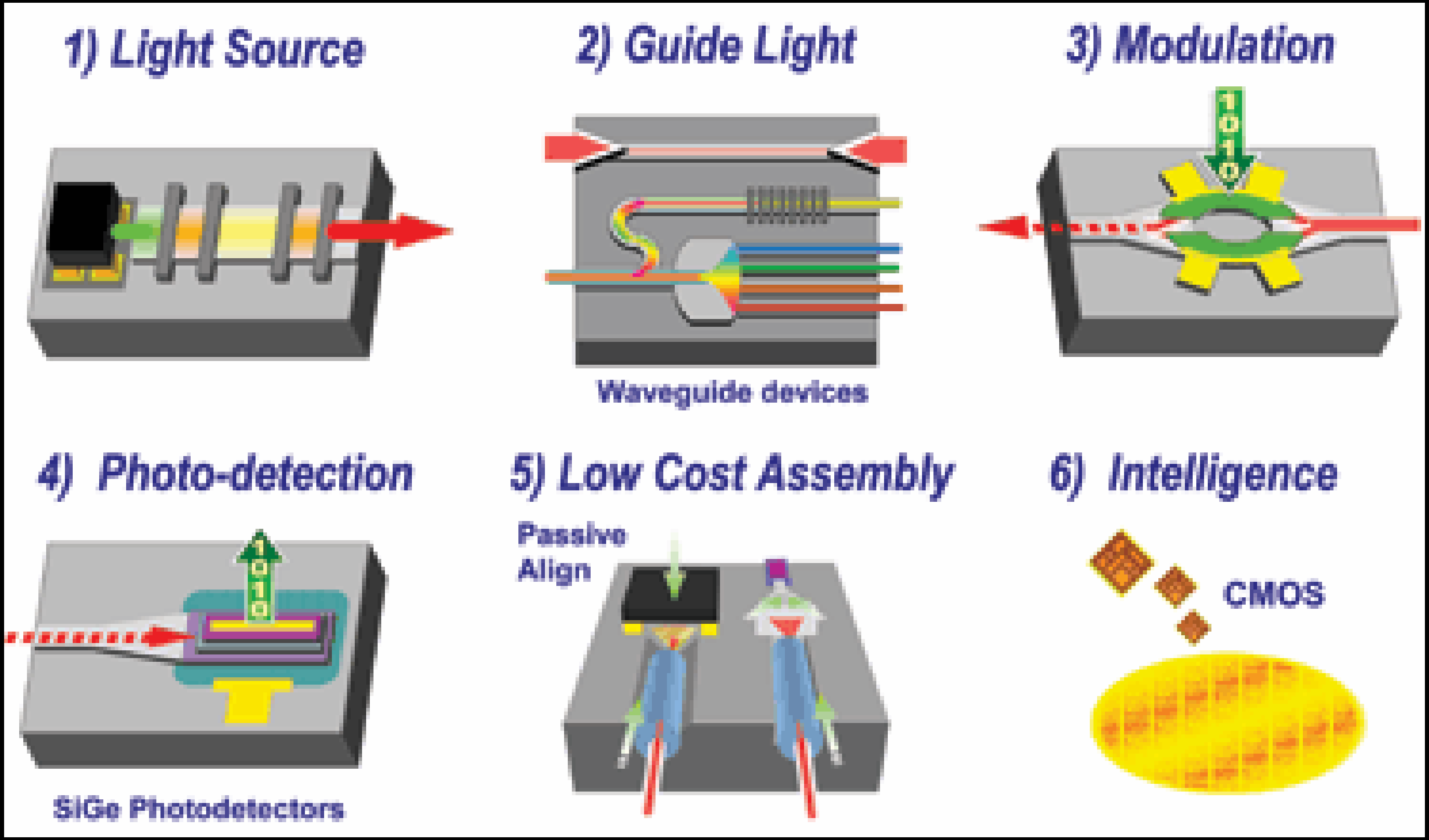
Elements for Photonic Integrated Circuits



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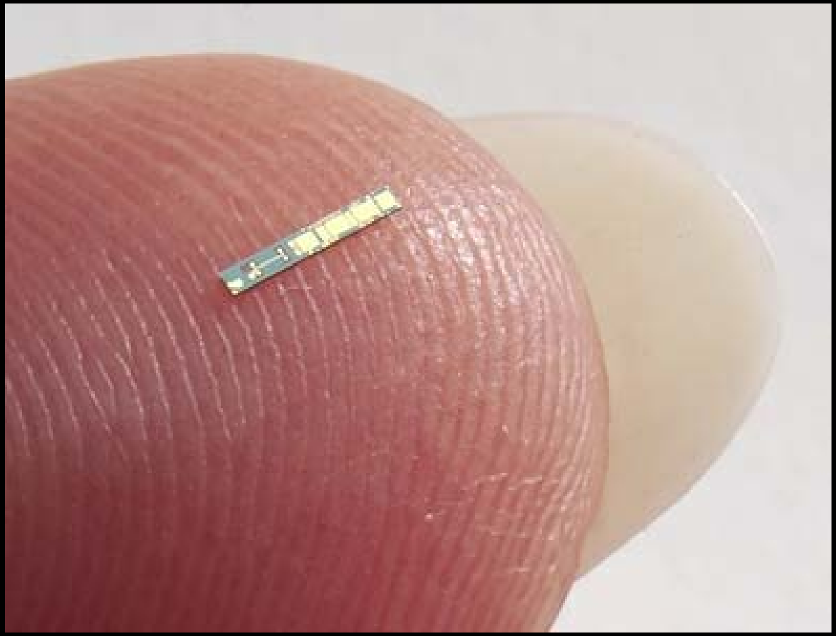
Example of Photonic Integrated Circuits



Photonic Integrated Circuit
combines tunable laser and optical modulator 10/09/2007

JDSU demonstrated a photonic integrated circuit (PIC) that combines a tunable laser and optical modulator, using a technology known as the Integrated Laser Mach Zehnder (ILMZ). The PIC will allow the company to develop smaller, higher performance and more cost-effective tunable solutions that support faster network speeds. Tunable lasers are a key element required or the deployment of agile optical networks (AON). Such networks are deployed by service providers to scale network infrastructures and replace slow, manual operations with simplified, dynamic network solutions that can quickly respond to fluctuating traffic traveling over fiber optic networks. Tunable lasers provide dynamic reconfigurability by allowing network operators to switch from one wavelength to another on demand, easing the cost of purchasing, storing and managing spare devices for wavelength management. The chip includes a widely tunable laser and Mach Zehnder modulator on a single chip that is small enough to fit on the tip of a finger. It will be incorporated into full-band tunable transponders and transceivers within compact packages, such as the 300-PIN small form factor (SFF) and pluggable small form factors (XFP) starting in 2008. This combination enables JDSU to support transmission speeds greater than 11.3 Gigabits per second and is scalable to support 40Gbit/s networks.

From www.epn-online.com

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Photon vs. Electron

Photon :

- For photon

$$(E,\vec{P}) = (h\nu, {}^{2\pi}\!/\!_{\lambda})$$

- Small interaction between the photons
- Can propagate outside the guide medium

Electron :

- For electron

$$(E,\vec{P}) = (\frac{\hbar^2 k^2}{2m}, \hbar k)$$

- Larger interaction between the electrons
- Propagate only inside the medium or on the surface of the medium

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Optical Wave

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{M}$$

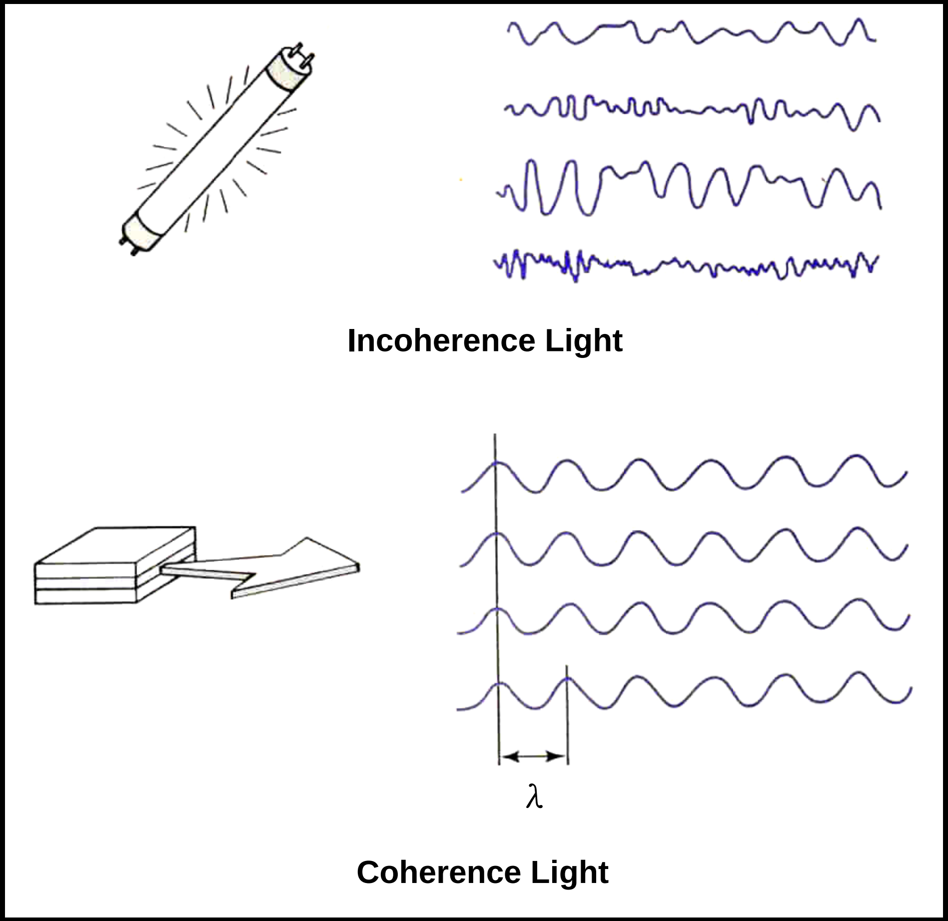
$$\nabla \times \vec{H} = -\frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \cdot \vec{B} = 0$$

Maxwell's equations

Coherence of Light



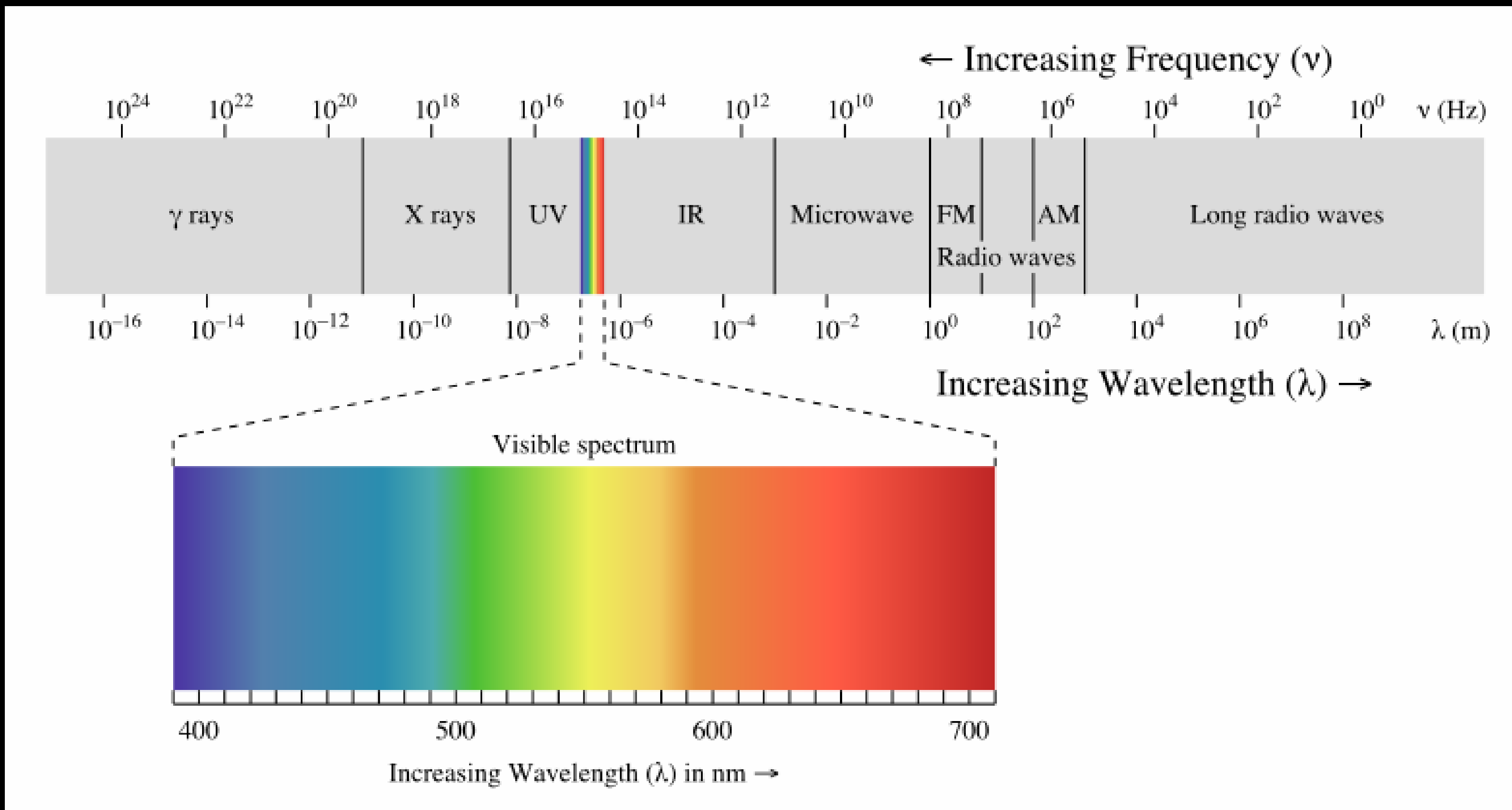
- <u>Incoherence light :</u>

  Random phases kill the signals

- <u>Coherence light :</u>

  The signal can propagate for longer distance without interferences. The laser light is coherence.

Light Spectrum



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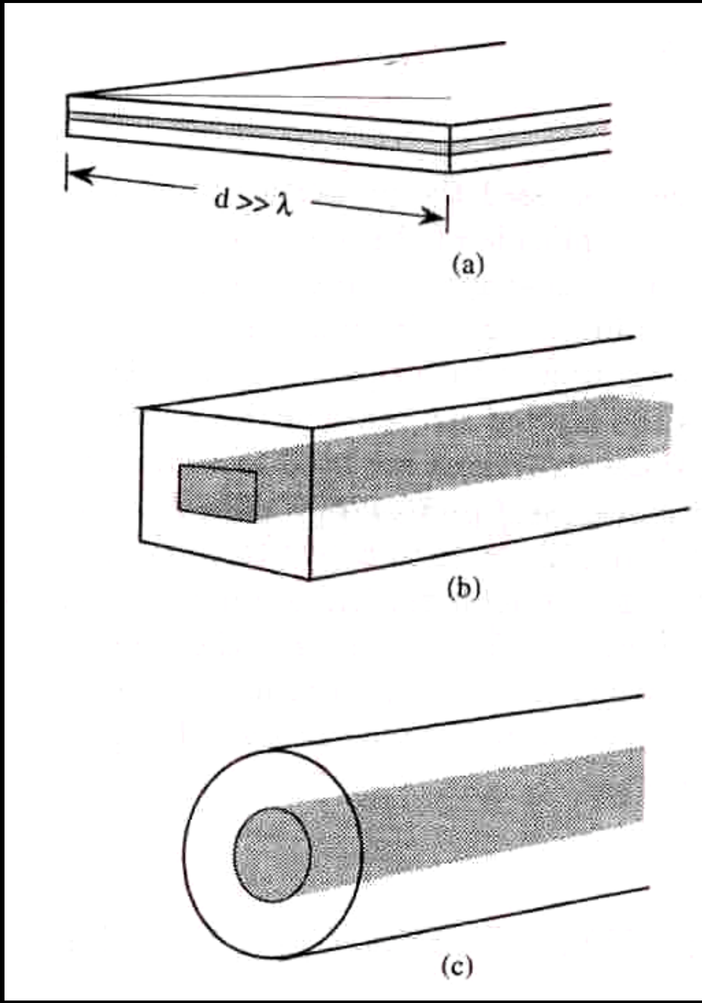
Optical Waveguides



- Planar waveguide
- Rectangular (or linear) waveguide
- Cylindrical waveguide

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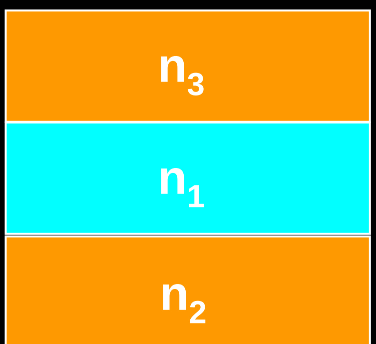
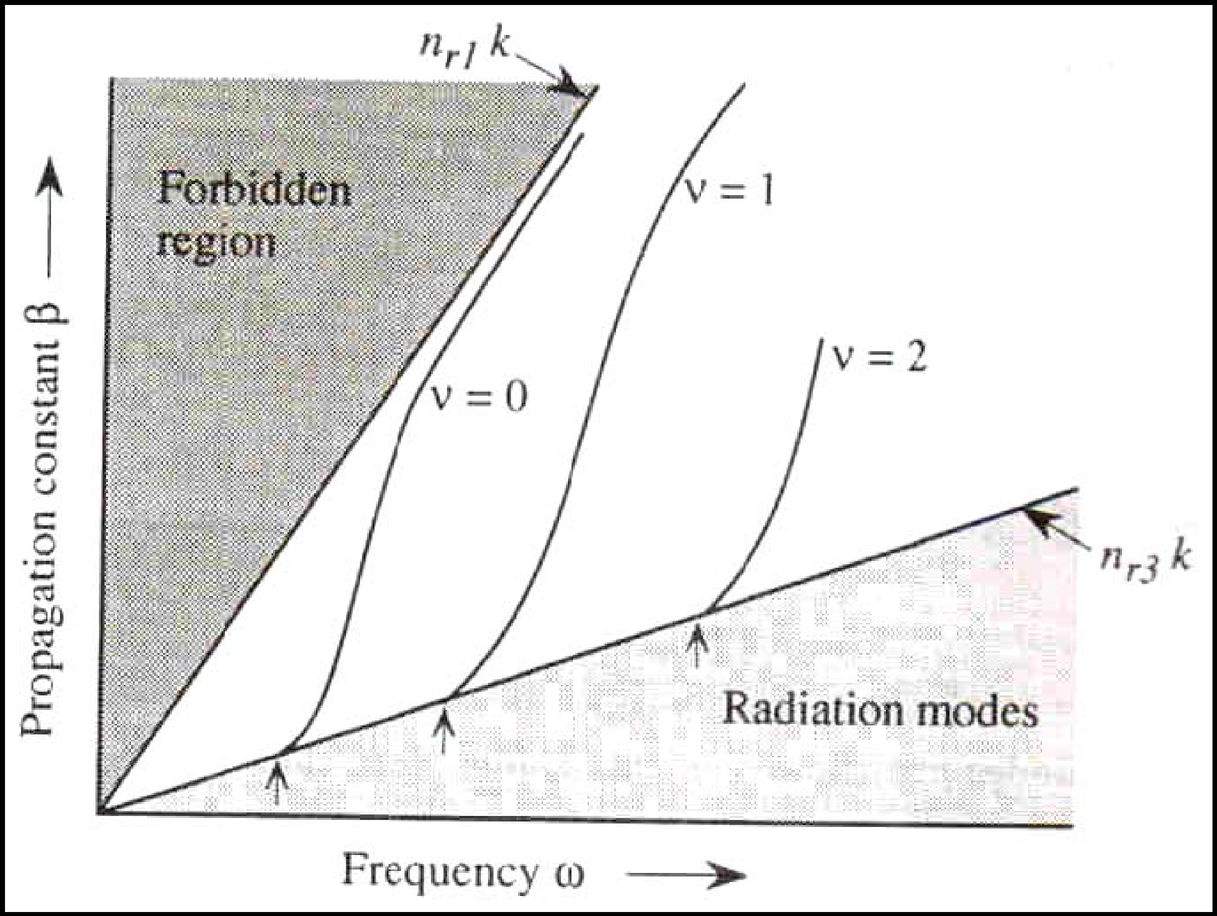
Dispersion Relation of Optical Waveguides



$n_1 > n_2 > n_3$



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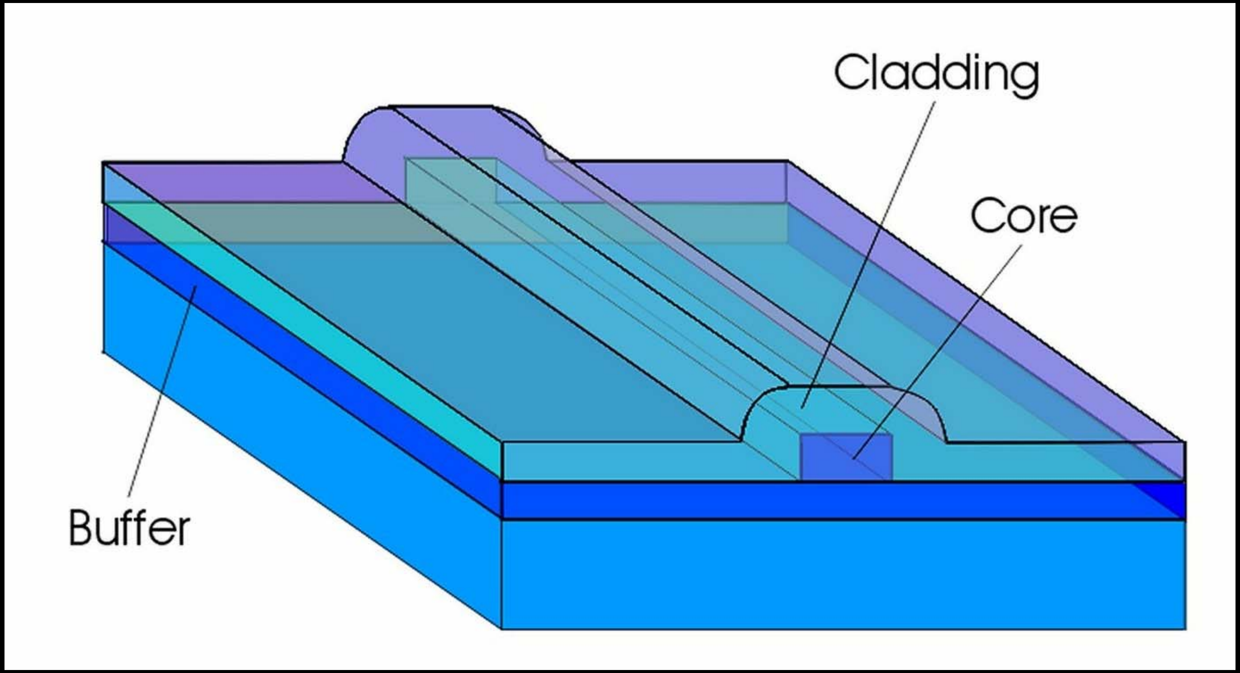
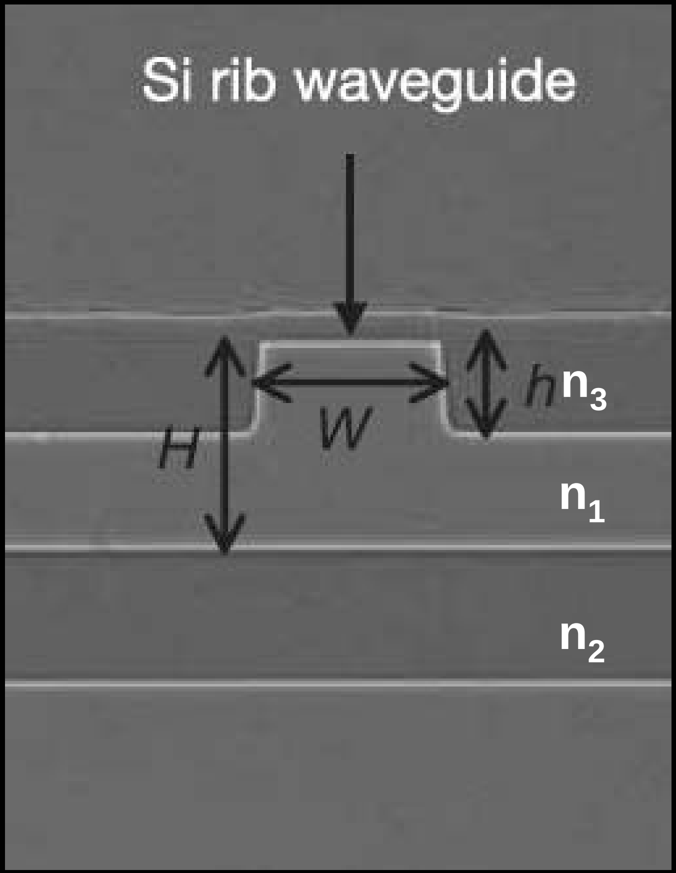
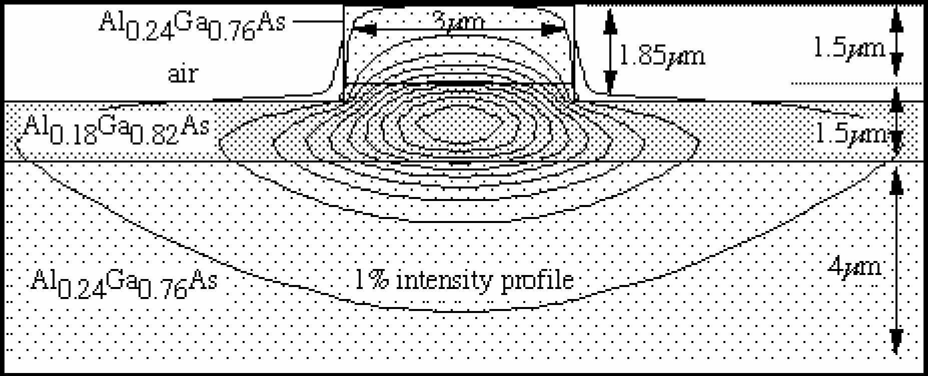
Optical Waveguides

Geometry of a Rib (Ridge) waveguide in planar photonic circuits



Types of Optical Waveguides





- SEM image of a dielectric rib (ridge) waveguide
- The calculated mode profile

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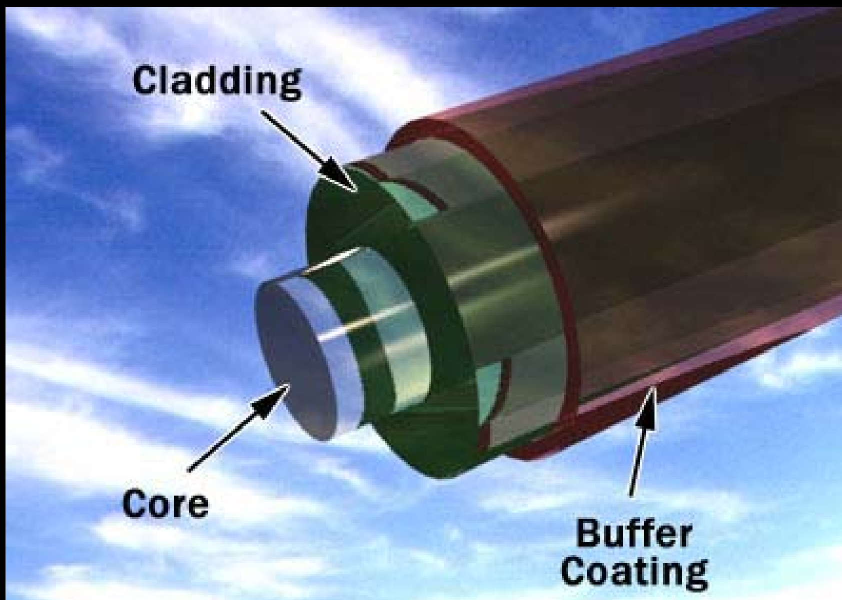
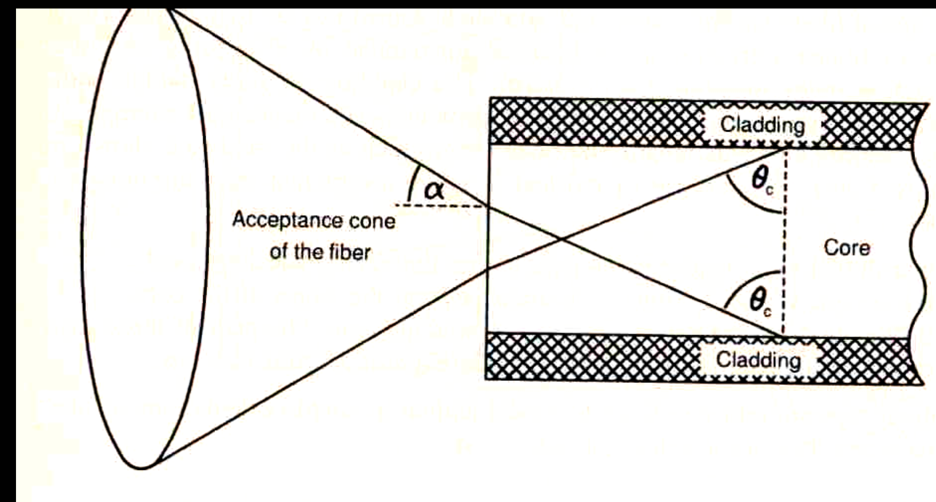
Optical Fiber





- High index core surround by lower index cladding
- The numerical aperture NA

$$NA = (n_{core}^2 - n_{cladding}^2)^{1/2}$$

$$\sin\alpha = \frac{NA}{n_0}$$

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Fiber vs. Cooper Wire

	Fiber	Metalic wire cable
Material	SiOx	Cu
Loss	Low (0.2 dB/km)	High (20dB/km)
Speed	High (> 10 GHz)	Low
Bandwidth	High	Low
Size	Small	Small
Weight	Very light	light
Crosstalk/Interference	Low	High
Cost	Very cheap	Cheap

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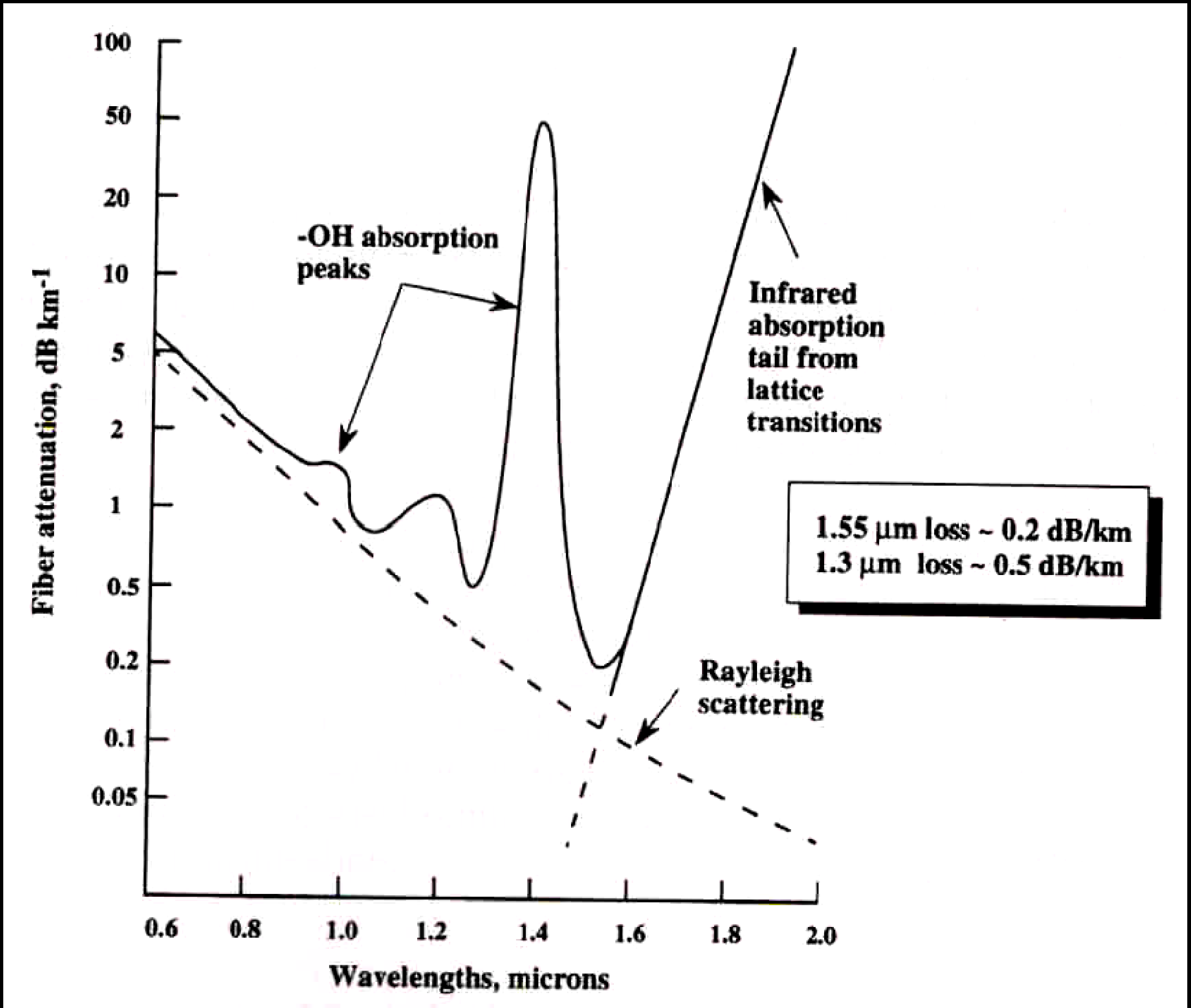
Fiber Loss Spectrum



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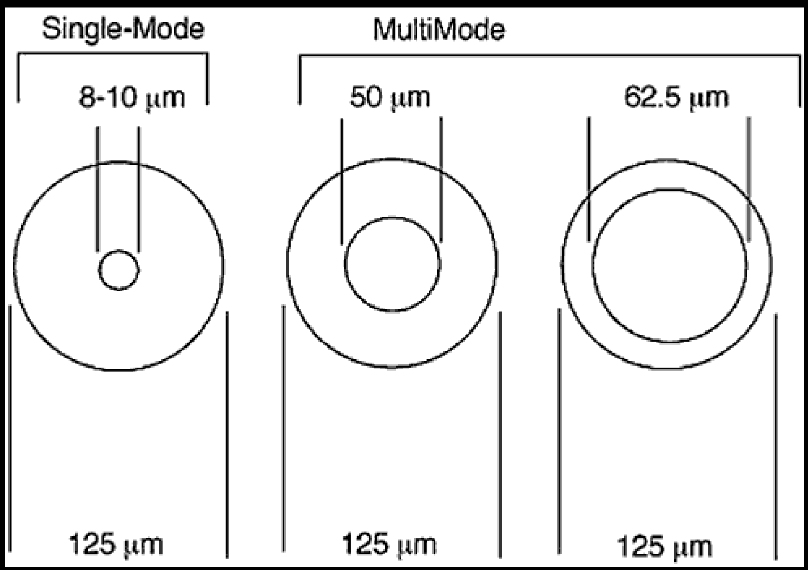
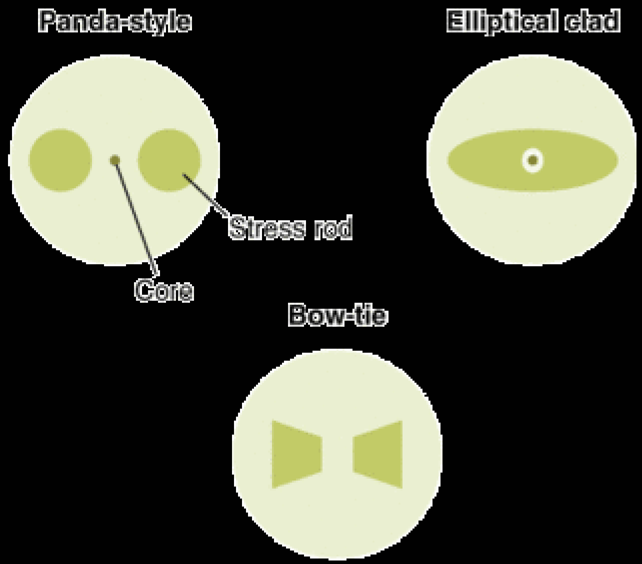
Types of Fiber





- Single-mode fiber (SM): 8-10 μm diameter
- Multi-mode fiber (MM): > 50 μm diameter
- Polarization maintaincede (PM) fiber : special cross section

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Semiconductor Lasers

- Laser types : Gas lasers, solid state lasers and semiconductor lasers
- Why semiconductor lasers for optical communication ???
- Advantages of semiconductor lasers

1. Compact size
2. Low threshold, low power consumption
3. High-speed modulation

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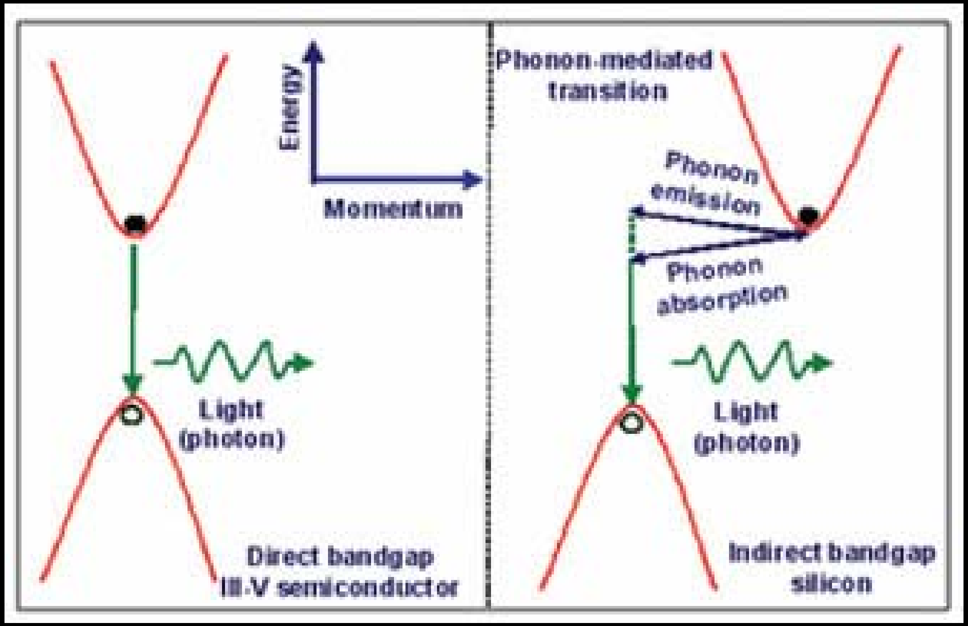
Direct Bandgap vs. Indirect Bandgap



- Energy conservation
- Momentum conservation
- Transition in the indirect band gap will include the phonon process

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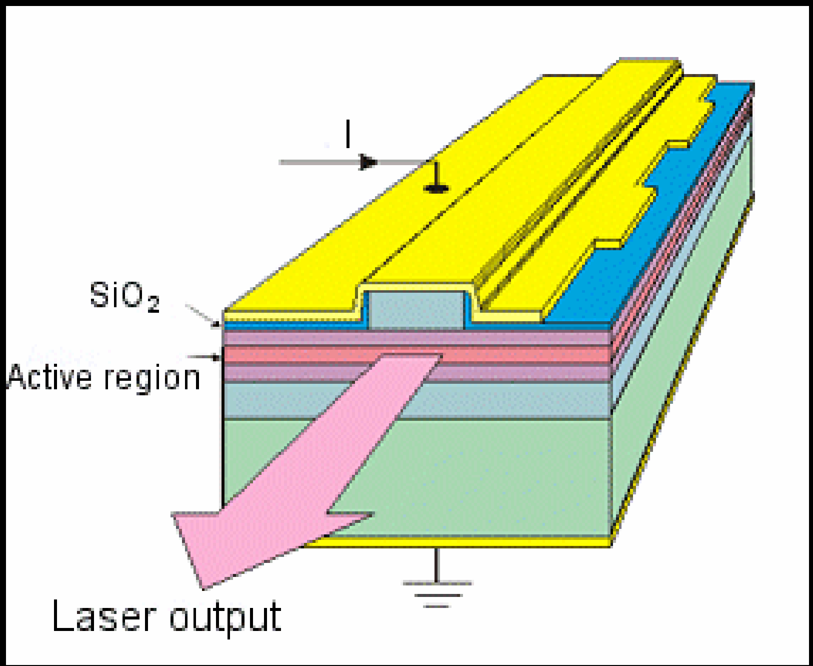
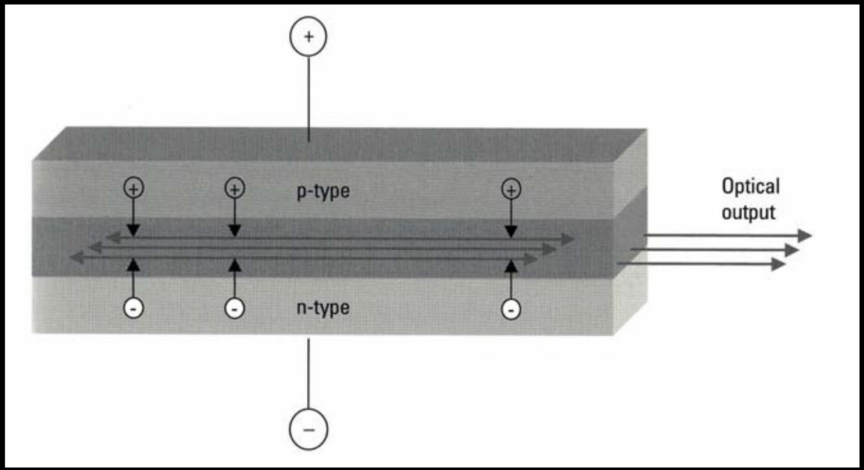
Why Silicon Photonics ?

Materials	III-V materials (InP, GaAs)	Si
Band-gap	Direct	Indirect
Fabrication Technology	Good	Mature
Compatible with electric circuits	OK	Very good
Cost	High	Low

Semiconductor Lasers – Edge-Emitting Laser





- Fabry-Perot cavity introduces the resonant modes for lasers
- Too many modes
- Low cost

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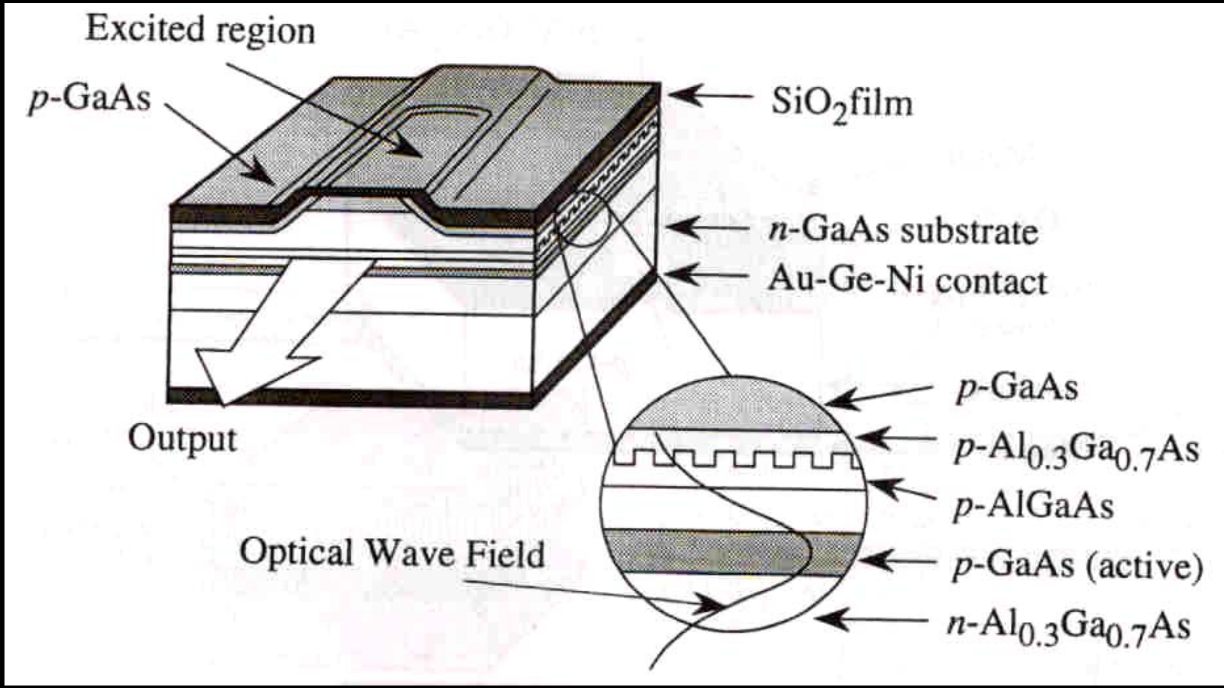
Semiconductor Lasers – DFB Lasers



- Distributed feedback (DFB) laser
- Grating structure embedded in the Fabry-Perot structure
- Grating reduce the No. of modes, and work stable for communication

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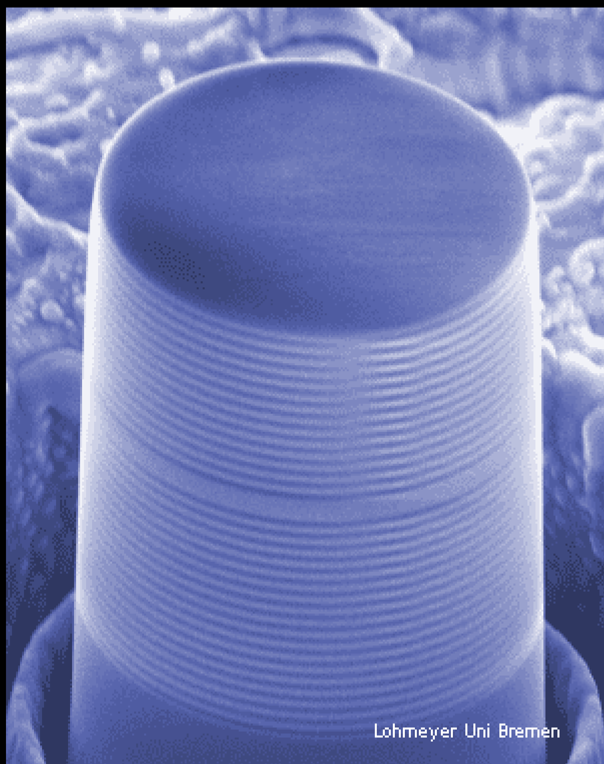
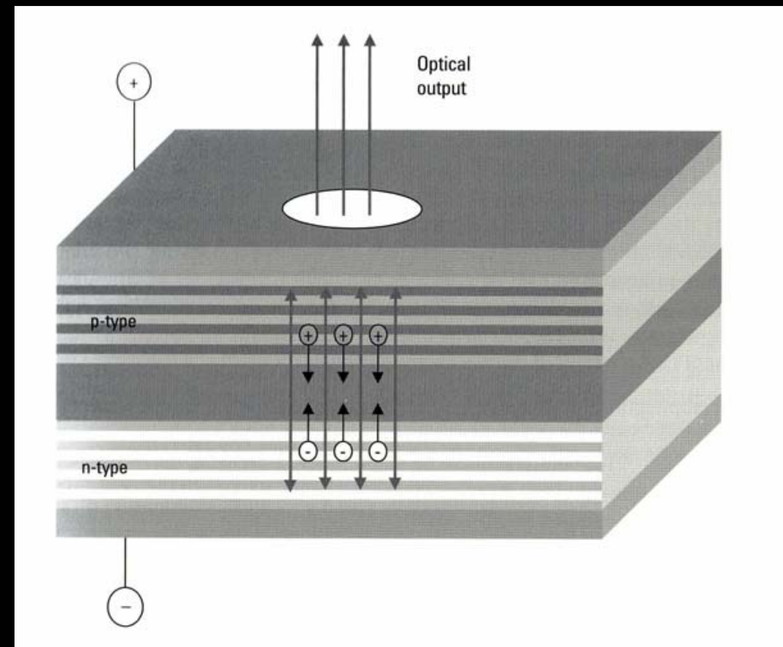
Semiconductor Lasers -- VCSEL





- Vertical cavity surface emitting laser (VCSEL)
- Smaller volume
- Well directly modulated
- Low cost for package

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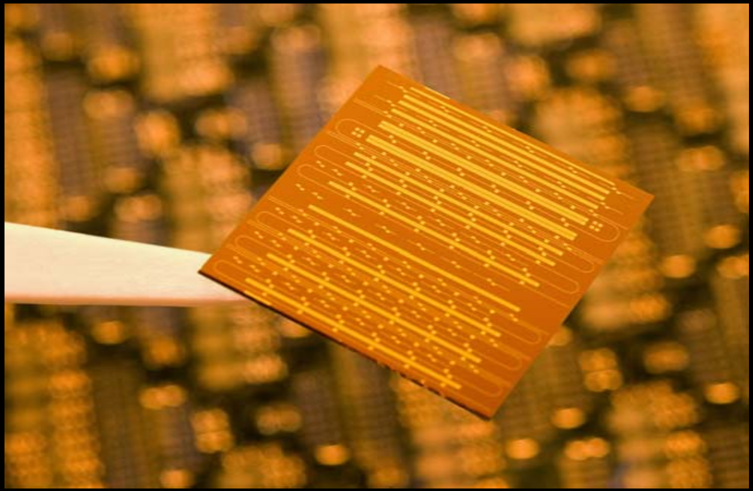
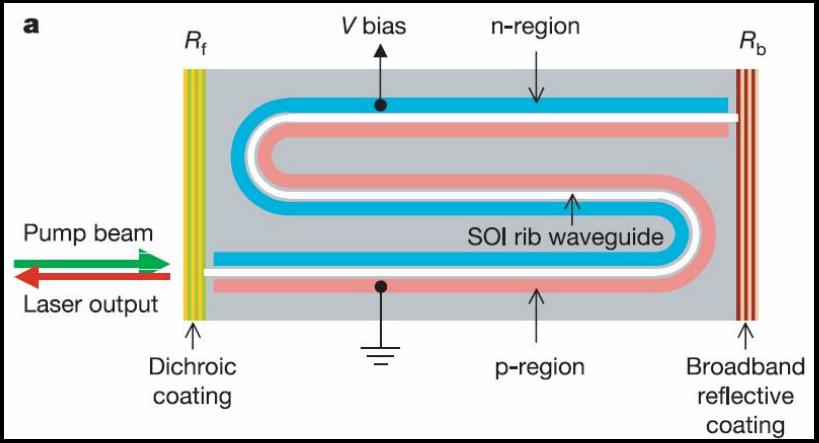
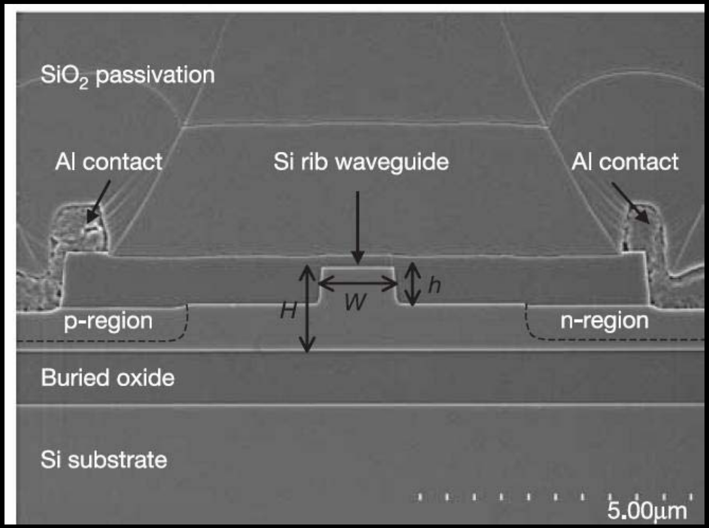
Silicon Raman Lasers



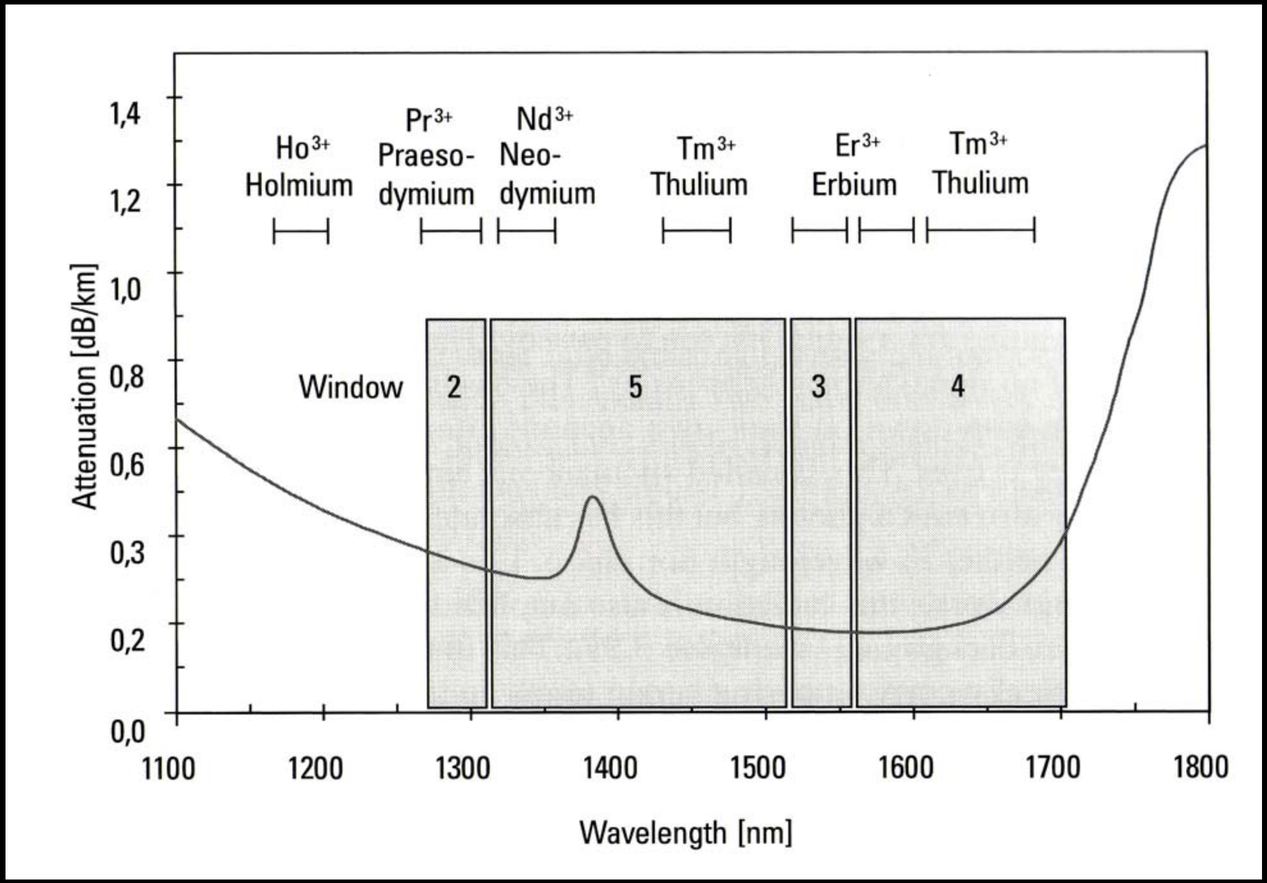




- SOI substrate with a micro-ring diameter =12 µm, height= 250 nm and 200 nm gap
- Use p-i-n structure, doping concentration ~ 1019 cm-3
- Total Q ~ 39000

Nature, vol 433, pp.725 (2005)

Optical Amplifiers - EDFA



Use EDFA(Er^{3+}) for wavelength region of DWDM system

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Optical Amplifiers - EDFA

- Erbium doped fiber amplifier (EDFA)
- Advantages
  1. Cover wide wavelength range
  2. Large total output power (> 1000 mW)
  3. Large dynamic power range
- Disadvantages
  1. Not linear over the working range
  2. Total power keep constant for channels

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Optical Amplifiers - EDFA

Erbium doped fiber amplifiers (EDFA)

	C-Band	L-Band
Wavelength range	1530-1565 nm	1570-1605 nm
Total output power	14-25 dBm	14-25 dBm
Length of active fiber	10-60 m	50-300 m

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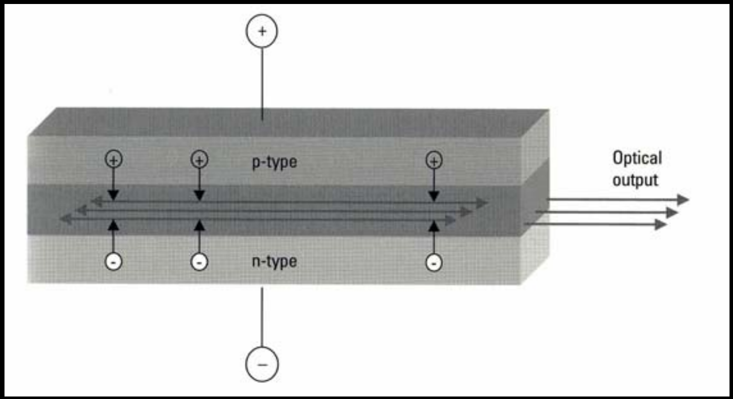
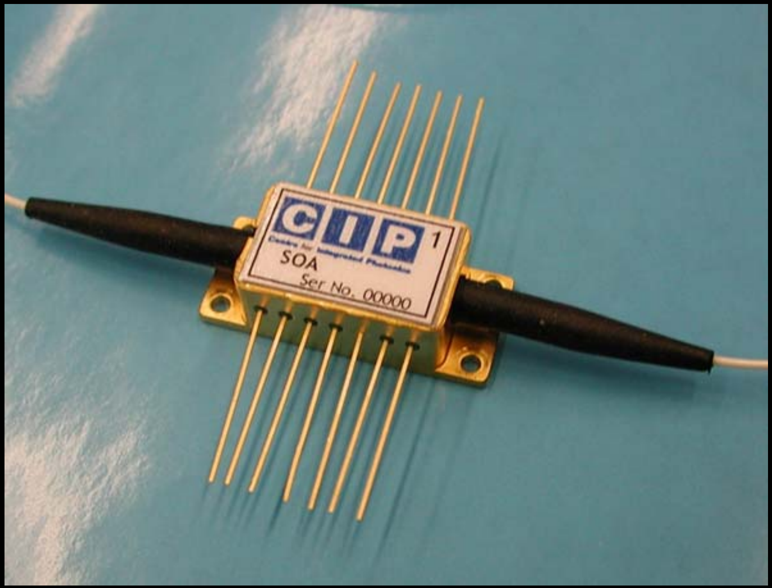
Optical Amplifiers - SOA





- Semiconductor optical amplifier (SOA)
- Advantages
    1. For larger range of wavelength
    2. Easy to integrate to other elements
- Disadvantages
    1. Lower output power(5-10 mW)
    2. Crosstalk influences

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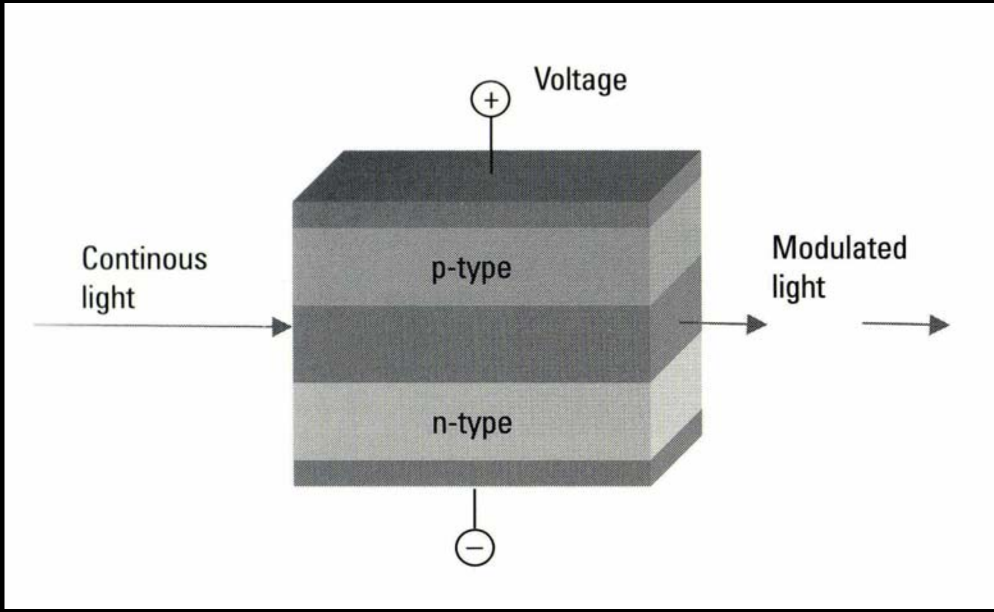
Optical Modulators

- **E-O modulator**
- **Mach-Zehnder modulator**
- **Micro-disk (Micro-ring) resonant Modulator**

Optical Modulators – EO modulator



- Electro-optical (EO) modulator
- Applied voltage to change the phase of propagation field
- KDP(potassium dihydrogen phosphate), LiNO3 and etc.

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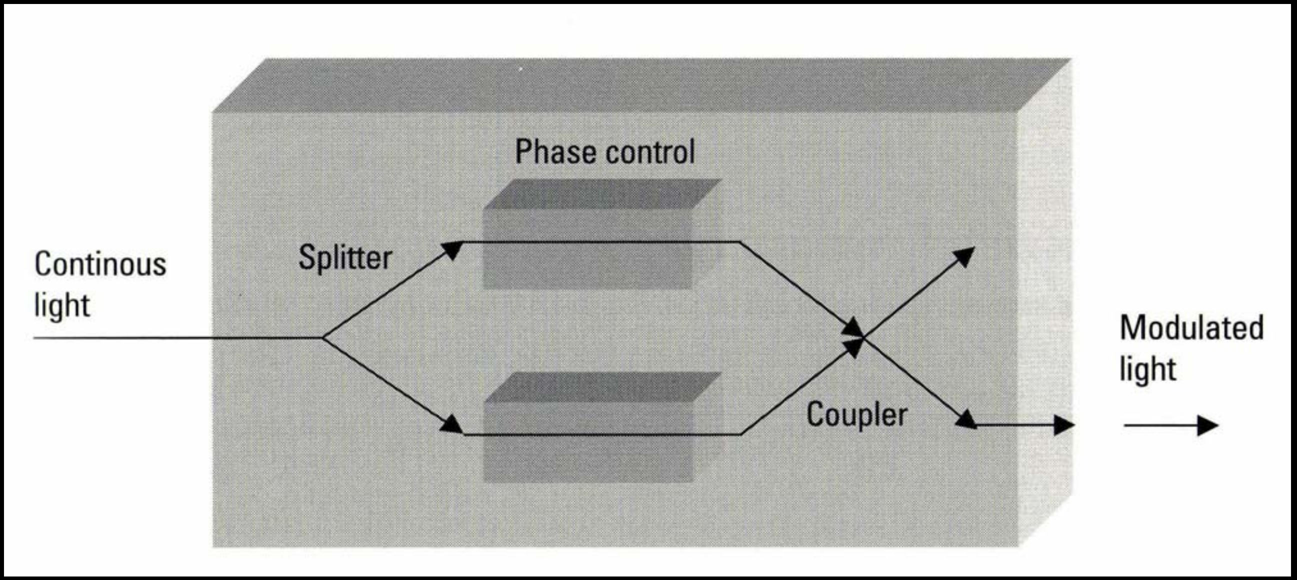
Optical Modulators – MZ modulator



- Mach-Zehnder (MZ) structure for modulator
- Apply voltage to control phase
- $LiNbO_3$, KDP are popular materials

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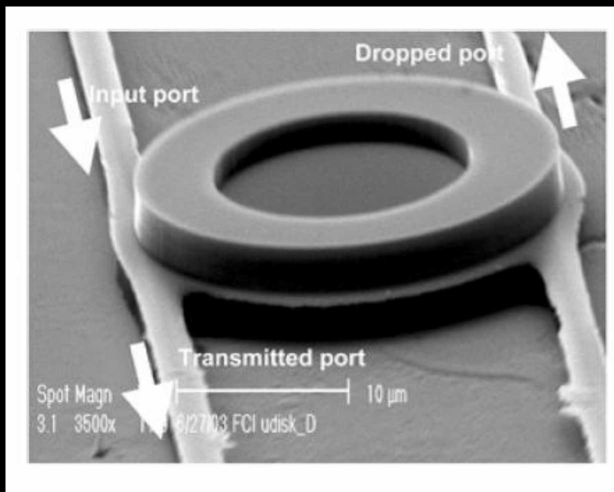
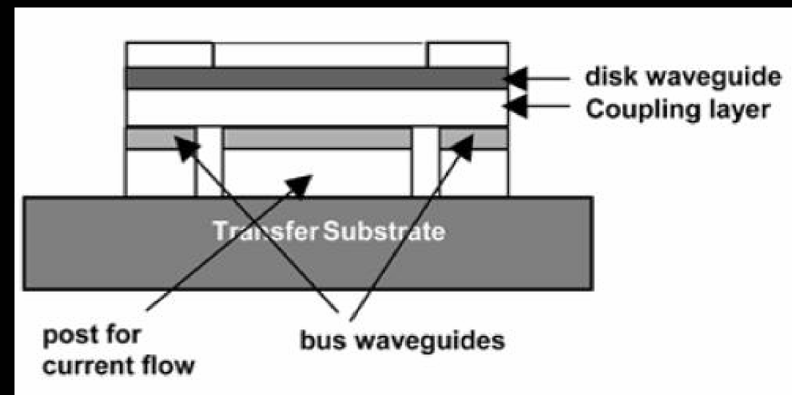
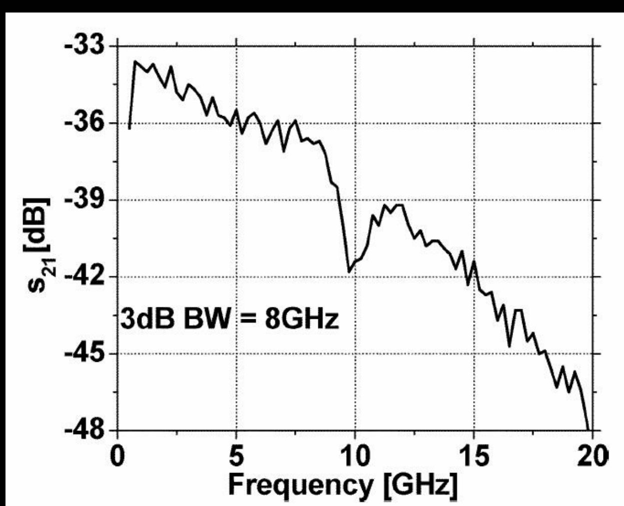
InGaAsP Microdisk Resonant Modulator







- Mico-disk integrated with 2 waveguides
- InGaAsP active layer with a micro-disk diameter ~12 μm, and 800 nm coupling distance
- Operated > 8 GHz

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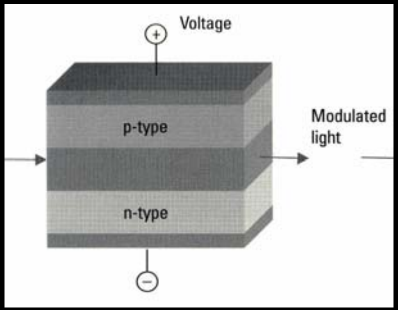
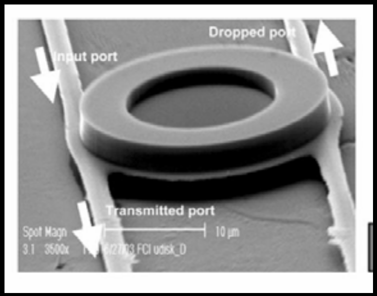
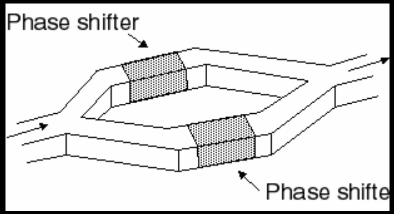
IEEE PTL, vol 17, pp.567 (2005)

Different Types of Optical Modulators







	E-O Modulator	Resonant Microdisk	Mach-Zehnder Structure
Size	Large	Compact	Larger
Speed	> 10 GHz	> 10 GHz	~ 1 GHz
V π	High	Low	Low
Cost	Low	High	Low

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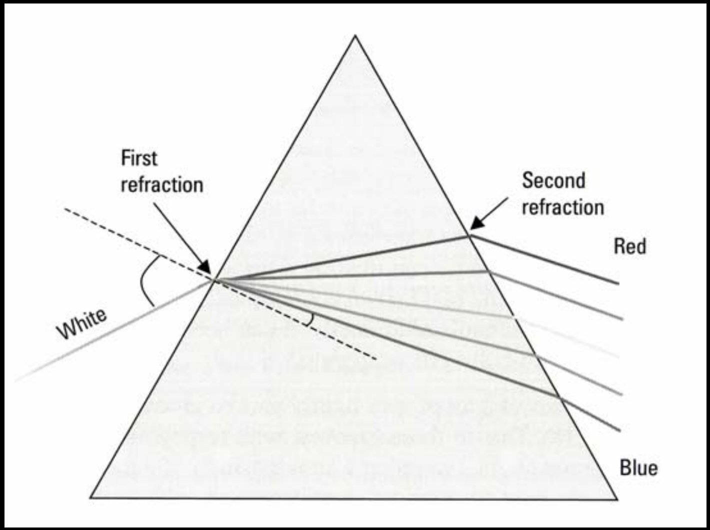
Demultiplexer Elements

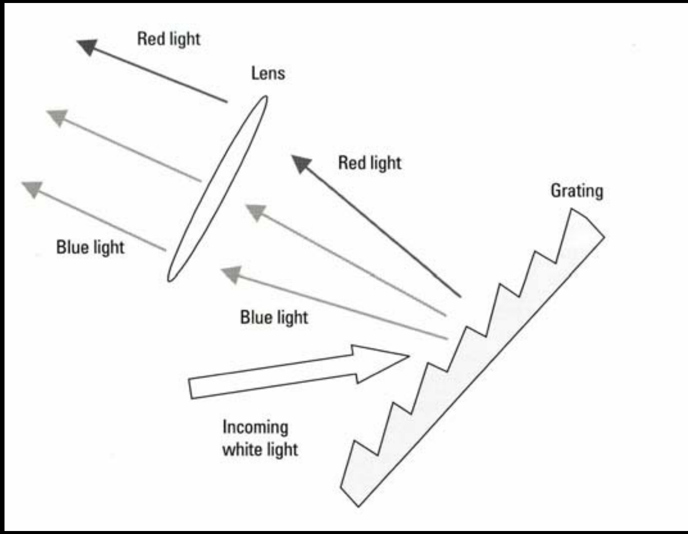
Prism

- Not used in DWDM system



Diffraction Grating

- Reflection light is not homogeneous
- Not used in DWDM system



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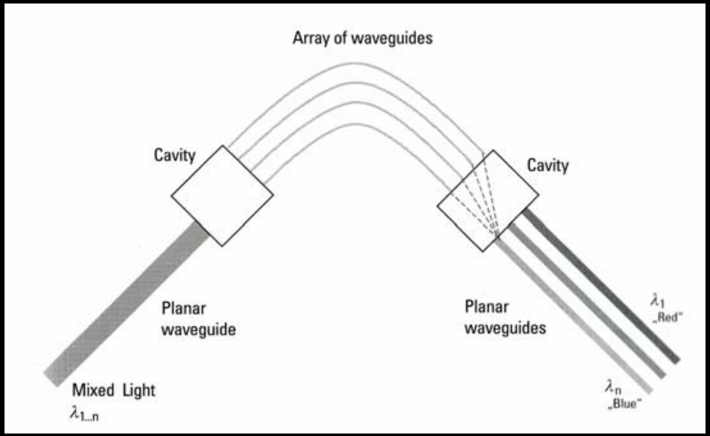
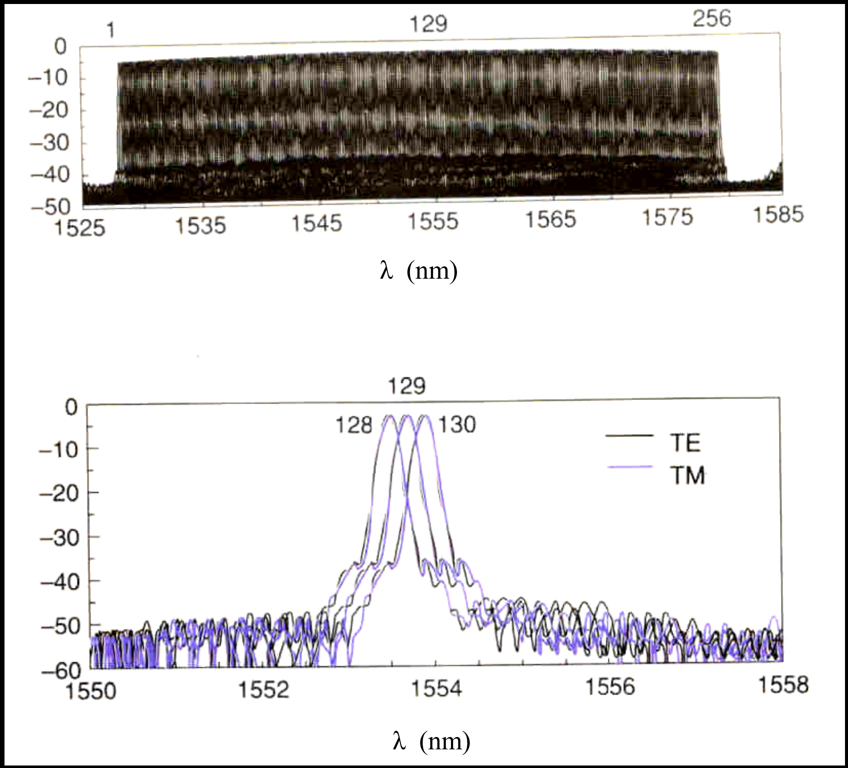
Demultiplexer Elements





<u>Array waveguide grating (AWG)</u>

- Array WGs make phase shift, and different focus in 2nd cavity
- Higher No. of channels (>64)
- Small wavelength spacing
- Temperature dependence & higher cost

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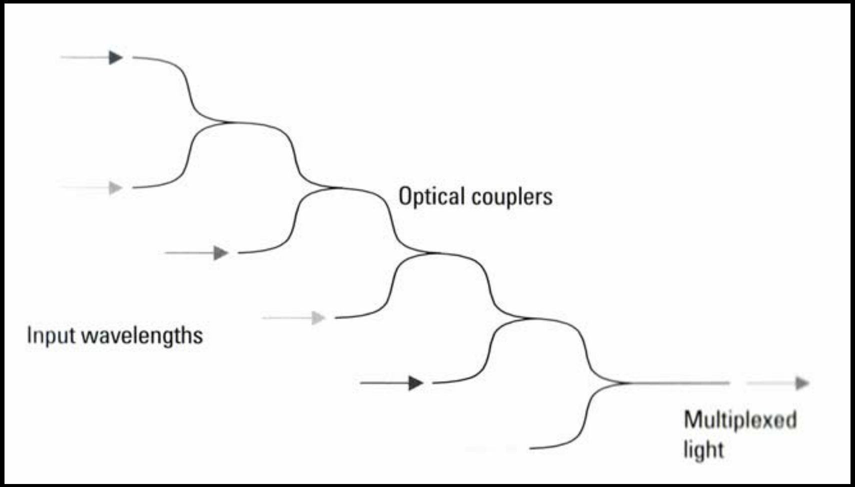
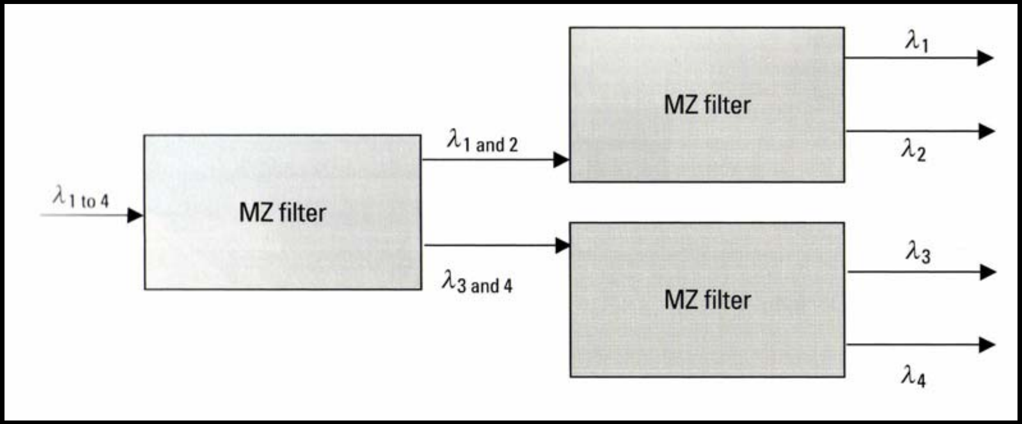
USC

Multiplexer Elements



- <u>Optical couplers</u>

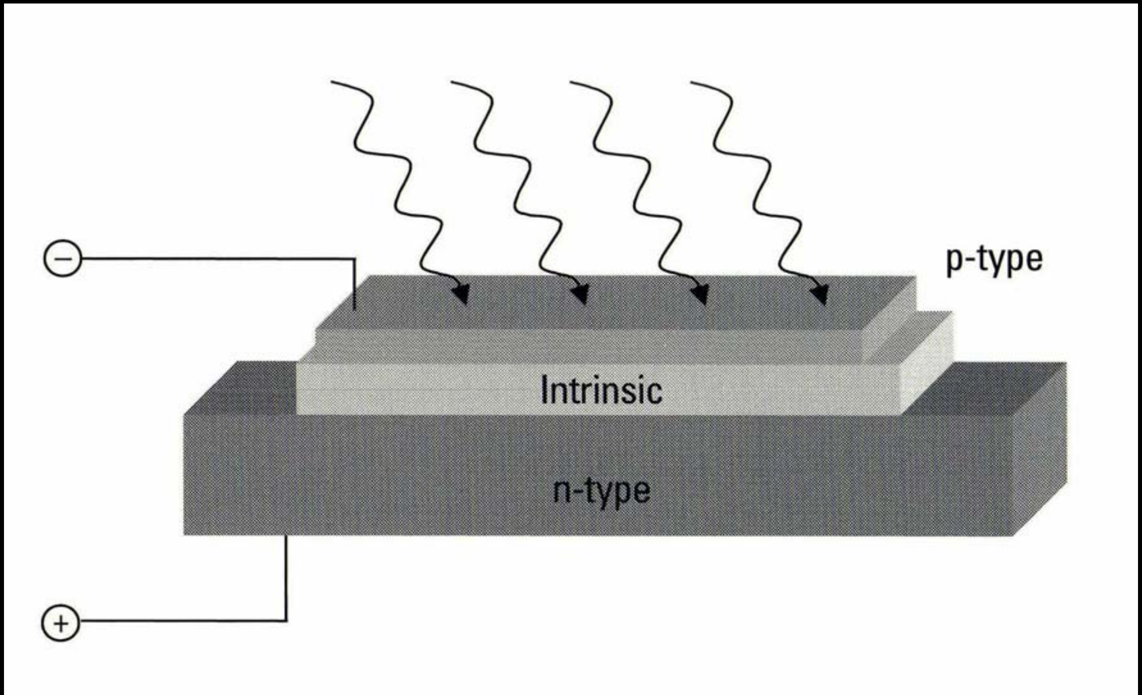
1. Simple, low cost
2. High insertion loss
3. Never be a DeMUX



- <u>Cascaded Mach-Zehnders</u>

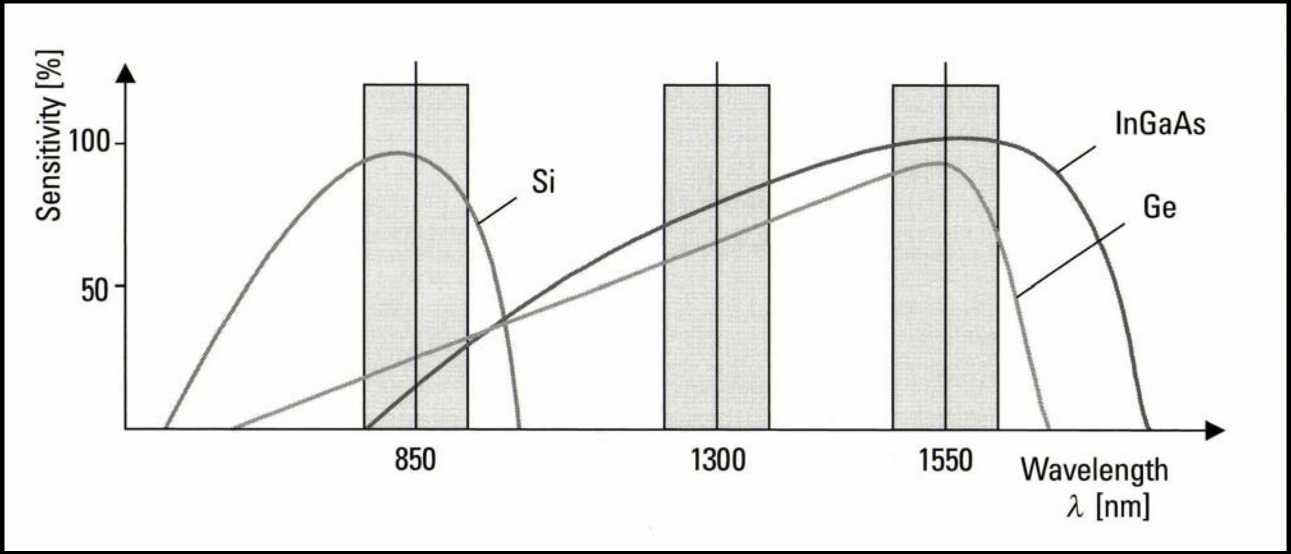
1. Easy integrated
2. Can be MUX/DeMU

Photodectectors in Photonic Circuits



- Transfer optical signals to electrical signals
- The opposite way to lasers

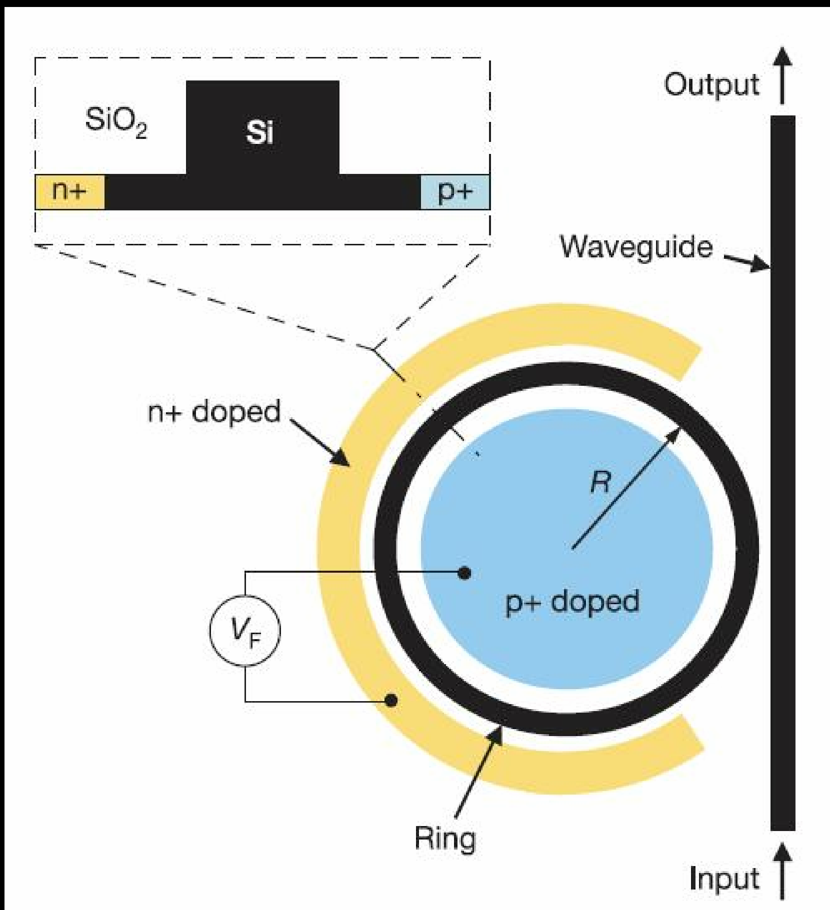
Photodectectors in Photonic Circuits

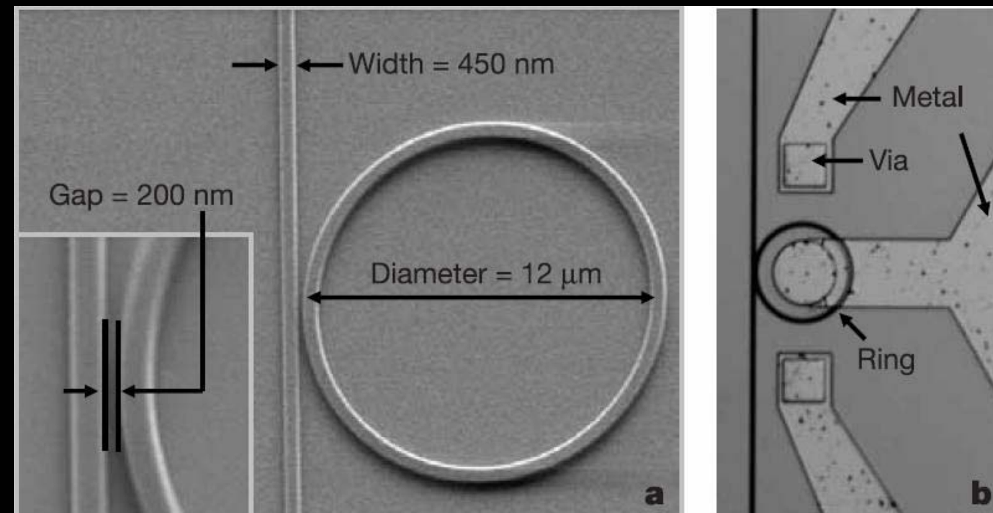


- Spectral response of different detector materials
- For fiber communication (~ λ =1300-1550nm), InGaAs and Ge are prefer materials for photodetectors

End……

SOI Microdisk Resonant Modulator

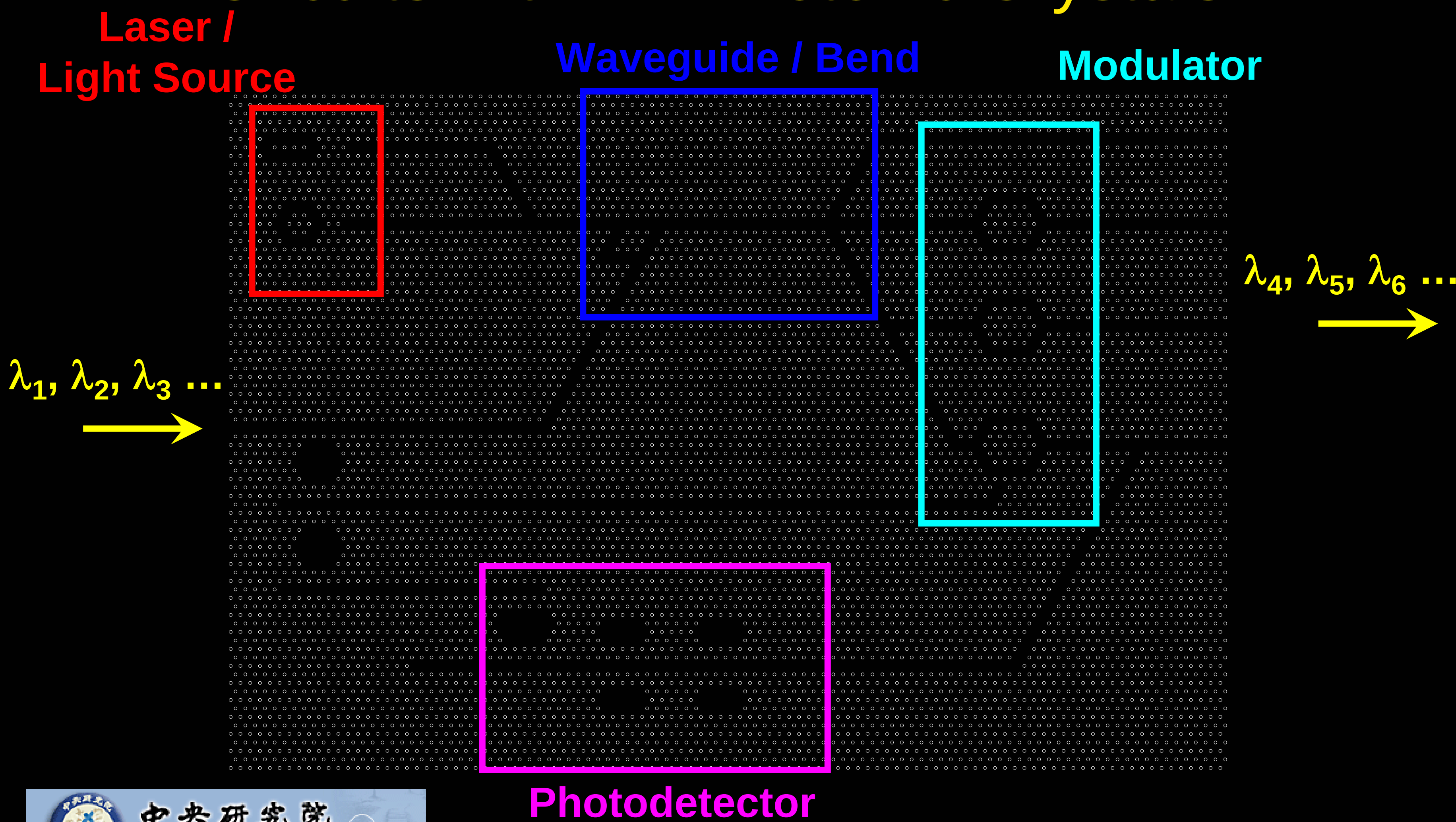




- SOI substrate with a micro-ring diameter =12 μm, height= 250 nm and 200 nm gap
- Use p-i-n structure, doping concentration ~ 10^{19} cm^{-3}
- Can operated at 1.5 GHz

Nature, vol 435, pp.325 (2005)

Building Blocks for Photonic Integrated Circuits with 2D Photonic Crystals



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