ECE 6323

PHOTONIC DEVICES AND MODULES

Outline

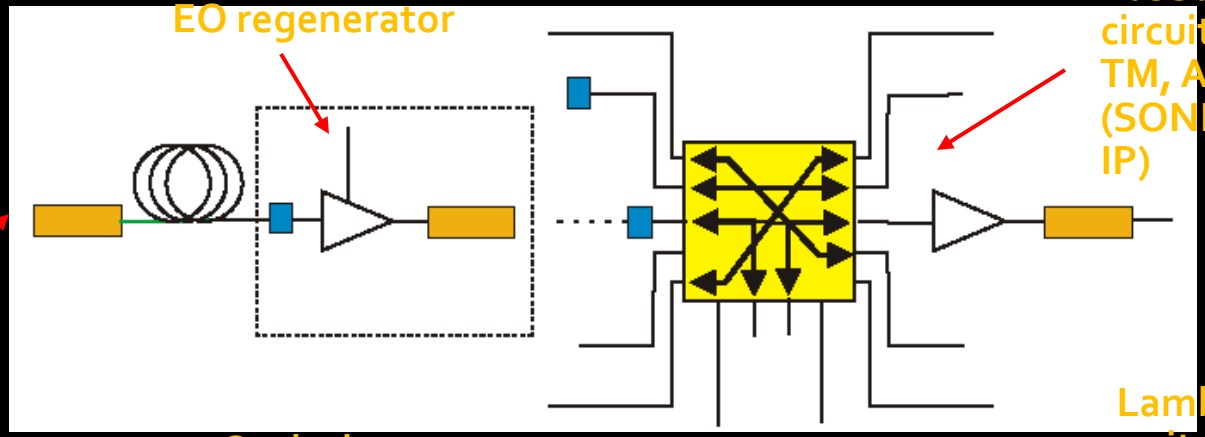
- Introduction and concepts
- Types of devices
  - Passive splitters, combiners, couplers
  - Wavelength-based devices for DWDM
  - Modulator/demodulator (amplitude and phase), compensator (dispersion)
  - Others: switch, high-functional modules, photonic integrated circuits (PIC)
- Summary

Introduction

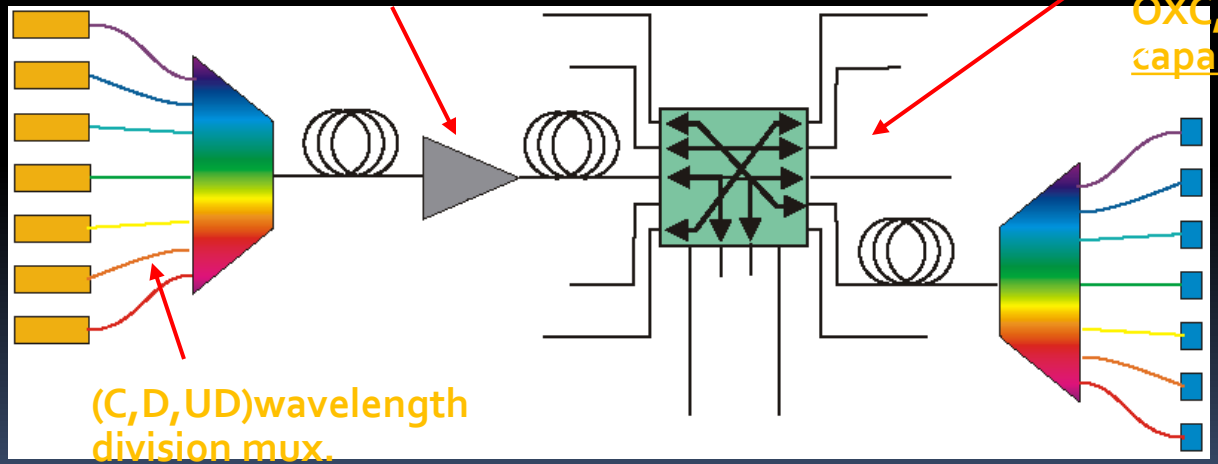
- What uses are of photonic devices and circuits?
- The new (DWDM) vs. the old optical communication

Old vs. new optical network

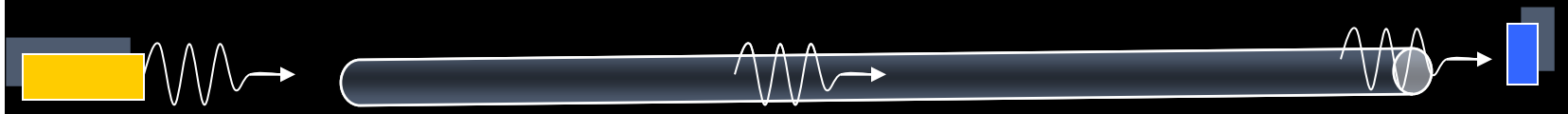
Old

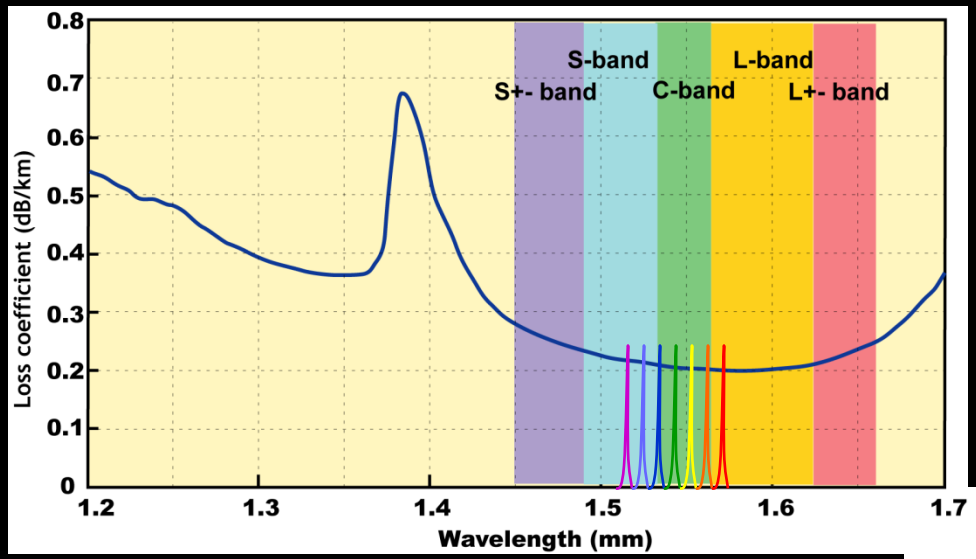


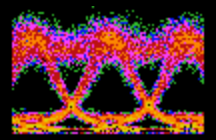
New

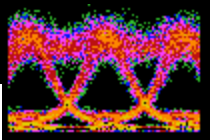


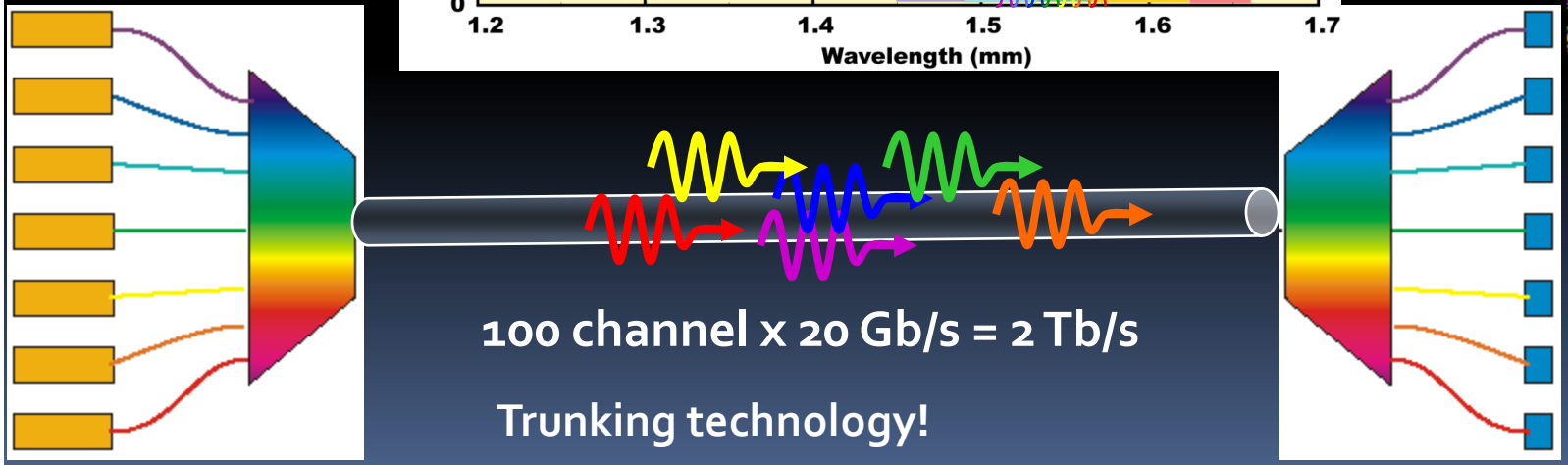
DWDM & OA for trunking









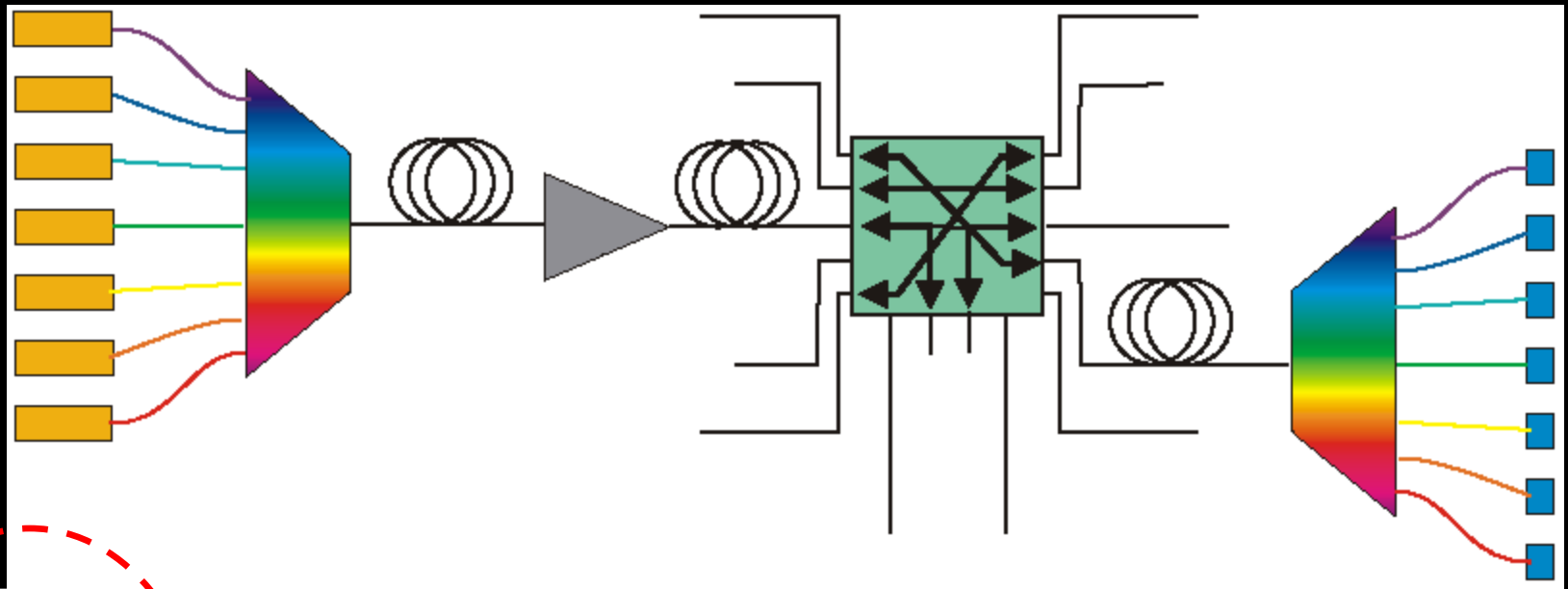


100 channel x 20 Gb/s = 2 Tb/s

Trunking technology!

The enabling technology…

Optical/DWDM networking technology



Transmitter

- Laser
  - -DFB, DBR, VCSEL
  - -Tunable, fiber
- Modulator
  - -Electro-optic
  - -Electroab-sorption

WDMux

- TF filters
- Fiber Bragg G
- Array wave-guide grating
- Diffraction G
- Other gratings

Fiber

- Convent. fiber
- DSF, NZDSF
- Improved fiber

Optical amplifier

- Erbium-doped Fib. Amp (EDFA)
- Semicond. (SOA)
- Others (Raman)

Optical switch

- Path switch
- Add/Drop mux
- λ-router
- Cross connect
- Couplers
- circulators

Receiver

- Ultrafast PD

Introduction

- What uses are of photonic devices and circuits?
- More than just being transmitted and received, light signals need processing:
  - Signal combining, splitting
  - Controlling of wavelength, amplitude, phase
  - Switched
  - Other processing (e. g. 3R, 4R)
- Photonic devices and circuits enable the processing of light signals

Knowing what it does (more important than how it works)

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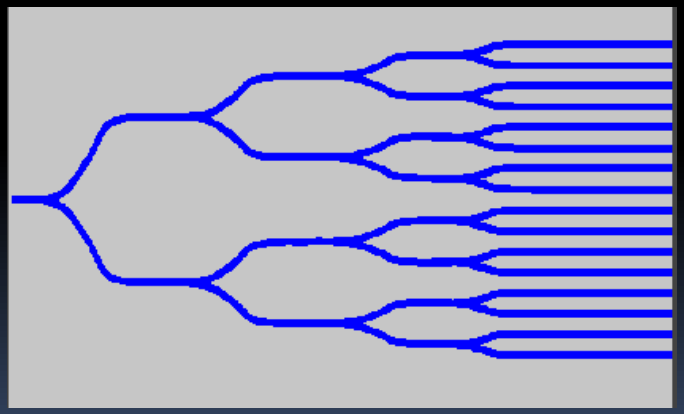
- Summary

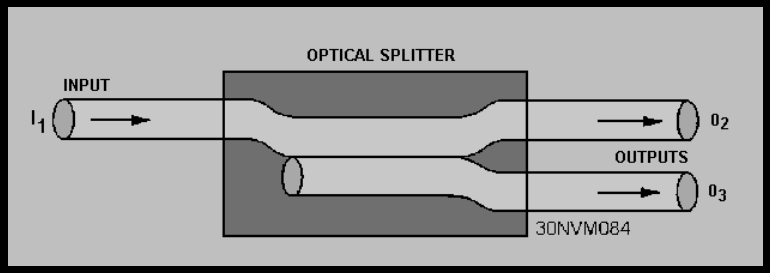
Passive splitters/combiners (non-filtering)

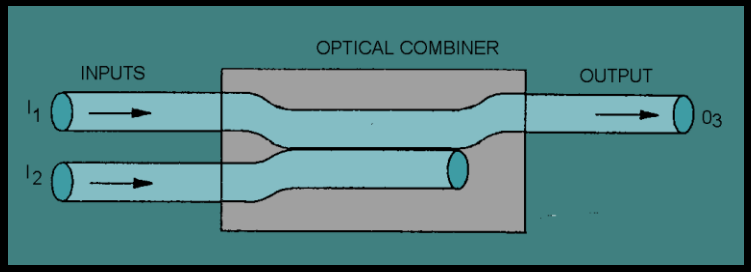
- The simplest among devices: just split a signal into many channels: lower power (1/N), but same everything else. Reverse for the combiner.
- Can be done with fibers or on a planar waveguide



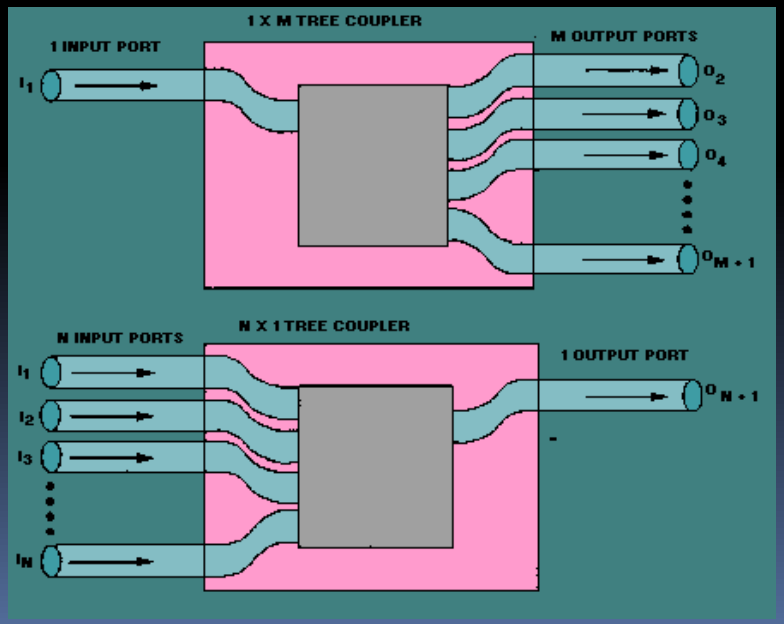
Splitter/combiner/coupler

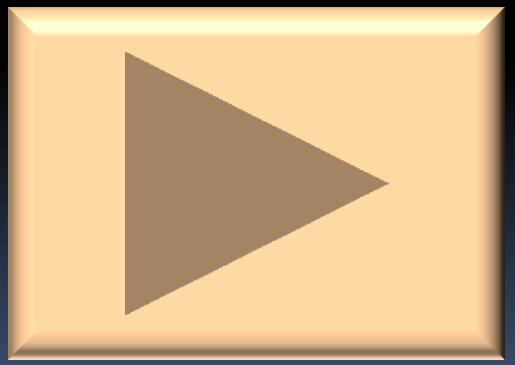
Simplest 1-2 or 2-1 coupler





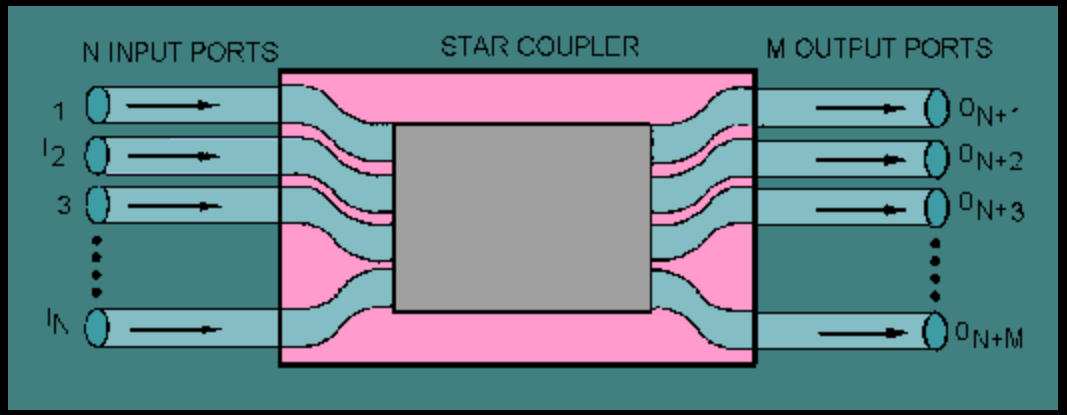
Coupler – 1 x N or Nx1



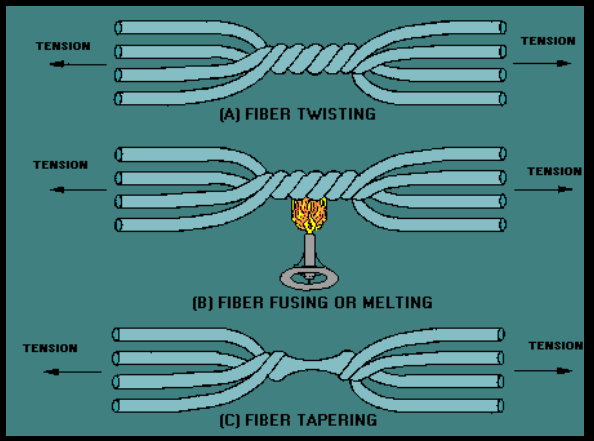


Splitter/combiner/coupler

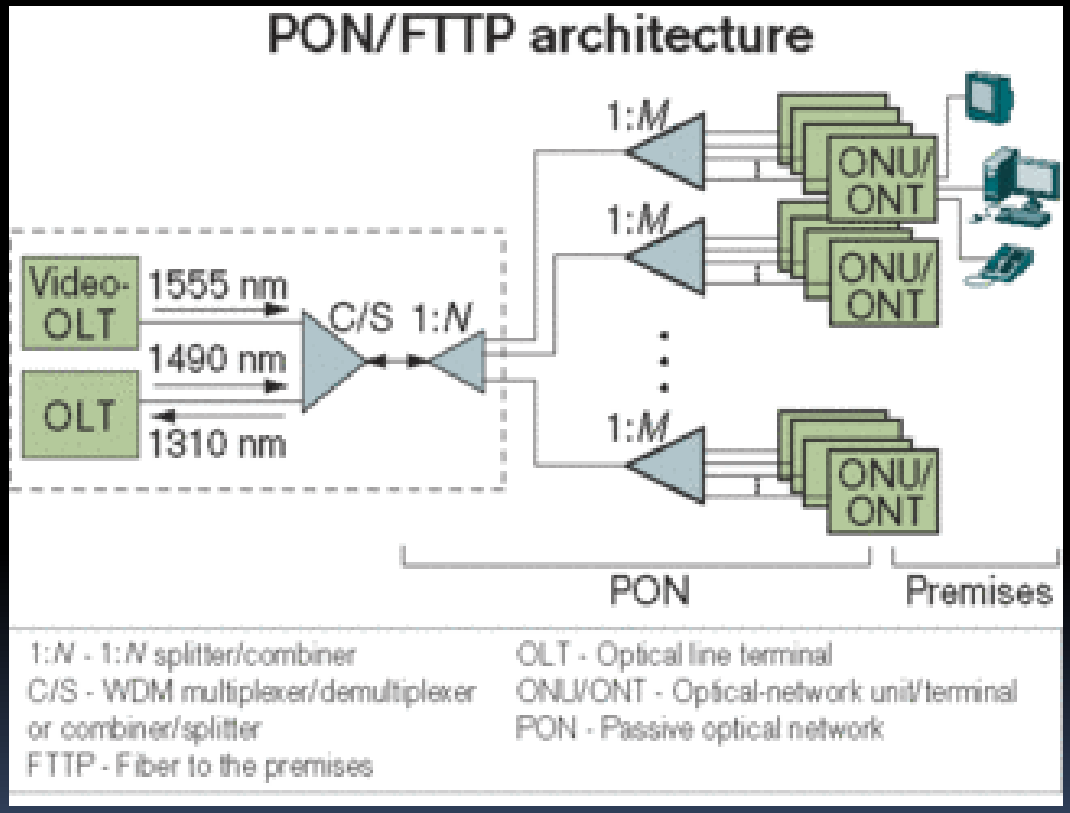
Star coupler – N x M



Fiber star coupler – N x M



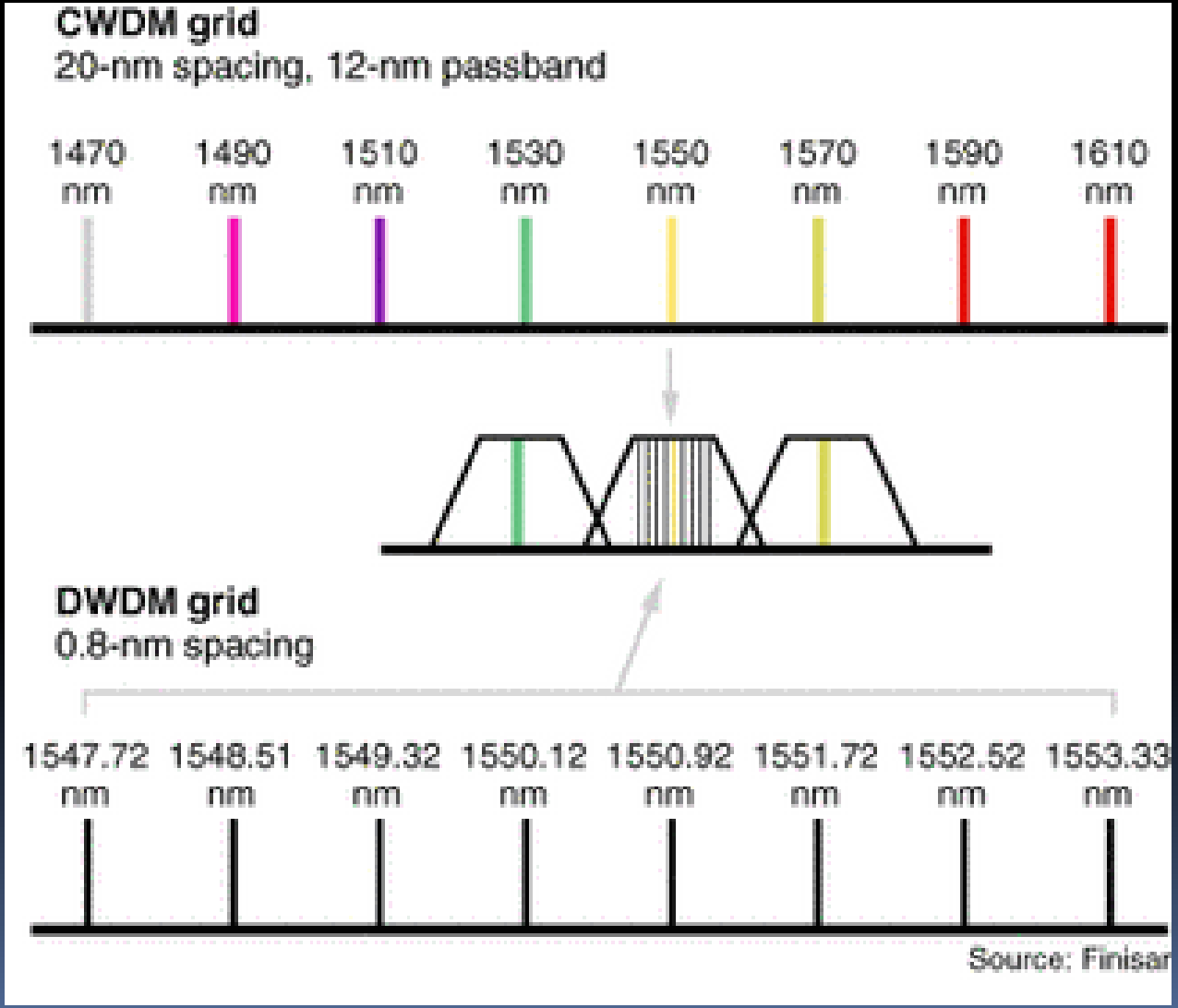
Example applications of passive s/c



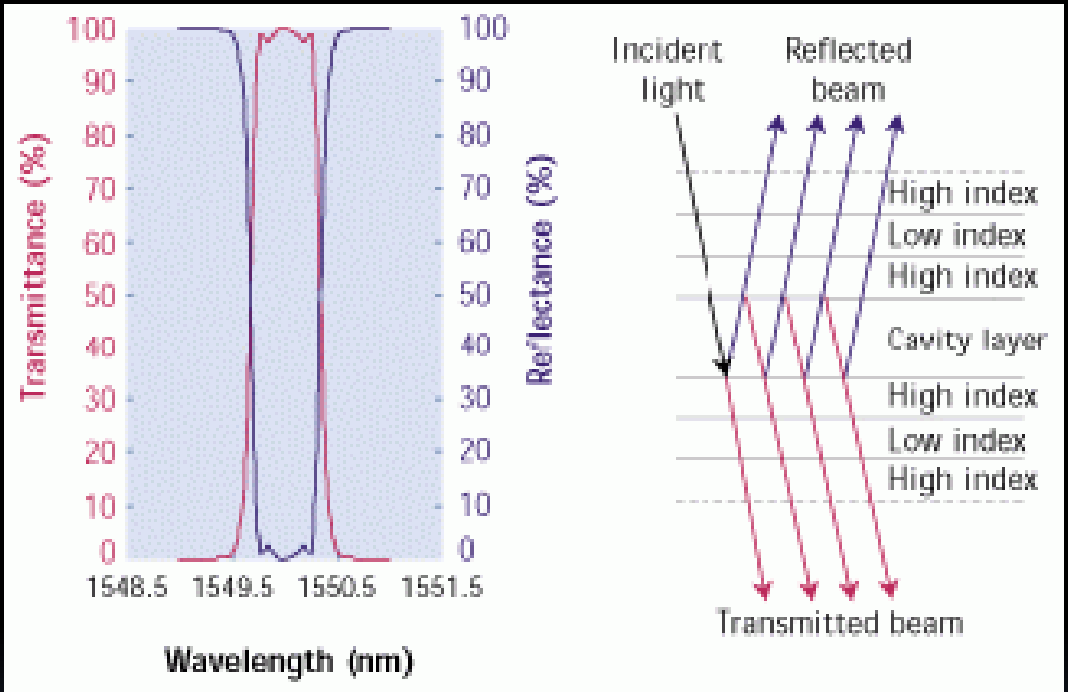
Wavelength-based devices for DWDM

- Functional concepts:
  - Basic: filtering: select/separate one wavelength or a wavelength range from the rest
  - More general concept: Wavelength division multiplexing/demultiplexing: separate or combine many wavelength channels into
- Devices:
  - Thin-film interference filter
  - Grating: planar, array waveguide, Bragg
  - Wavelength-division coupler (mux/demux)

Example of applications



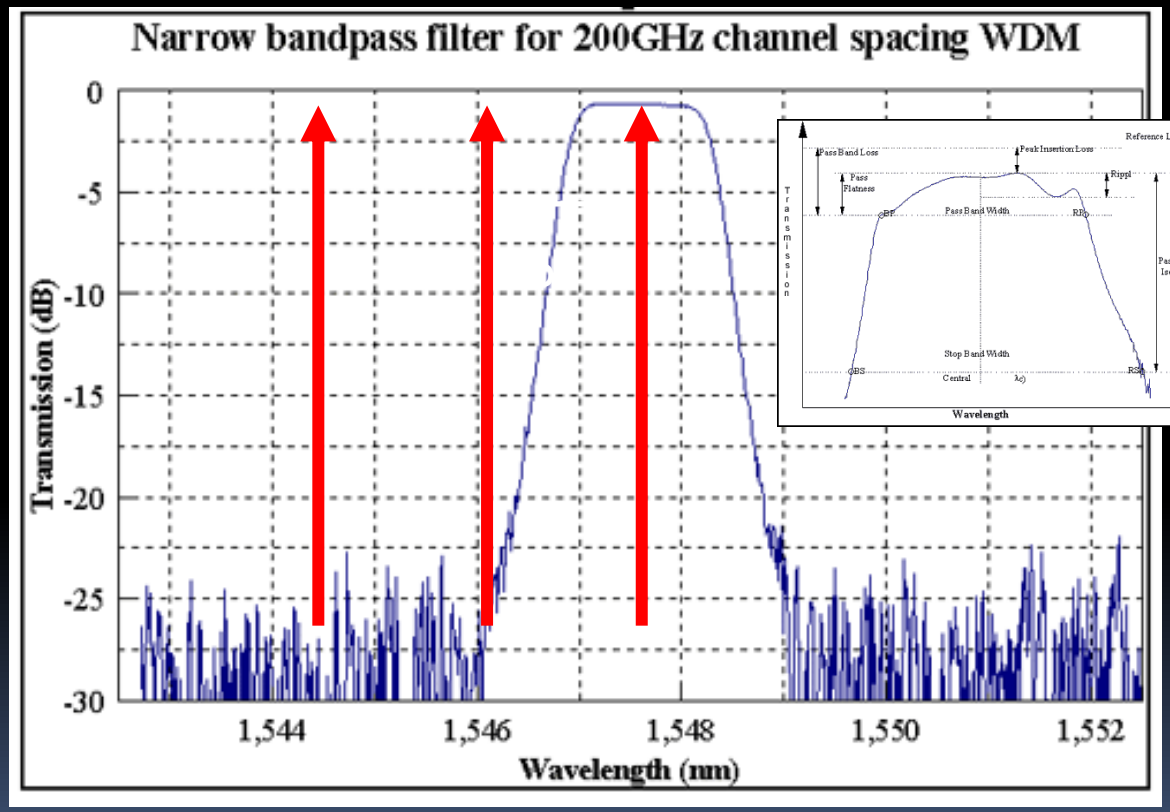
Thin-film interference filter



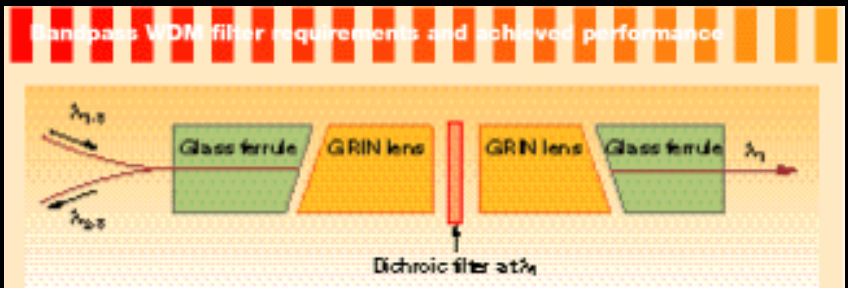
- Principle of Fabry-Perot cavity (similar to laser)
- Very thin film, short cavity ~$\lambda/2$, λ, $3\lambda/2$ …
- Multiple-coupled cavities, from 3 to 7 or more

Thin film filter for WDM

- Plasma assisted deposition (covalent-like bonding instead of Van der Walls)
- 90 to 150 layers, 3 to 7 cavities
- Advanced in-situ monitoring



Thin-film interference filter applications



Bandpass WDM filter and the requirements of a DWDM system show that a hybrid device can satisfy the requirements of 0.4-nm channel spacing DWDM devices.

SPECIFICATIONS	REQUIRED	ACHIEVED
Peak insertion loss	< 0.5 dB	0.3 dB
Passband ripple	< 0.3 dB	0.15 dB
Passband bandwidth	> 1.0 nm	1.2 nm
Bandwidth at -25 dB	< 3.0 nm	2.9 nm
Wavelength thermal shift	< 0.003 nm/°C	0.0008 nm/°C
PDL	< 0.1 dB	< 0.05 dB

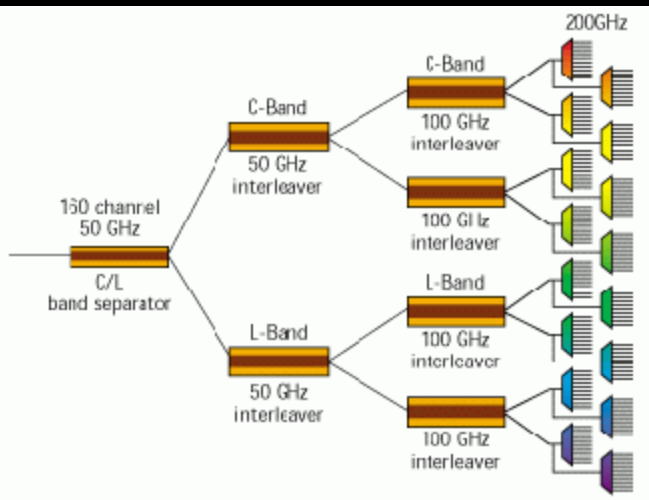
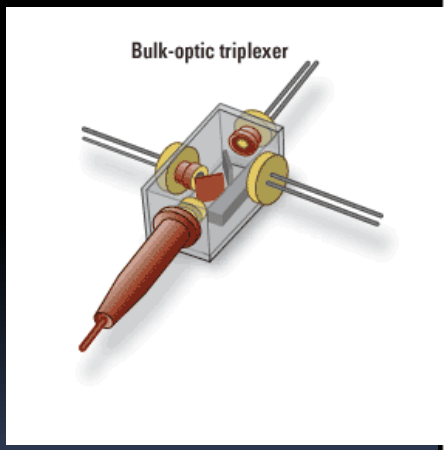
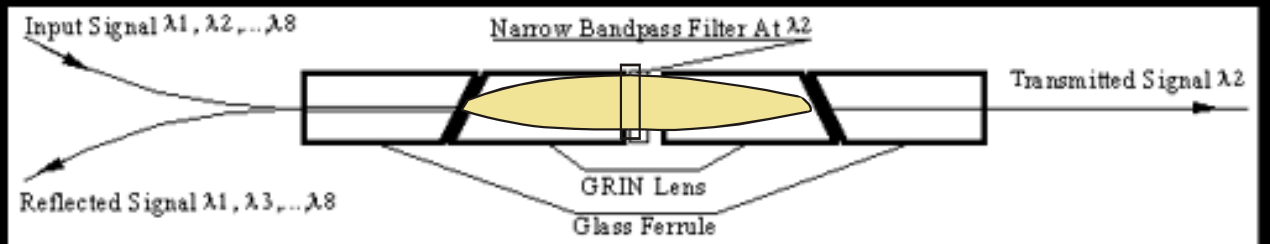


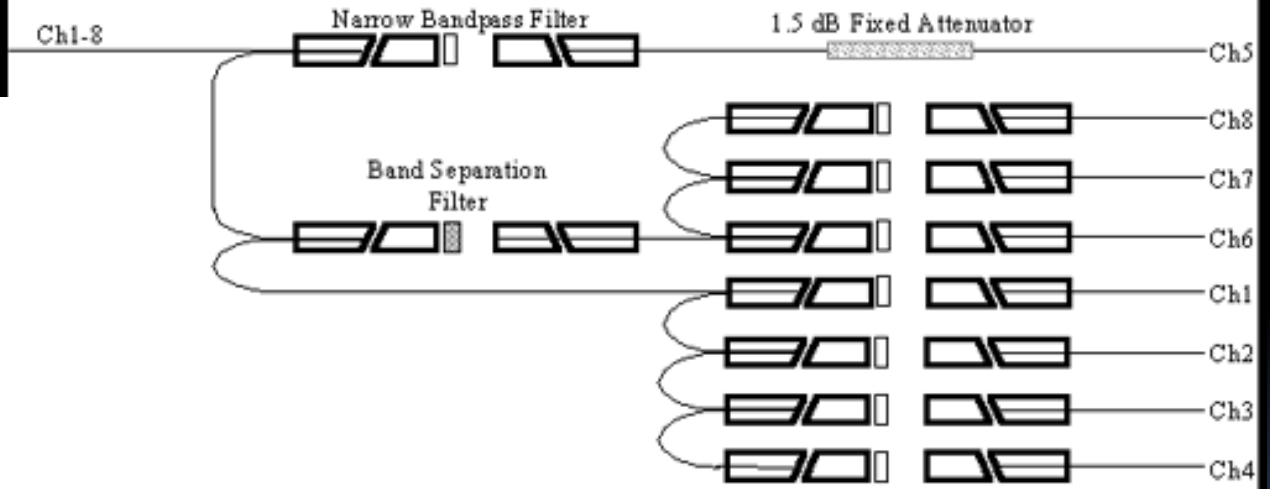
FIGURE 4. Interleavers separate densely spaced, multiple channels into channels spaced further apart, thus allowing a series of relatively inexpensive thin-film filter devices to process signals.

WDM channel filter



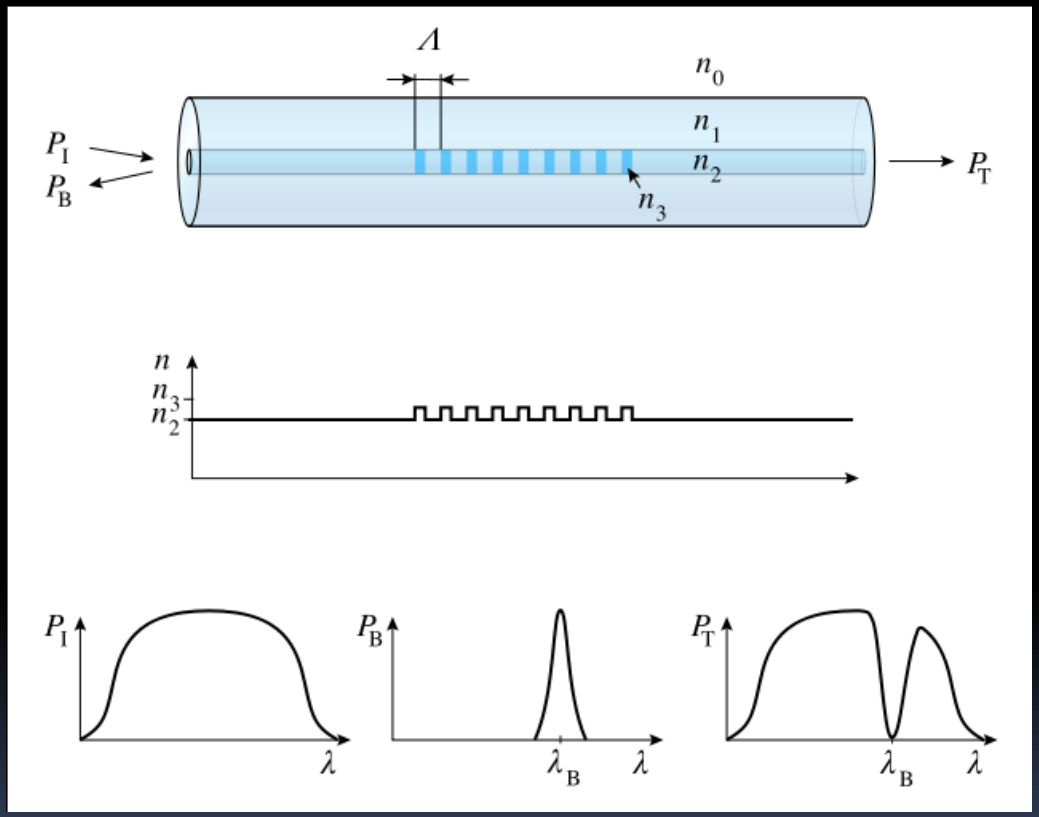


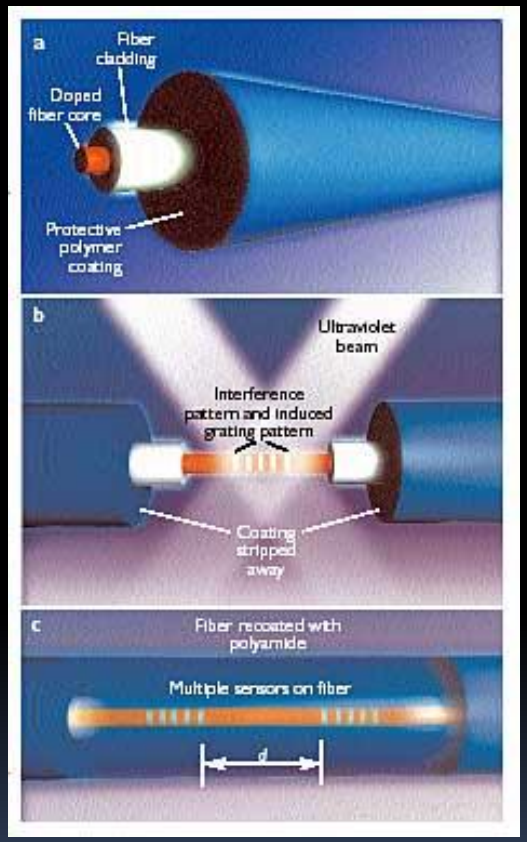
(a). Structure of a WDM unit by narrow bandpass filter.



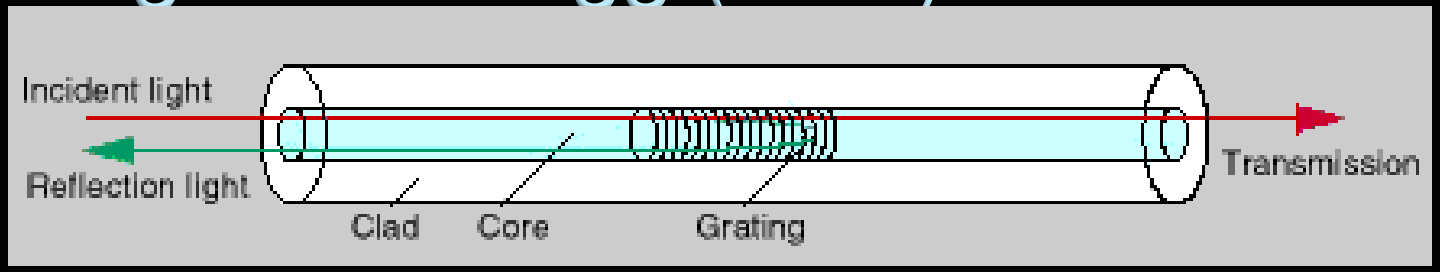
(b). Configuration of an eight channel WDM.

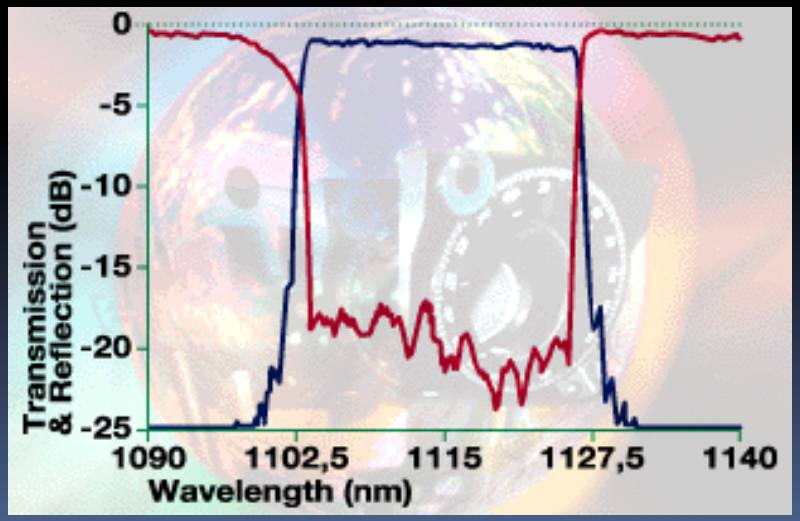
Grating: fiber Bragg (FBG)





Grating: fiber Bragg (FBG)

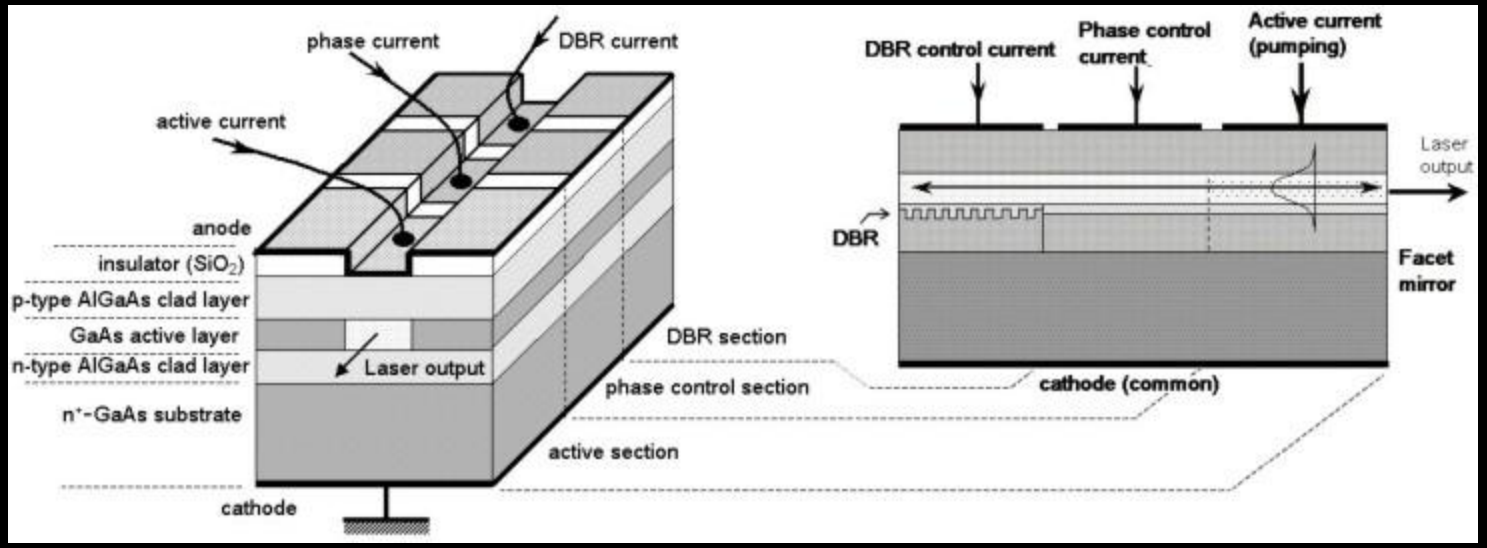




FBG: Use in numerous apps: WDM coupler, disp. comp., sensors

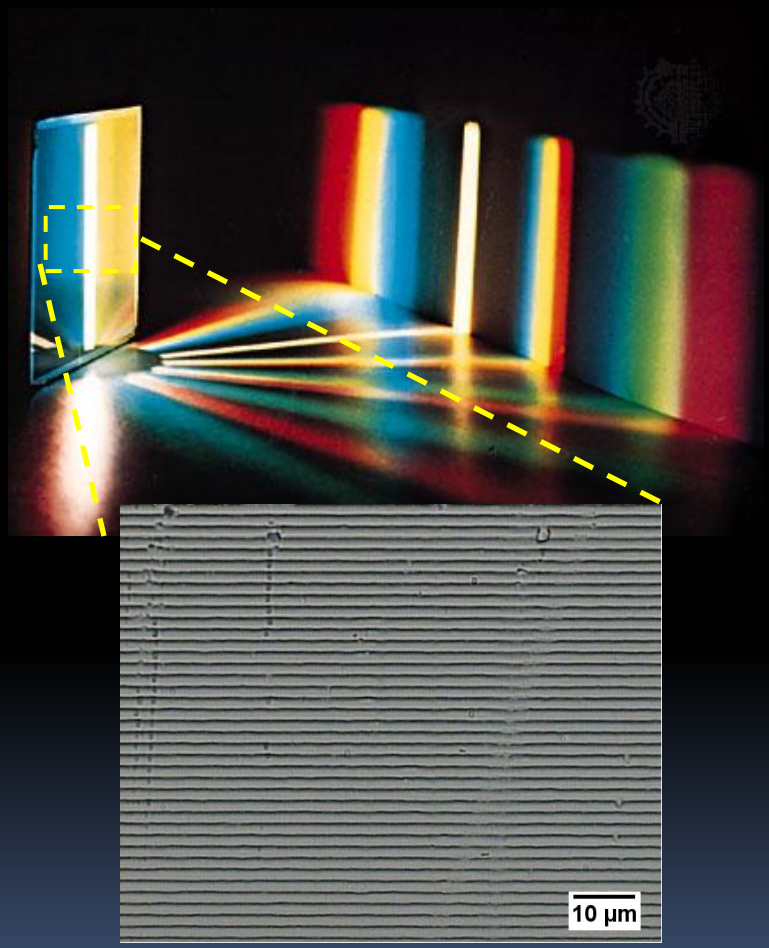
Source: NEL, Infibers

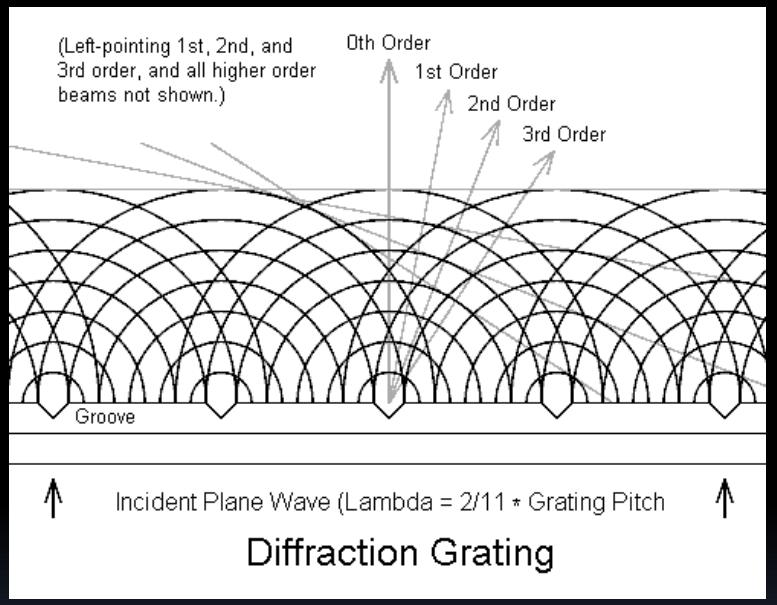
Review: Other applications of Bragg grating



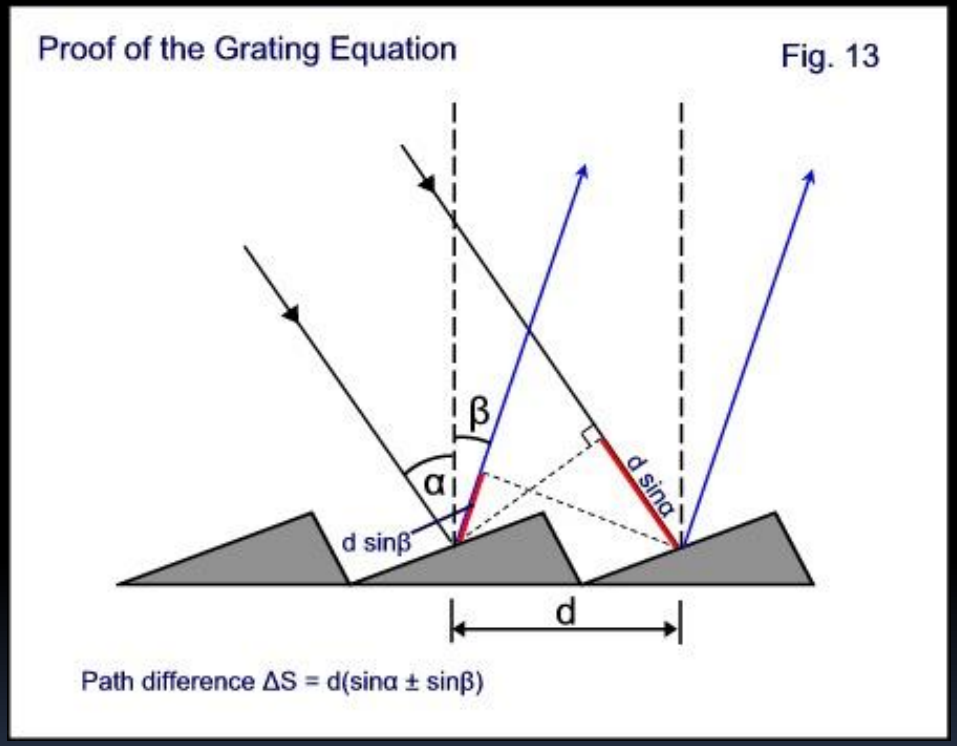
- Also with integrated Bragg grating (BG) BUT different from DFB: DBR is used as a narrow band mirror
- Similar with DFB about fabrication sensitive: but slightly more tolerance
- Also fine tuning frequency with temperature or internal phase segment when operated
- Less popular than DFB, but a variation is with Bragg fiber grating is also useful

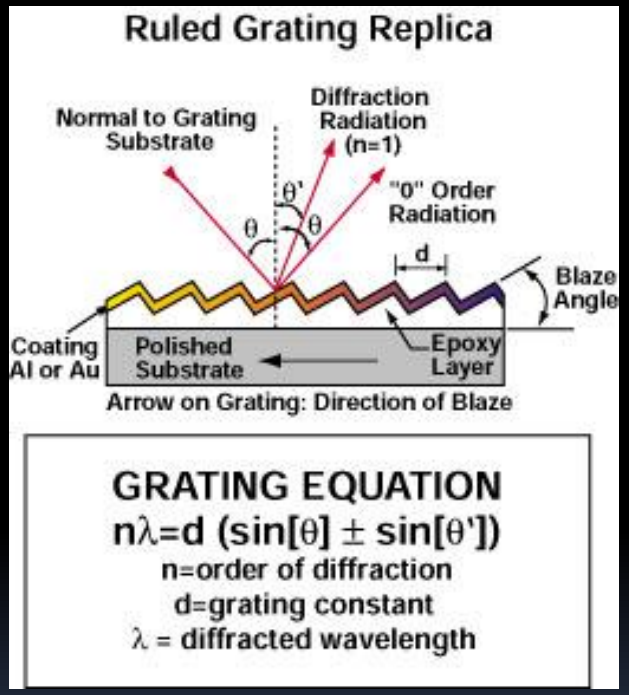
Grating: Diffraction Grating





Diffraction grating equation

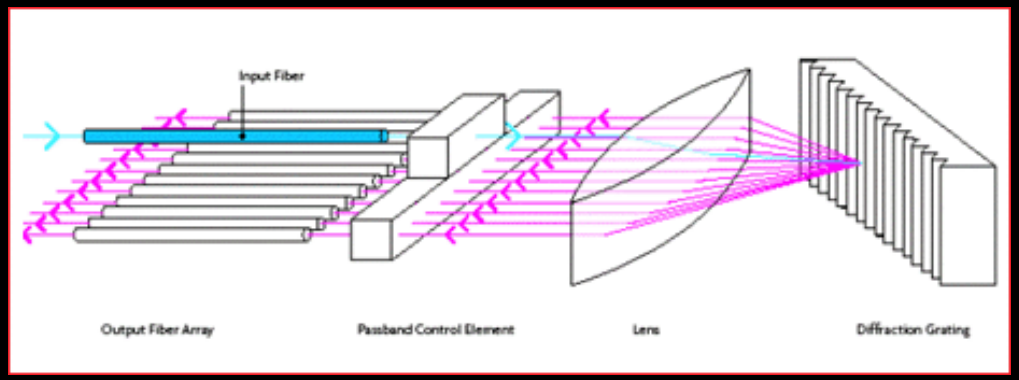


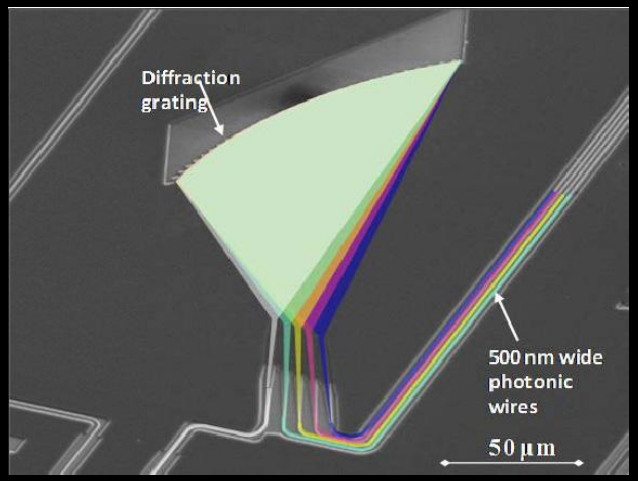


$$d\left(\sin[\alpha]+\sin[\beta]\right)=m\lambda$$

(note: the angles are algebraic: CCW: positive, CW negative)

Grating: diffraction grating for WDM

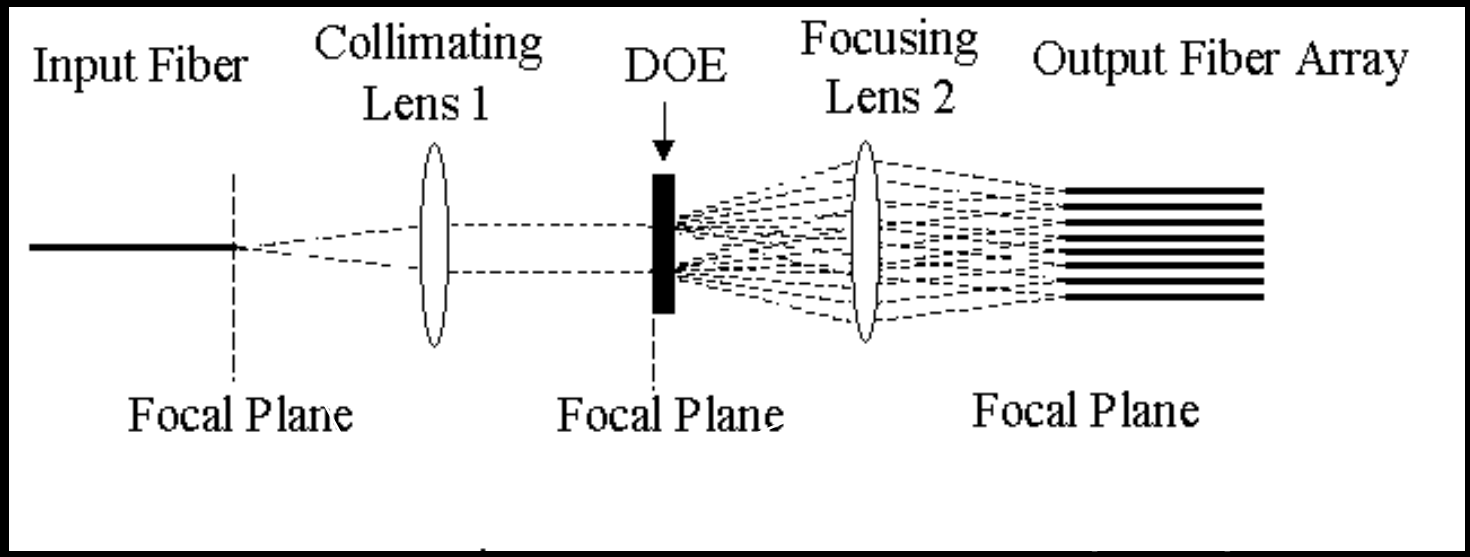


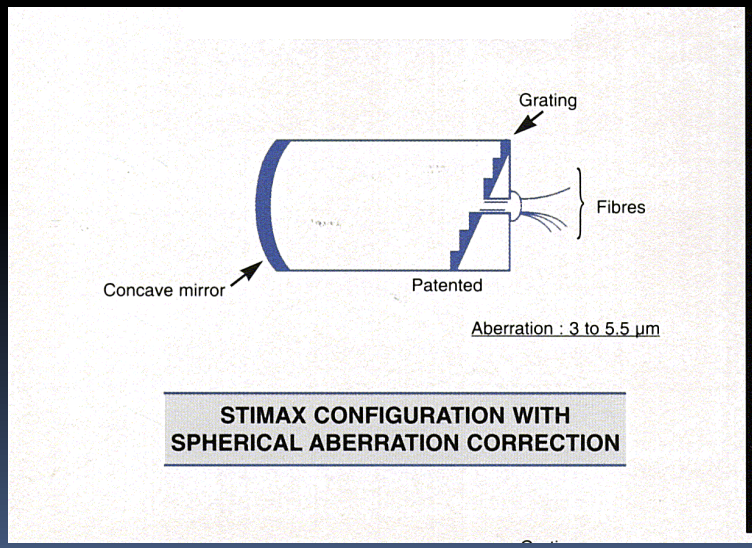


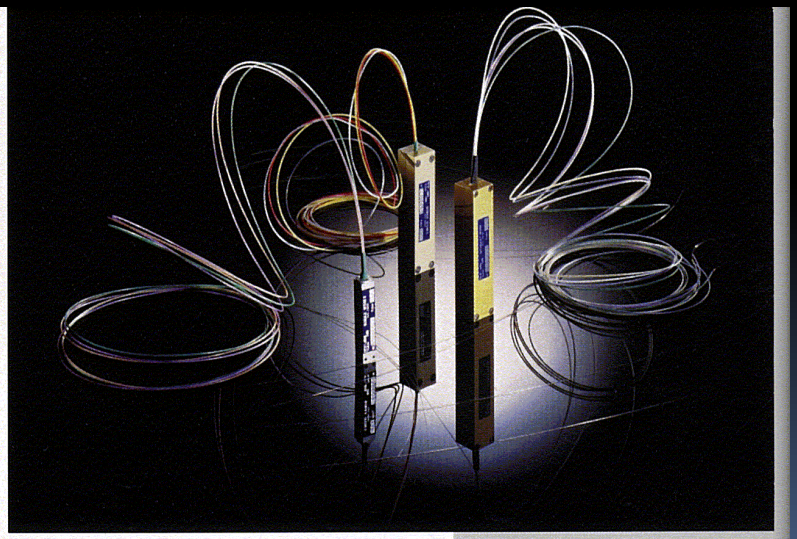
Application:

- Split a multi-wavelength channel into many channels, each with a unique wavelength (demux)
- And vice versa (mux)

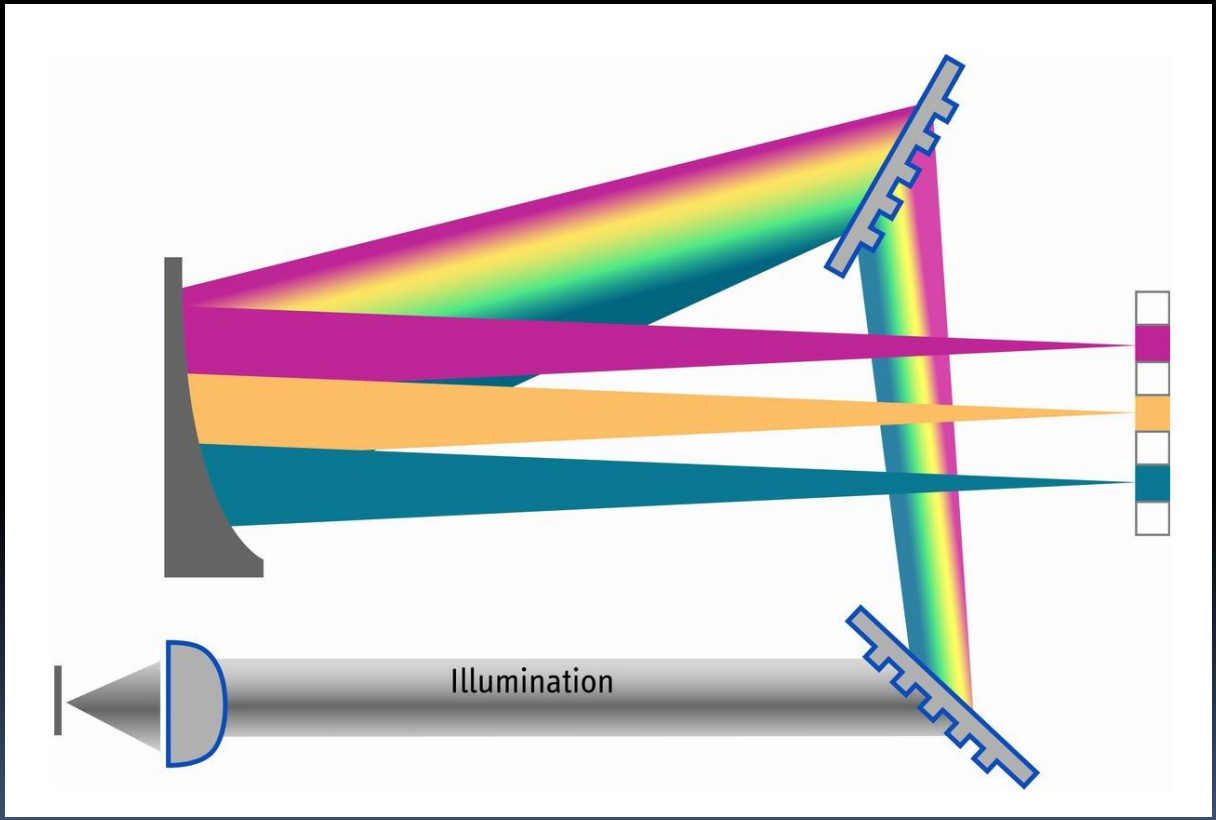
Grating: free space λ mux/demux



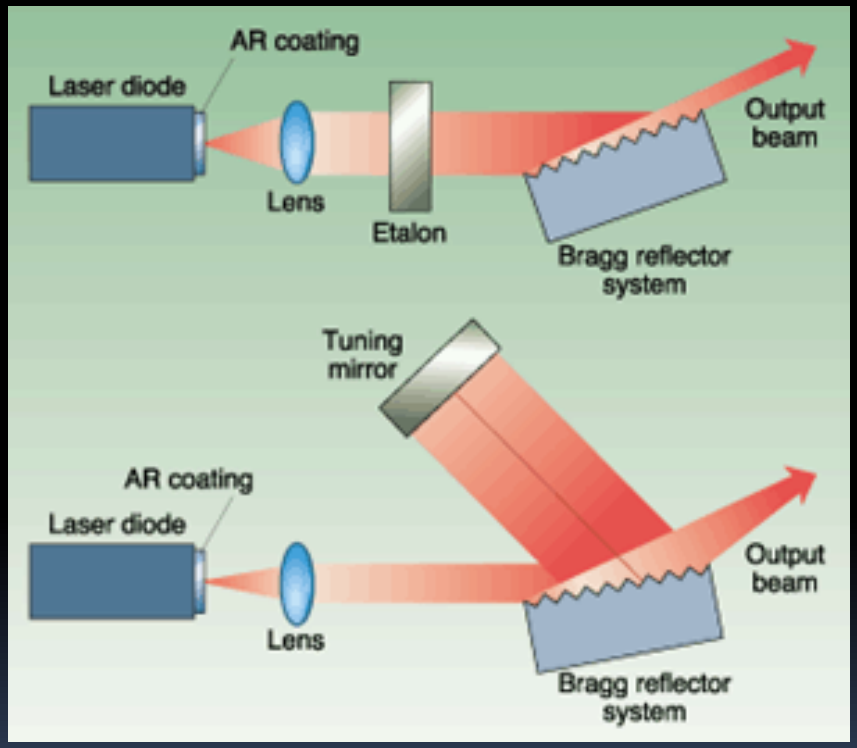




Diffraction grating: other applications



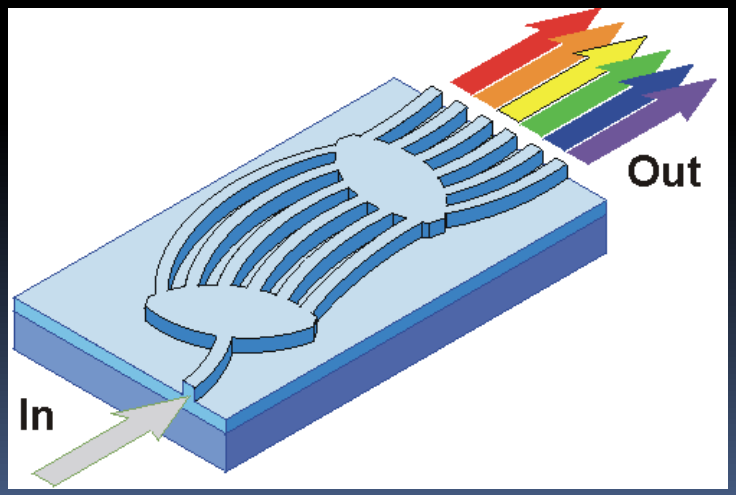
DG : Example of other application: tunable laser

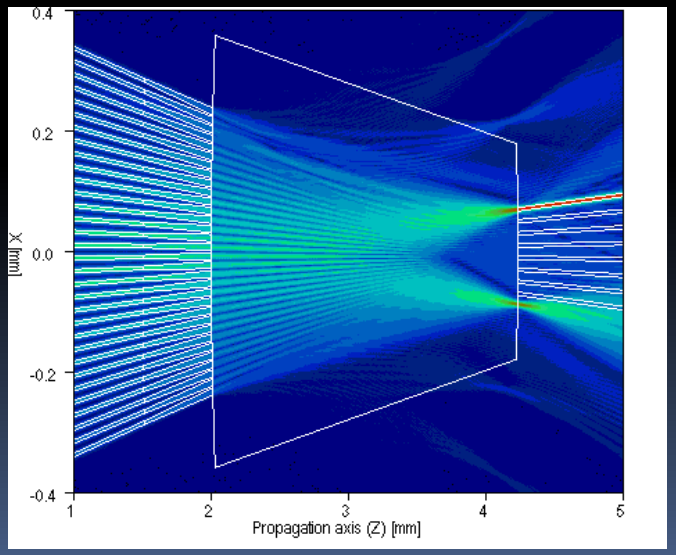


Array waveguide grating

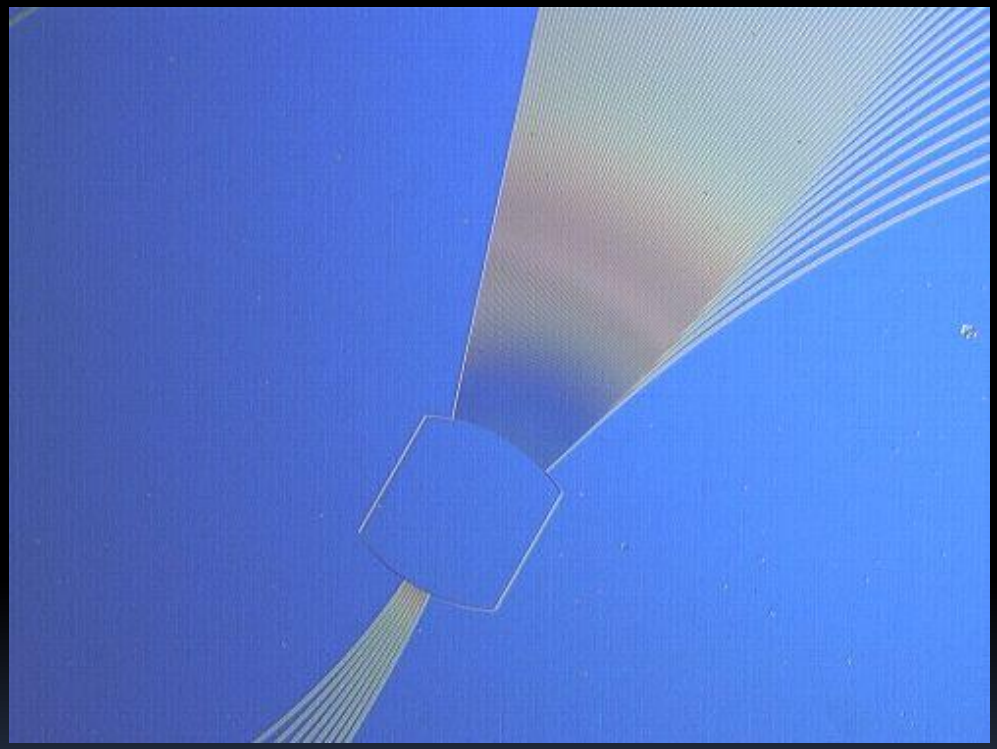
- Same principle as diffraction grating, except that the path delay is controlled by waveguide length

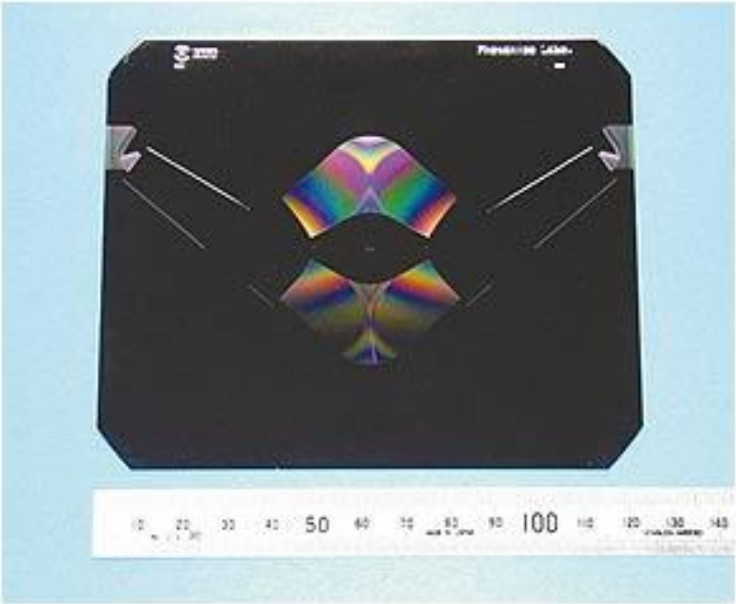
$$\frac{d\theta}{d\lambda} = \frac{\Delta L}{\lambda_{wg}} \frac{n_g}{d\, n_s}$$





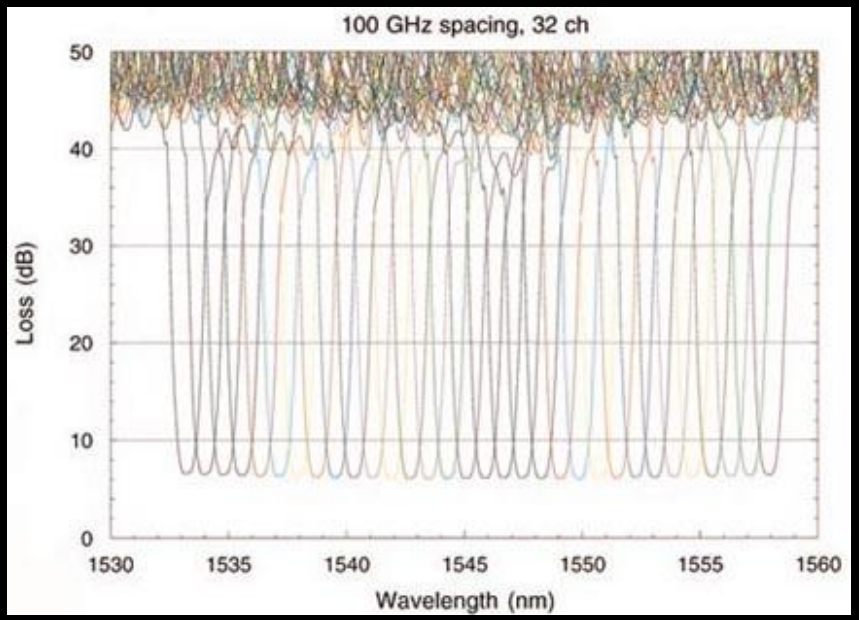
Grating: AWG



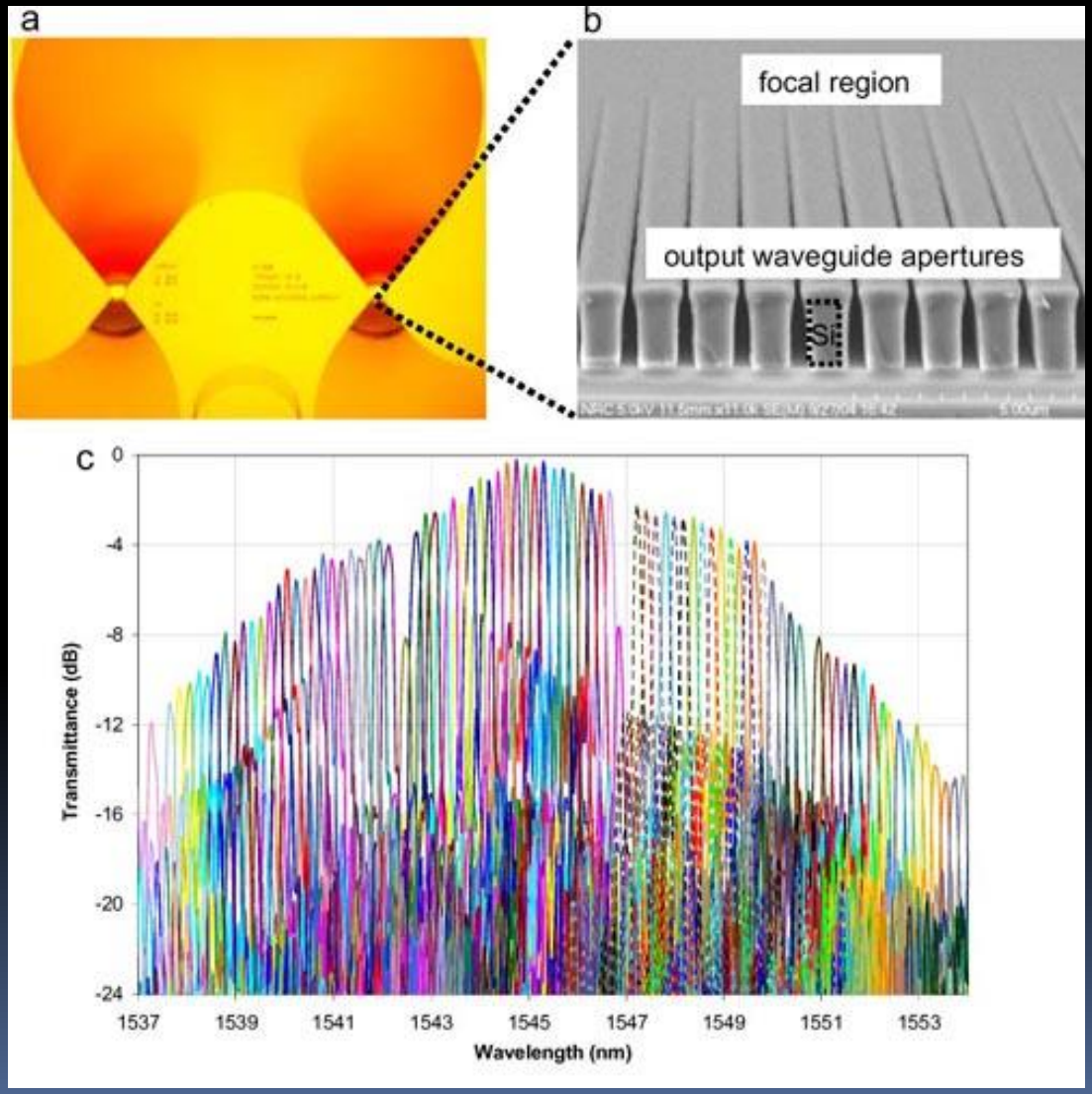


Developed by NTT Laboratories, the AWG is a key product for achieving large-capacity WDM transmission. It is manufactured using low-loss, high-precision, silica-glass-based planar-lightwave-circuit technology. The AWG is used around the world as a compact and high-performance optical filter capable of multiplexing/ demultiplexing several tens of signals of different wavelengths.

Grating: array waveguide (AWG)

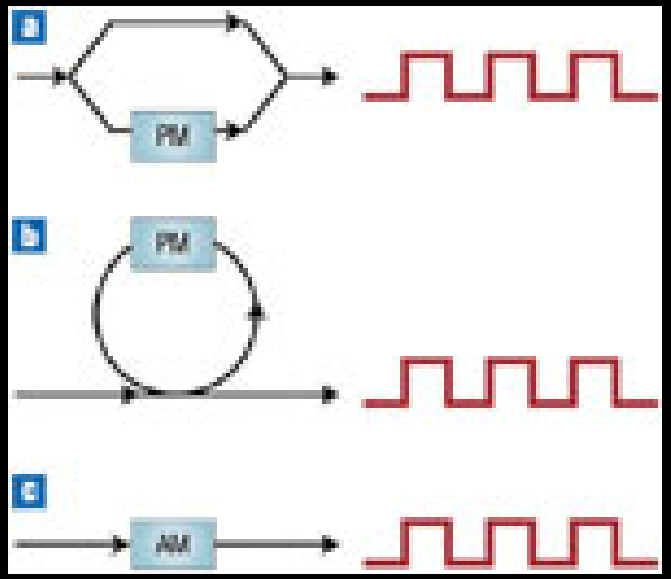


Grating: very large AWG



Modulator

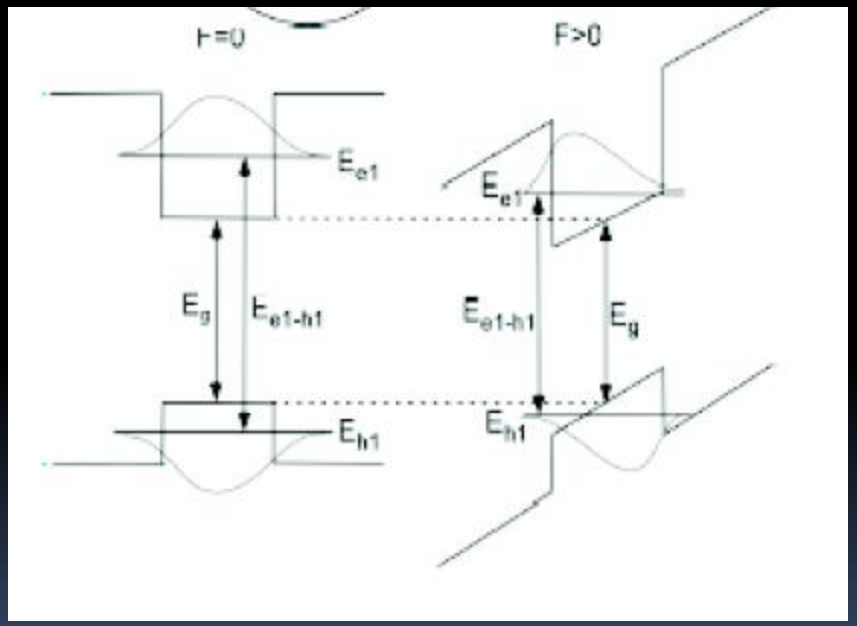
- Light can be modulated on its intensity, phase or frequency
- For optical communication, most common is intensity modulation
- Modulation can be direct on a laser (rare) or through an external absorber: electro-absorption modulation

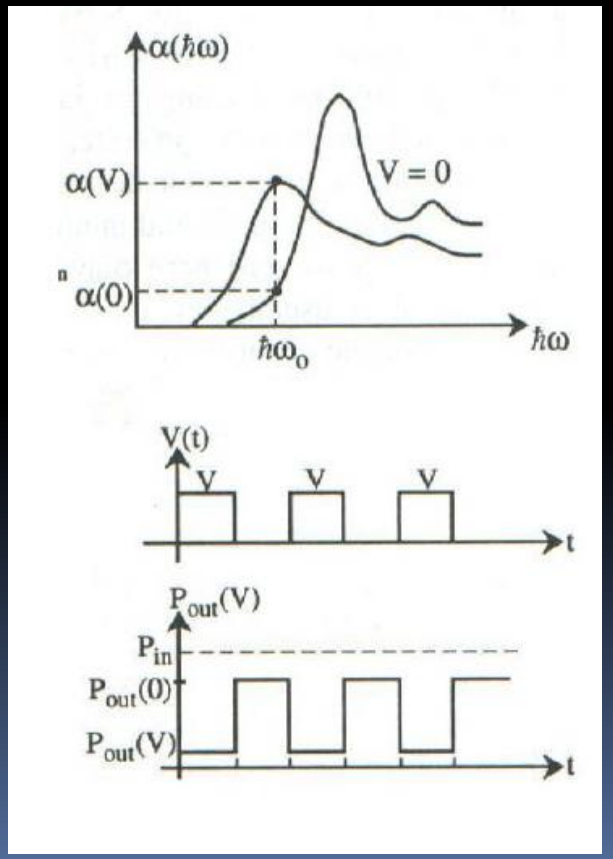


- Phase modulation is often used to convert into intensity modulation with a device like a MZ interferometer or ring resonator

Electroabsorption modulator (EAM)

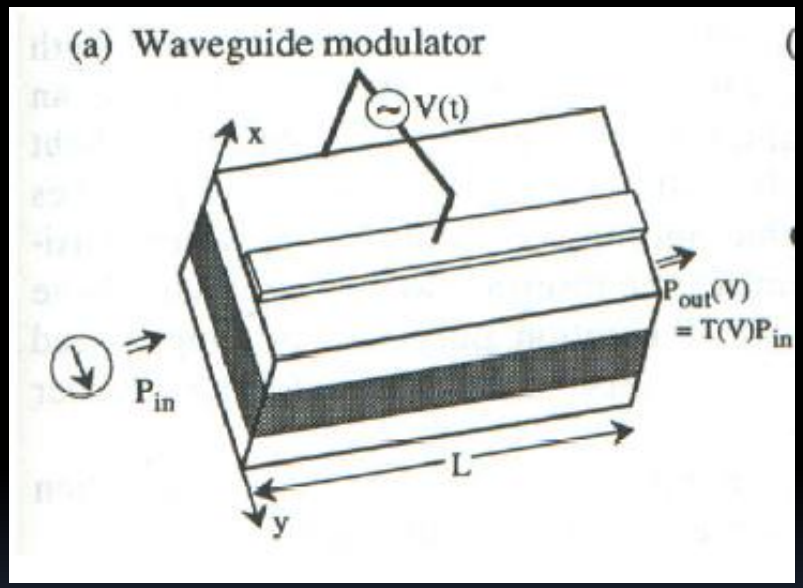
- Principle: application of an electric field to semiconductor QW changes the energy levels, hence the absorption wavelength spectrum



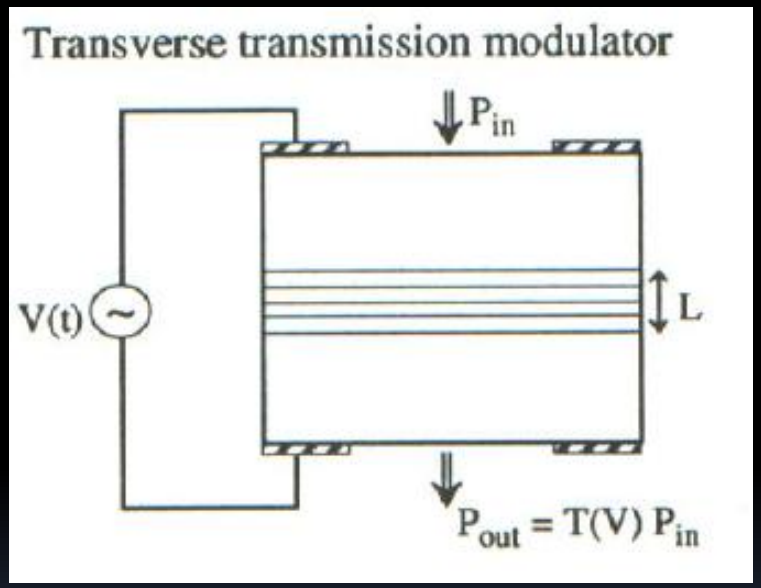


EAM device configuration

Waveguide geometry

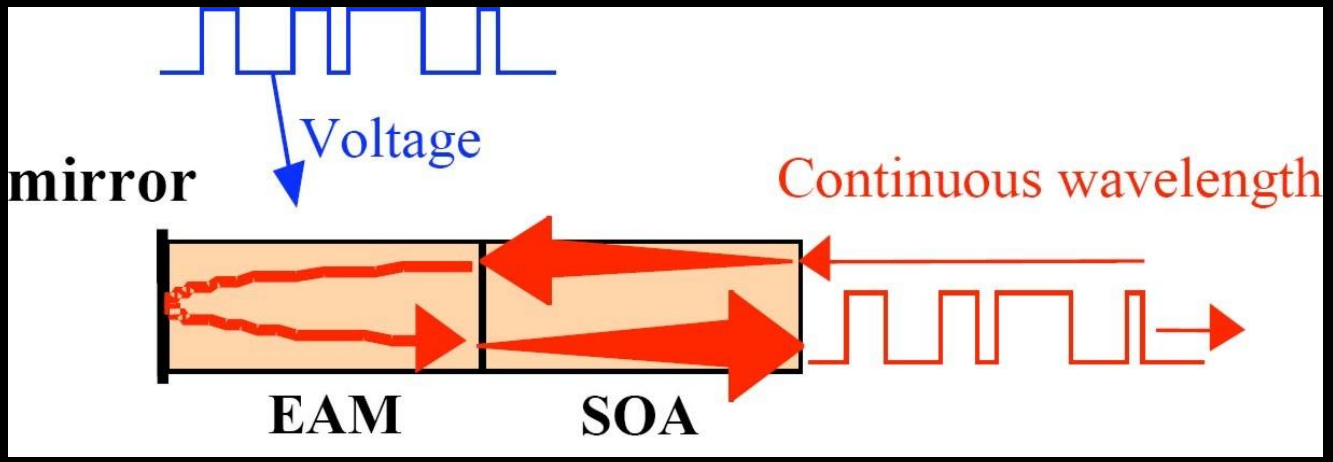


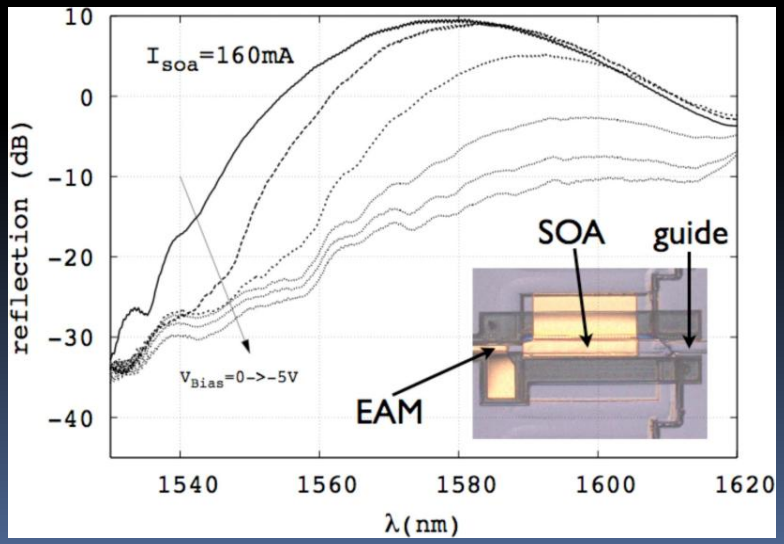
Vertical geometry



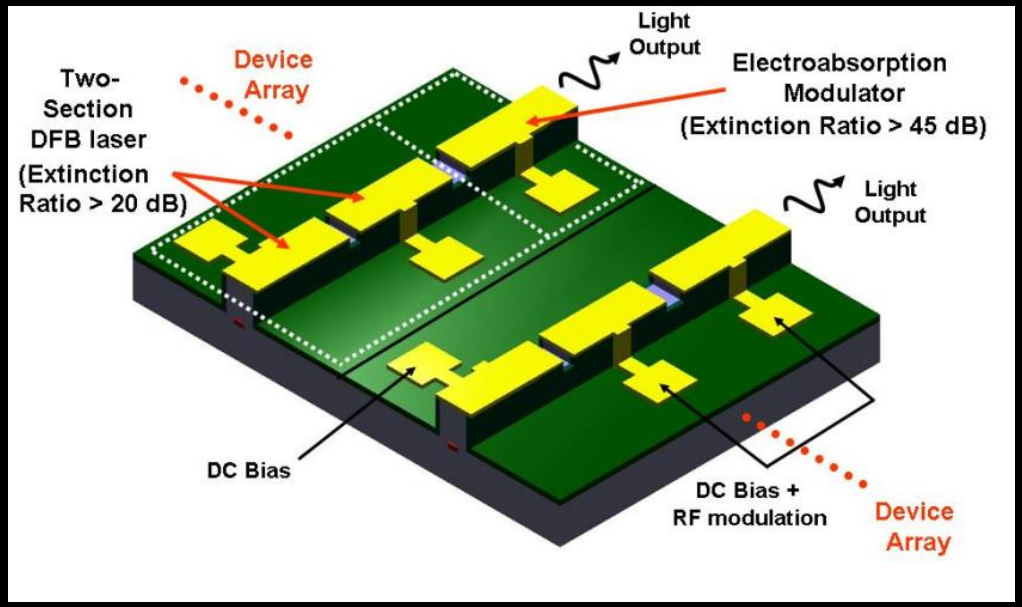
- Majority devices are in waveguide geometry, often integrated with a laser

Electroabsorption modulator device





EAM applications



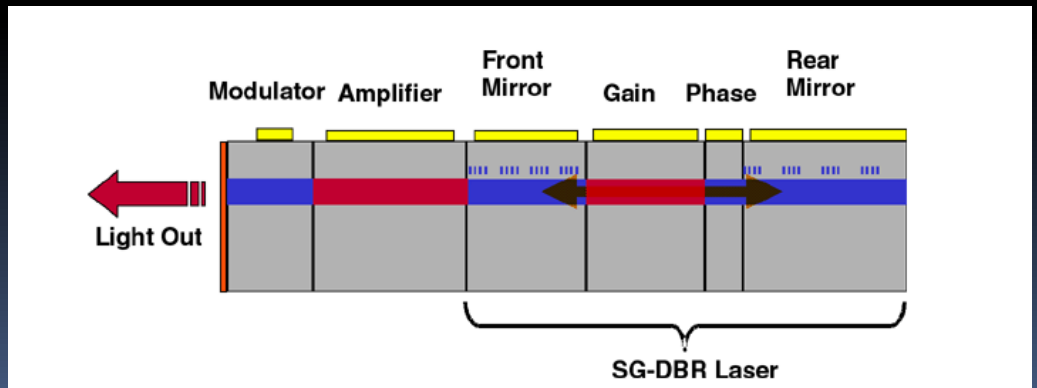
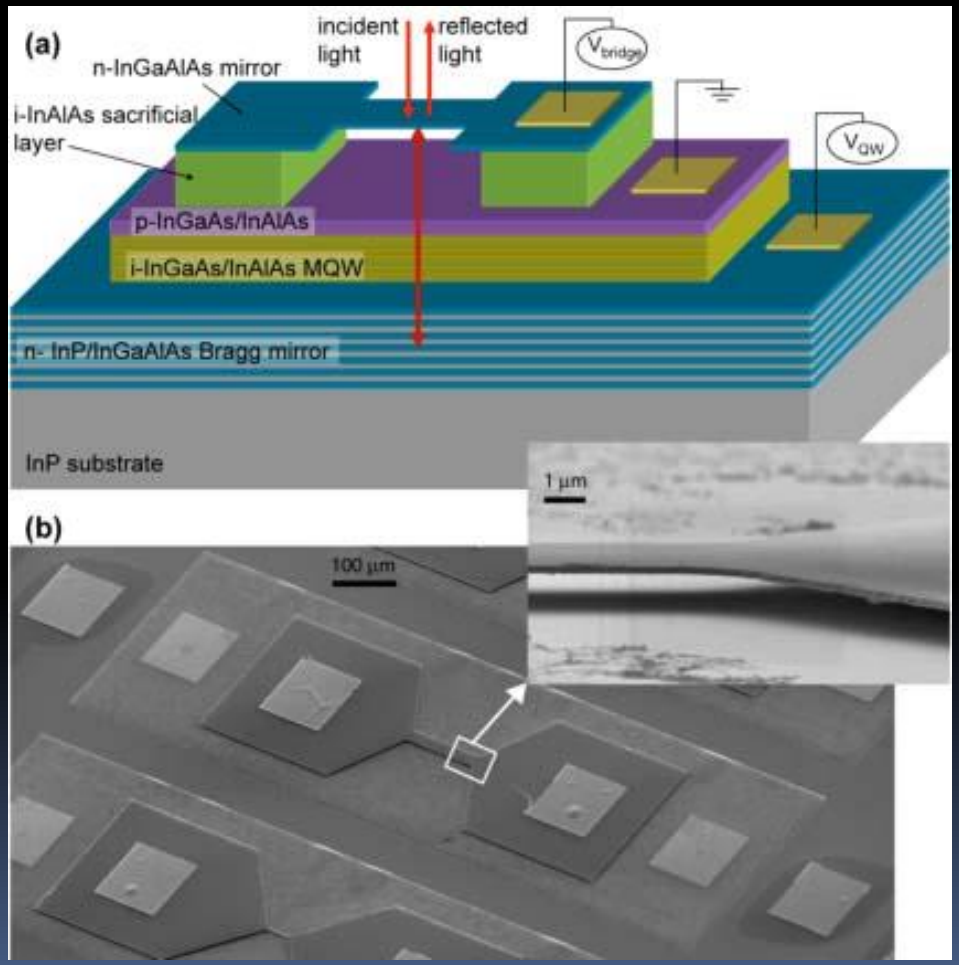
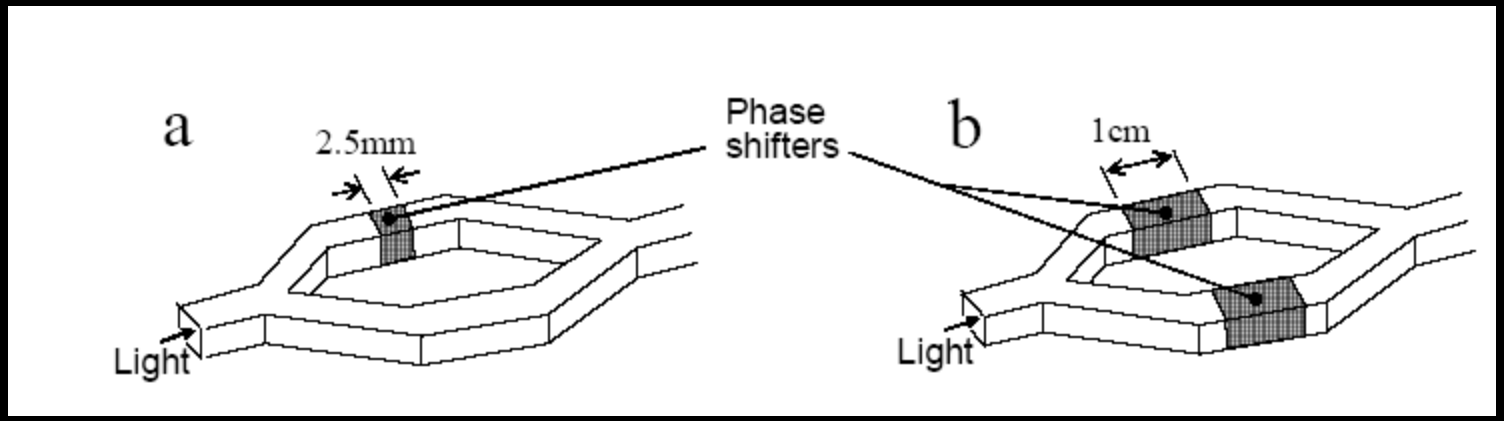


FIGURE 12: *SG-DBR laser integrated with semiconductor optical amplifier and electro-absorption modulator.*

Some advanced EA modulator design



Mach-Zehnder interferometer (MZI) electro-optic modulator

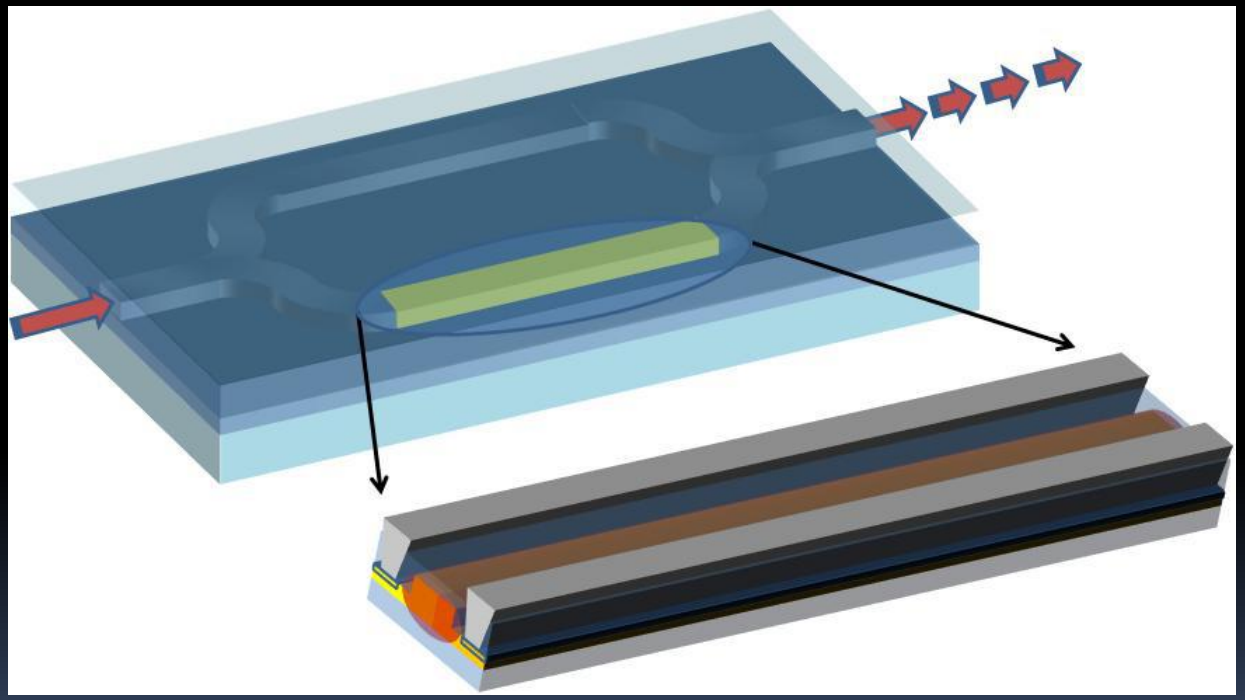


$$\Delta\phi = \frac{2\pi L}{\lambda}\Delta n_{eff} = \frac{2\pi L}{\lambda} \times \left[\frac{dn_{eff}}{dQ_{acc}}\right] \times C_{acc}\left[V_D - V_{FB}\right]$$

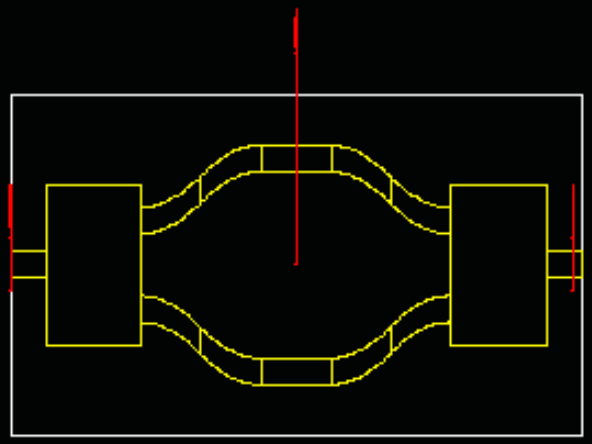
$$\Delta n = -\frac{n^3}{2} r E$$

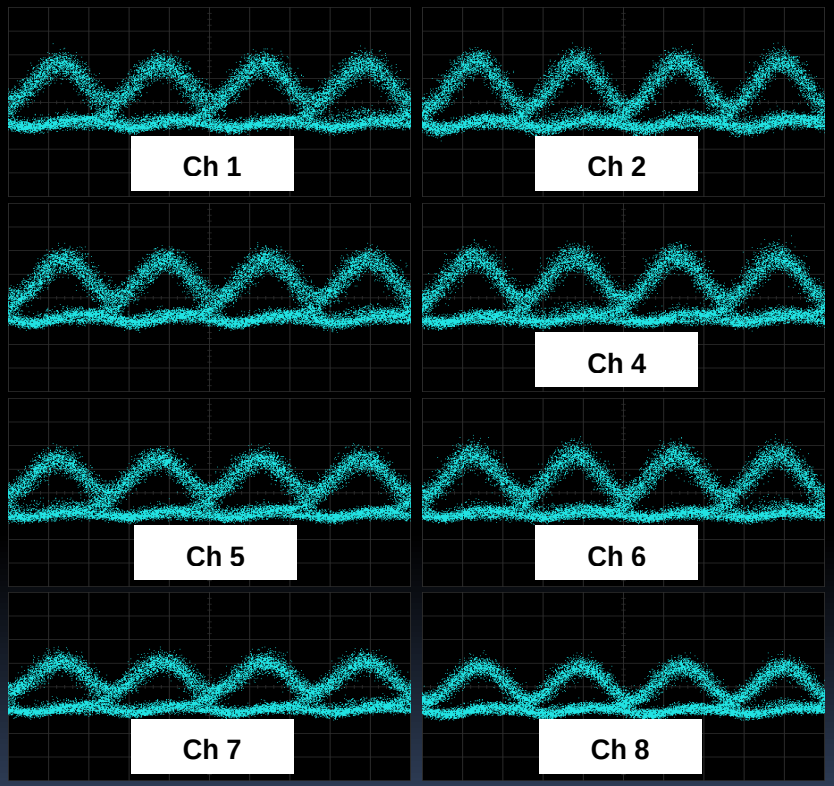
The electro-optic effect: refractive index changes as a function of E field

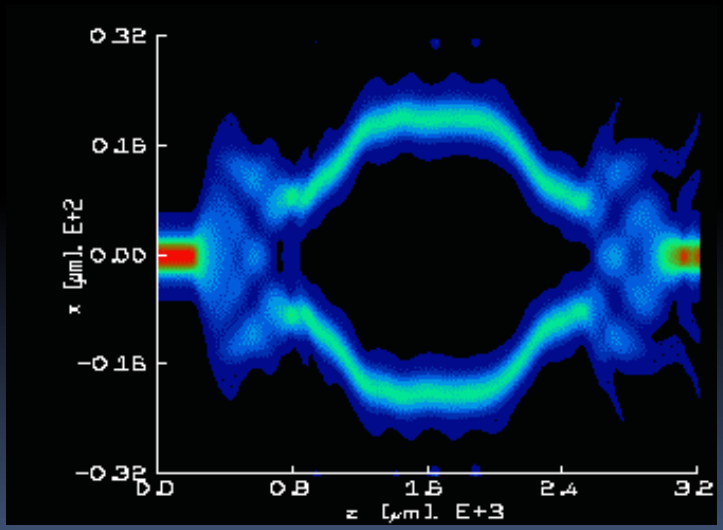
MZI structure



Mach-Zehnder Electro-optic modulator

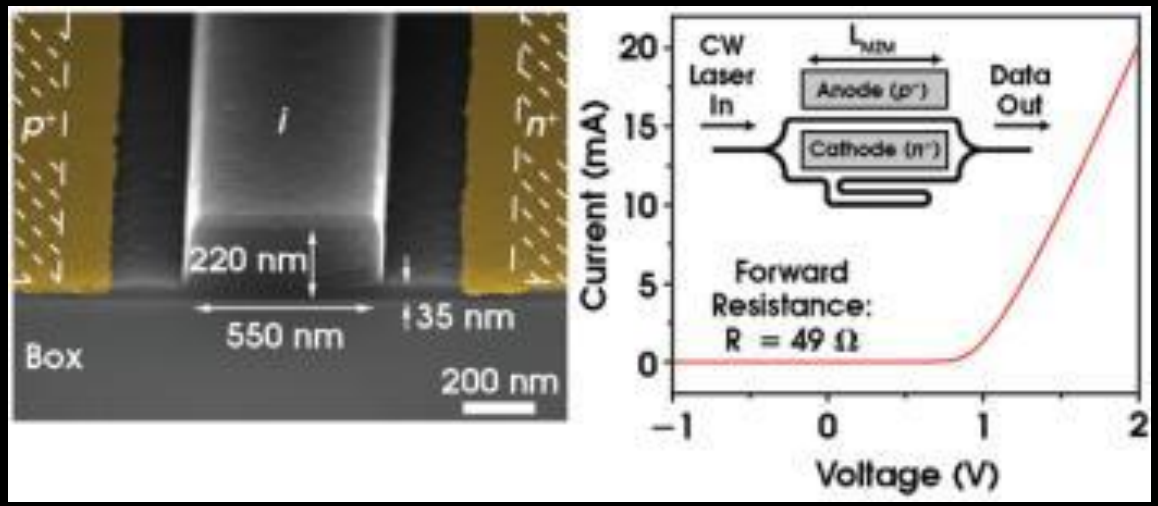


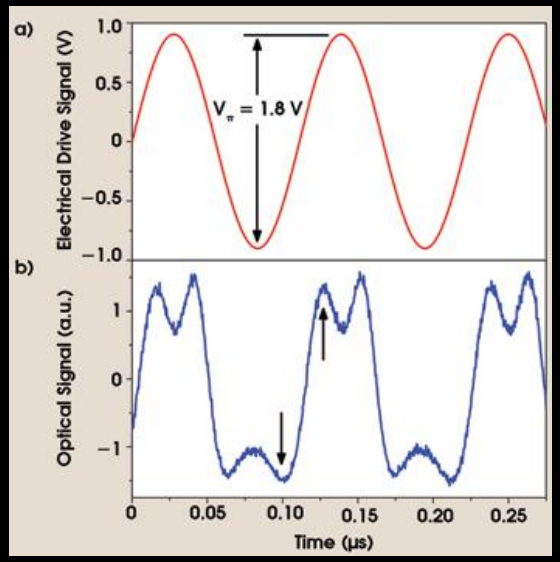




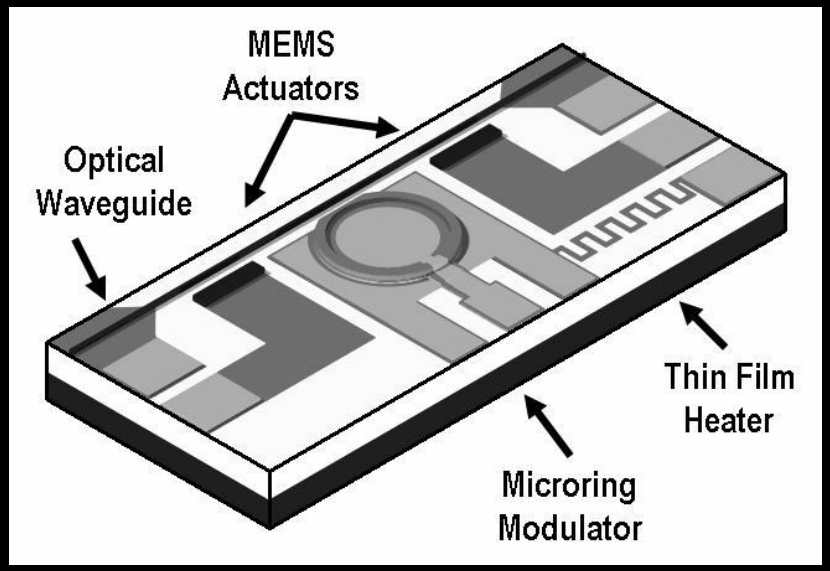
- $LiNbO_3$ still is the #1 seller
- Semiconductors in specialized cases

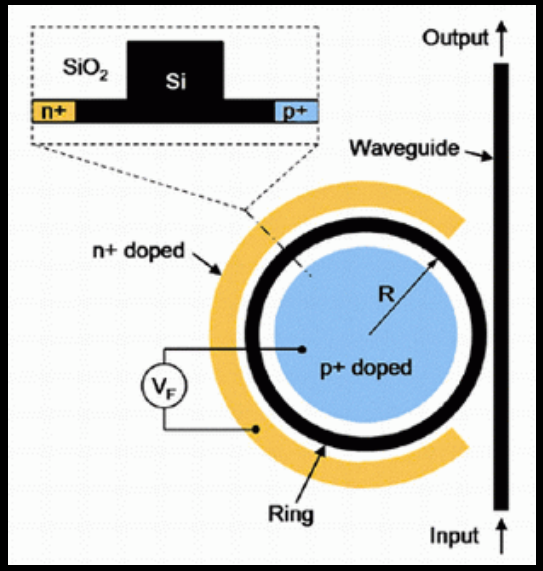
MZI Electro-optic modulator: advanced

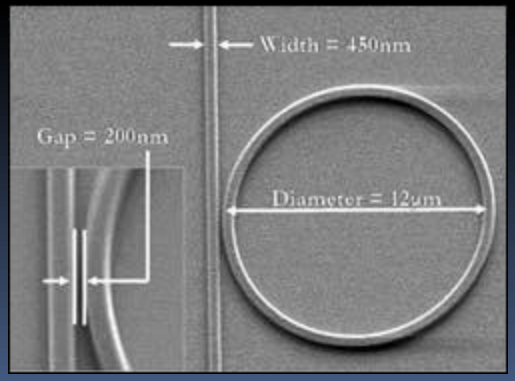


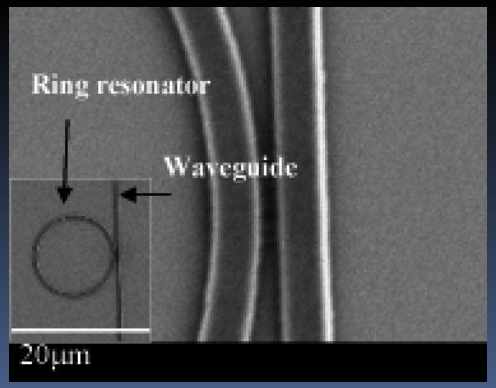


Ring-resonator electro-optic modulator







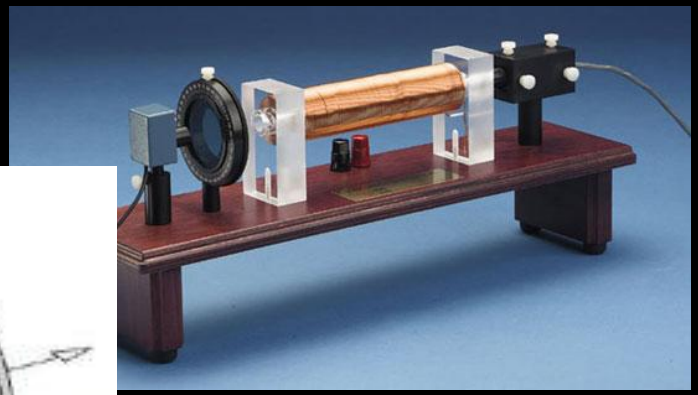


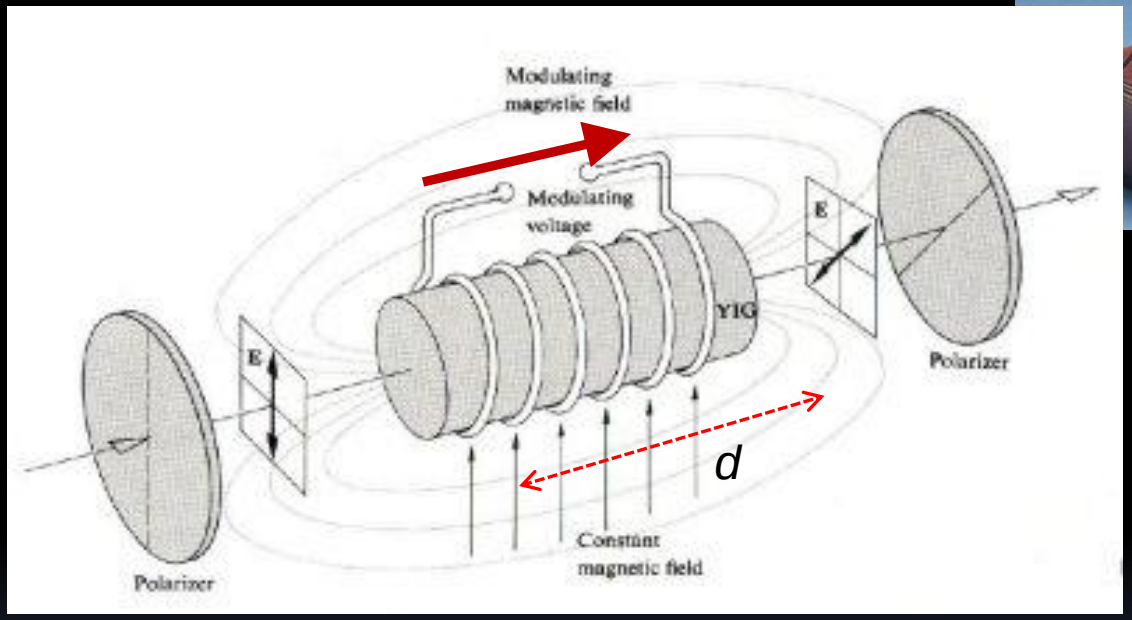
Optical isolator and circulator

- It is desirable to prevent light going backward (especially into lasers) that causes instability
- A device that allows light to go one way, but not on reverse is called an optical isolator
- More than the importance of isolating light to prevent feedback: isolator can be made into circulator: allowing light to travel (circulate) through several devices one way but not the other.
- The most important isolator/circulator design is based on Faraday rotation: a magneto-optical effect

Optical isolator and circulator

Faraday rotation



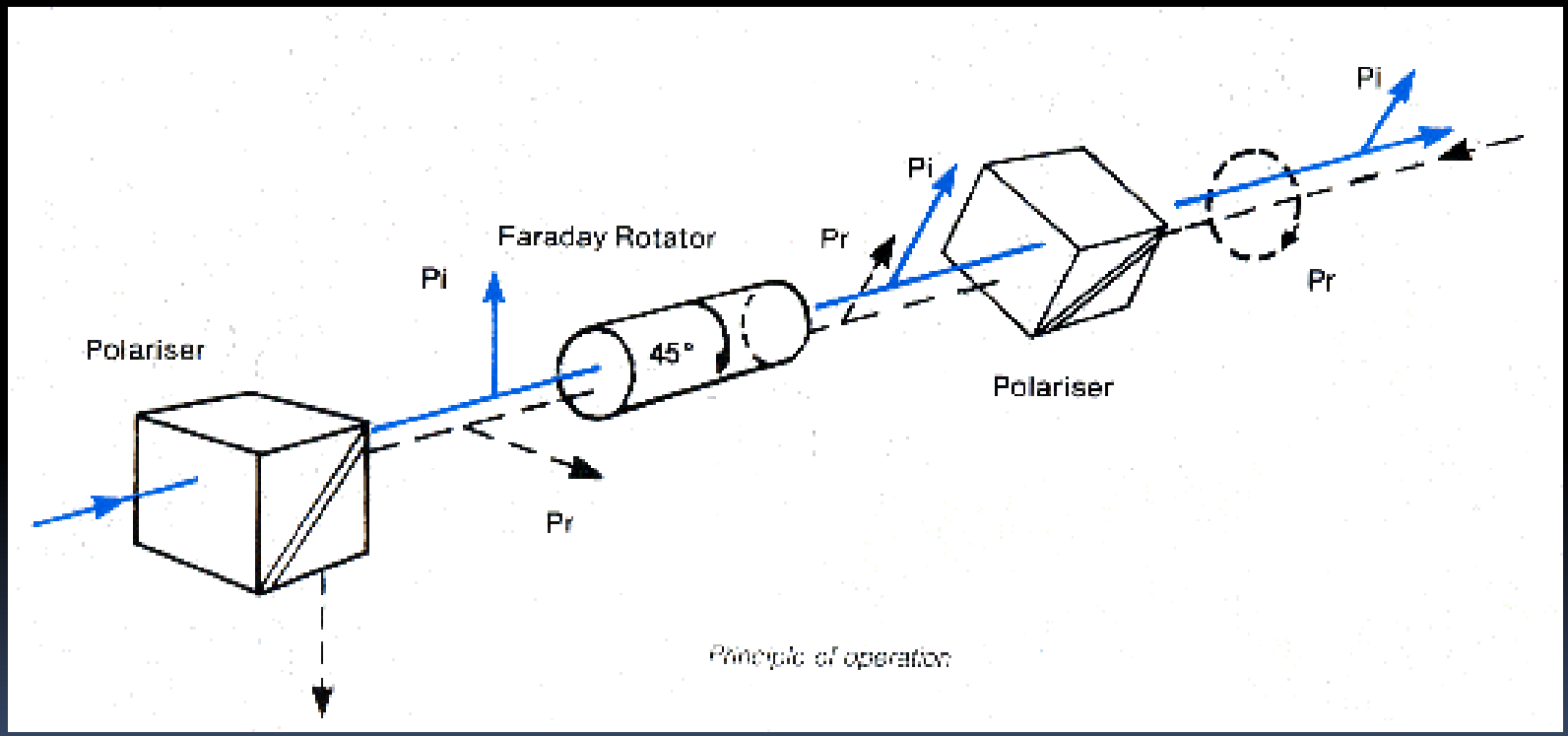


In some crystal, light polarization is rotated when it is applied by a magnetic field: magneto-optical effects

Verdet's constant

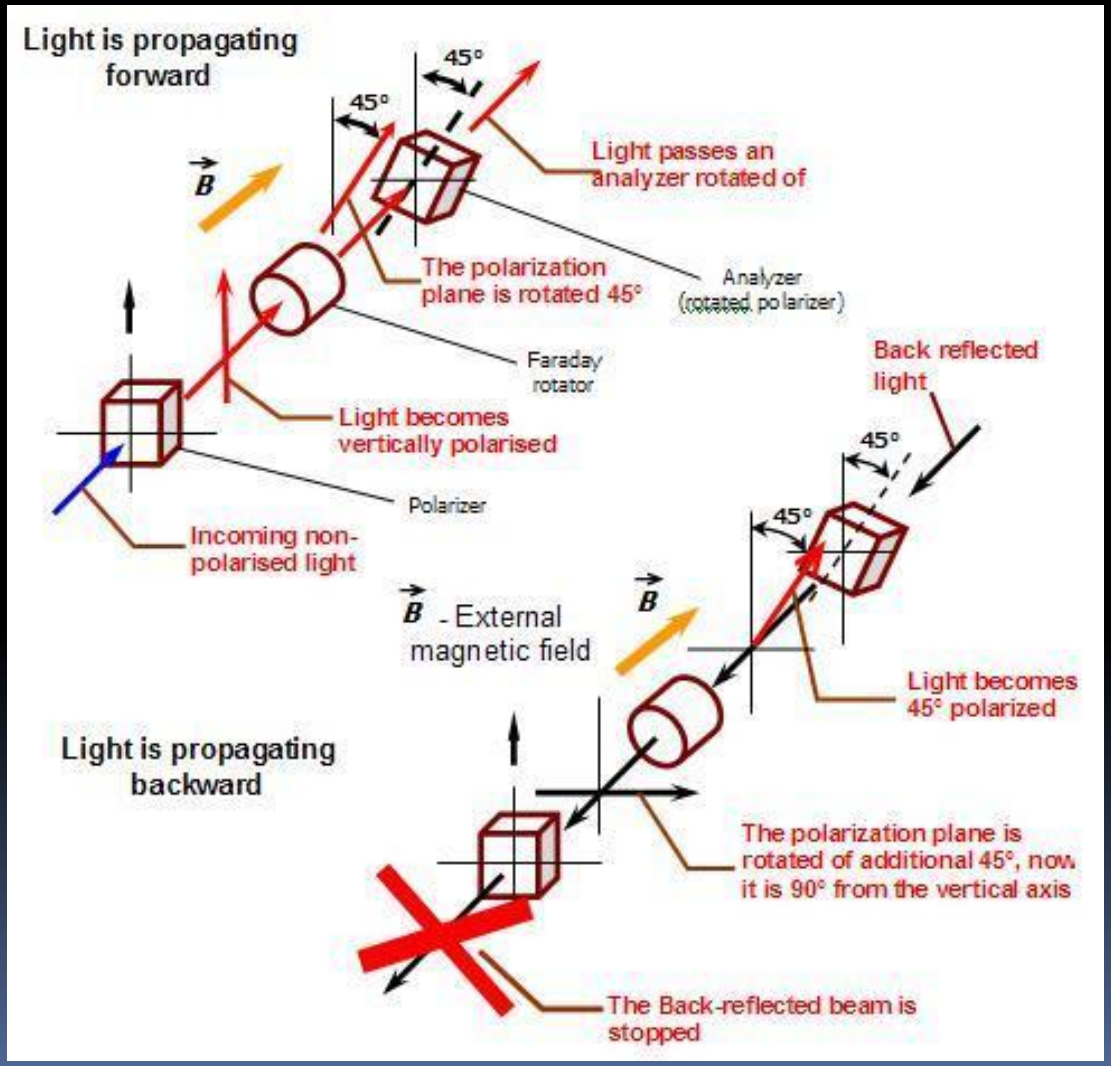
$$\Delta\varphi = \nu B d$$

Optical isolator based on Faraday rotation

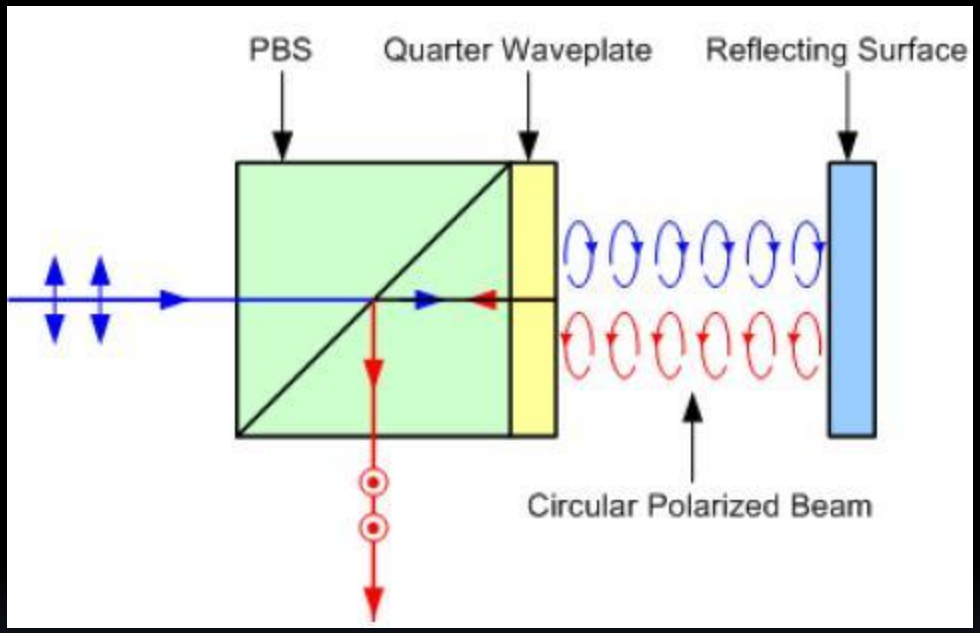


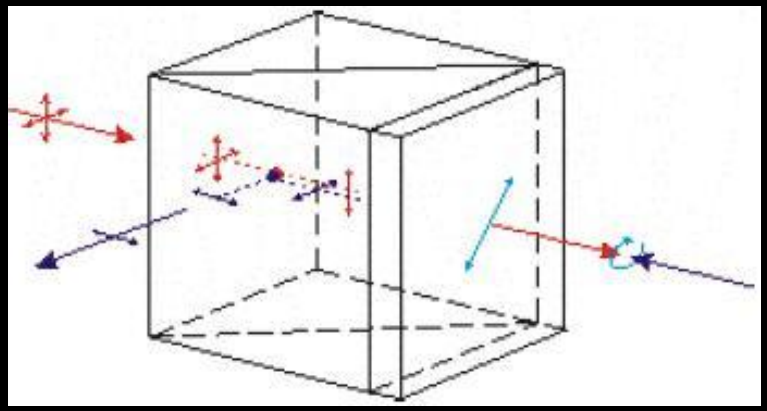
Principle of operation

Another explanation



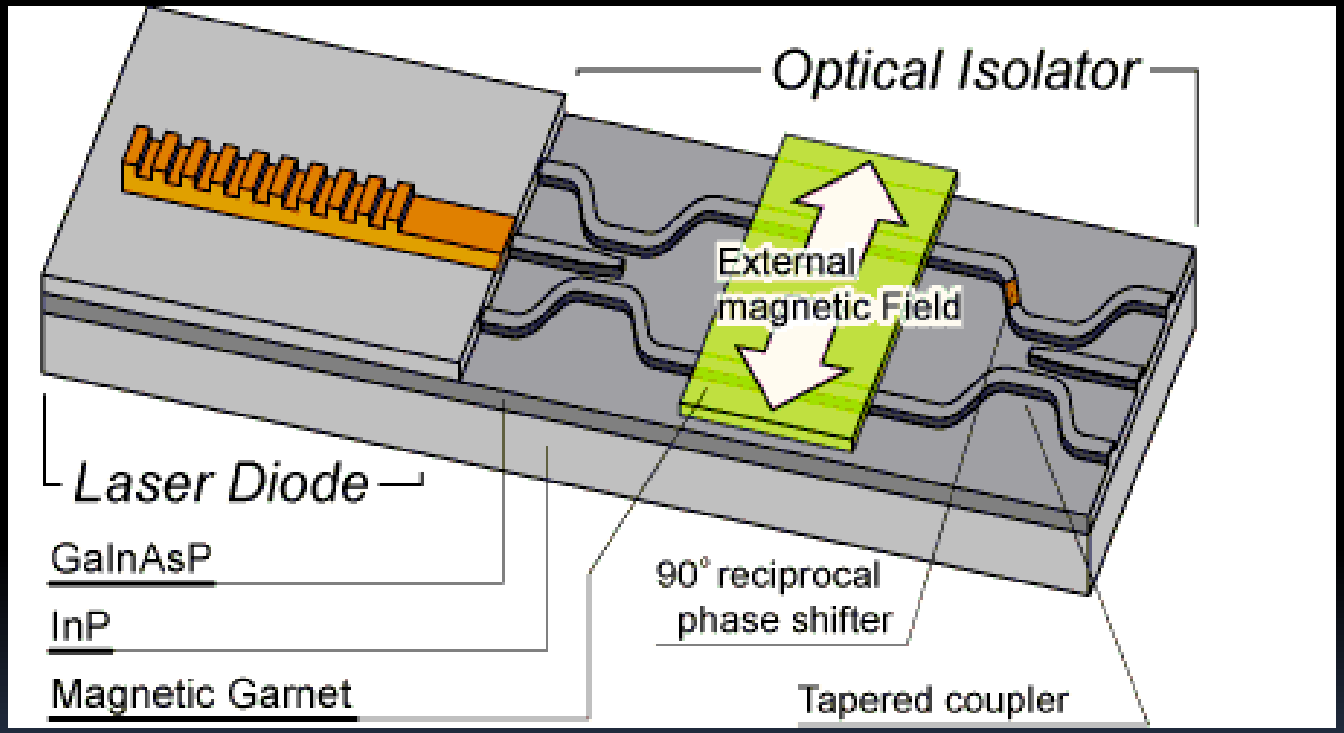
Other optical isolator design



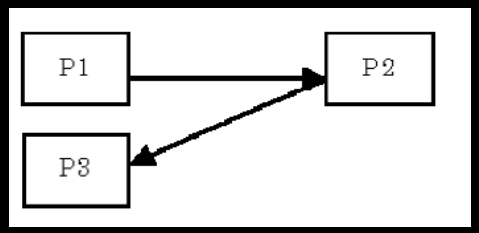


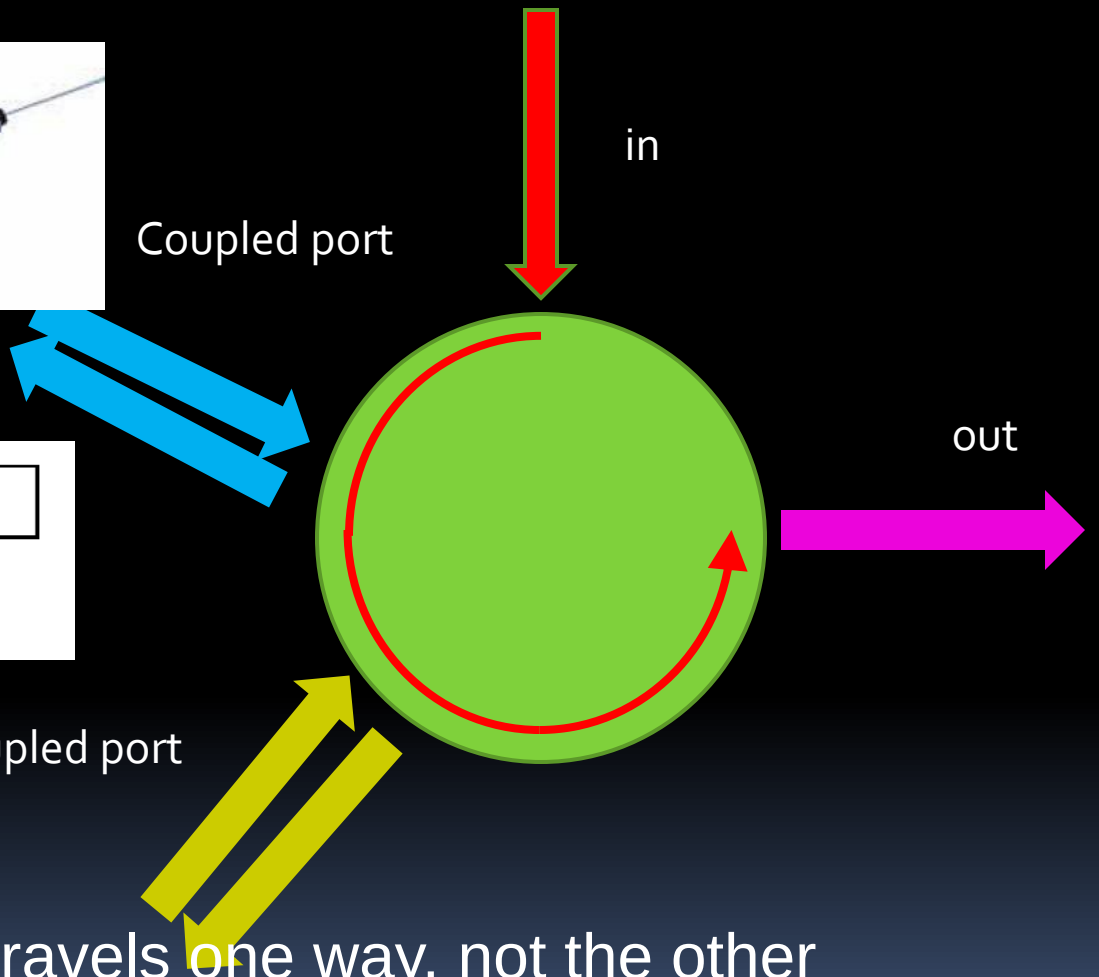
This design is strongly polarization-dependent: it works only for the indicated polarization (PBS is sometimes not preferred)

Other optical isolator design



Optical circulator



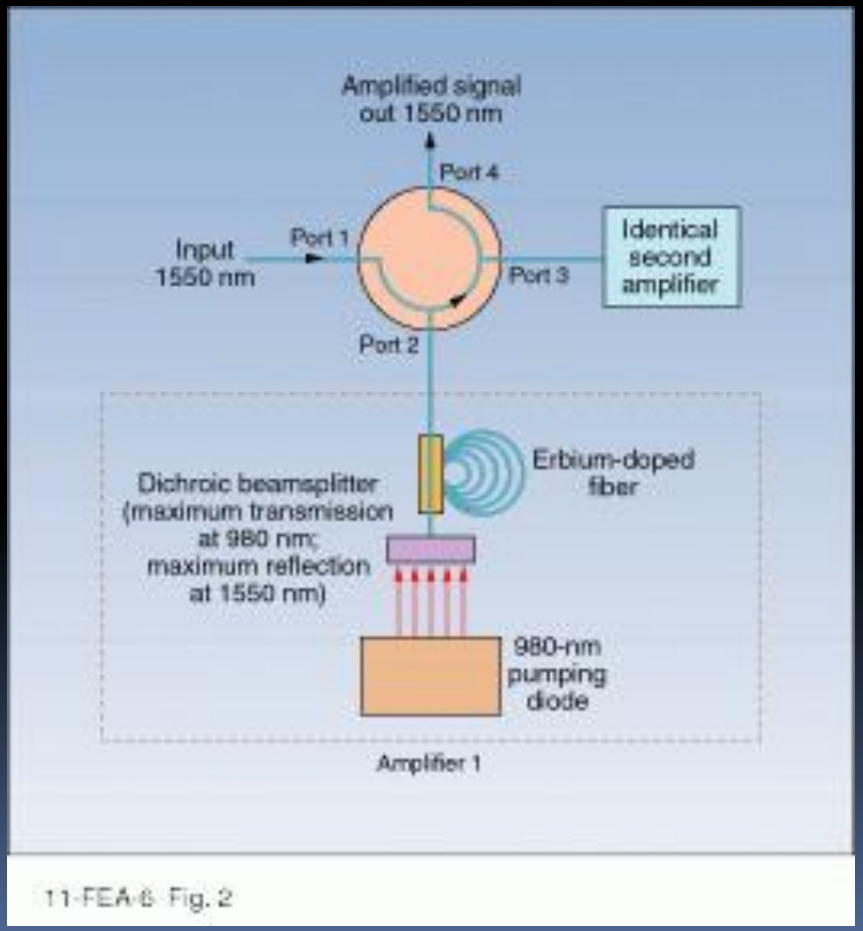


- Light travels one way, not the other
- Usually 3 or 4 ports can be add/drop
- Designed for low polarization-dependence

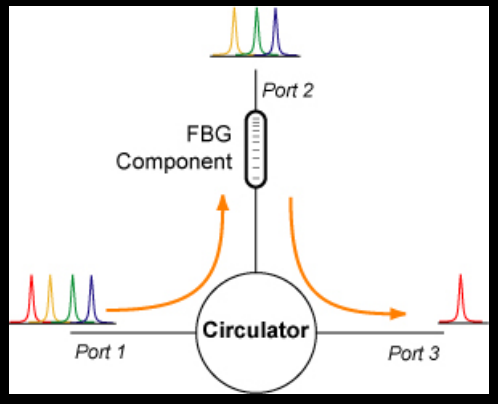
Fiber optics optical circulator design

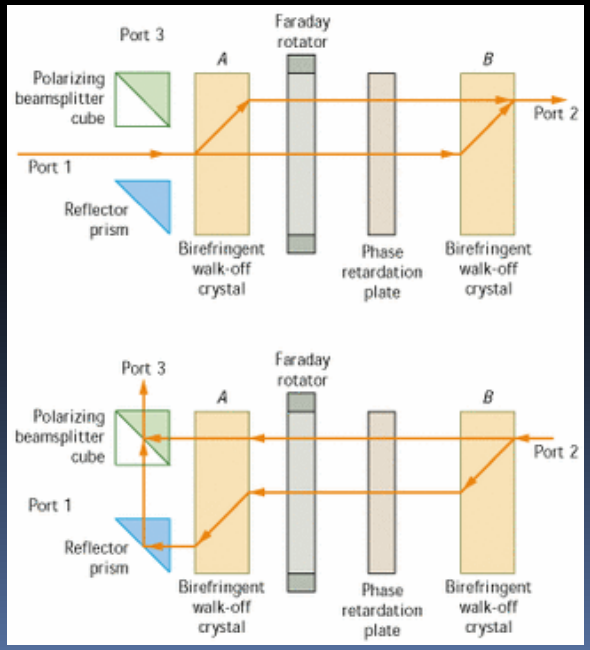
Polarization insensitive

Application 1: amplifier

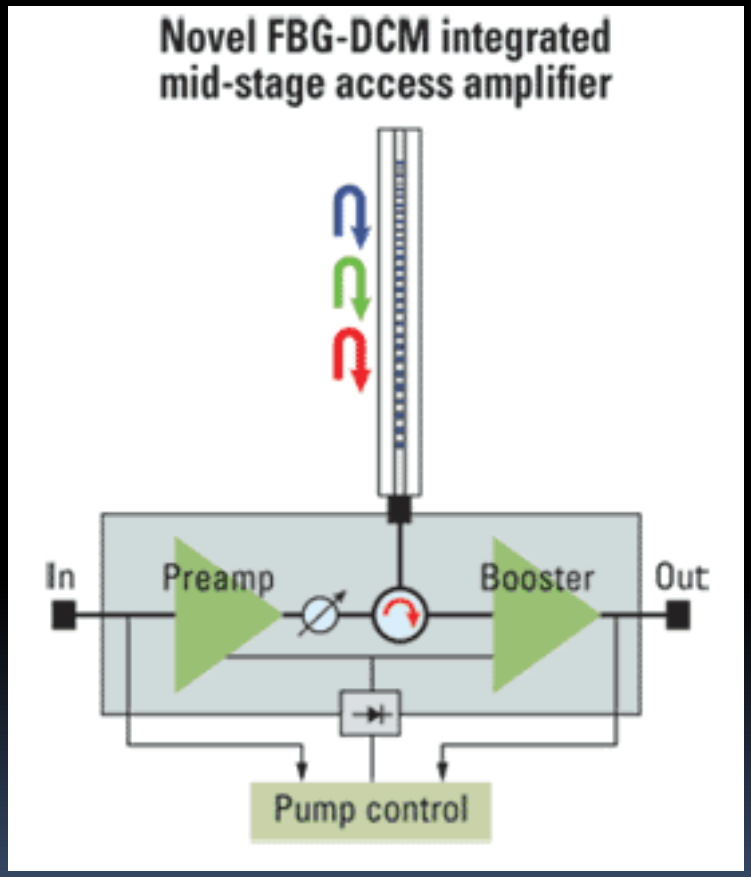


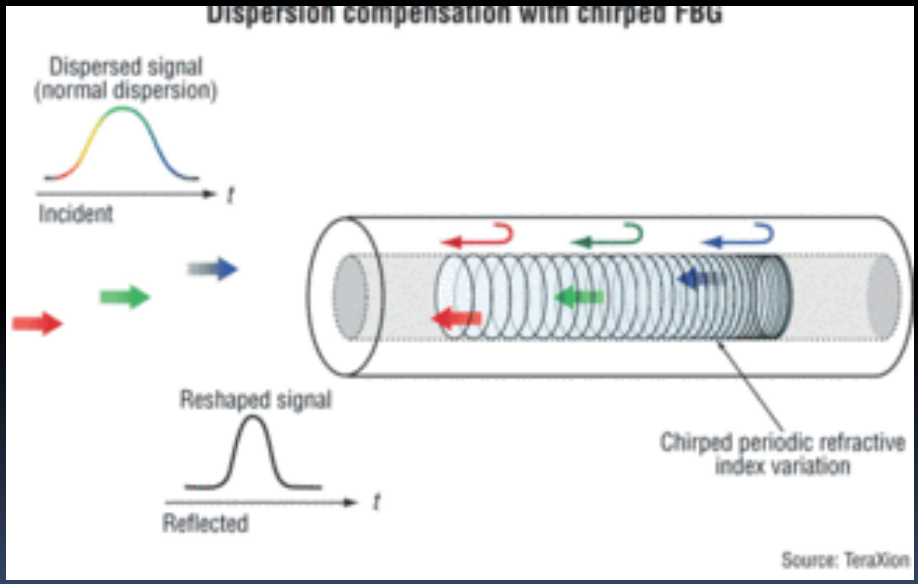
Application 2: Disp comp.





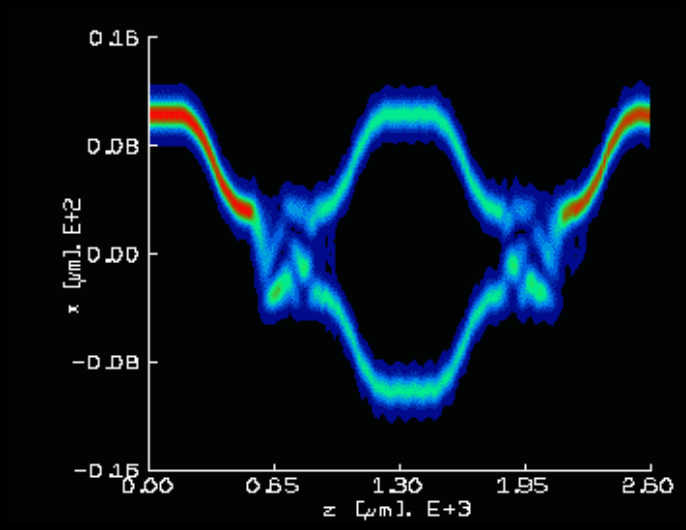
Example applications of optical circulator

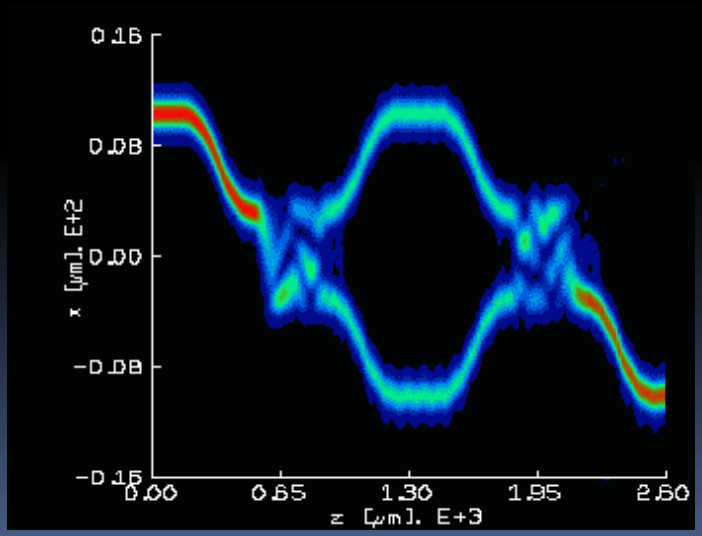




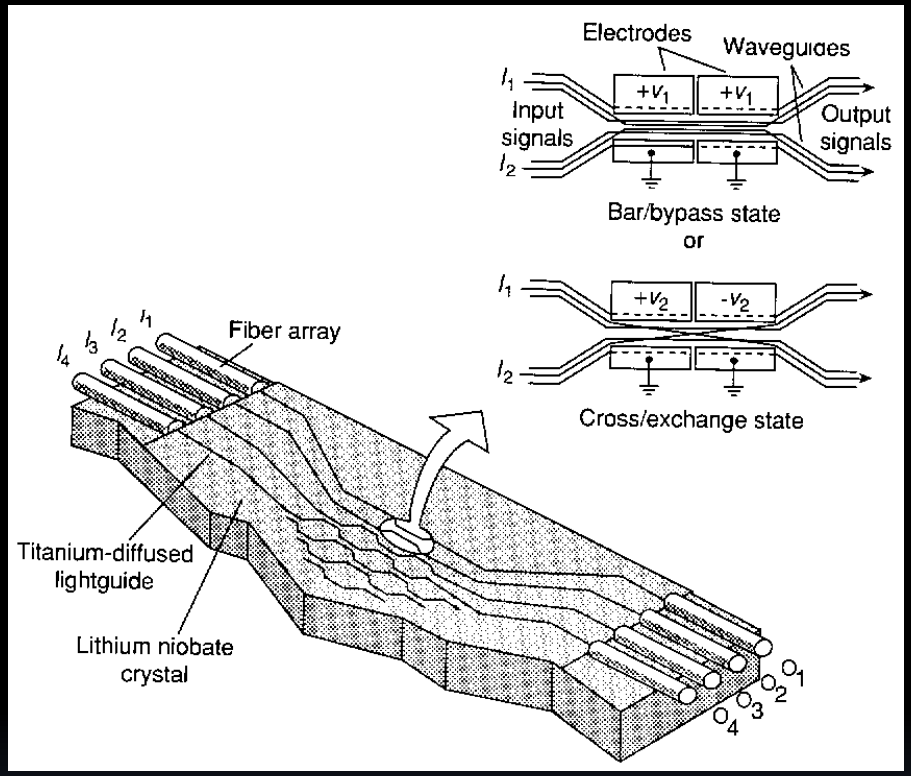
SWITCHES

Interferometer switch (cross bar)



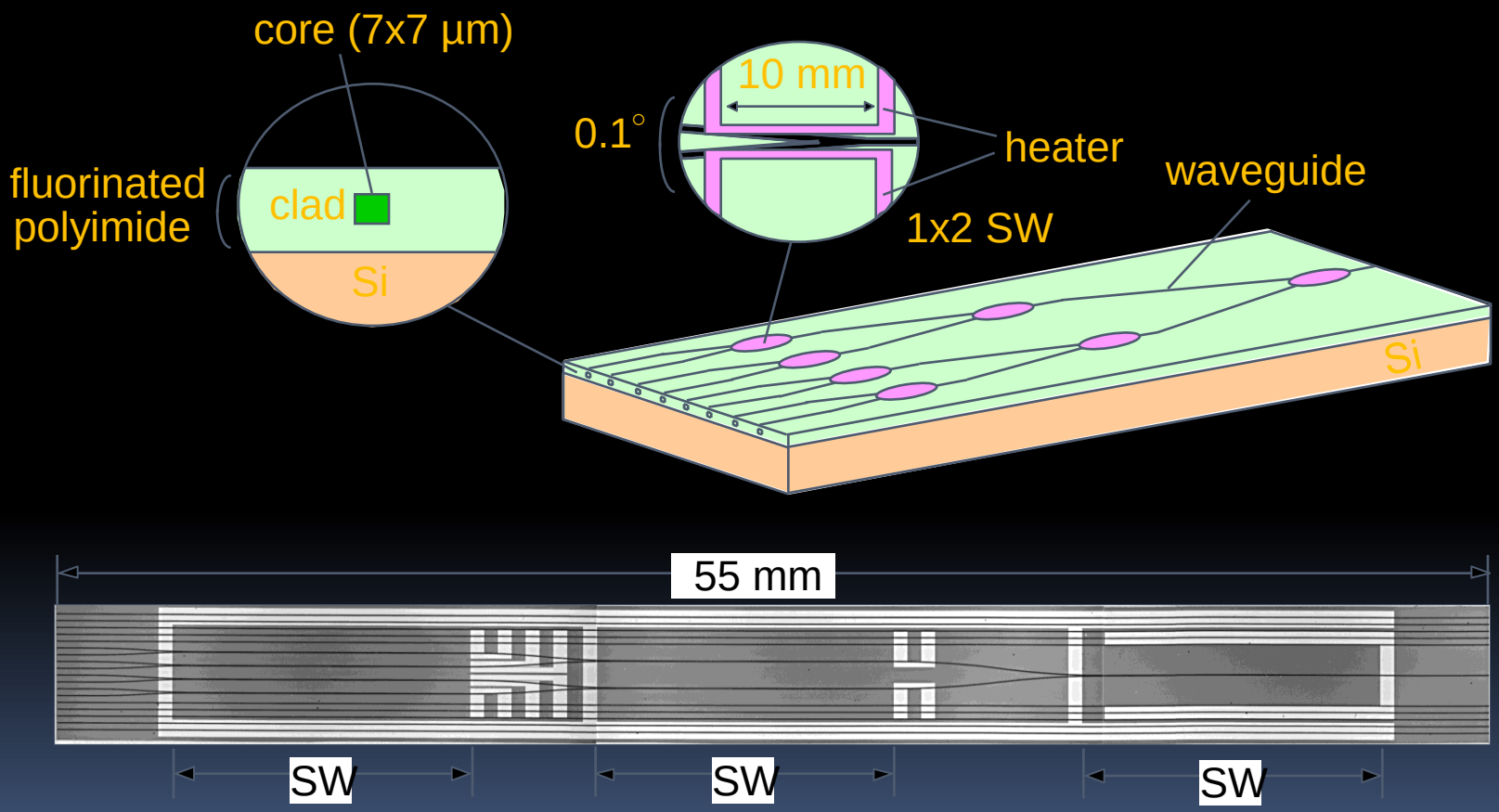


Source: BBV simulation



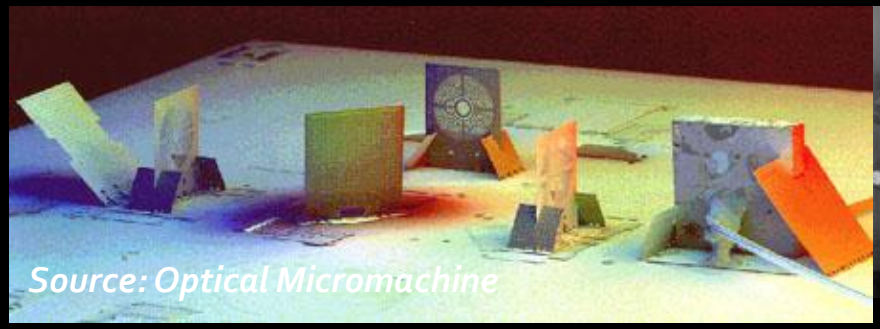
- E-O, Thermo-optic, AO switch
- Can also be designed for I-switching
- Oxide (LiNbO3), EO organic/polymers, SOI, Polyimide

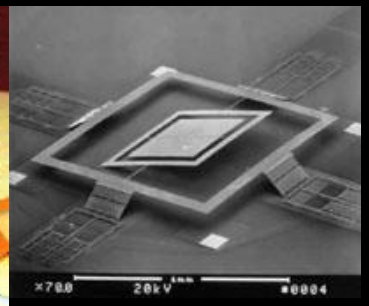
1 x 8 Polymeric Digital Optical Switch

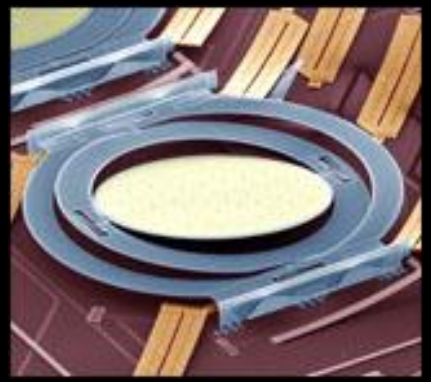


Source: Hitachi Central Research Lab.

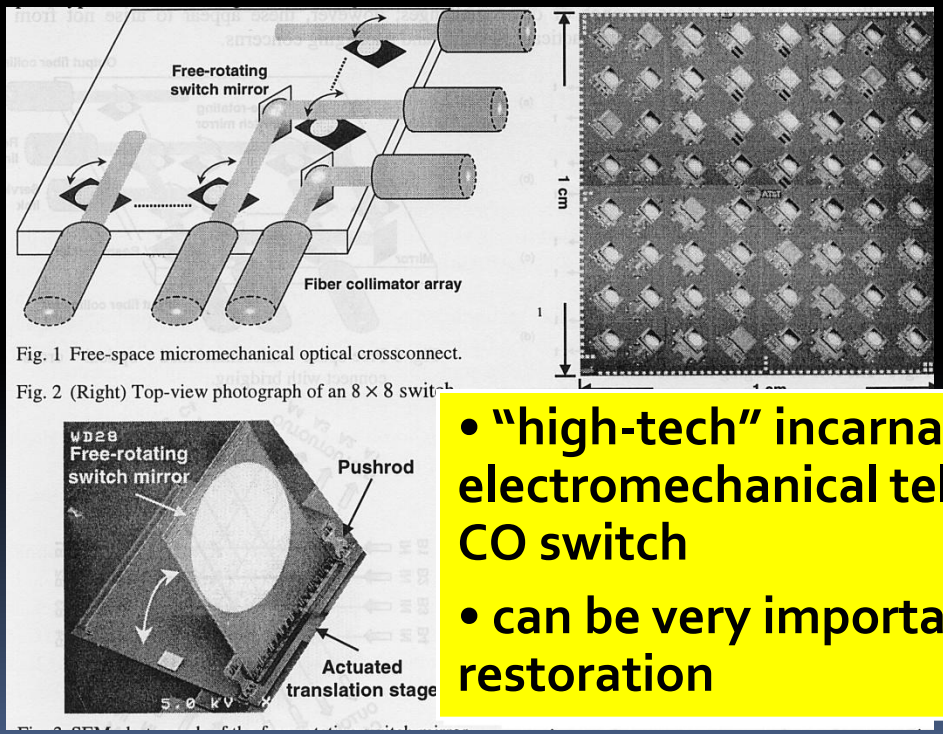
MEMS mirror switch







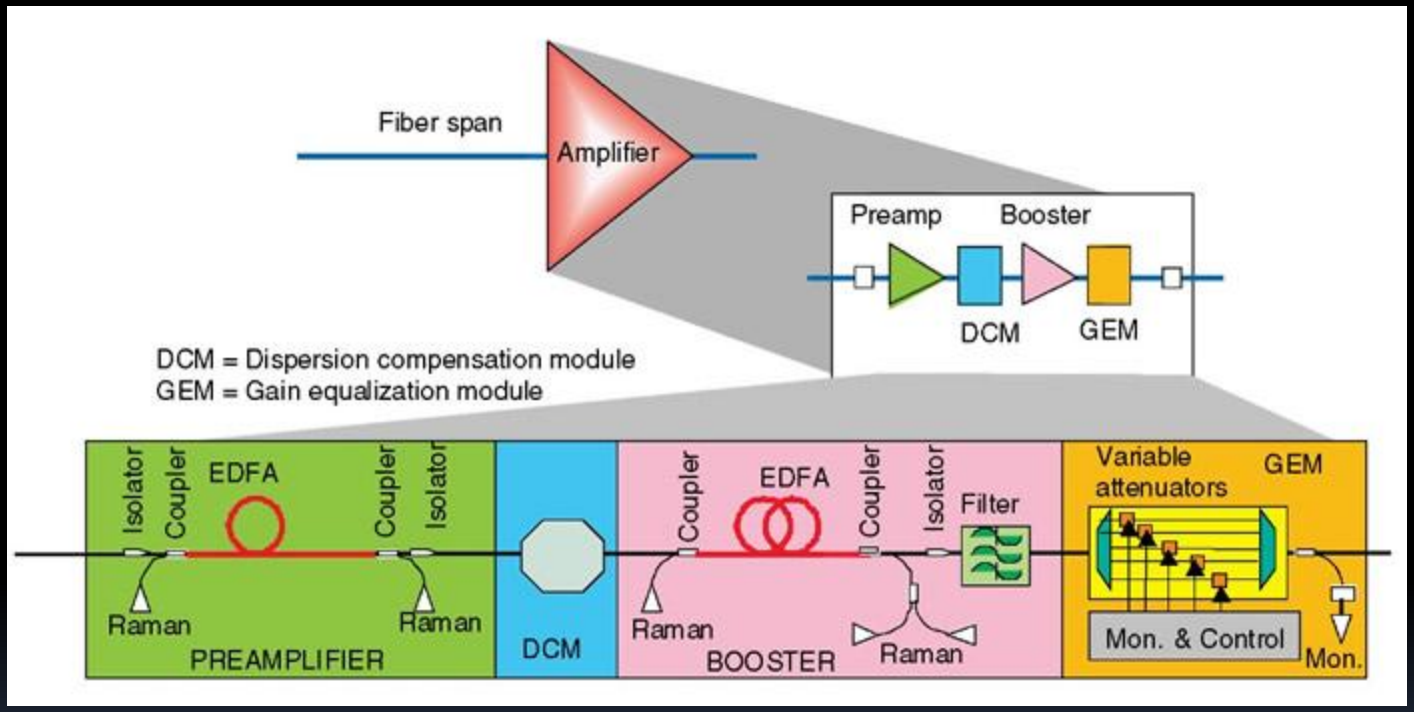
Lucent WaveStar™ mirror



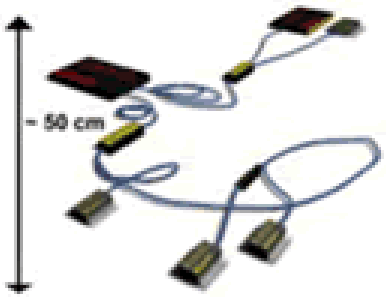
- "high-tech" incarnation of electromechanical telephone CO switch
- can be very important in restoration

Source: AT&T Labs

PHOTONIC INTEGRATED CIRCUIT (PIC)

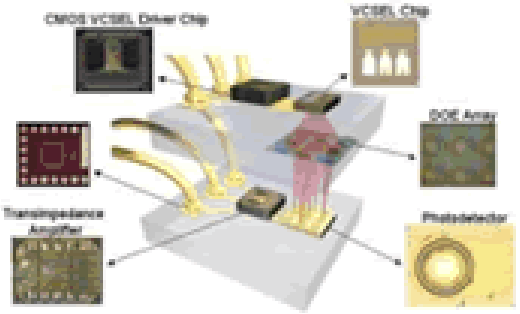

Fiber span
Amplifier
Preamp
Booster
DCM
GEM
DCM = Dispersion compensation module
GEM = Gain equalization module
Isolator
Coupler
EDFA
Coupler
Isolator
Raman
Raman
PREAMPLIFIER
DCM
Coupler
EDFA
Coupler
Isolator
Filter
Raman
Raman
BOOSTER
Variable attenuators
GEM
Mon. & Control
Mon.

Current Technology



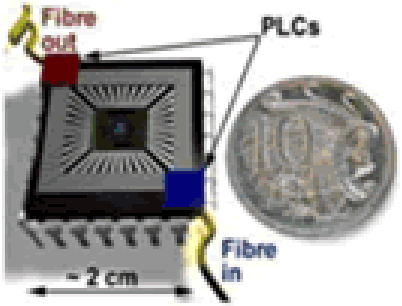
Expensive discrete components linked by optical fiber (non-silicon materials)

Example of Proposed Interim Solution



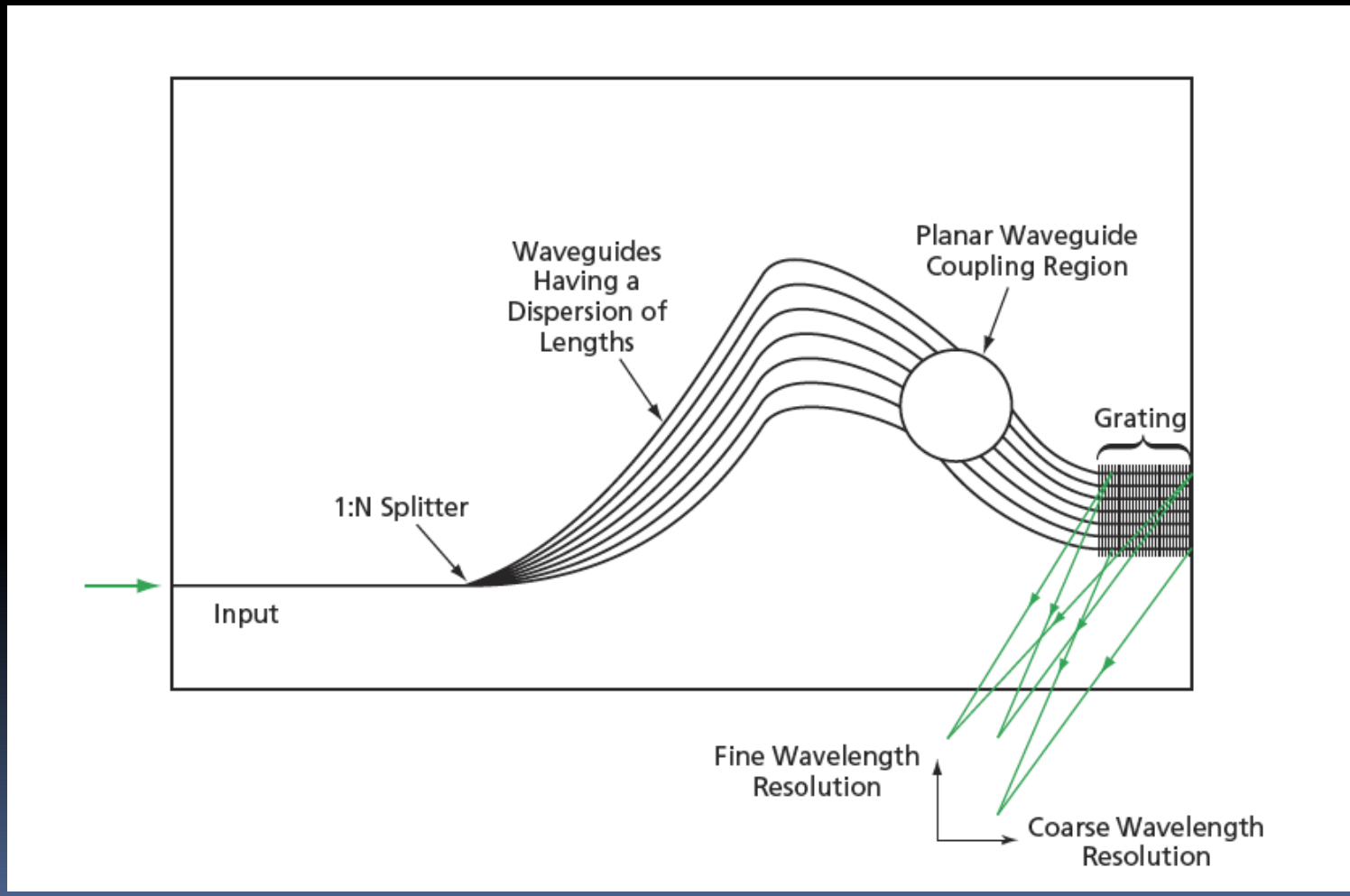
Expensive discrete components integrated on a common platform

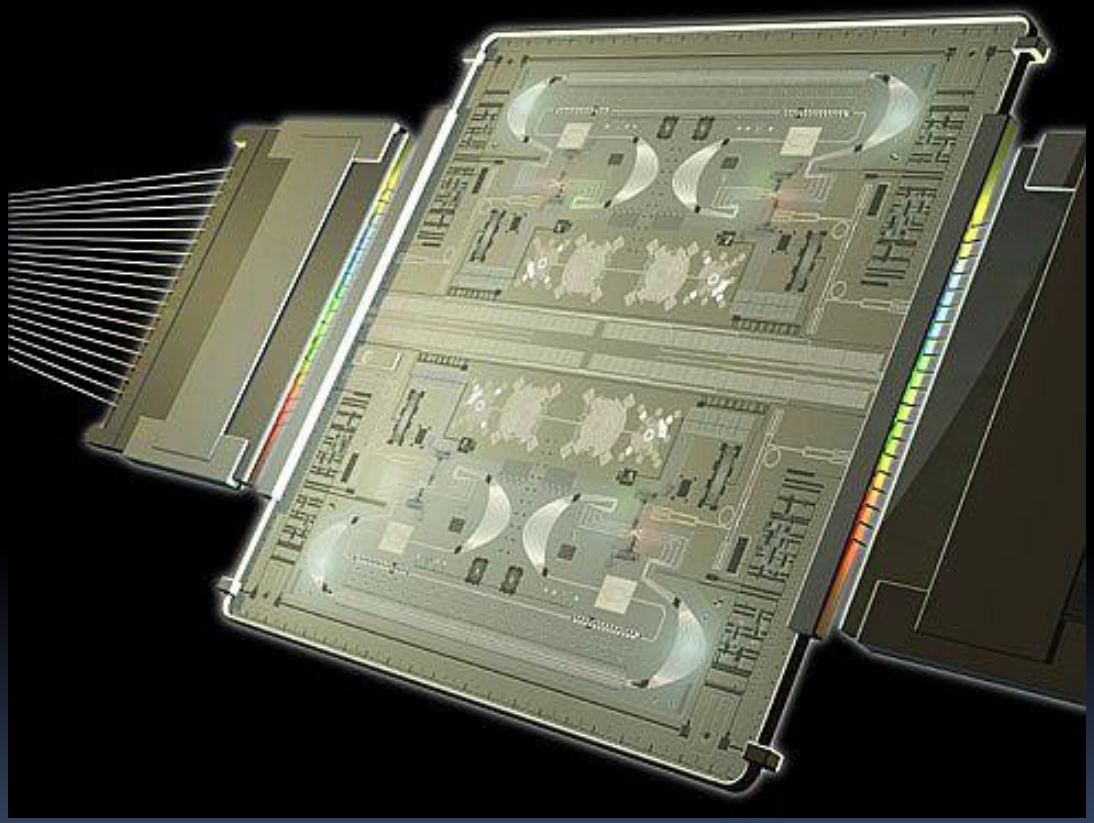
Ultimate Objective

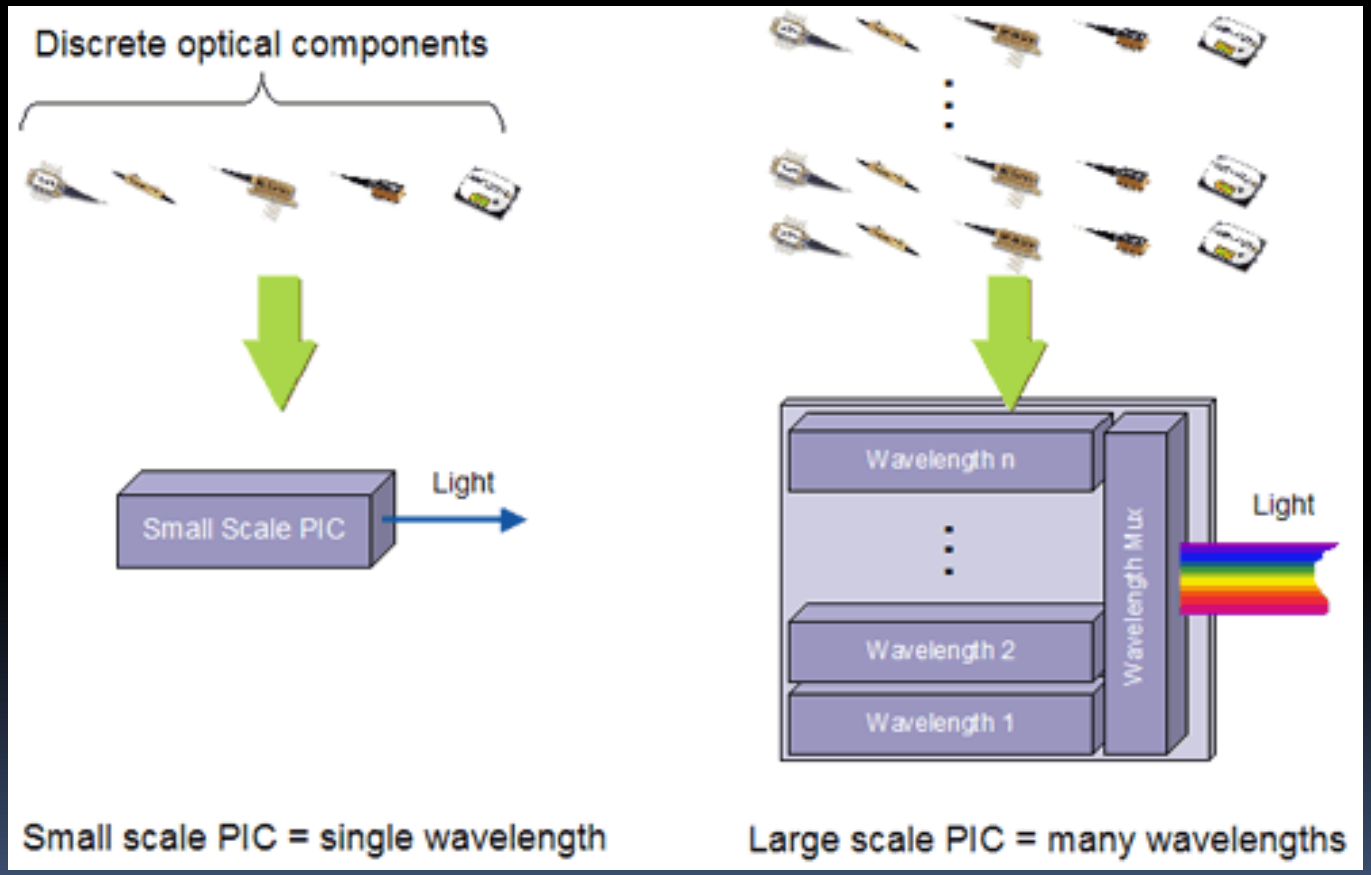


Fully Integrated ULSI (all-silicon based materials)

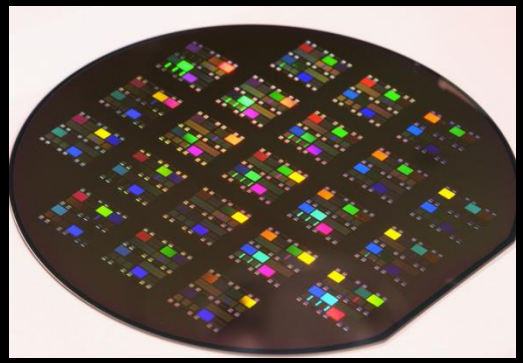
Potential for significant reduction in costs!

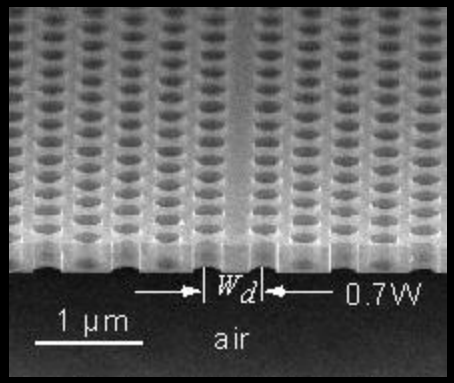

Waveguides
Having a
Dispersion of
Lengths
Planar Waveguide
Coupling Region
Grating
1:N Splitter
Input
Fine Wavelength
Resolution
Coarse Wavelength
Resolution

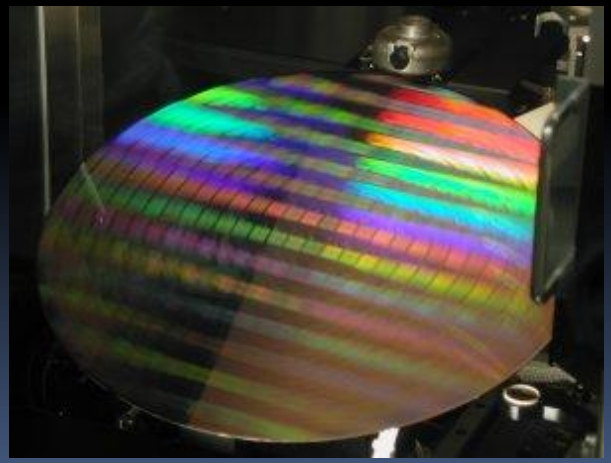


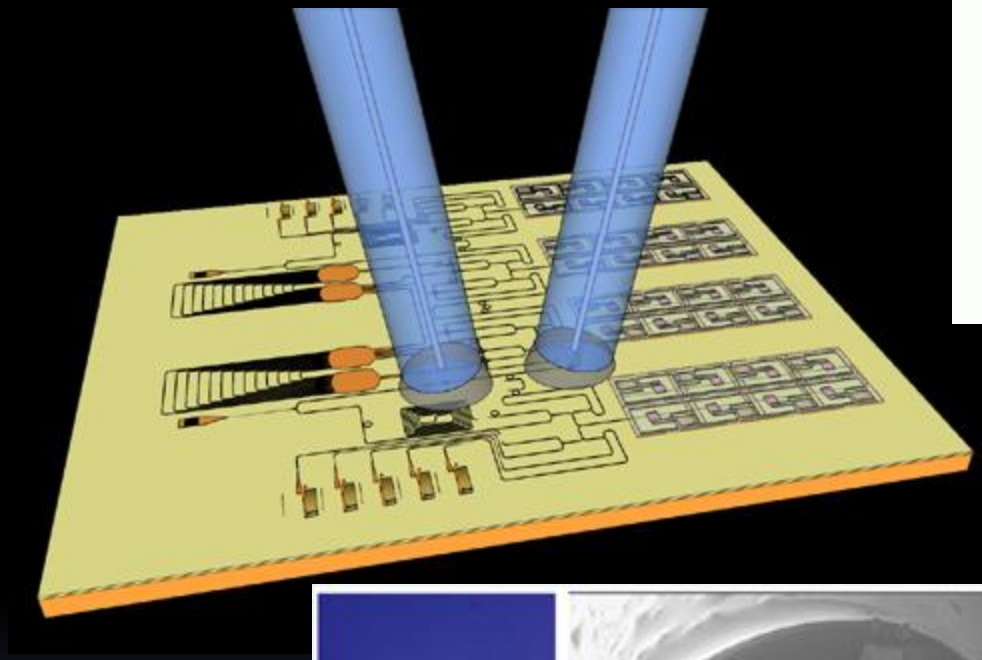

Discrete optical components
Small Scale PIC
Light
Small scale PIC = single wavelength
Wavelength n
Wavelength 2
Wavelength 1
Wavelength Mux
Light
Large scale PIC = many wavelengths

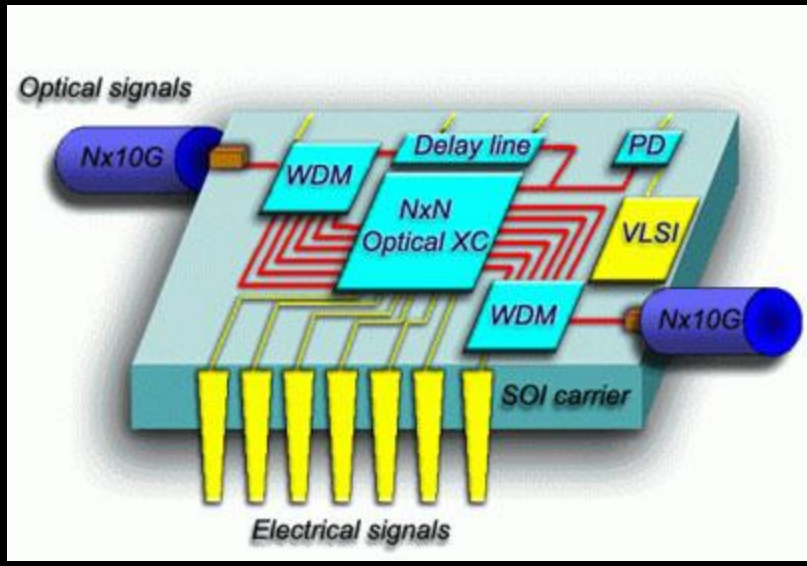
Photonic wafer and chip

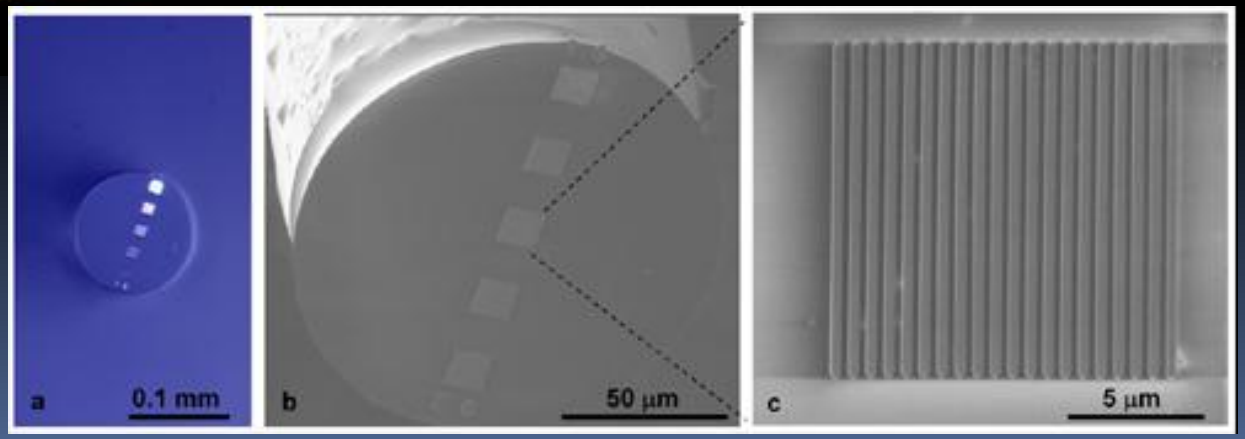






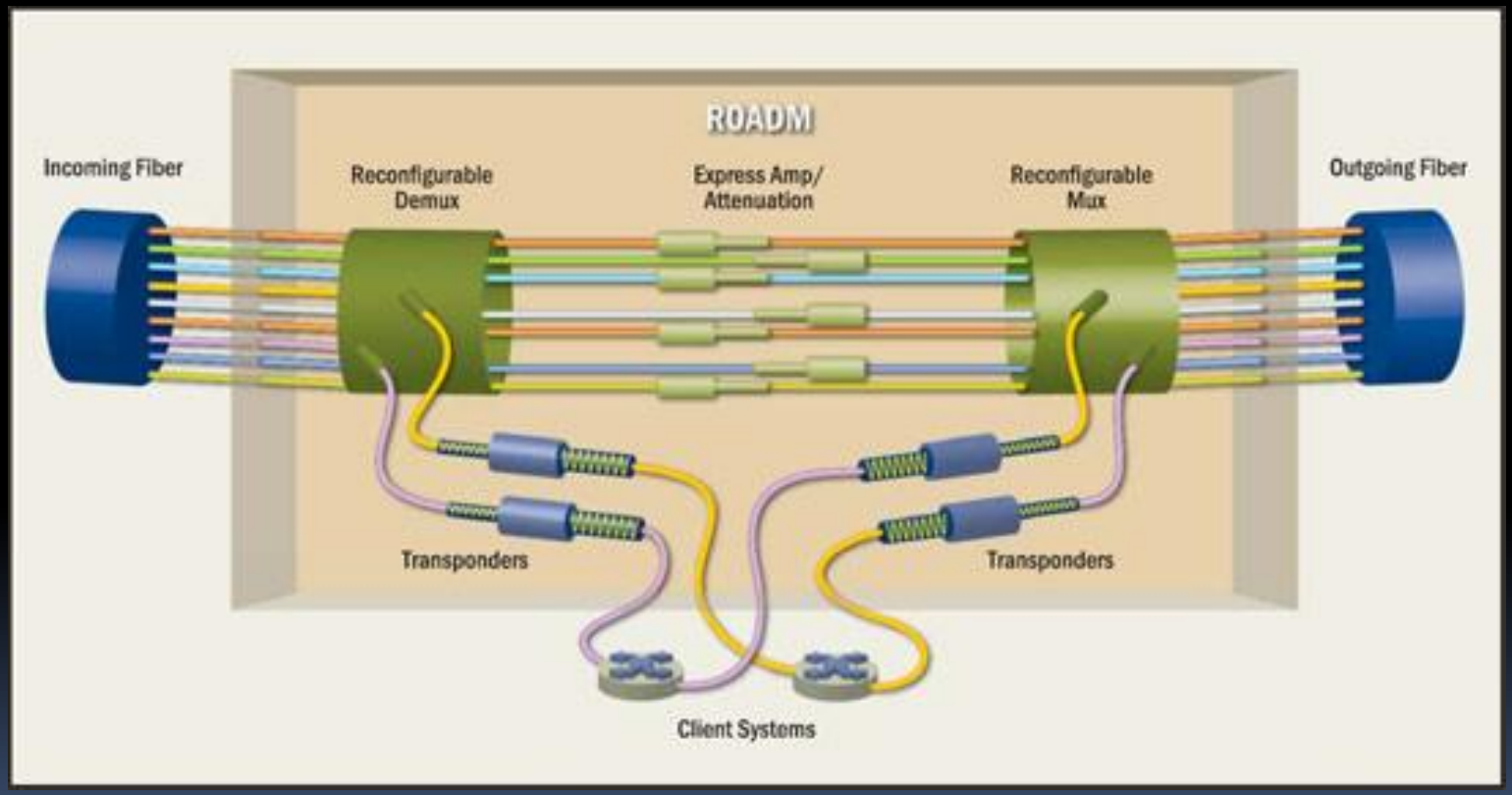



Optical signals
Nx10G
WDM
Delay line
PD
NxN
Optical XC
VLSI
WDM
Nx10G
SOI carrier
Electrical signals

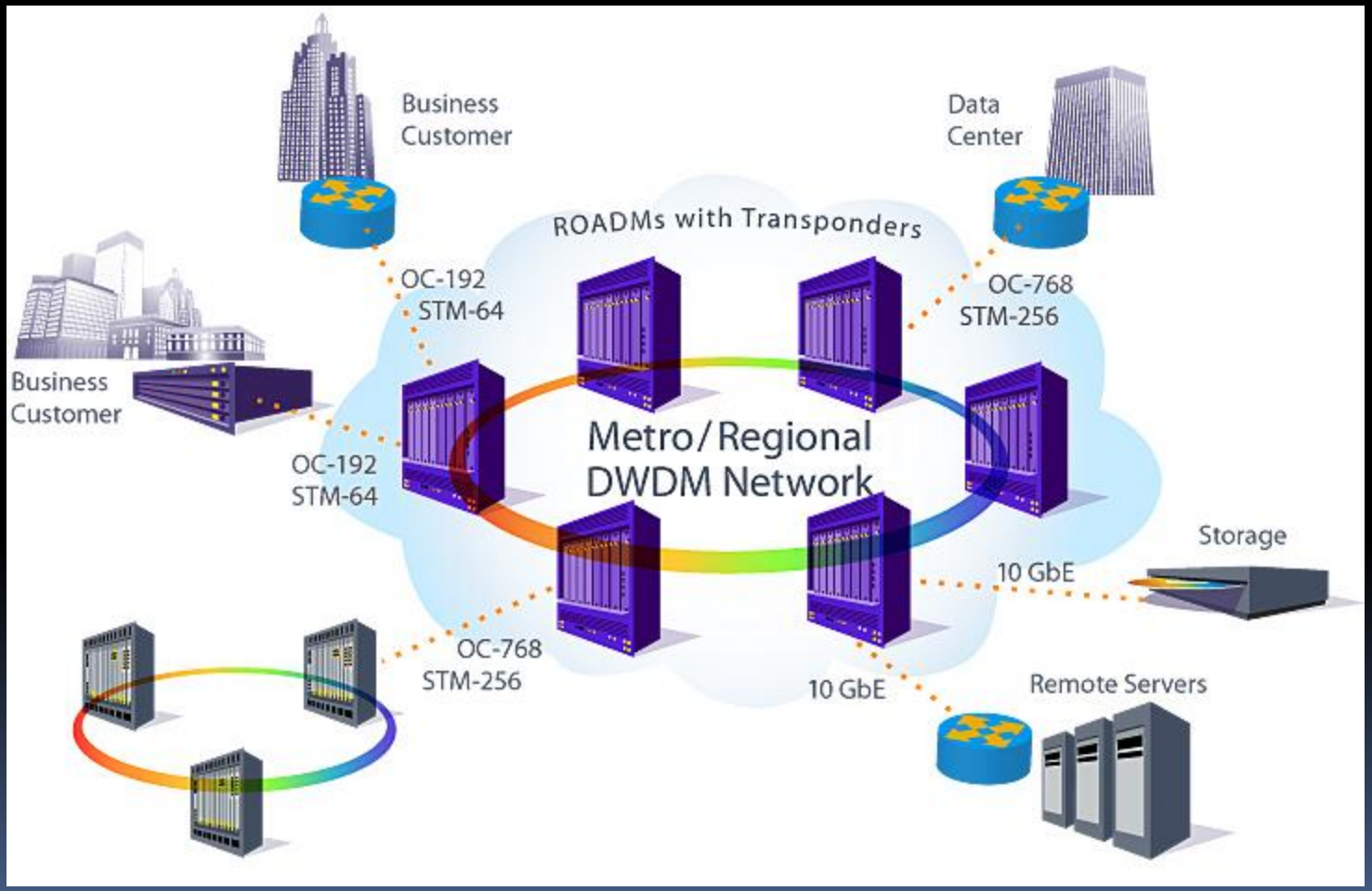

a
0.1 mm
b
50 μm
c
5 μm

PHOTONIC INTEGRATED CIRCUIT APPLICATION: RECONFIGURABLE OPTICAL ADD/DROP MUX (ROADM)

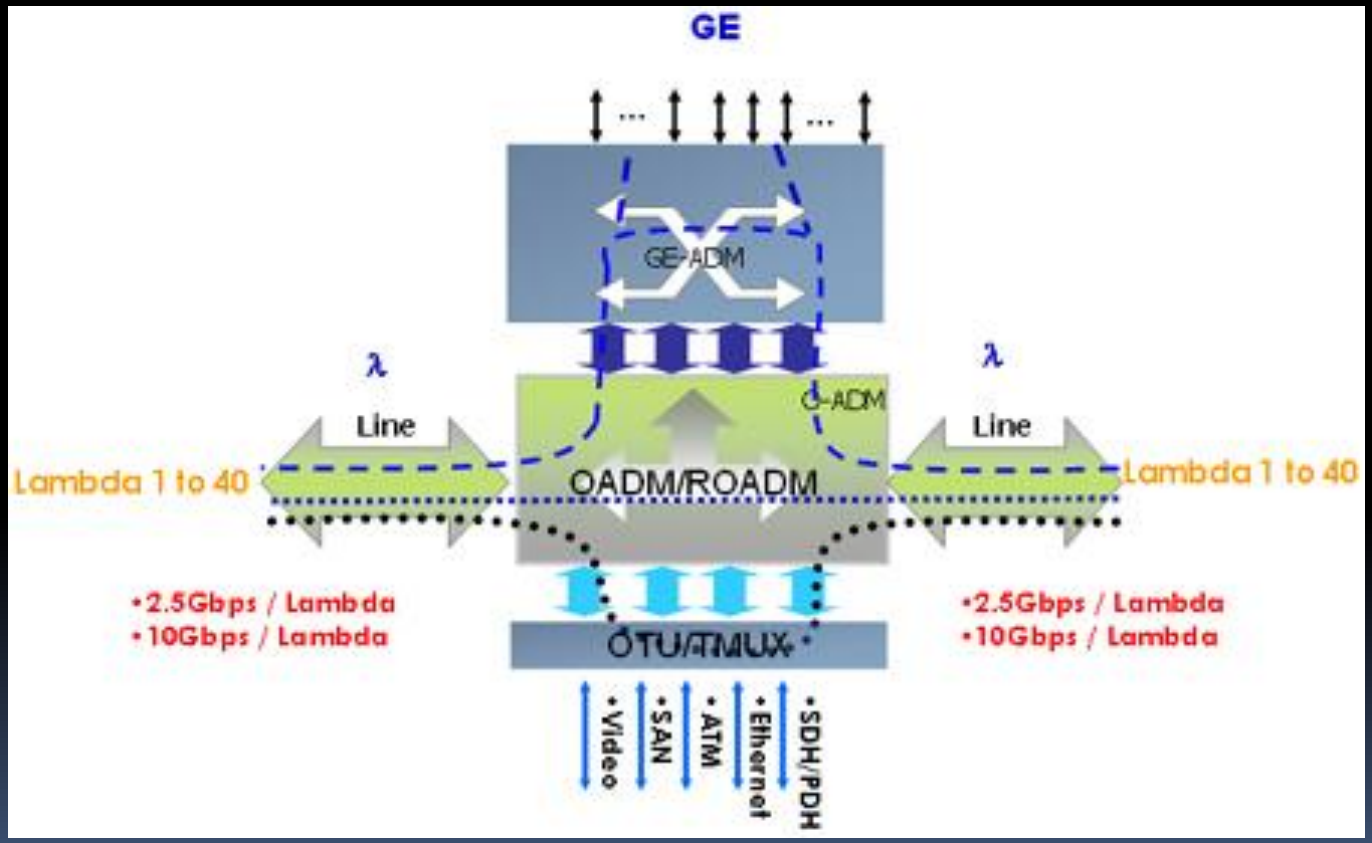
ROADM: Functional concept



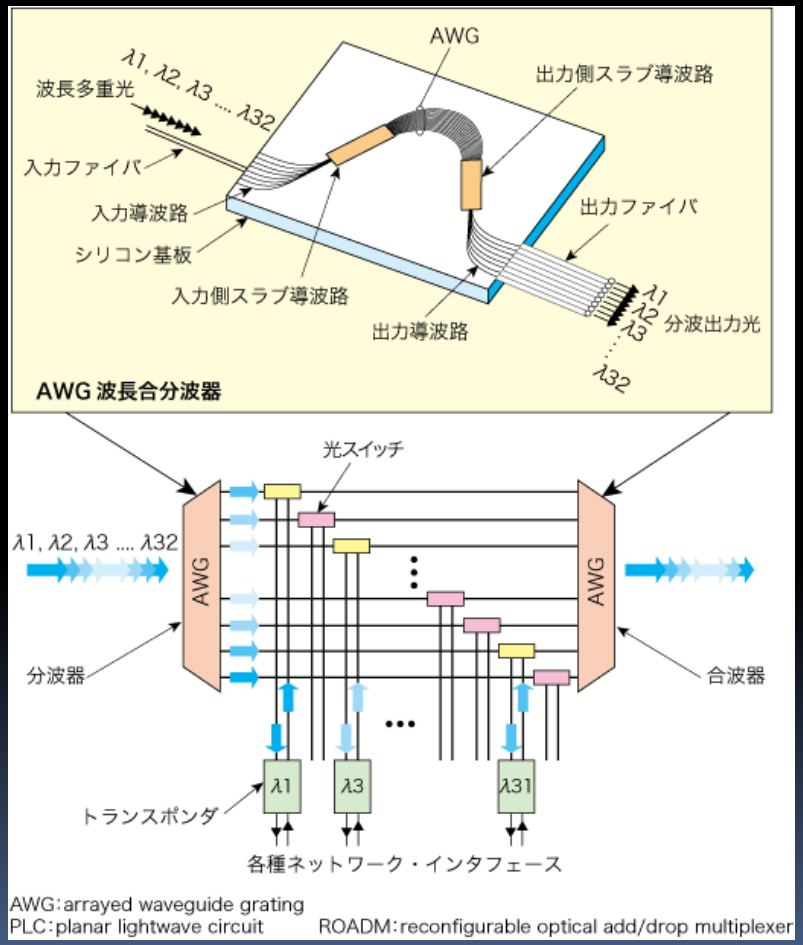
ROADM in Network applications



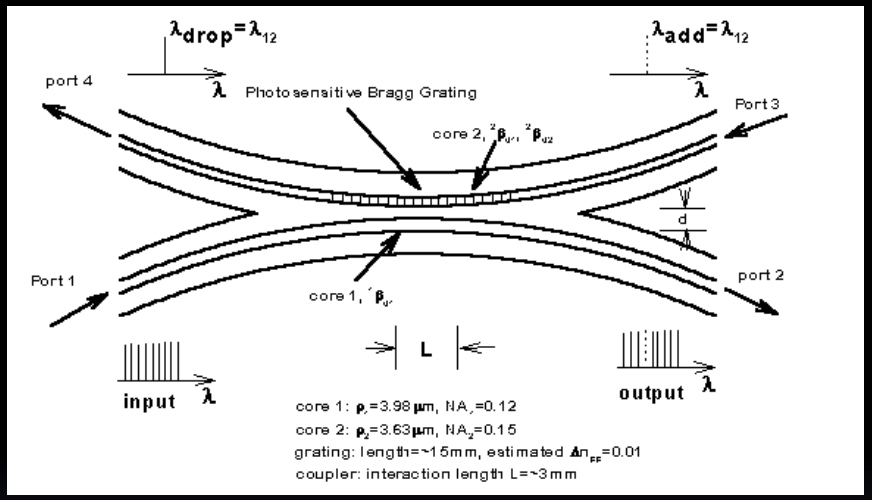
ROAD concepts



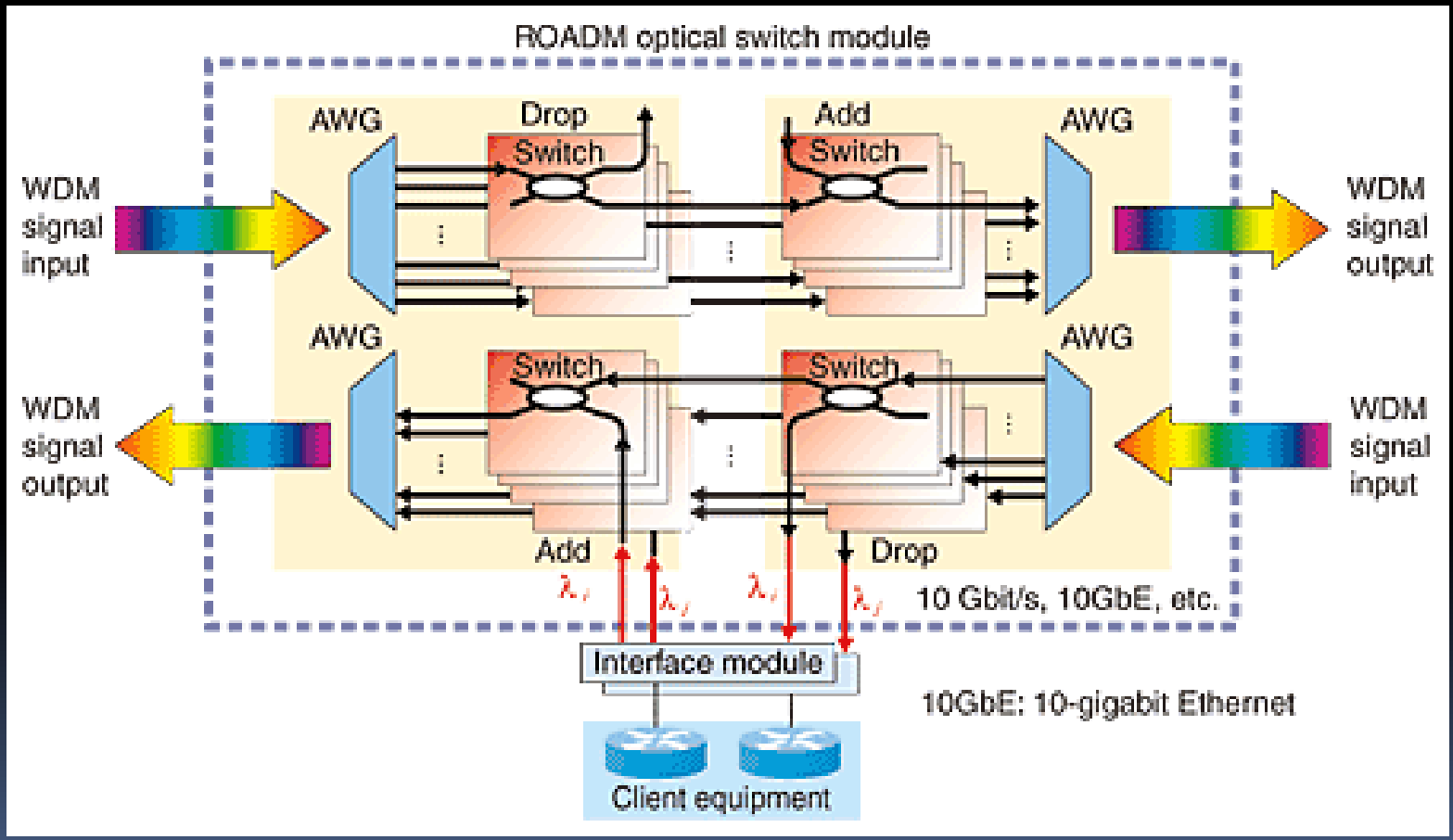
ROADM



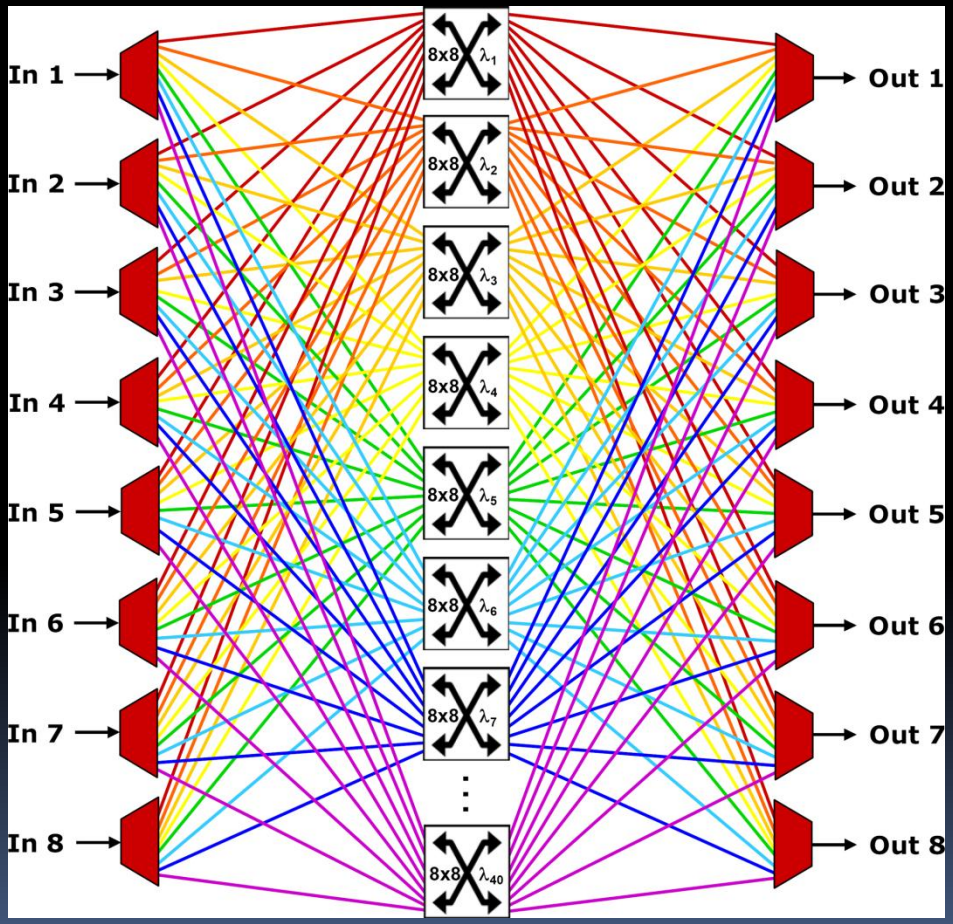
Application of Bragg grating coupler



ROAD concepts



ROADM with Optical Cross Connect



Outline

- Introduction and concepts
- Types of devices
  - Passive splitters, combiners, couplers
  - Wavelength-based devices for DWDM
  - Modulator/demodulator (amplitude and phase), compensator (dispersion)
  - Others: switch, high-functional modules, photonic integrated circuits (PIC)
- Summary

Photonic Devices and Integrated Circuits

- A wide range of devices that perform all key functions in a modern optical communication network: end-to-end
- Crucial in enabling advanced network architecture (compared to old optical communication system) by offering unique functionality along with practicality
- The shaping, conditioning of light will continue to be the most important technology in future optical communication