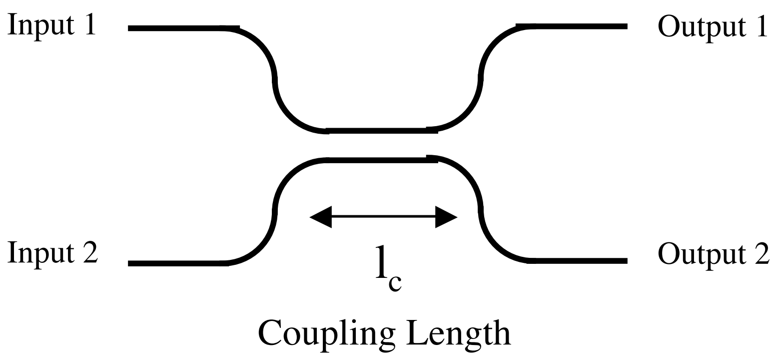
Lecture 13: Optical Combiners, Filters, Multiplexers, AWGRs and Switches

Optical Couplers

Directional Coupler



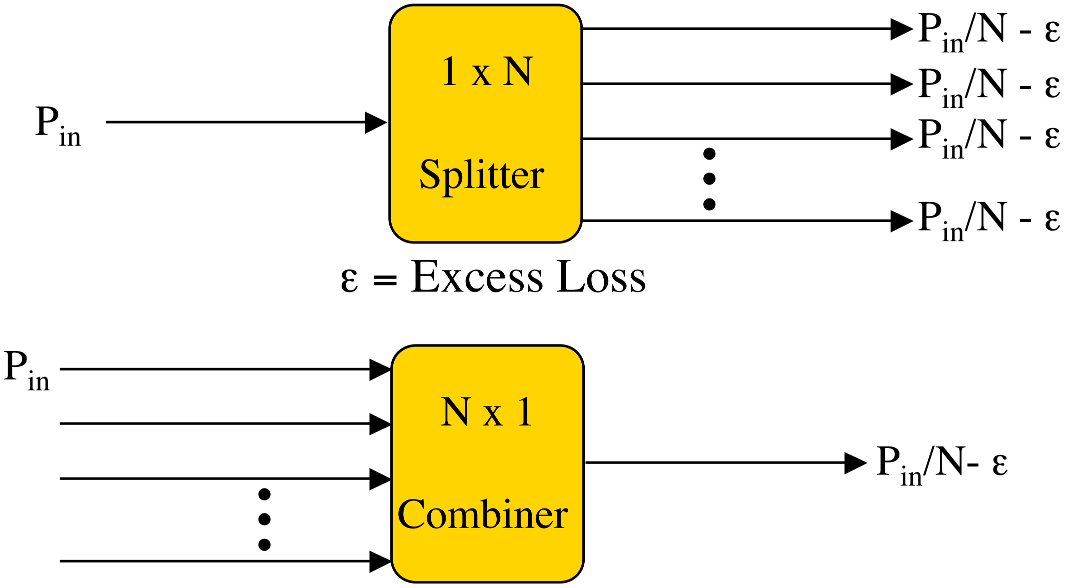
$$\begin{pmatrix} T_{11}(\lambda) \\ T_{12}(\lambda) \end{pmatrix} = \begin{pmatrix} \cos^2(\kappa l_c) \\ \sin^2(\kappa l_c) \end{pmatrix}$$

$T_{11}(\lambda)$ is the power transfer function from input 1 to output 1.
$T_{12}(\lambda)$ is the power transfer function from input 1 to output 2.
κ is a function of the waveguide geometry, separation and physical parameters

Example: For $\kappa l = (2m+1)\pi/4$, and m is a nonnegative integer, power at the input will be split evenly between the two output ports. This is also known as a 3-dB coupler. Note that for a signal incident at one input the signals at both outputs will have a $\pi/2$ relative phase shift.

N x N Splitters and Combiners

- Important rule for optical splitters 1xN and combiners Nx1
  - If the device is frequency and polarization independent, the power loss is at least equal to *1/N*

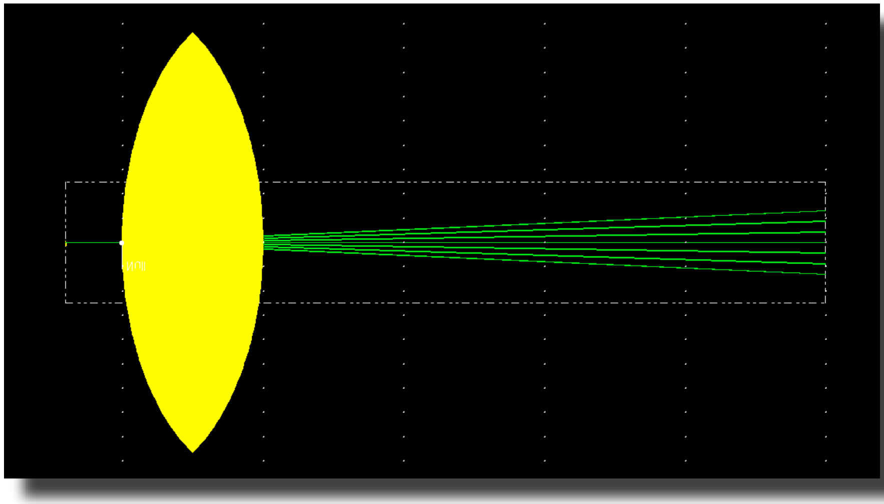


ε = Excess Loss

- The total loss of the device is thus:

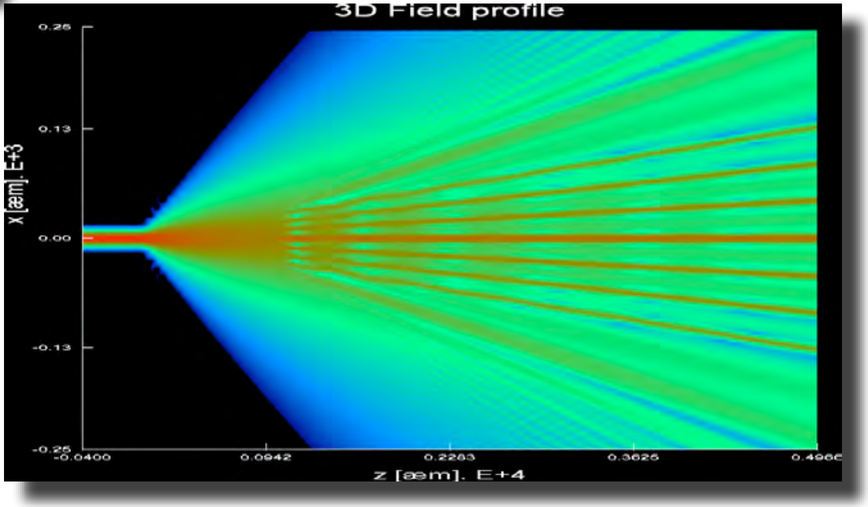
$$\boxed{Loss\big|_{dB} = 10 \cdot \log_{10}(N) + \varepsilon_{dB}}$$

1xN Splitters and Combiners



Integrated optic 1xN device layout

Optical beam propagation simulation showing beams (red) directed from input port to output ports



Splitter/combiner typical characteristics

- The excess loss is of the order of 1 dB
  - Commercial devices are available up to 16 ports
  - Polarization dependent loss may be as low as 0.2 dB
  - Standard devices show partial frequency dependence (1-2 dB over the 30nm C-band)
  - Ultra-flat devices (over more than 30 nm) are available
- 1x2 splitters with different splitting ratios
  - 50/50 splitters (3 dB couplers)
  - 10/90, 5/95, 1/100 splitters (sometimes called “optical taps”)

Wavelength Filters and Multiplexers

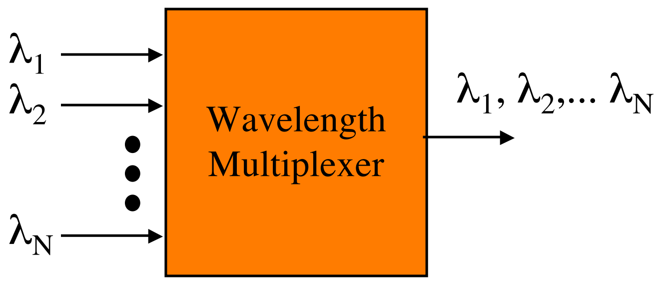
Class I

$\lambda_1, \lambda_2, \ldots \lambda_N$

Wavelength Filter

λ_i

Class II



λ_1

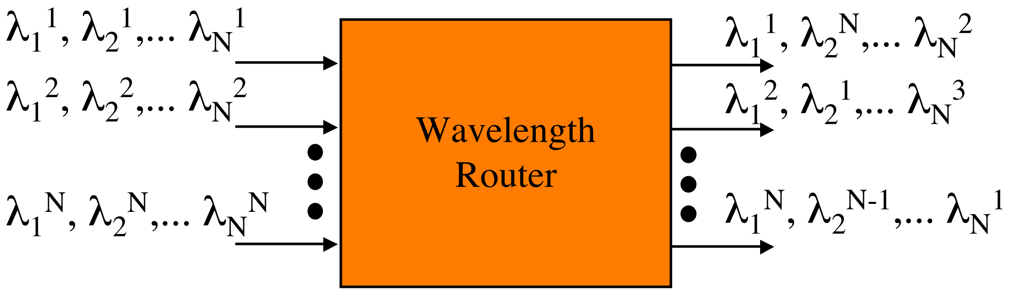
λ_2

λ_N

Wavelength Multiplexer

$\lambda_1, \lambda_2, \ldots \lambda_N$

Class III



$\lambda_1^{1}, \lambda_2^{1}, \ldots \lambda_N^{1}$

$\lambda_1^{2}, \lambda_2^{2}, \ldots \lambda_N^{2}$

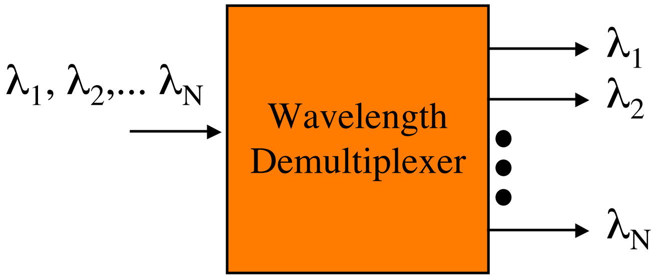
$\lambda_1^{N}, \lambda_2^{N}, \ldots \lambda_N^{N}$

Wavelength Router

$\lambda_1^{1}, \lambda_2^{N}, \ldots \lambda_N^{2}$

$\lambda_1^{2}, \lambda_2^{1}, \ldots \lambda_N^{3}$

$\lambda_1^{N}, \lambda_2^{N-1}, \ldots \lambda_N^{1}$



$\lambda_1, \lambda_2, \ldots \lambda_N$

Wavelength Demultiplexer

λ_1

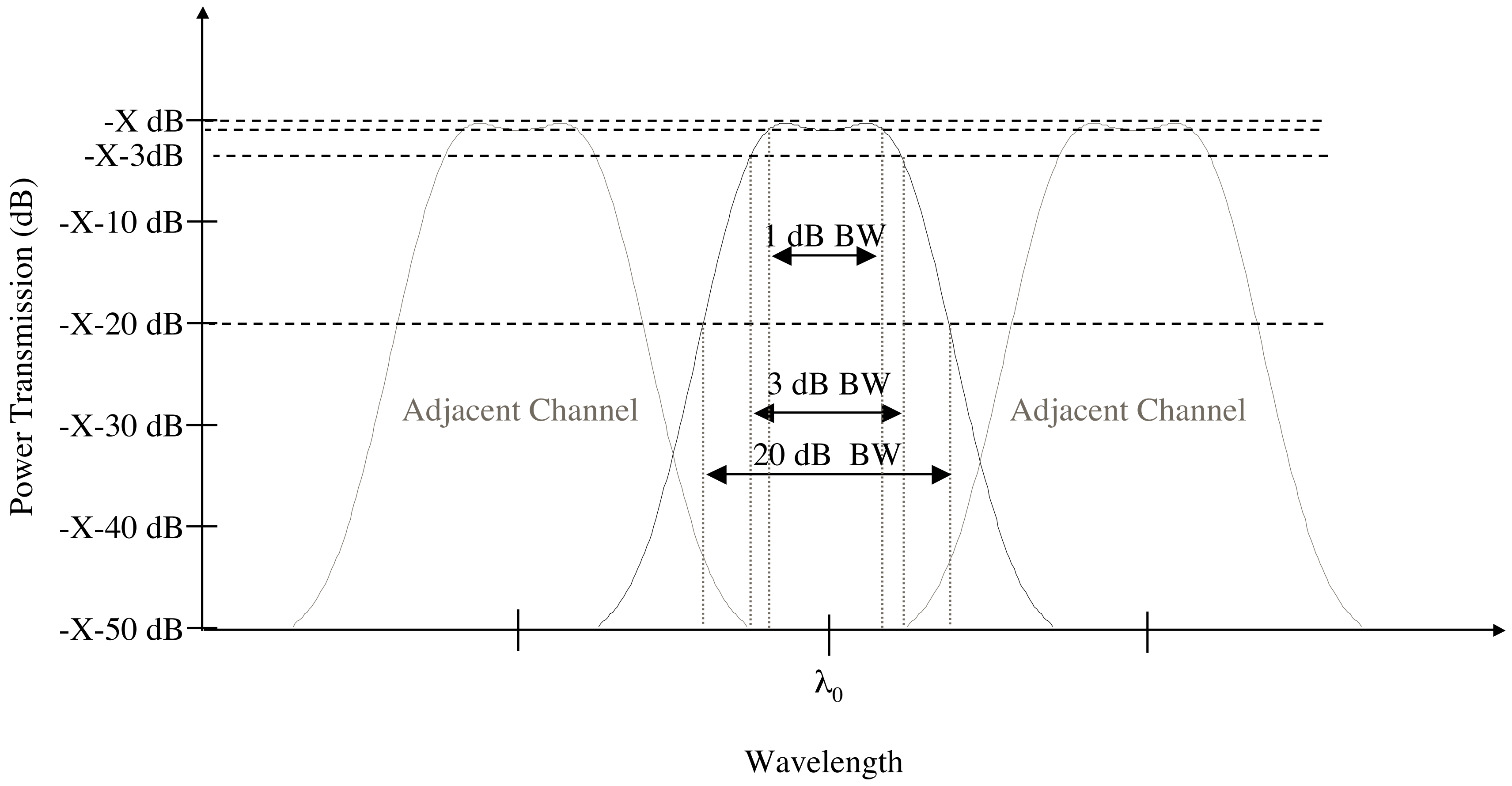
λ_2

λ_N

Wavelength Filters and Multiplexers

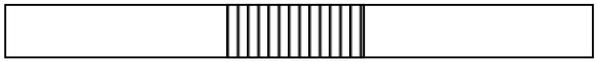
- Desirable Characteristics
  - Long term frequency stability and accuracy (low temperature sensitivity)
  - Flat passband function (important for cascading filters and tolerance to channel drift and misalignment)
  - Low crosstalk
  - Polarization independent
  - Low polarization mode dispersion (PMD)
  - Low insertion loss and polarization dependent loss (PDL)
  - High return loss
  - High resolution for DWDM systems
  - Large free spectral range (FSR) for most applications

Wavelength Filter Passband Characteristics



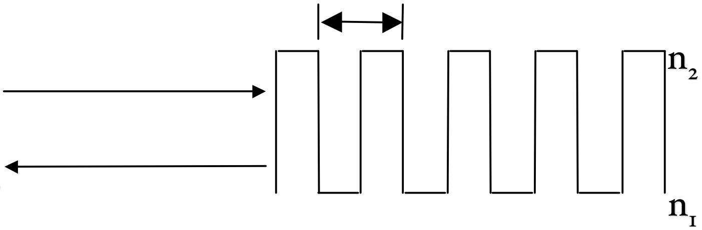
Fiber Bragg Gratings (FBG)

Low loss (0.1 dB)
Accurate wavelength (±0.05nm)
Flat top filter passband
High adjacent channel crosstalk suppression (40 dB)
Temperature coefficient ≈ 0.07 - 1.25 x 10^{-2} nm/°C
Passband can be tuned by stretching fiber



Bragg grating section

Optical fiber



Incident optical wave at λ_o

Reflected optical wave at λ_o

Periodic variation in refractive index along direction of propagation

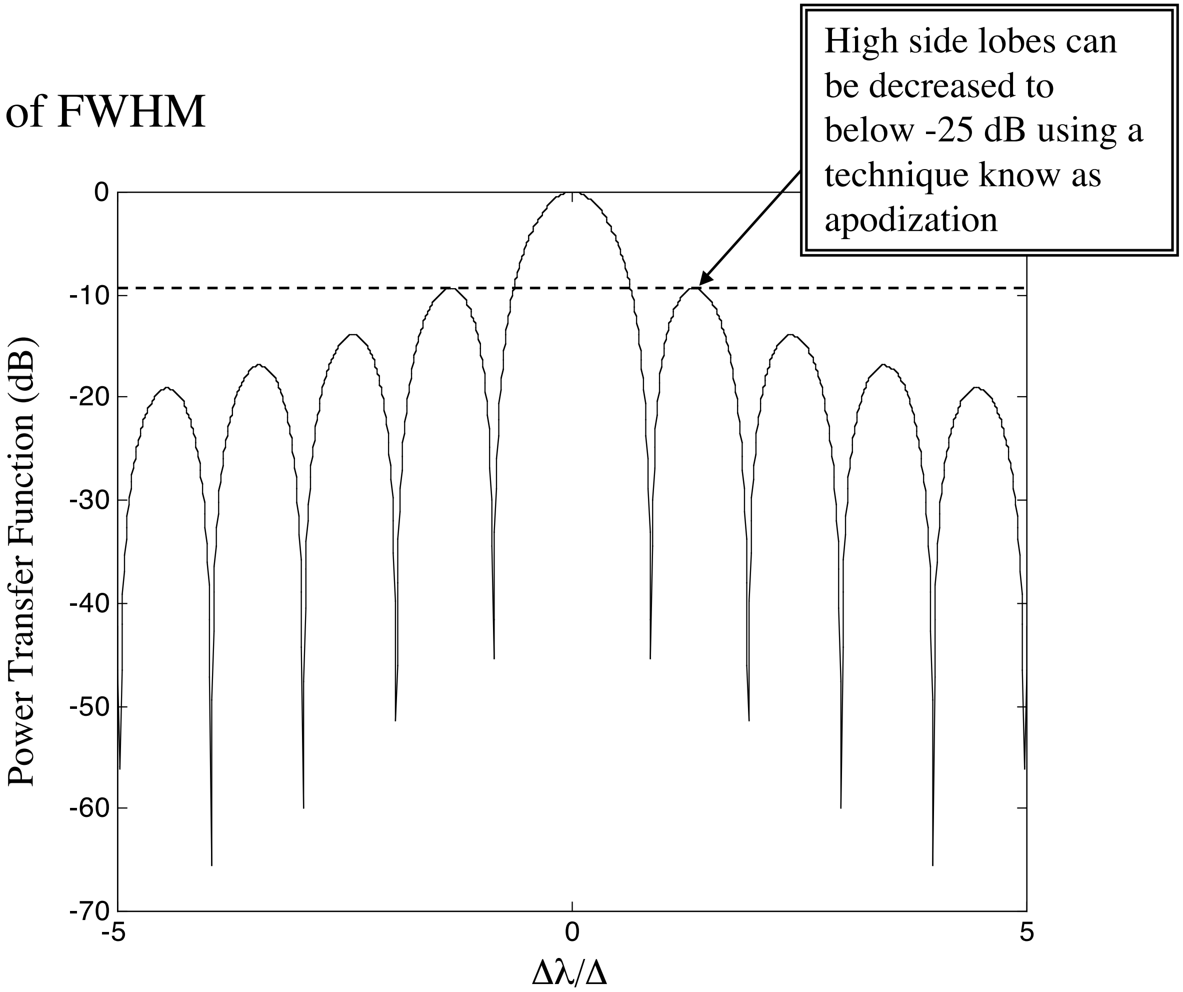
λ_o will be reflected back if the following condition is meet

$$\lambda_0 = 2n_{eff}\Lambda$$

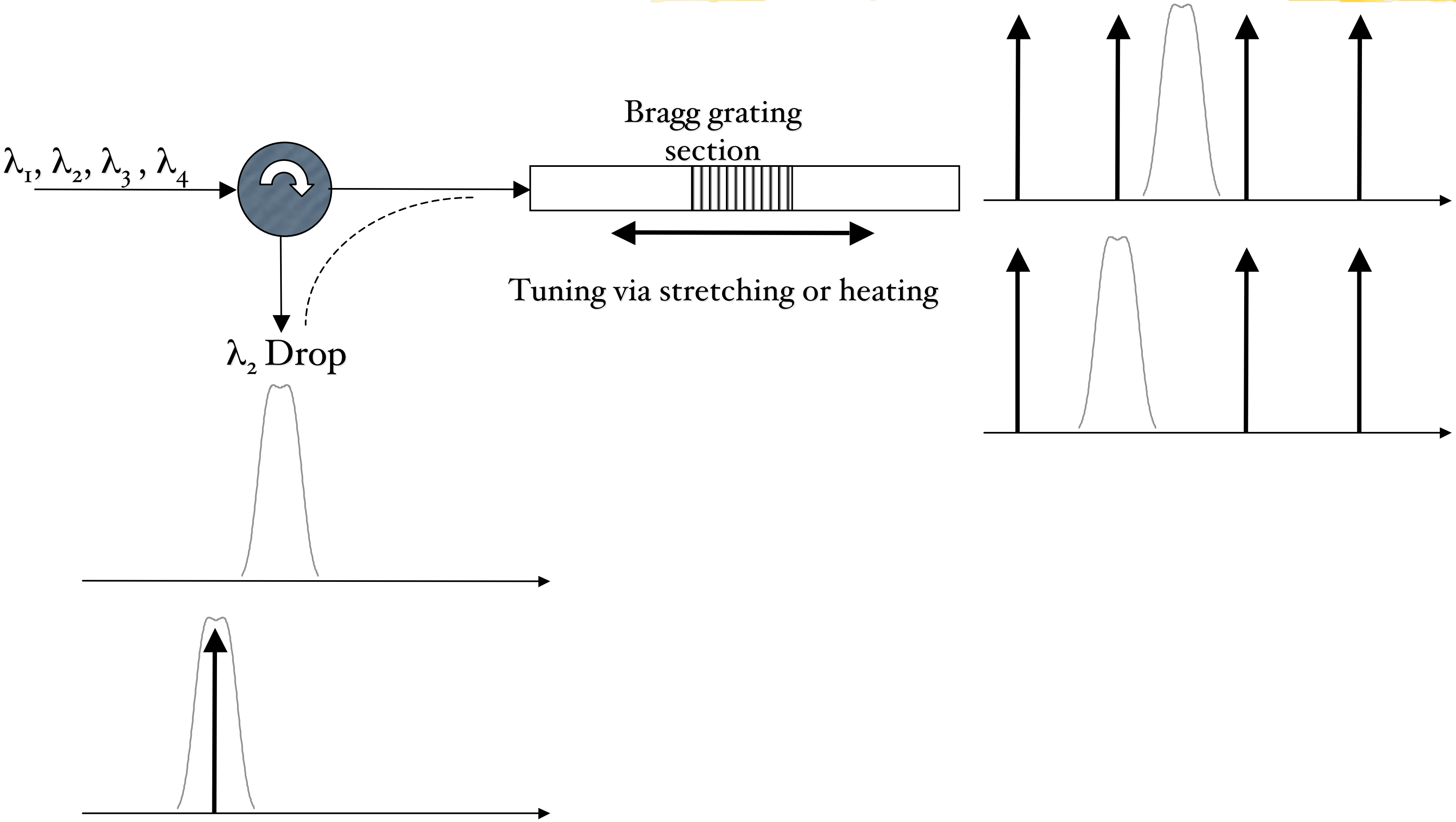
Bragg Grating Filter Transmission

$\Delta\lambda = \lambda - \lambda 0$

Δ is a measure of FWHM



Tunable FBGs for ROADM



$\lambda_1, \lambda_2, \lambda_3, \lambda_4$

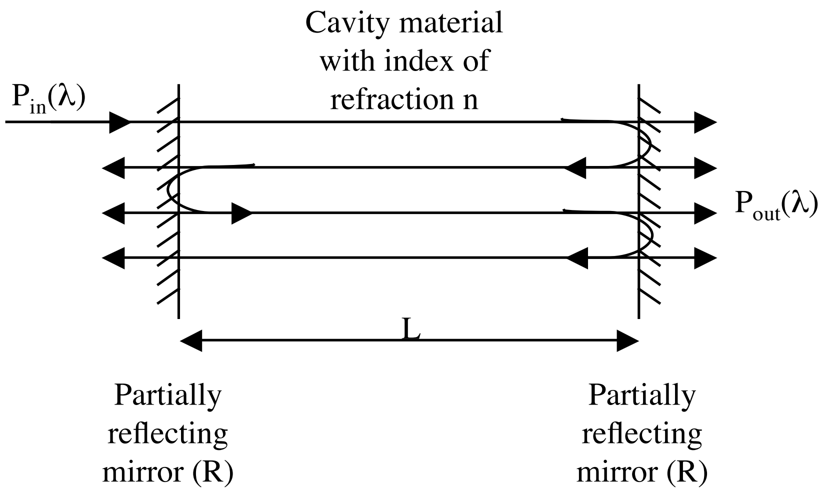
Bragg grating section

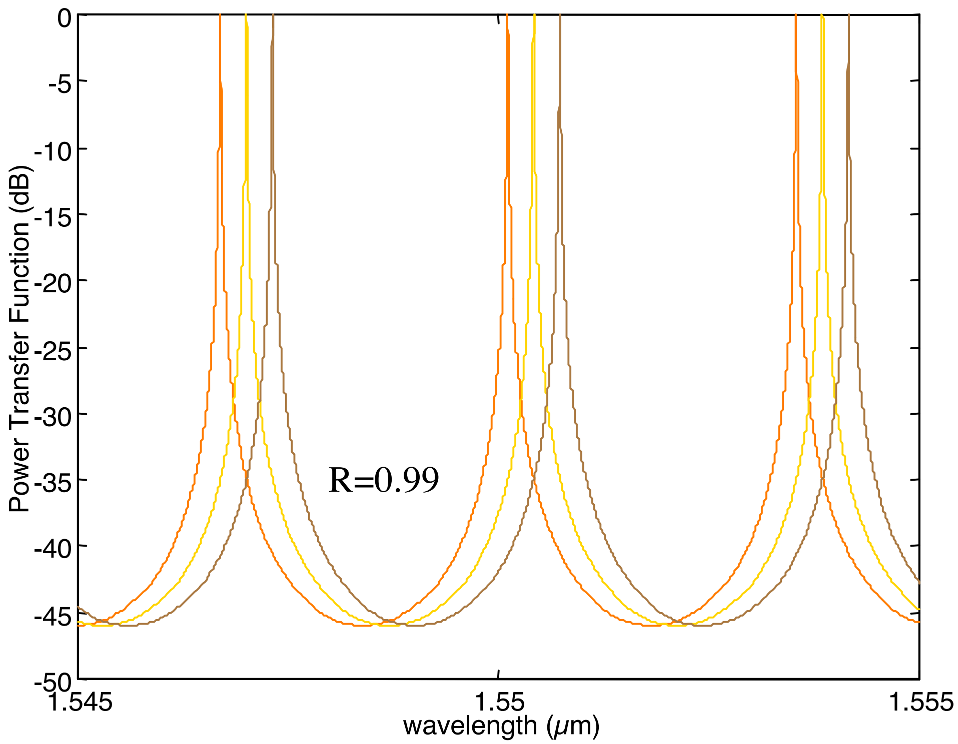
Tuning via stretching or heating

λ_2 Drop

Fabry-Perot Filters

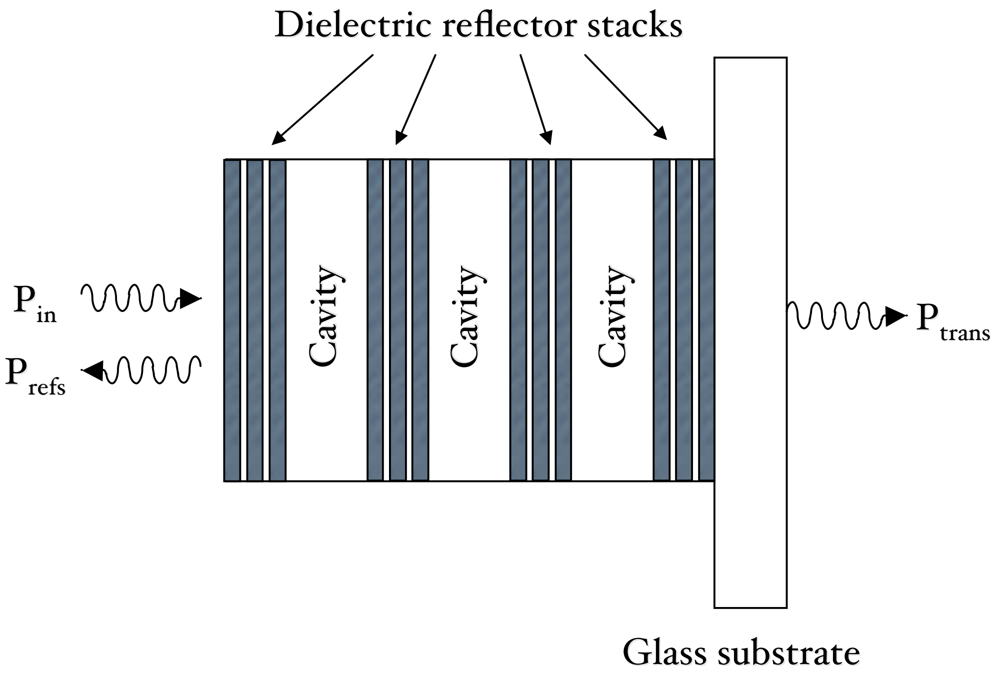
- Can be tuned to a different wavelength by adjusting the cavity length (e.g., by piezoelectric crystal. High loss, polarization dependence and sharp passband limit use as WDM filter.

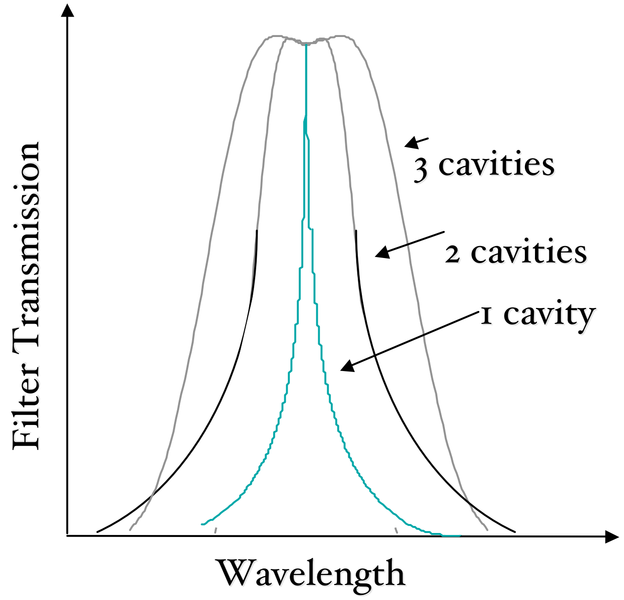




Multilayer Dielectric Thin-Film Filters (TFF)

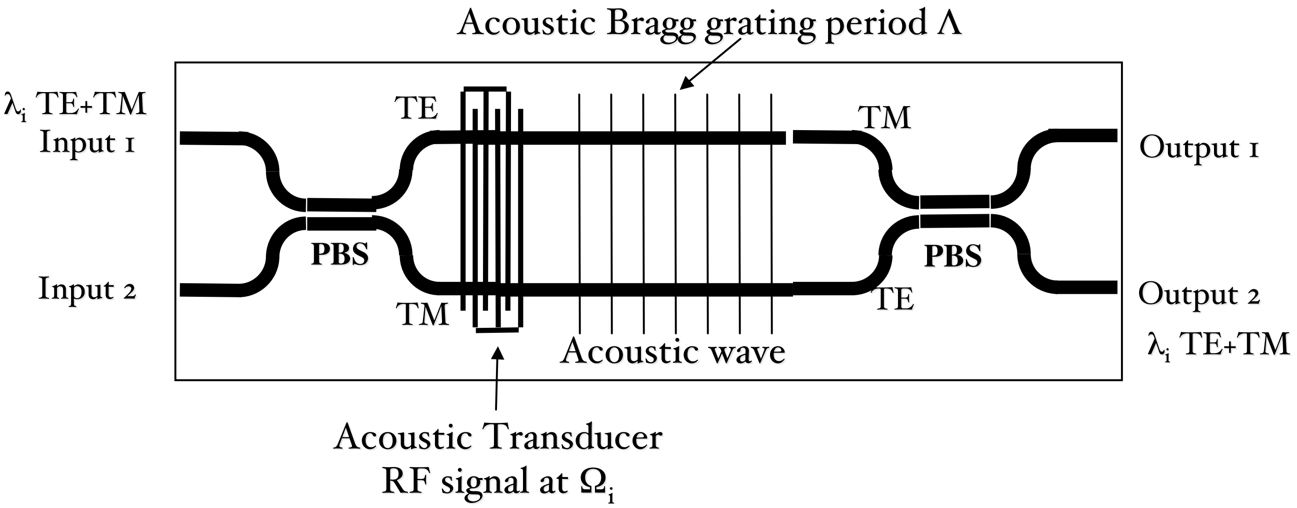
DTMFs can be designed to have flat passbands, low lows, low PDL and polarization sensitivity as well as sharp frequency rolloff.





Acoustooptic Tunable Filters

- Medium loss (greater than 6 dB)
- High PMD and PDL, polarization diverse architectures necessary
- Multichannel crosstalk issues

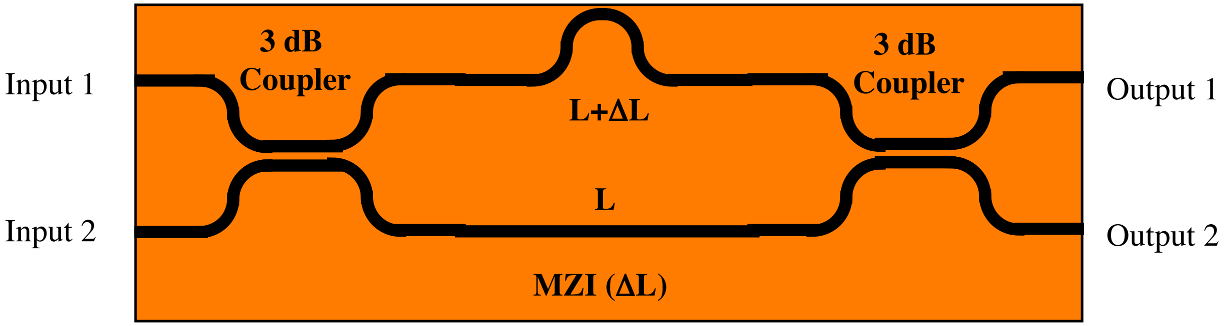


TE to TM conversion for λ_i
TM to TE conversion for λ_i

$$\frac{\eta_{TM}}{\lambda} = \frac{\eta_{TE}}{\lambda} \pm \frac{1}{\Lambda}$$

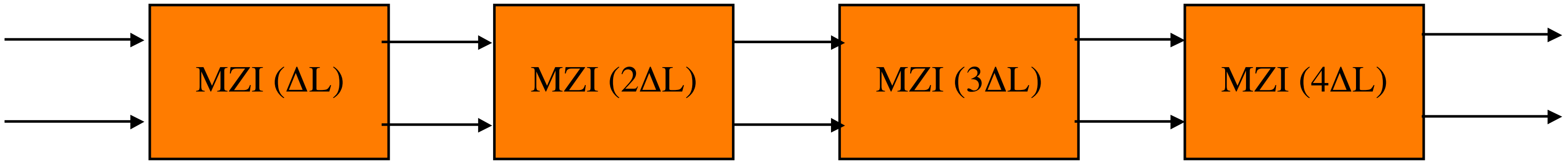
Mach-Zehnder Interferometer Filters

Single Stage (can separate 1.3μm from 1.55μm)

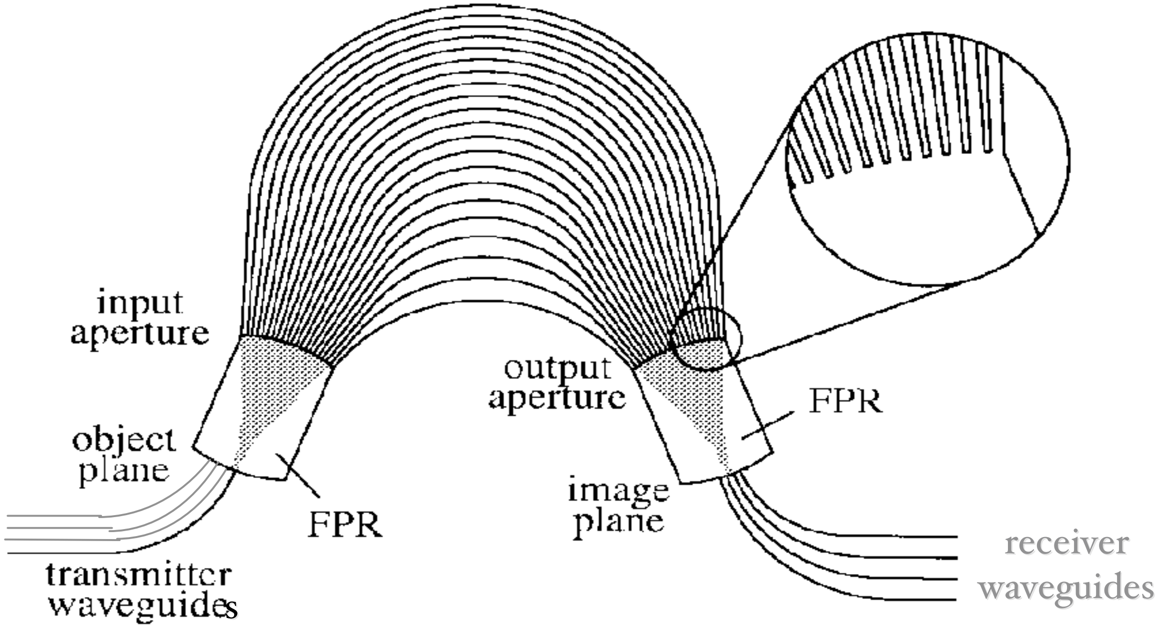


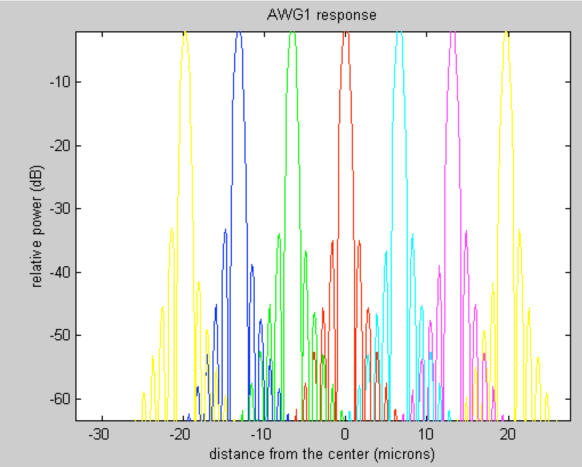
$$\begin{pmatrix} T_{11}(\lambda) \\ T_{12}(\lambda) \end{pmatrix} = \begin{pmatrix} \sin^2(\beta\Delta\lambda/2) \\ \cos^2(\beta\Delta\lambda/2) \end{pmatrix}$$

Multi Stage (for narrow passband)



Arrayed Waveguide Grating Router (AWGR)



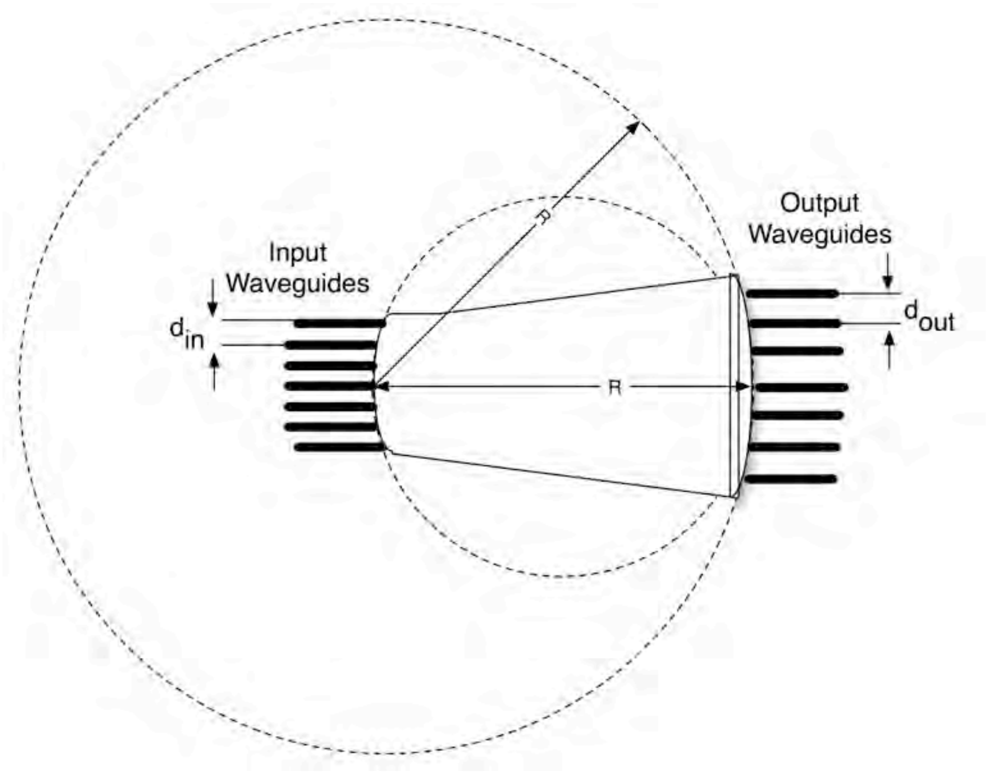


Wavelength λ will be "routed" from input *i* to output *j* if it satisfies the following equation:

$$n_1\delta_i^{in} + n_2\Delta L + n_1\delta_j^{out} = p\lambda \text{ (for integer p)}$$

Rowland Circle Construction

- Used in the design of AWGRs

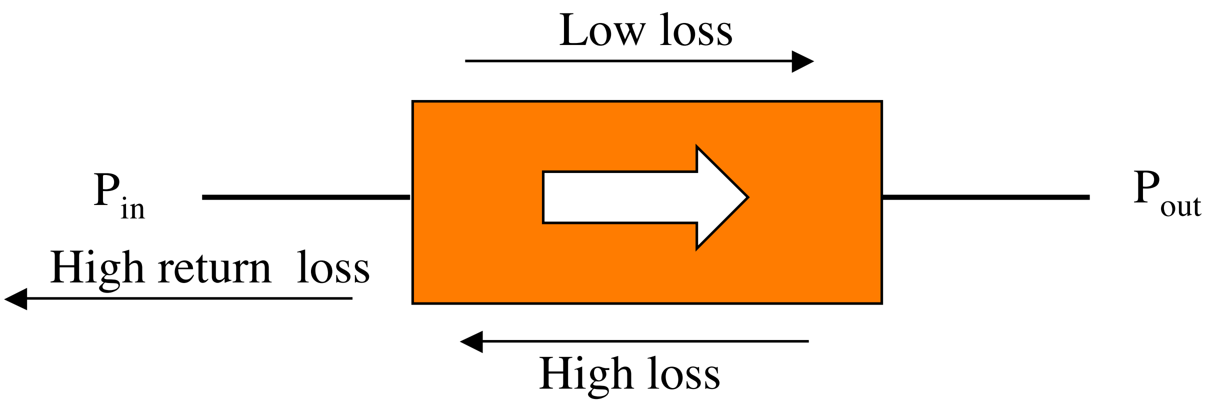


Conclusions on filters

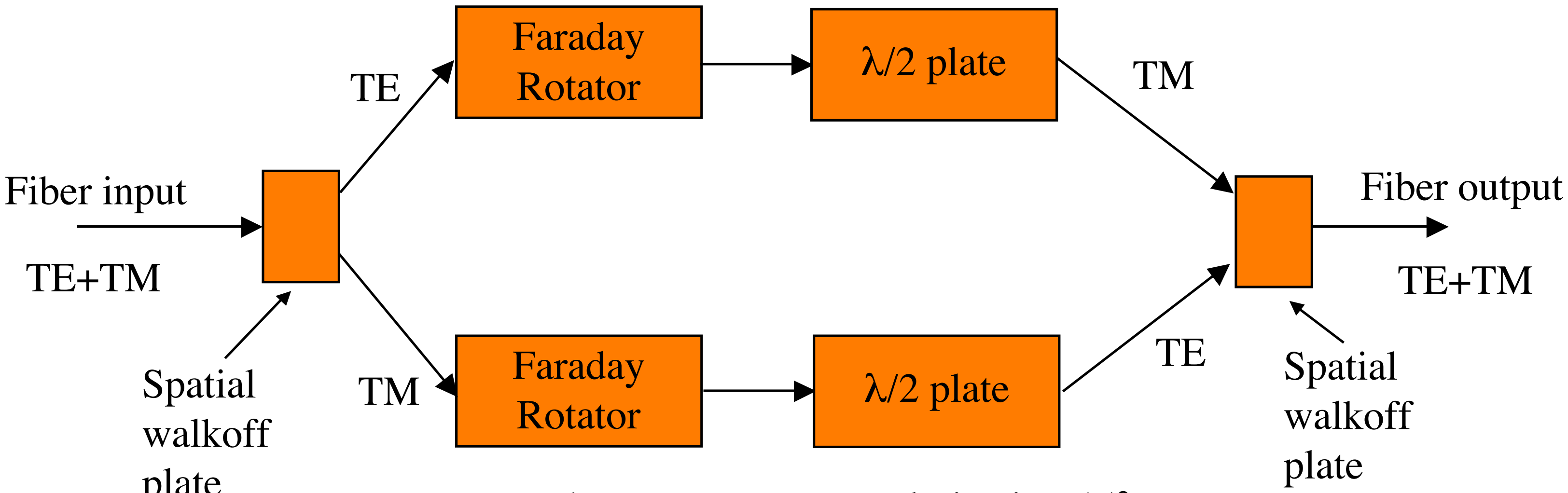
- Optical Filters, demultiplexers and demultiplexers have reached a very high level of reliability
  - They are widely used in WDM applications
  - Have application in dispersion compensation
- The issue of fast (µs) tunable filter is still an open issue
  - AOTF, though very promising, has not reached a total maturity
- Slowly (ms) tunable filters are now available
  - Based on mechanical movements of a grating or an external cavity mirror

Optical Isolators

- Optical equivalent of a diode
  - Used to prevent back reflections from fiber/air or fiber/semiconductor interfaces.
  - Reflections can cause instability in SC lasers and increase interferometric noise.
  - Typical specifications : Low loss = insertion loss ~1 dB.
    High loss = Return loss 40 - 50 dB.



Polarization independent optical isolators



Fiber input

TE+TM

Spatial walkoff plate

TE

TM

Faraday Rotator

λ/2 plate

Faraday Rotator

λ/2 plate

TM

TE

Fiber output

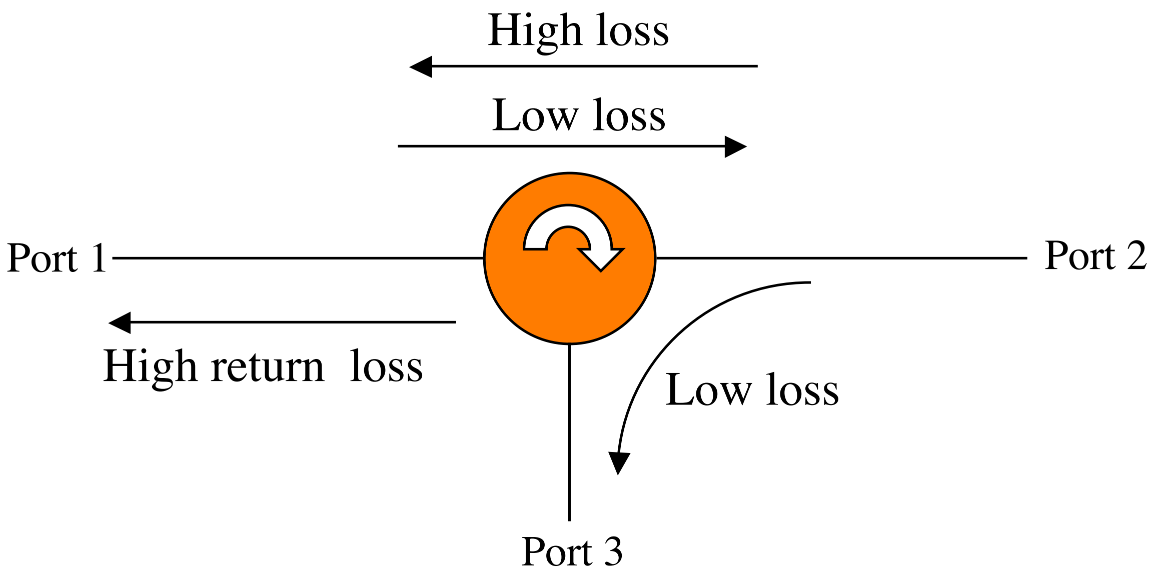
TE+TM

Spatial walkoff plate

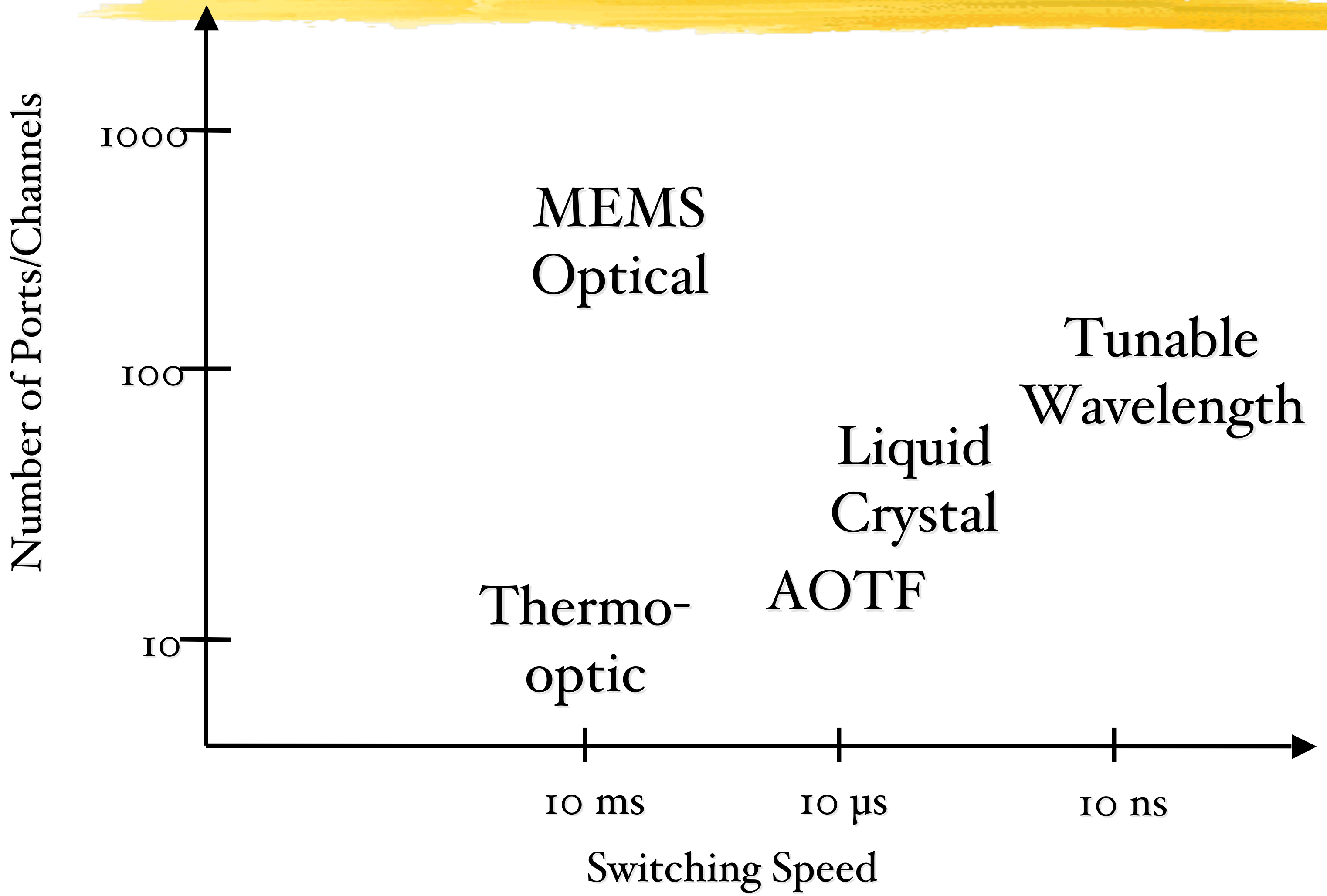
- Faraday rotator rotates polarization 45°

Optical Circulators

Input	Output
Port 1	Port 2
Port 2	Port 3



Optical Switch Technology Switching Speed and Port Count

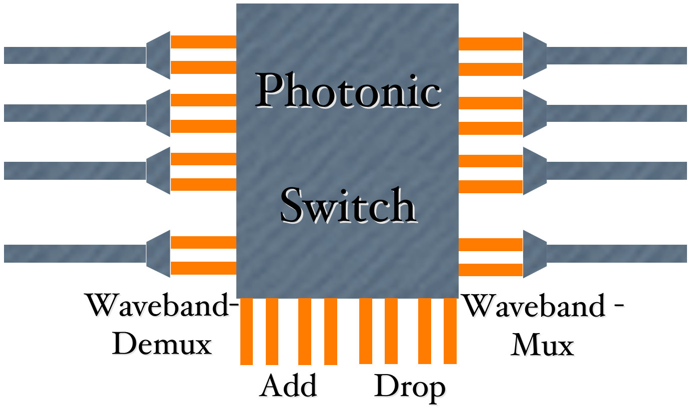


Photonic Crossconnects

Fiber Bundled/Switched

Photonic Switch

Waveband Bundled/Switched



Photonic Switch

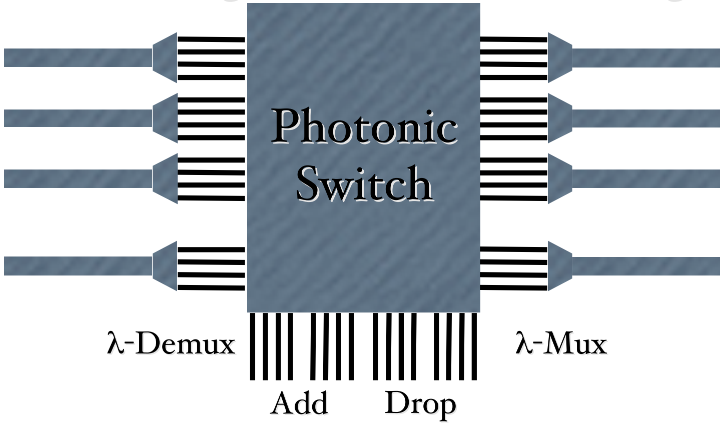
Waveband-Demux

Waveband - Mux

Add

Drop

Wavelength Switched (blocking)



Photonic Switch

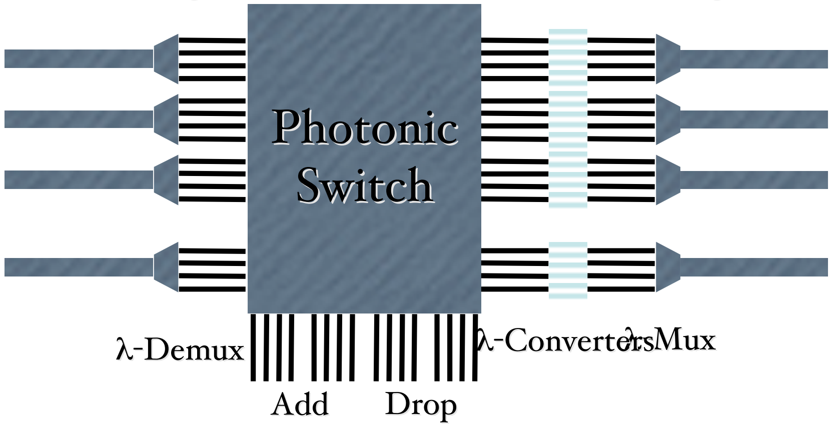
λ-Demux

λ-Mux

Add

Drop

Wavelength Switched (nonblocking)



Photonic Switch

λ-Demux

λ-Converters

λ-Mux

Add

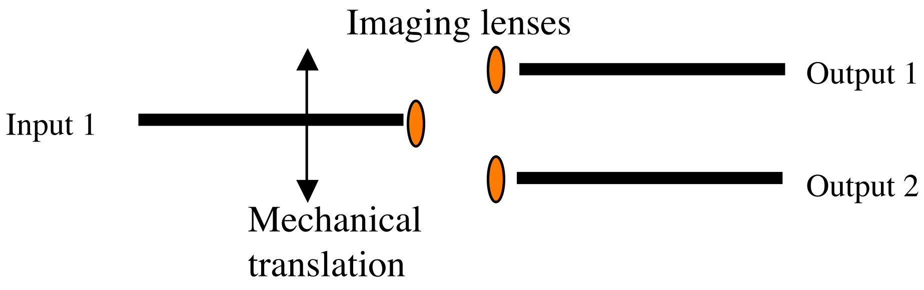
Drop

Photonic Crossconnect Technologies

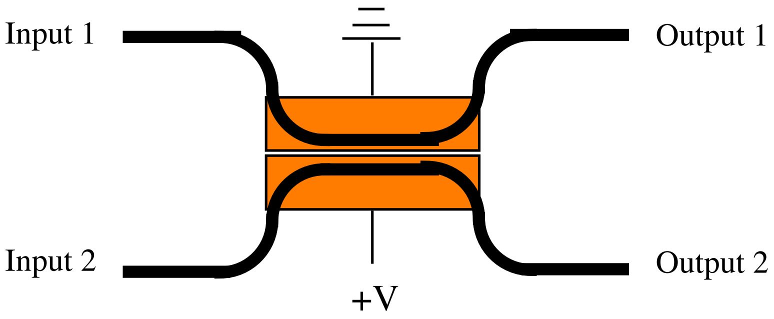
- 2D:
  - Wavelength routed
  - Bubble (Total internal reflection)
  - Thermo-optic (Glass or silicon)
  - Electro-optic
    - LiNbO3, InGaAsP, GaAs, Liquid Crystal
    - Mach-Zehnder, Fabry-Perot, Michelson Interferometers
  - Acousto-optic
  - Gain (splitter with gain on each arm)
    - Er:SiO2, InGaAsP
  - MEMS (MicroElectroMechanical Systems)
- 3D:
  - MEMs

Optical Space Switches

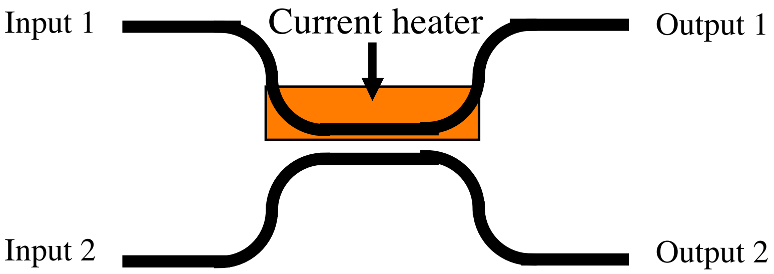
Mechanical Switch



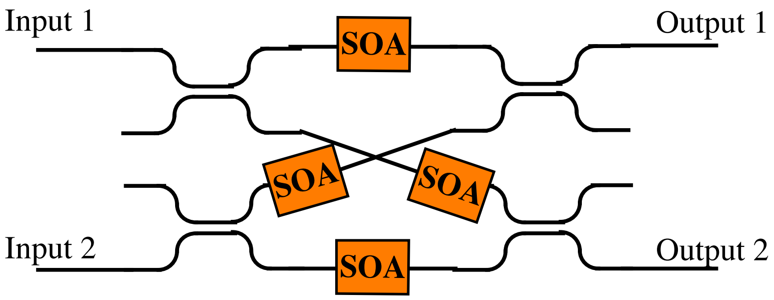
Electrooptic Switch



Thermooptic Switch

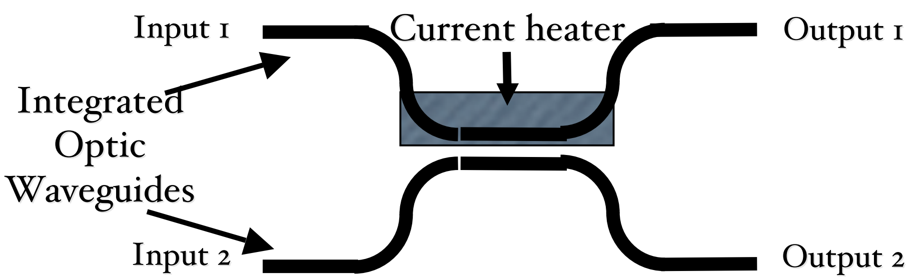


SOA Gate Switch



Thermo-Optic Switches

- 2D so small switches are best (<32 ports)
- Power consumption (0.5 W per switch)
- Speed (typically 6-8 ms)
- Loss (1 dB/cm typical)
- Size: 4” wafer for 16x16 switch

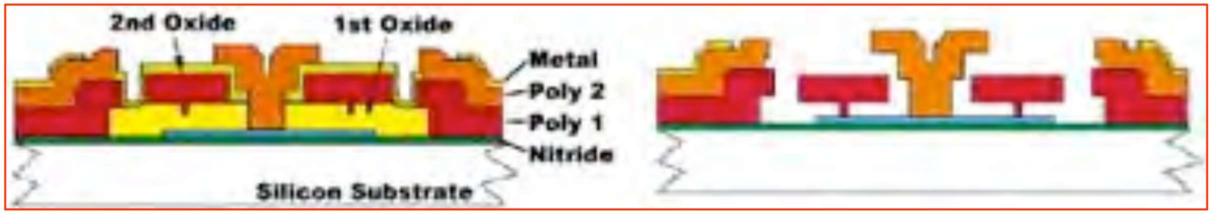


(Mach-Zehnder with thermal phase shift)

NTT 8X8 thermo-optic switch

Micro Electro-Mechanical Switches - MEMS

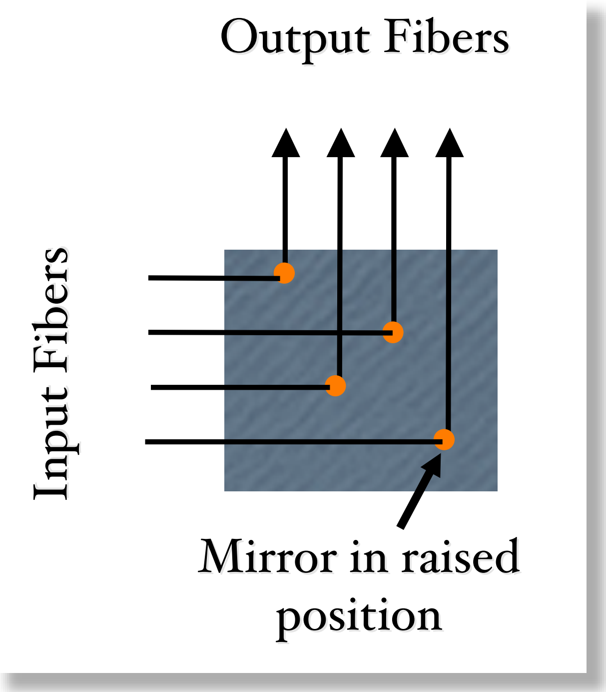
- Micromachines are miniature machines built in ways similar to the way an integrated circuit is built.
- By patterning various layers of polysilicon as they are deposited, one can build structures which look like those shown below
- After the release step in which part of the structures are etched away, the devices are capable of motion



http://www.bell-labs.com/org/physicalsciences/projects/mems/mems1.html

2D MicroElectroMechanical Systems (MEMS) Mirrors

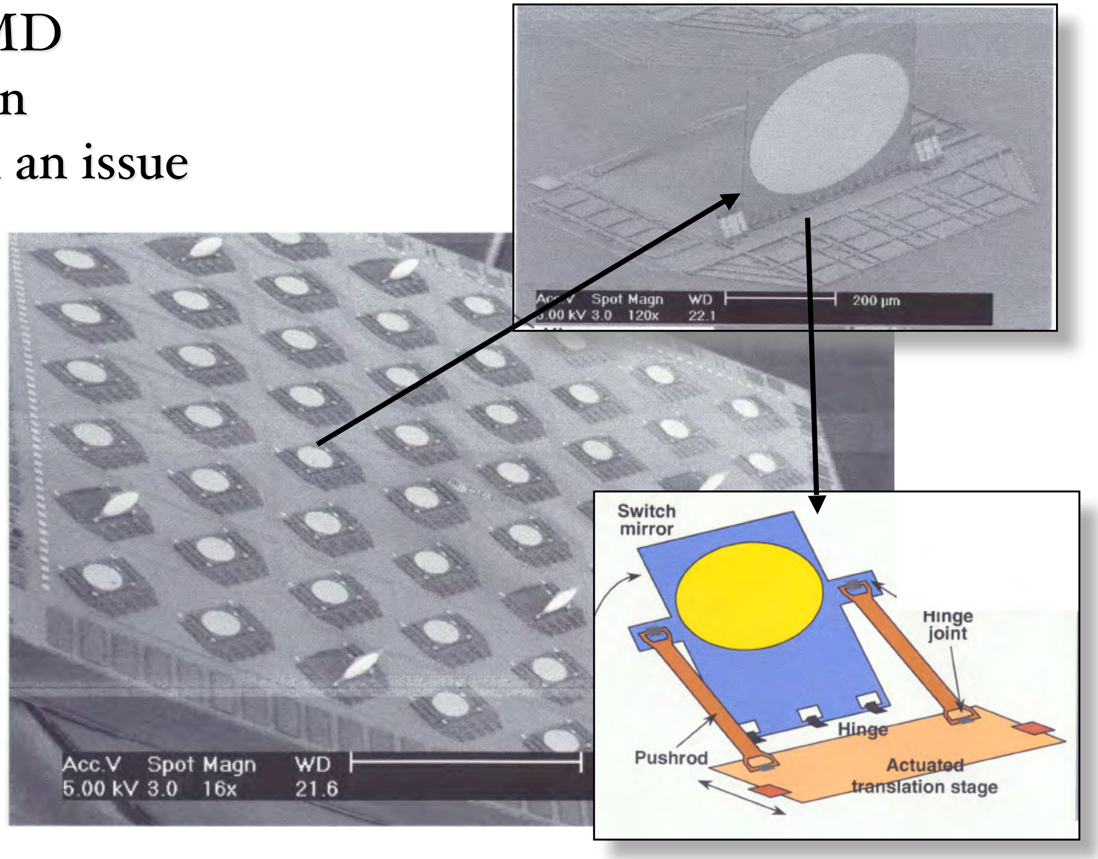
- Low loss for small sizes (< 32x32)
- Low PDL and PMD
- Digital operation
- Sticking due to friction an issue



Output Fibers

Input Fibers

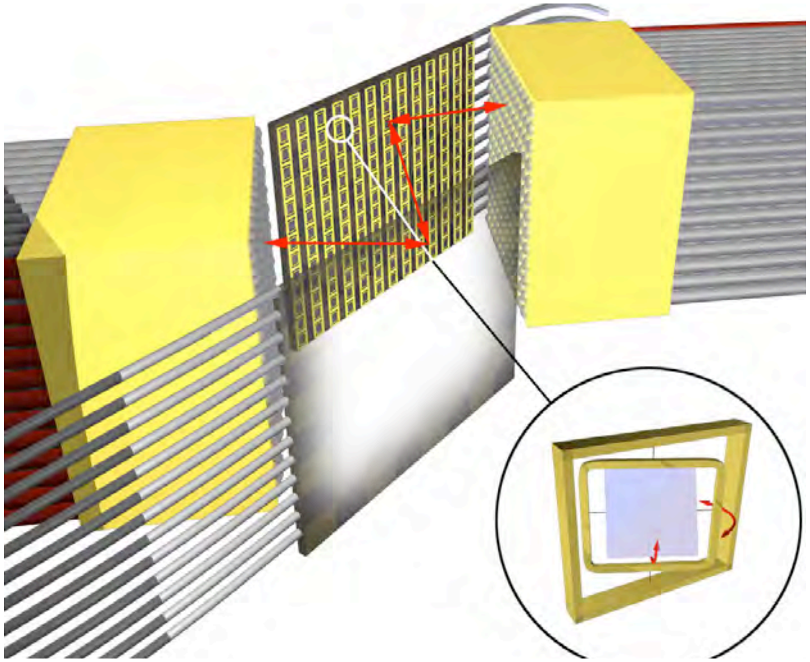
Mirror in raised position



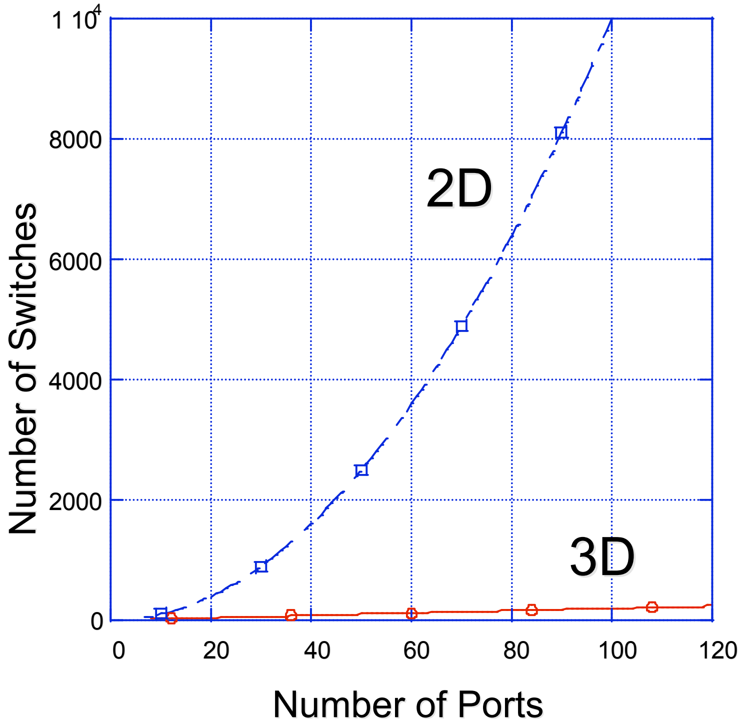
L. Lin, "Free-Space Micromachined Optical-Switching Technologies and Architectures," Topical Meeting on Photonics in Switching, Santa Barbara, CA (1999)

3D MEMS Switch

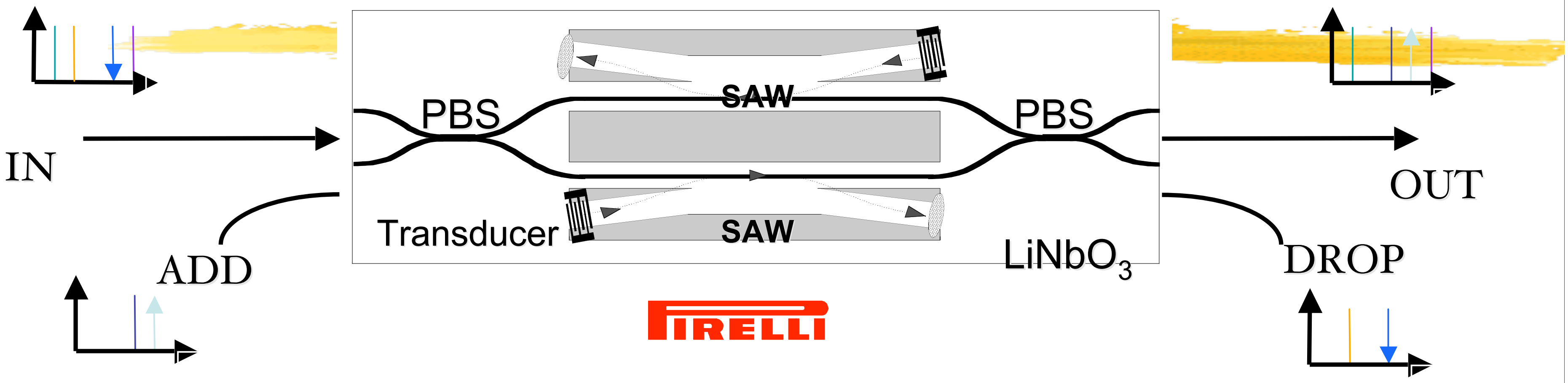
- N ports
- 2N switches
- Two planes of N mirrors are needed.

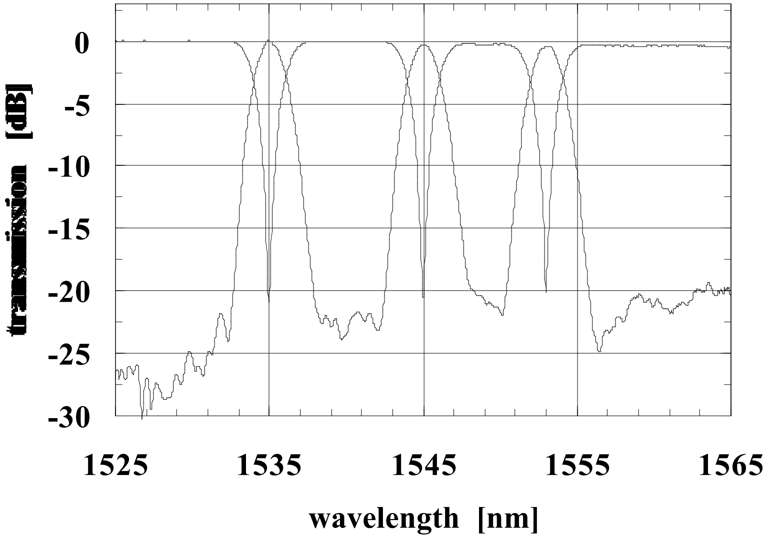


Courtesy of Calient Networks



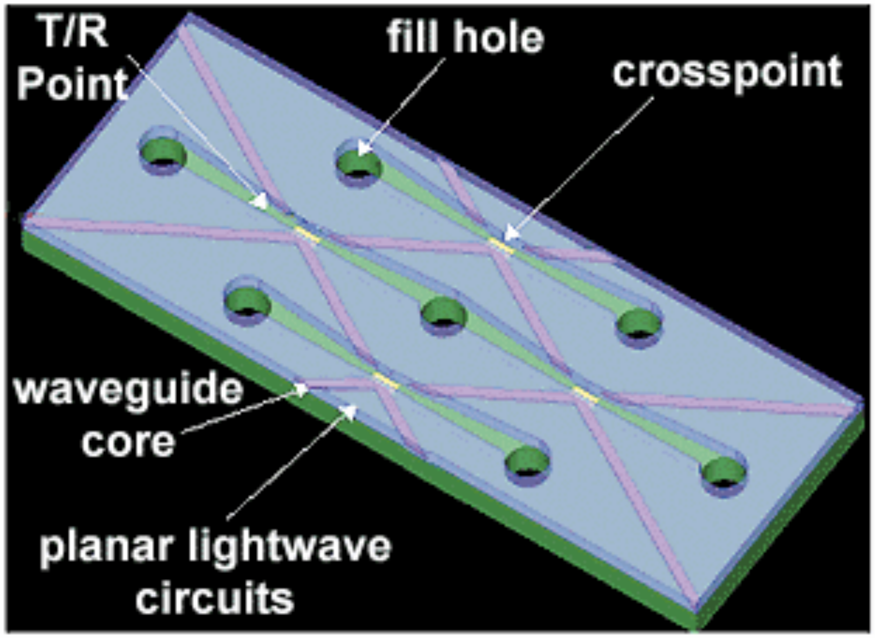
AOTF Multichannel OADM

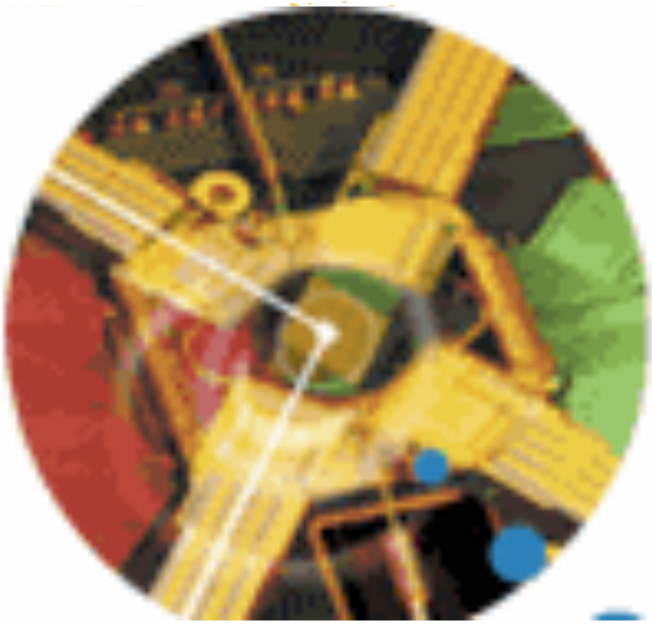




Fulvio Arecco, Danilo Scarano and Steffen Schmid ECOC 1998

Agilent Bubble Switches



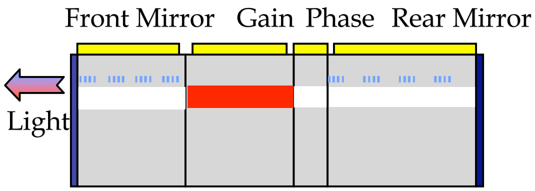


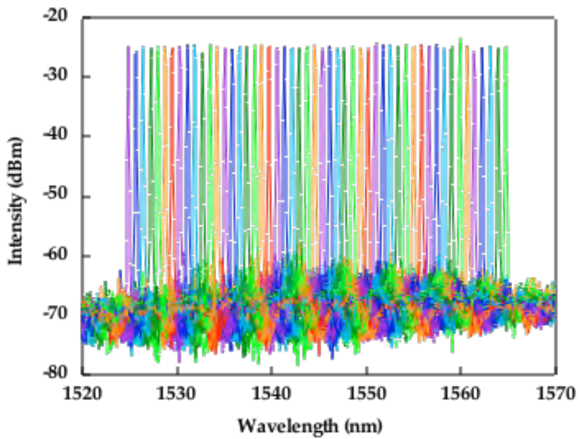
- No moving parts. Ink jet technology
- 2D so small switches (<40 ports) are best
  - Wavelength range: limited
  - Power consumption: heater power significant

Tunable Laser Technology

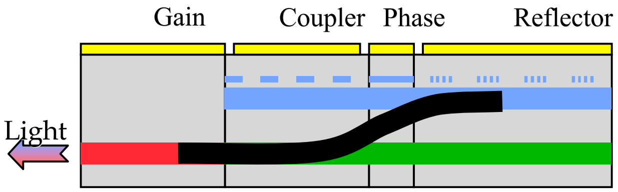
Medium to Fast Tuning: Multisection Semiconductor Lasers

SGDBR

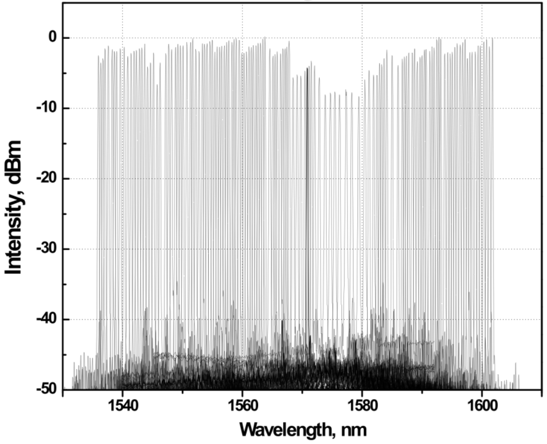




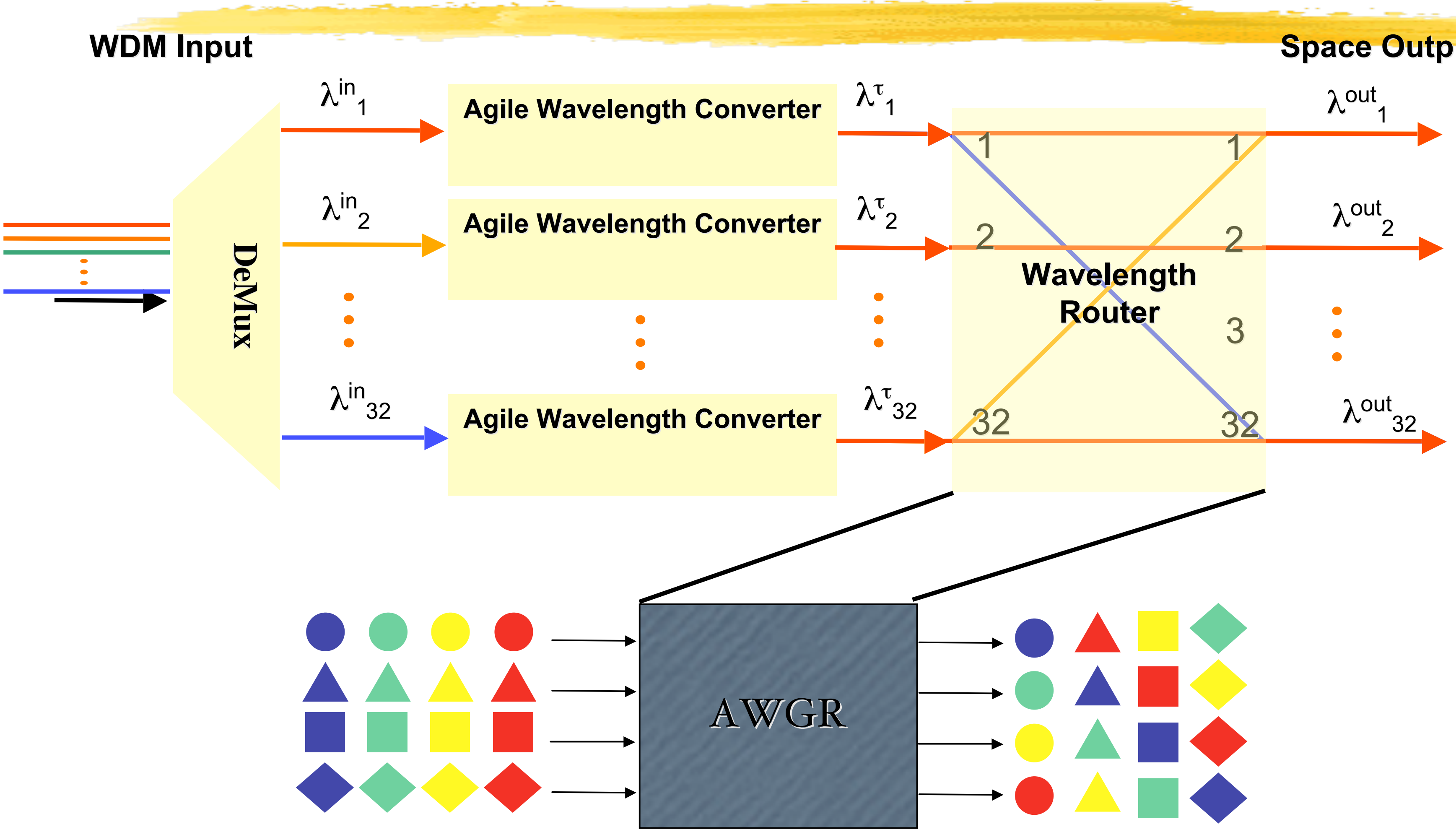
GCSR



•over 250 equally spaced (50 GHz) channels



Wavelength Switch/Router



WDM Input

Space Outputs

DeMux

λ^{in}_1 **Agile Wavelength Converter** λ^{τ}_1

λ^{in}_2 **Agile Wavelength Converter** λ^{τ}_2

λ^{in}_{32} **Agile Wavelength Converter** λ^{τ}_{32}

Wavelength Router

1 2 32 → 1 2 3 32

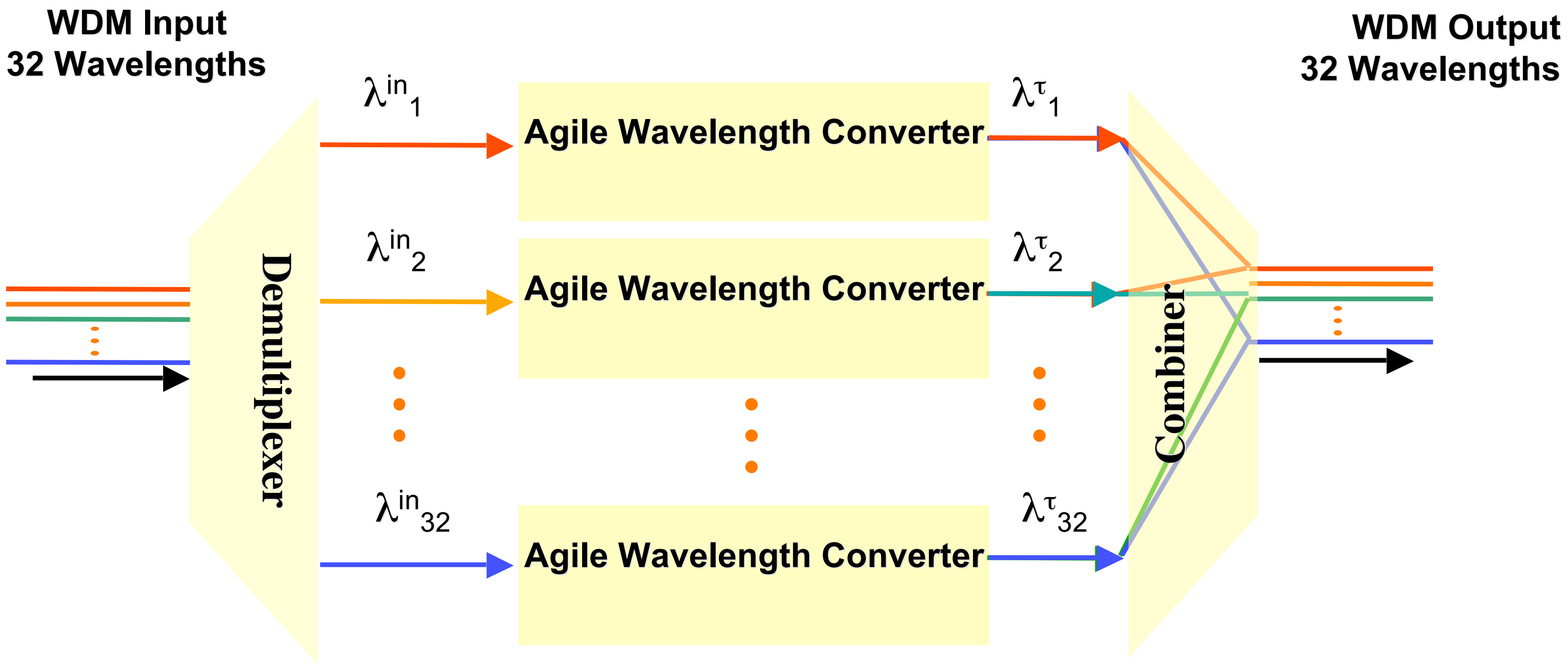
λ^{out}_1

λ^{out}_2

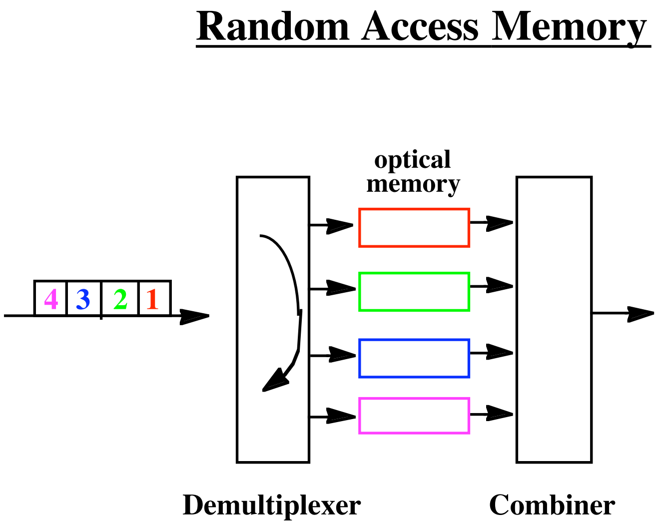
λ^{out}_{32}

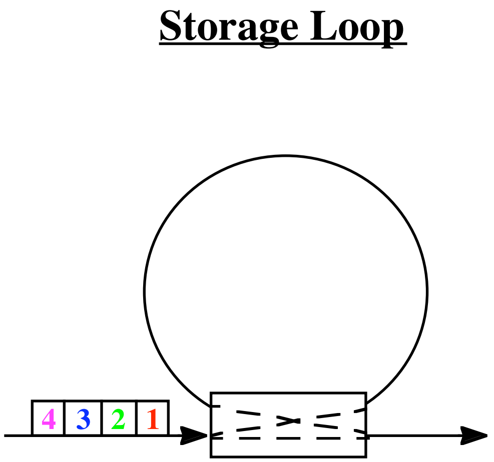
AWGR

Wavelength Interchanger



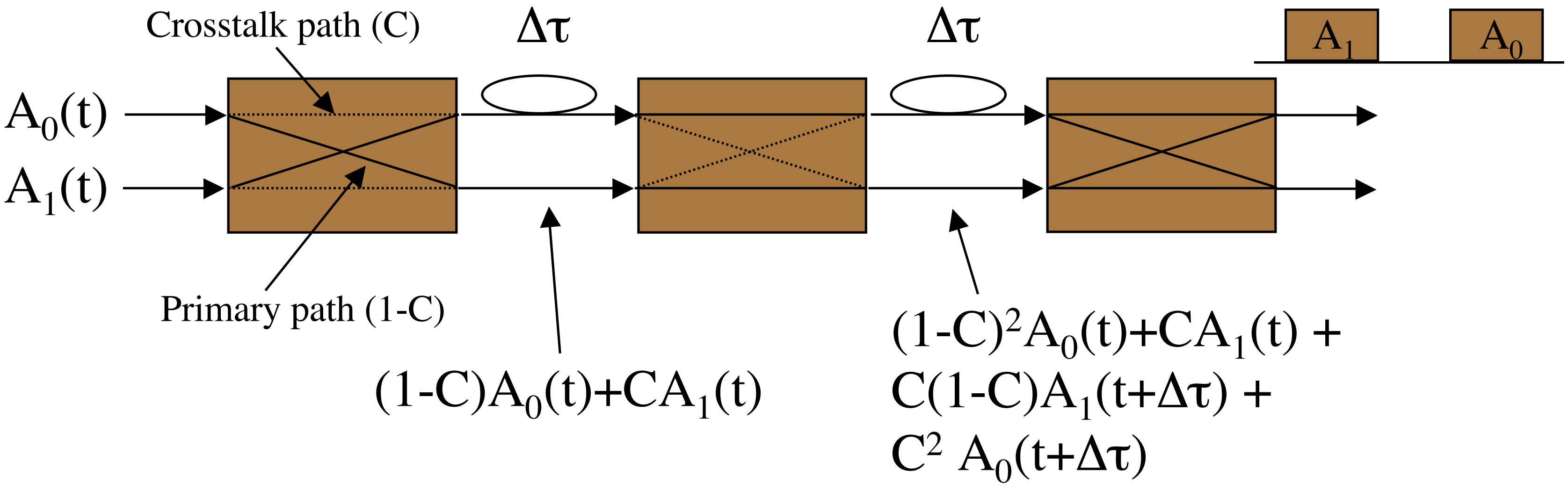
Time Switches





Switched Delay Lines

- Switching fabric (R. Thompson, JLT)
- Resolve NxN switch output port contention (D. K. Hunter, JLT, 1993)
- Resolve internal blocking states, shared buffers (Boncek, Electron. Letts)
- Resolve wavelength switching conflicts (Kazovsky, CORD, PTL, 1995)
- Homodyne coherent crosstalk (M. Tur, Optics Letts., 1995)



Crosstalk path (C)

$\Delta\tau$

$\Delta\tau$

A_1 A_0

$A_0(t)$

$A_1(t)$

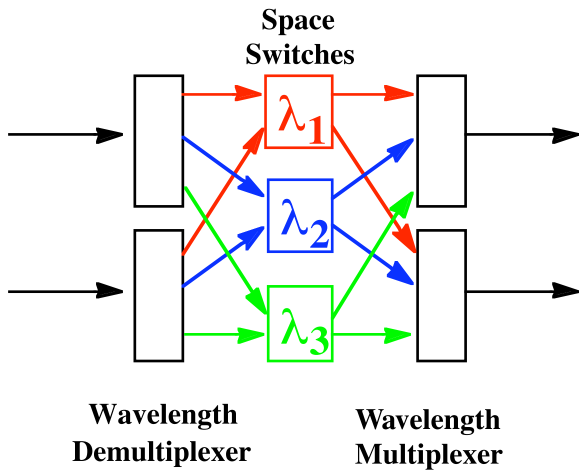
Primary path (1-C)

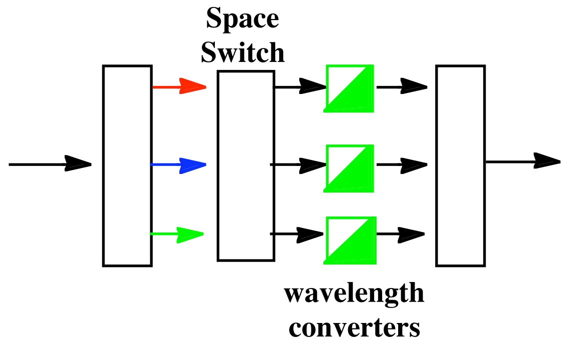
$(1-C)A_0(t)+CA_1(t)$

$(1-C)^2A_0(t)+CA_1(t)$ +
$C(1-C)A_1(t+\Delta\tau)$ +
$C^2\ A_0(t+\Delta\tau)$

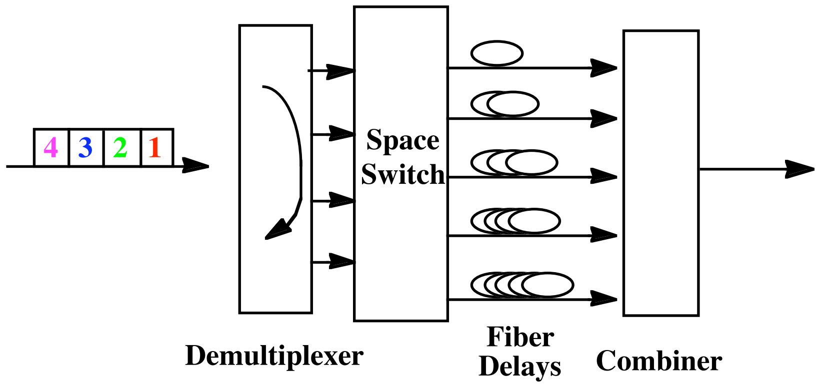
Mixed Switching Fabrics

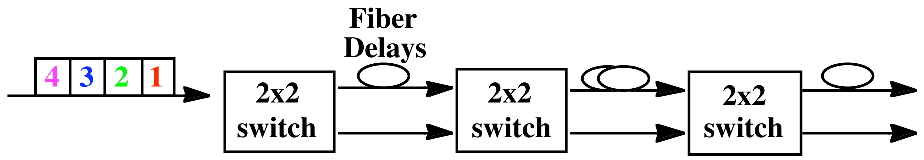
Space/Wavelength



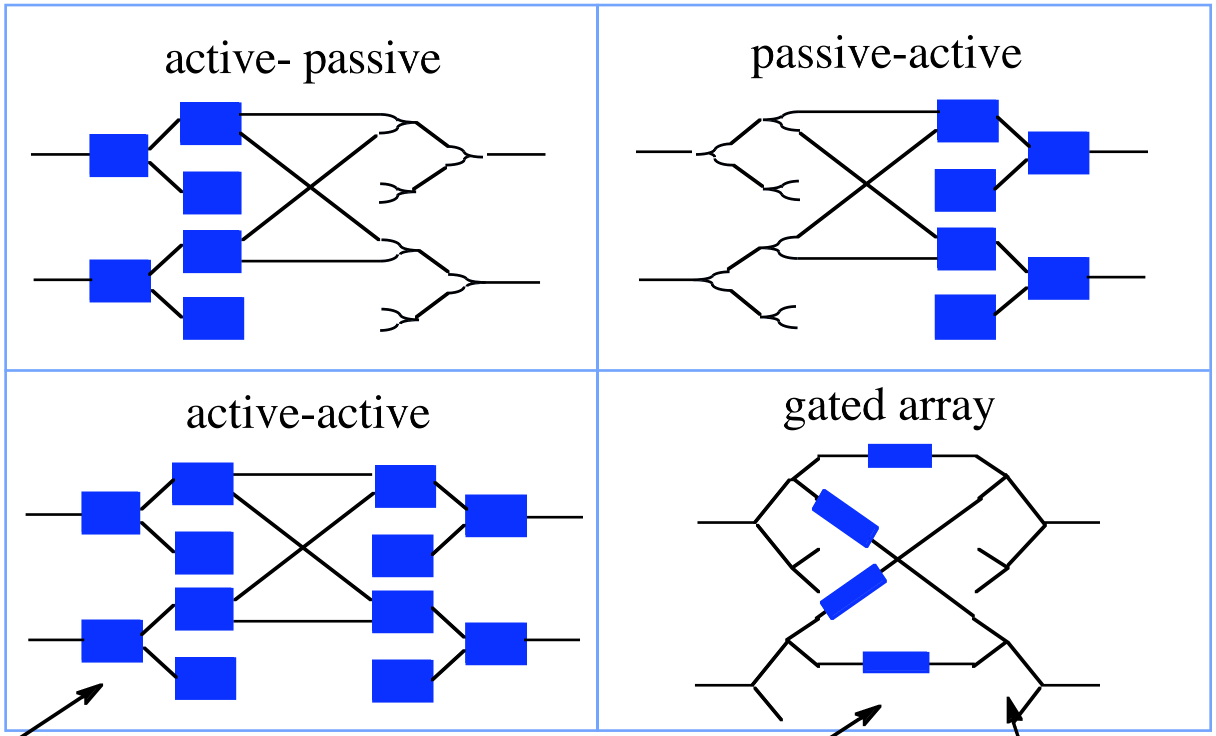


Space/Time





Integrated Optic Space Switches



2 x 2
Active Switches
(e.g., directional coupler, digital switch)

Optical Gates
(e.g., SOAs)

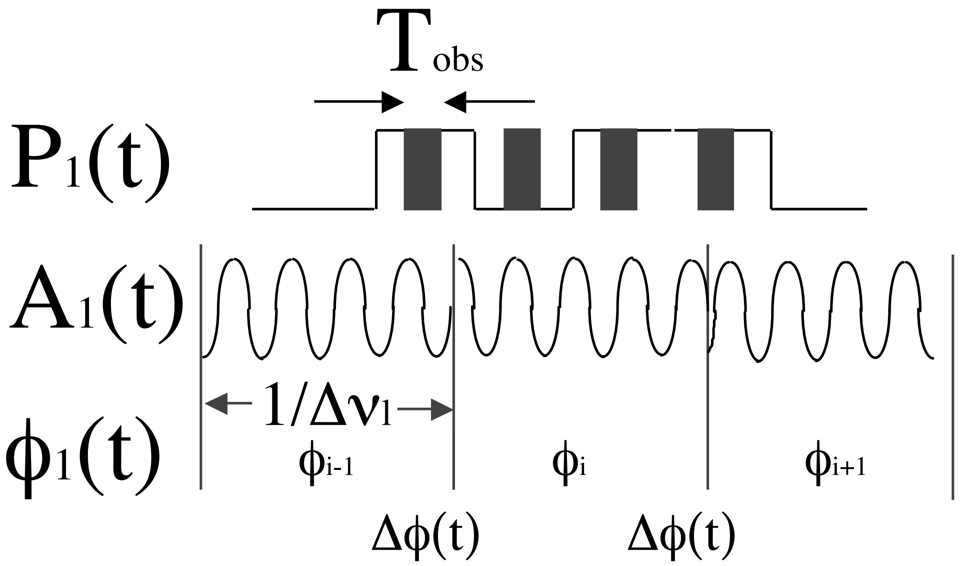
3 dB Passive Combiners

Sources of Optical Crosstalk

- Crosstalk is generically a superimposition of two different useful signals
- It may be due to:
  - Reflections and Recirculatory Paths
  - Fiber and Amplifier Nonlinearities
  - Photonic Switching and Gating Elements
  - WDM Add/Drop Components
  - WDM Multiplexers/Demultiplexers
- In traditional point-to-point link without optical add-drops, crosstalk mainly comes from nonlinear effects
- In next-generation all optical network, it can be generated by any device that handle the signal in the photonic domain

Digital Optical Crosstalk

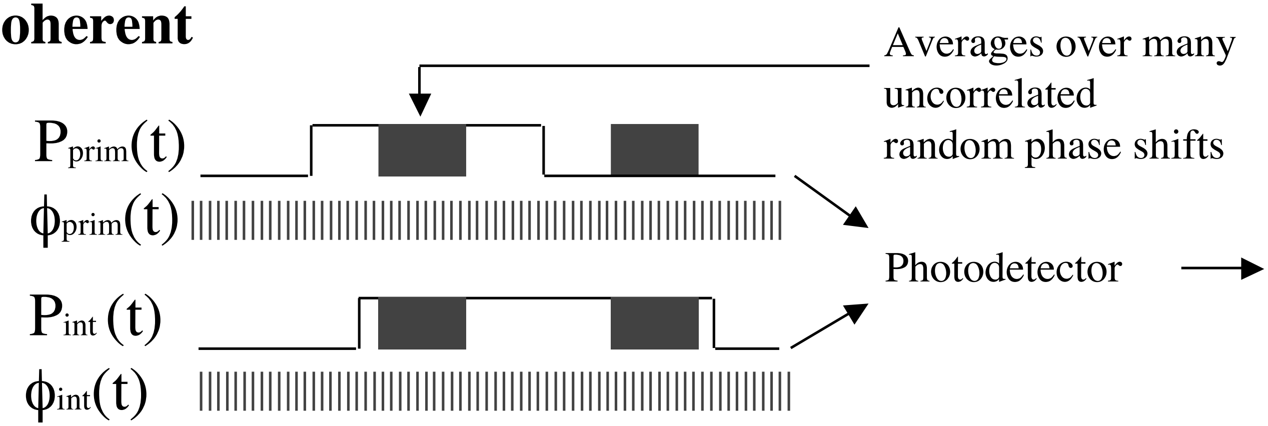
- Do signals from different optical digital sources mix incoherently or coherently ?
  - Coherence determined by the rate of random laser phase fluctuations relative to the observation interval
  - The observation interval is determined by the bit rate



Assume ϕ_i and $\Delta\phi$ uniform distributed on $[0,2\pi]$

Incoherent and Coherent Crosstalk

- **Incoherent**



$P_{prim}(t)$

$\phi_{prim}(t)$

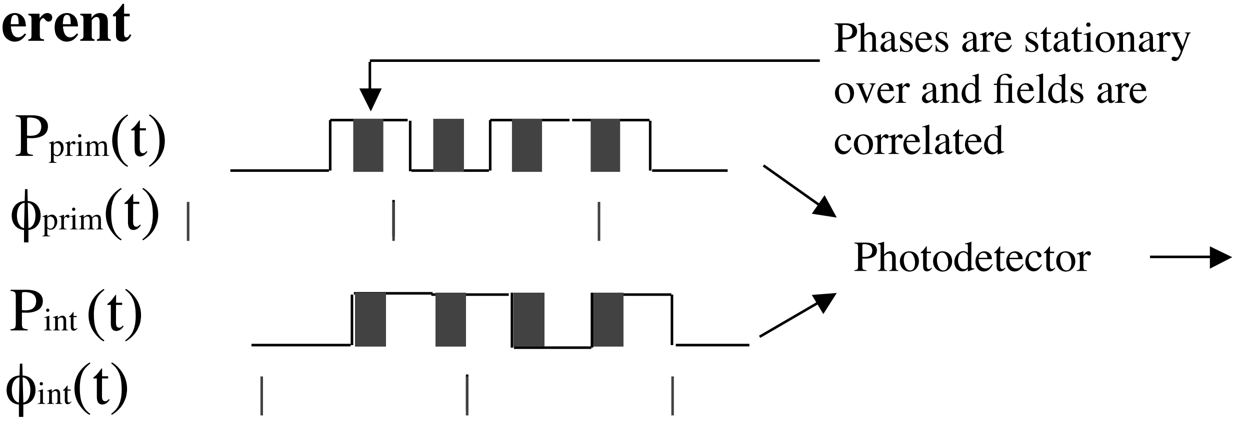
$P_{int}(t)$

$\phi_{int}(t)$

Averages over many uncorrelated random phase shifts

Photodetector

- **Coherent**



$P_{prim}(t)$

$\phi_{prim}(t)$

$P_{int}(t)$

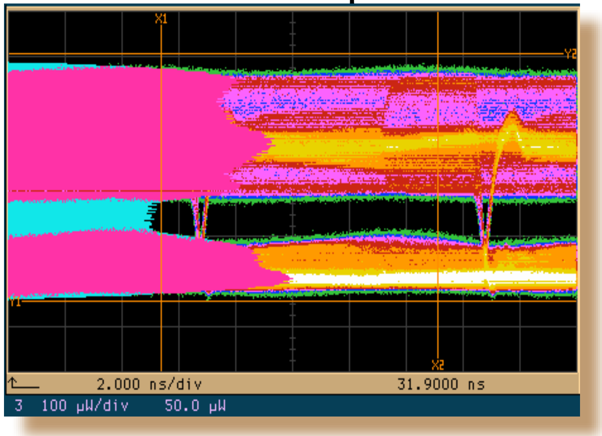
$\phi_{int}(t)$

Phases are stationary over and fields are correlated

Photodetector

Acceptable Crosstalk levels

- Incoherent crosstalk can in most cases be kept under control with good optical filtering at the receiver
- Coherent crosstalk may easily become detrimental
  - The coherently interfering channels should be at least 30 dB smaller than the useful channel
  - Note that in mesh configuration, coherent crosstalk may be generated by the interaction of a signal with a delayed version of the same signal, that has followed another path



Received eye diagram from strong coherent crosstalk levels