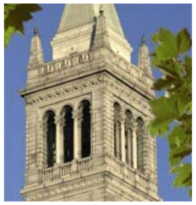

OFC 2005
Tutorial

Current Trends in Optical MEMS

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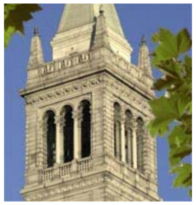

Acknowledgment

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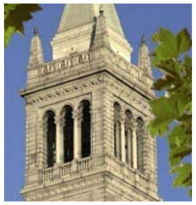
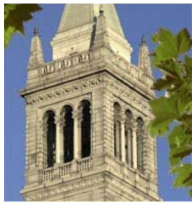
  - WSS: J.C. “Ted” Tsai, Dooyoung Hah, Sophia Huang
  - PhC switch: M.C. “Mark” Lee
  - MEMS Microdisk: M.C. “Mark” Lee, Jin Yao
  - MEMS PLC switch: Josh C.H. Chi, Jin Yao



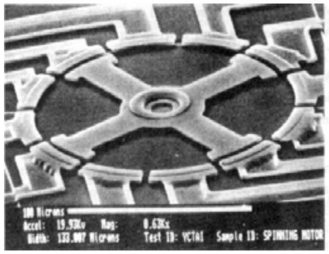
OUTLINE

- Introduction
- Optical design considerations
- Space division switches
  - 2D MEMS optical switches
  - 3D MEMS optical switches
- Spectral domain processors
  - Wavelength-selective switches
- Planar lightwave circuits (PLC)-MEMS Integration
- Diffractive optical MEMS
- New directions
- Summary

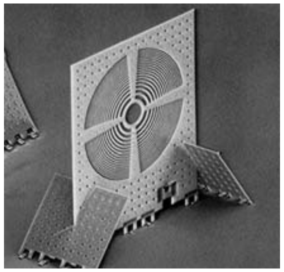


25 Years of Optical MEMS

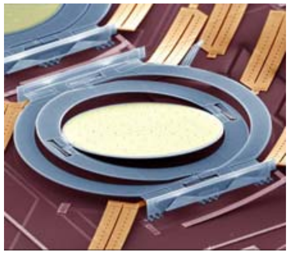
Scanning Mirror (Petersen, IBM)



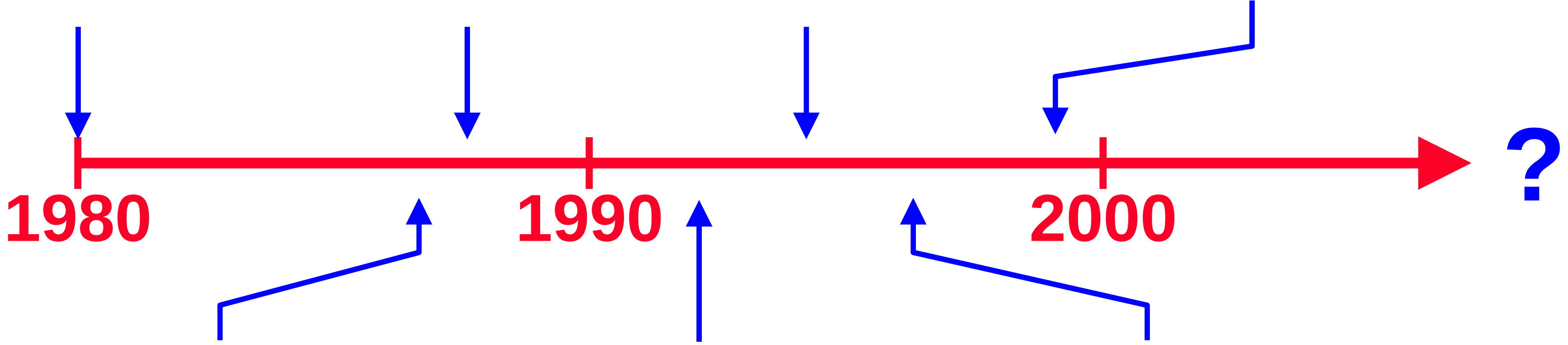
Micromotoers (Berkeley)



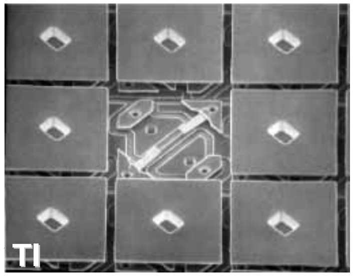
Free-Space Optical Bench (UCLA/Berkeley)



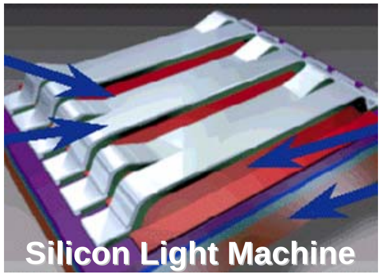
3D MEMS Switches



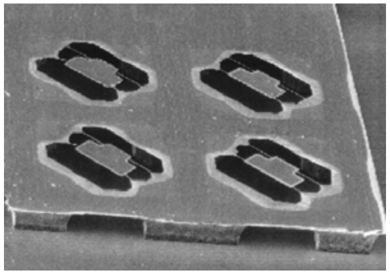
Digital Micromirror Device (DMD, TI)

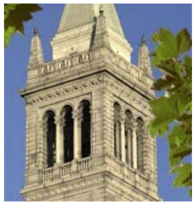


Grating Light Valve (GLV, Stanford)



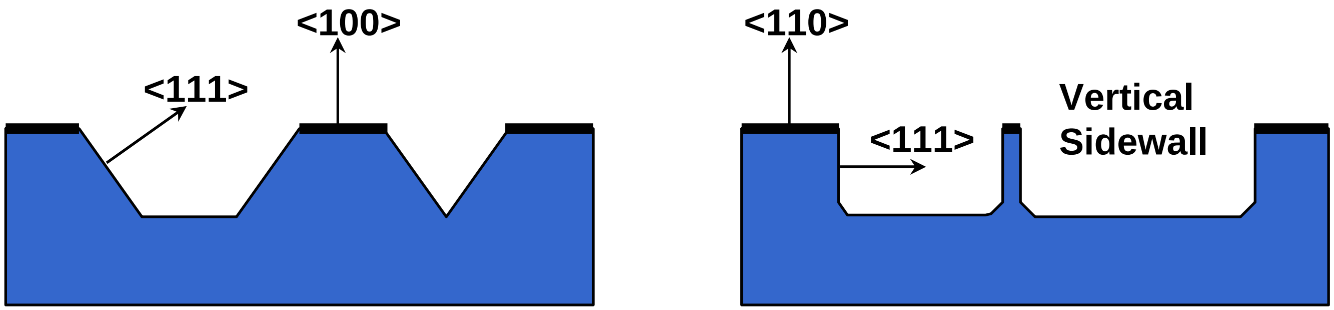
2D MEMS Switches (Tokyo U)



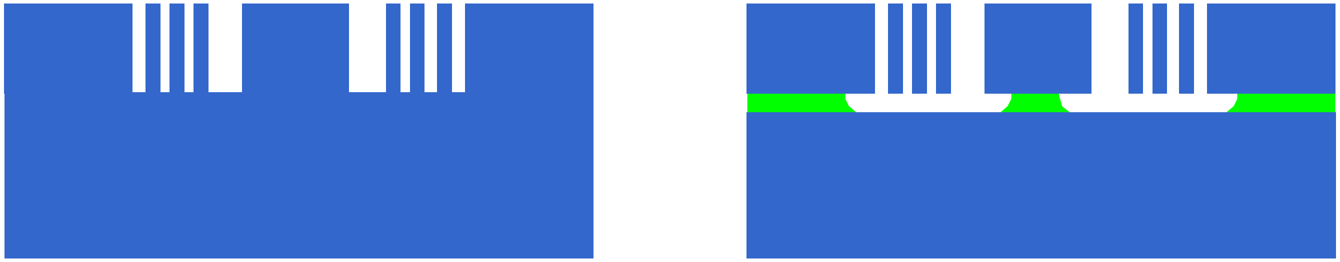


Bulk Micromachining

- **Anisotropic wet chemical etching** (restricted to fixed crystalline orientations)

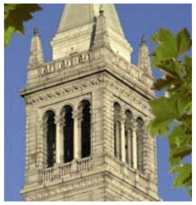


- **Deep reactive ion etching (DRIE or ICP-RIE)**



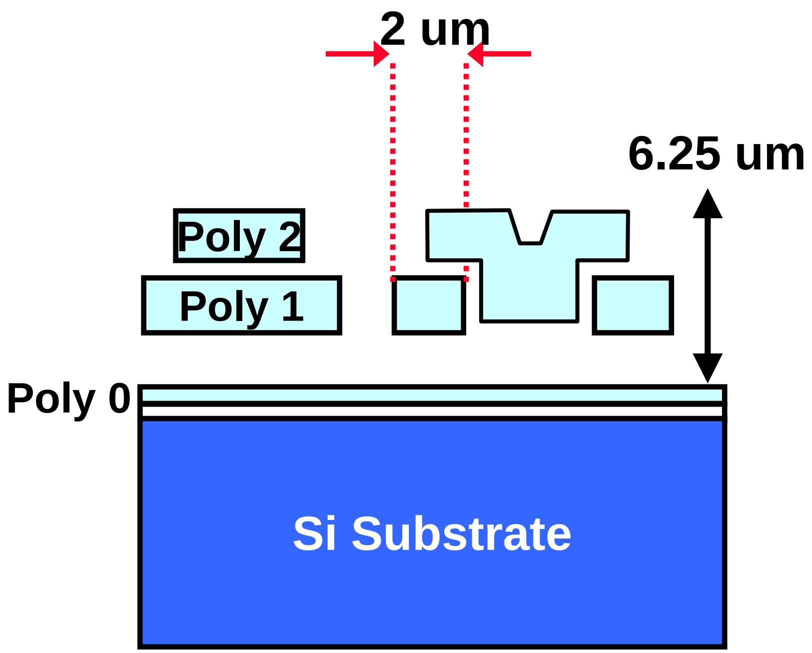
- **High aspect ratio (> 20:1)**
- **Independent of crystal orientation**
- **More efficient use of real estate of substrate (e.g., can produce closely spaced structures)**

- **Combine with silicon-on-insulator (SOI) or III-V epi wafer**
- **Suspended structure in one-step etching + releasing**
- **Multi-layer structure by additional wafer bonding**



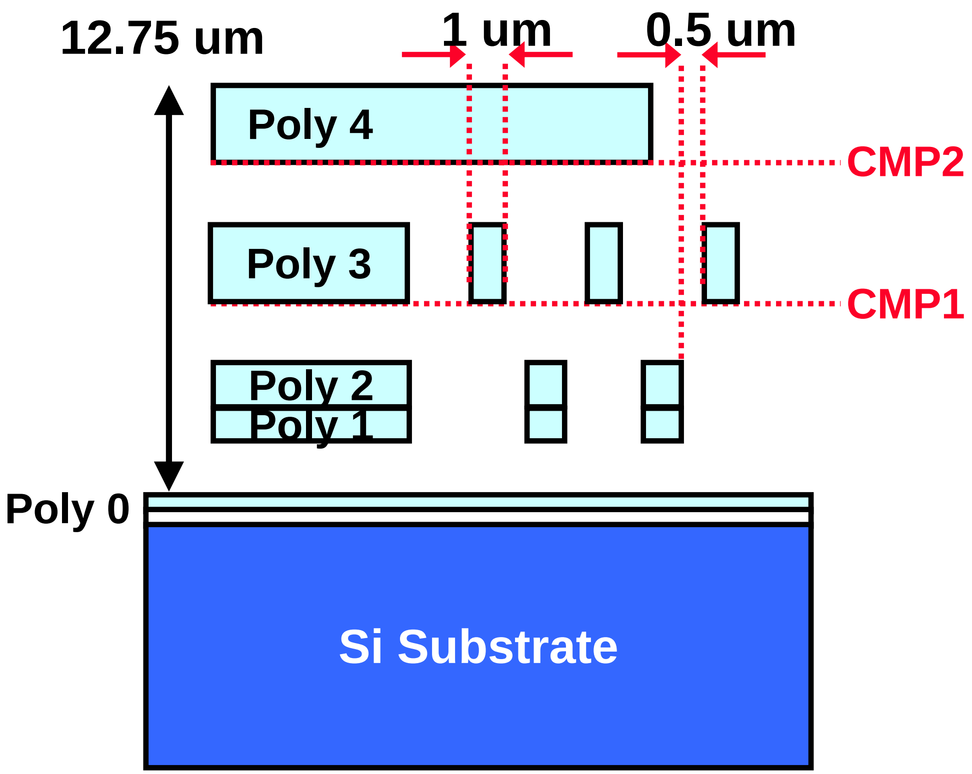
Surface-Micromachining:
2 “Standard” Foundry Process

MUMPs

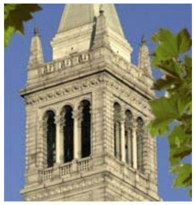


- MEMSCAP

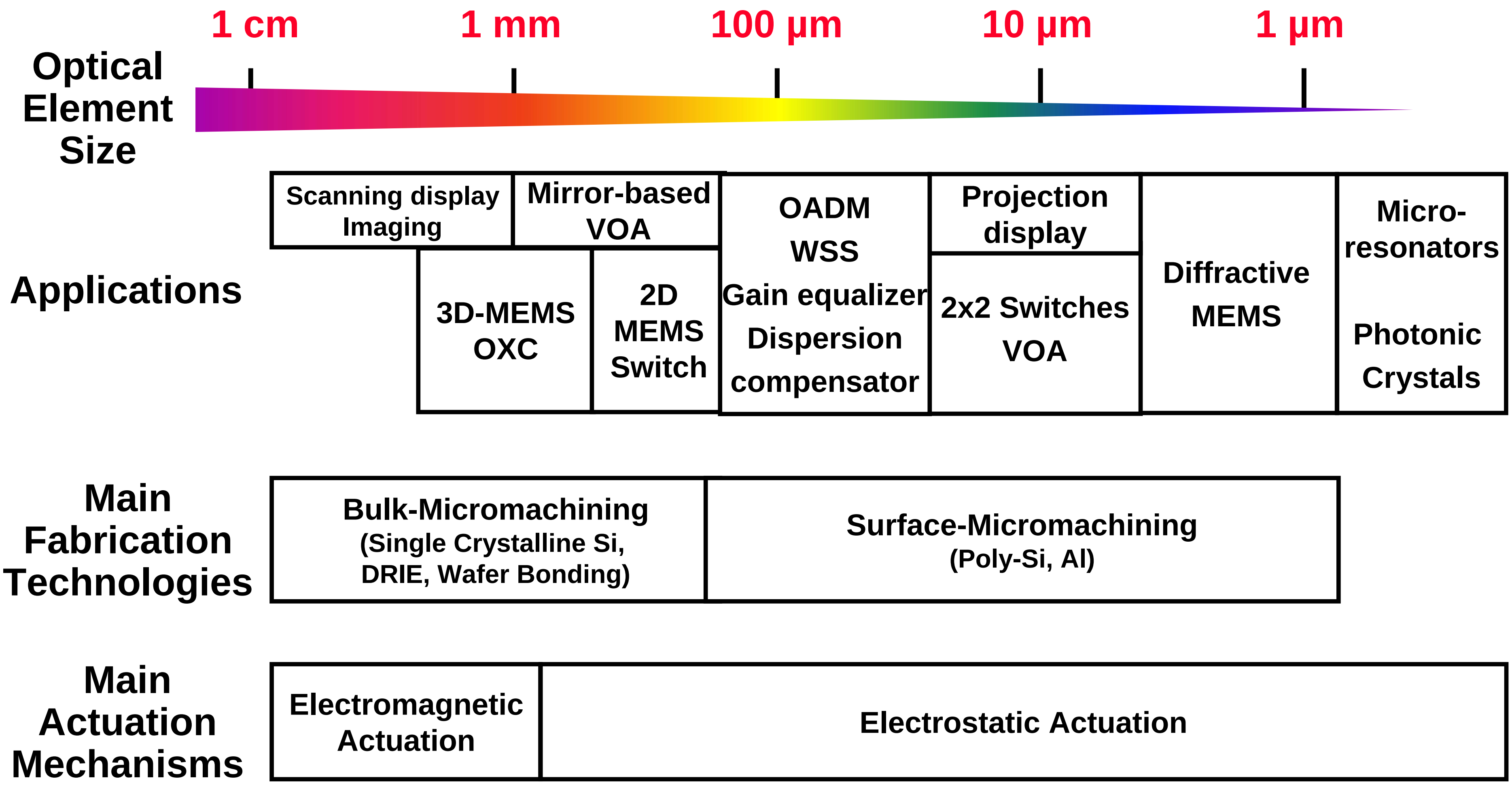
SUMMiT



- Sandia National Lab
- Fairchild (SUMMiT-4)



MEMS Technologies and Optical Element Size



Optical Element Size

1 cm — 1 mm — 100 µm — 10 µm — 1 µm

Applications

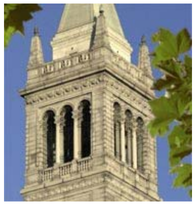
- Scanning display
Imaging
- Mirror-based VOA
- 3D-MEMS OXC
- 2D MEMS Switch
- OADM, WSS, Gain equalizer, Dispersion compensator
- Projection display
- 2x2 Switches, VOA
- Diffractive MEMS
- Micro-resonators
- Photonic Crystals

Main Fabrication Technologies

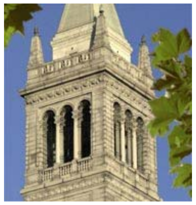
- Bulk-Micromachining (Single Crystalline Si, DRIE, Wafer Bonding)
- Surface-Micromachining (Poly-Si, Al)

Main Actuation Mechanisms

- Electromagnetic Actuation
- Electrostatic Actuation

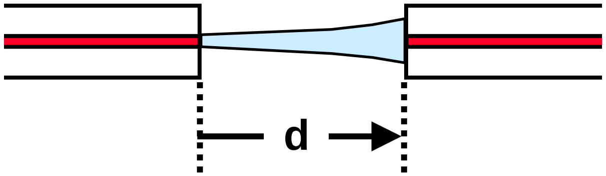


Optical Designs

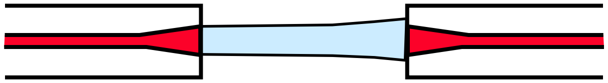


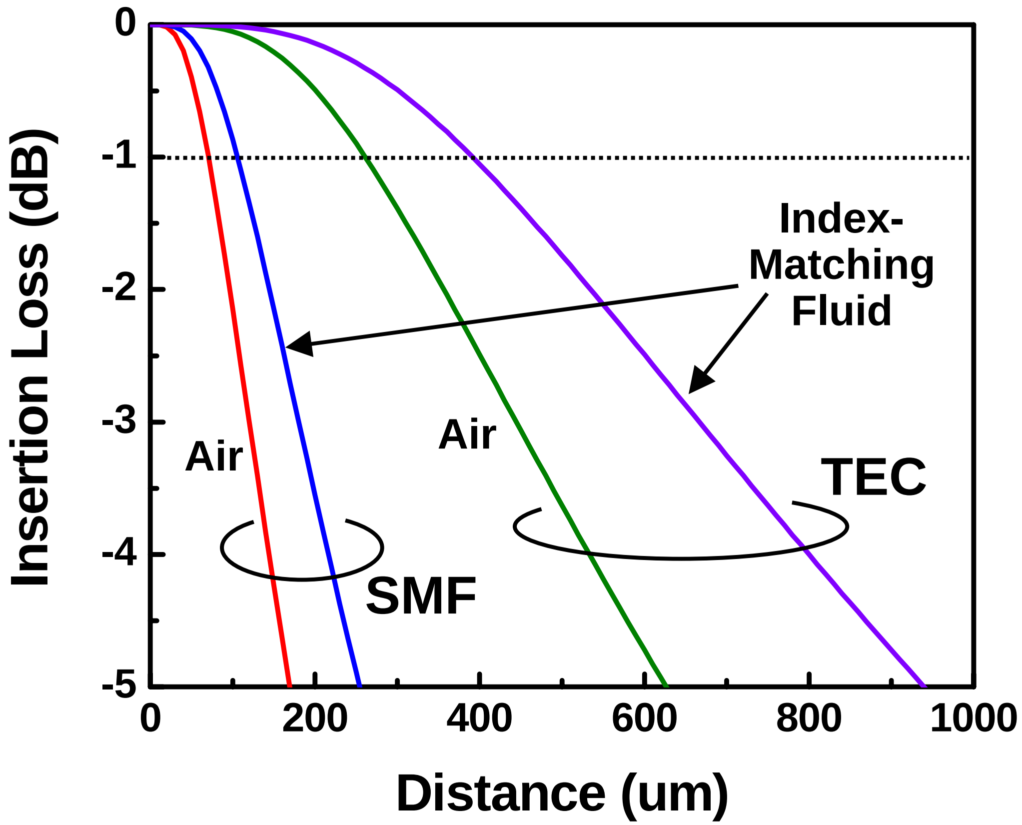
Direct Coupling Without Lenses

Single Mode Fiber (SMF)



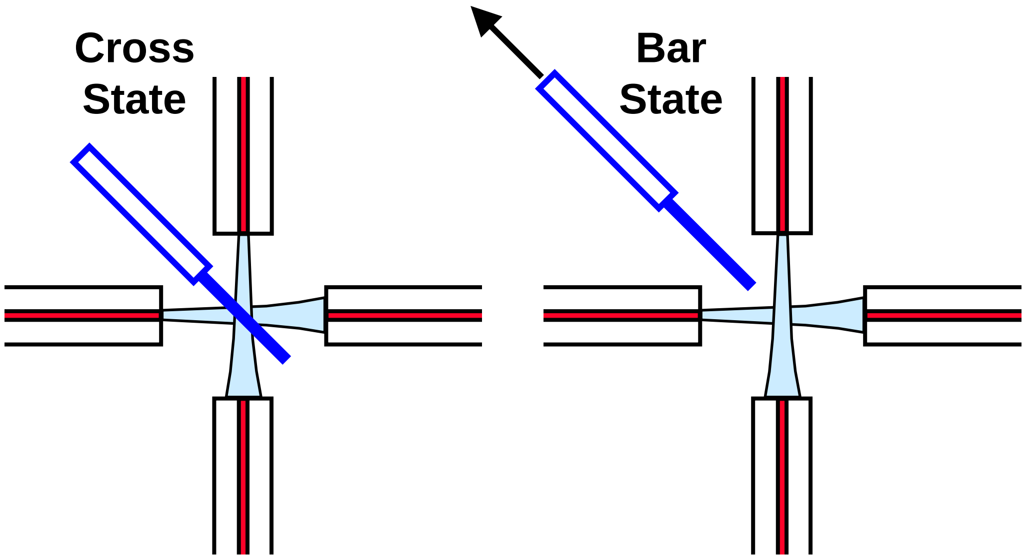
Thermally Expanded Core (TEC) Fiber

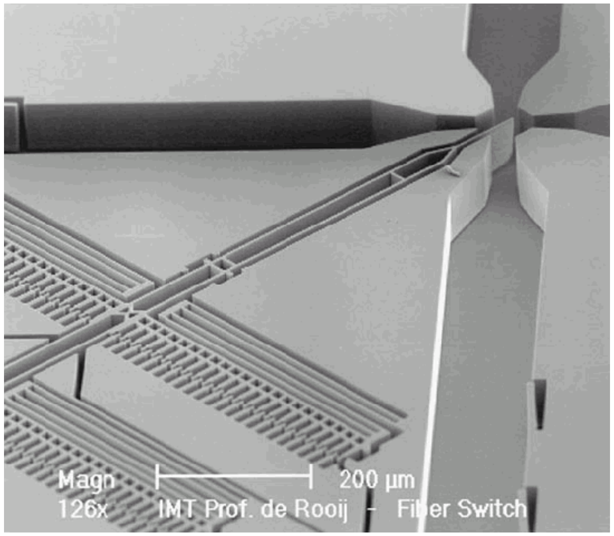


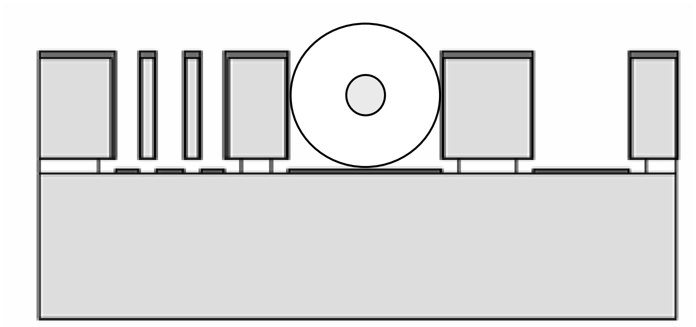


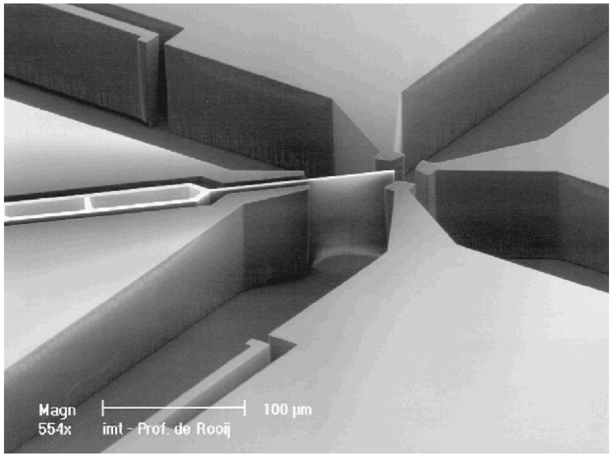
- Short propagation distance
- May be used for small switches or VOAs

Example: 2x2 Switch

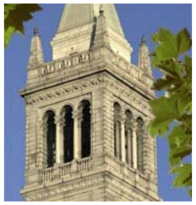




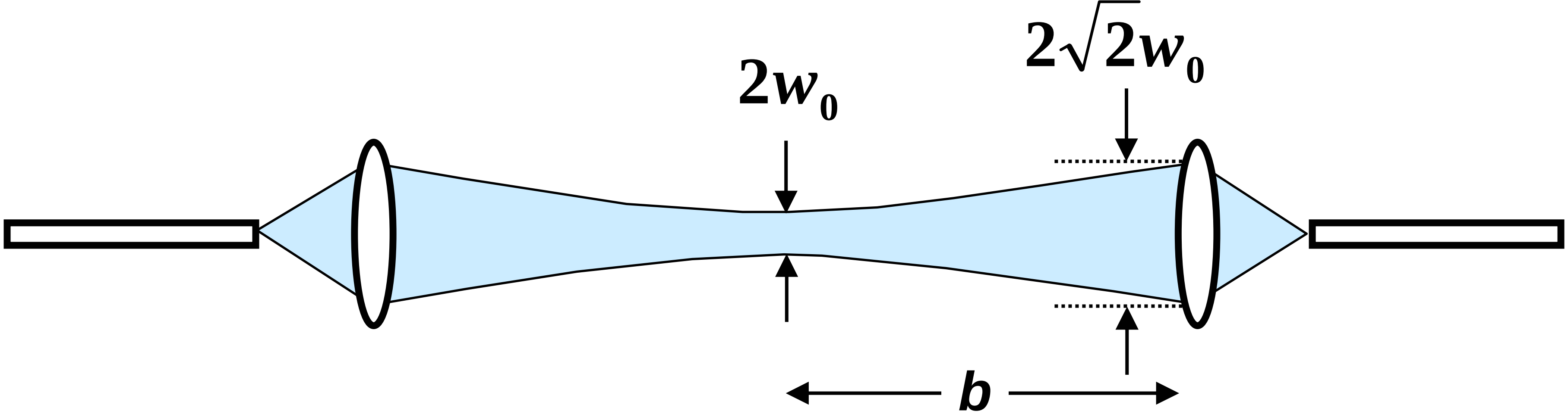




Marxer, et al., J-MEMS, vol.6, 1997. p.277-85.



Free-Space Optics: Gaussian Beam

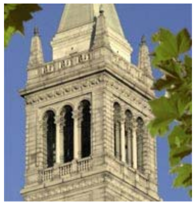


$$w^2(z) = w_0^{\,2}\left[1+\left(\frac{z}{b}\right)^2\right]$$

$$\boxed{b = \frac{\pi w_0^2}{\lambda}}$$

(Confocal Parameter)

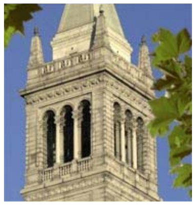
- **Larger beam waist → Long collimation length**
- **System size ~ 2*b***
- **Mirror diameter ~ 2aw_0,   a ~ 1.5 to 2**



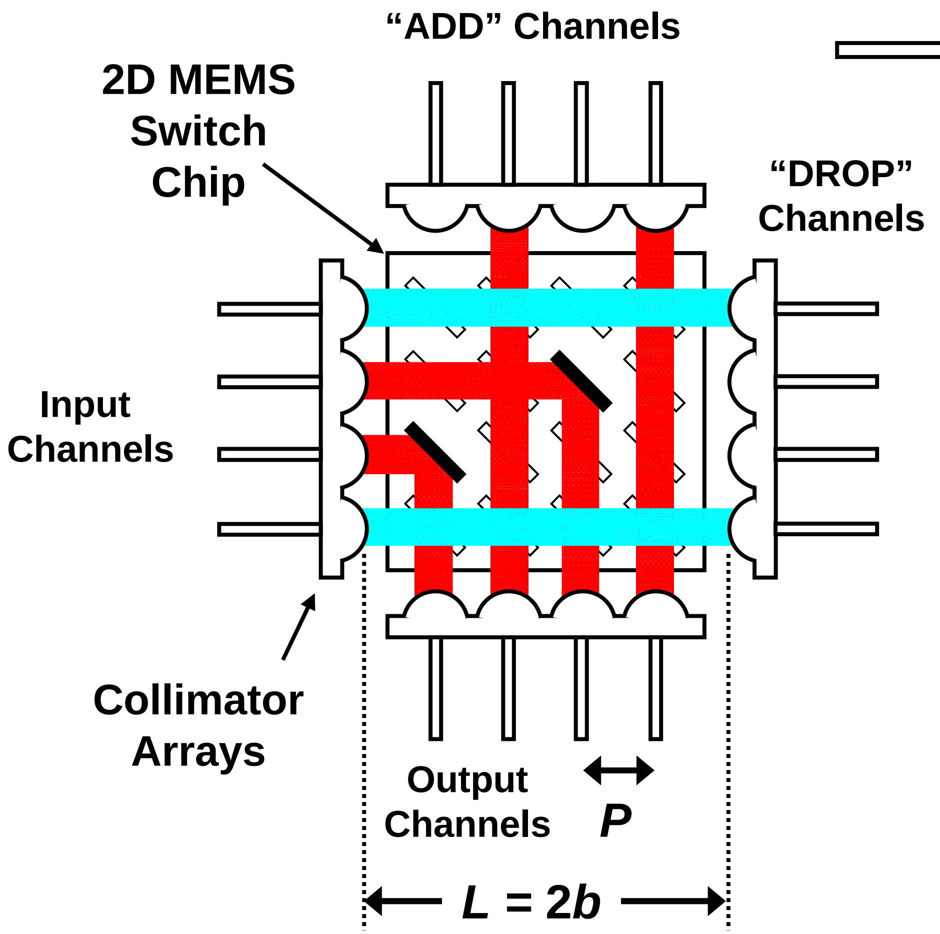
Space Division Switches:

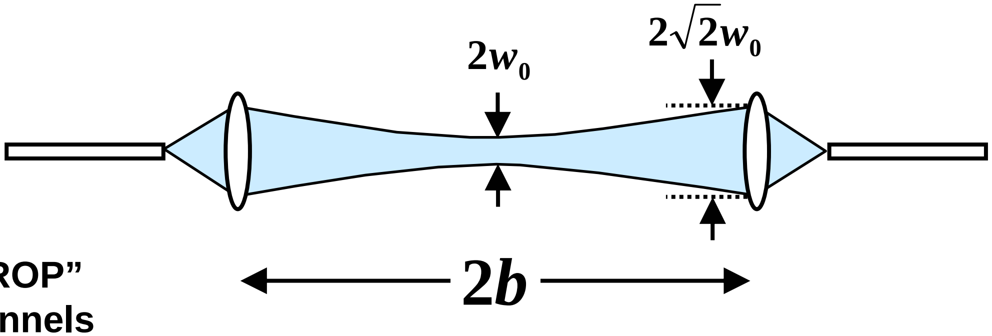
(1) 2D MEMS Optical Switches

(2) 3D MEMS Optical Switches



Scaling of 2D MEMS Optical Switches





N : Port Count

P : Fiber Pitch

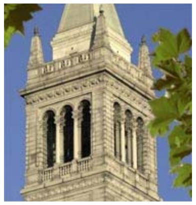
$L = NP \approx 2b = \frac{2\pi w_0^2}{\lambda}$: Chip Length

$\eta = \frac{2R}{P}$: Fill Factor of Micromirror

$R = aw_0$: Mirror Radius (vertical)

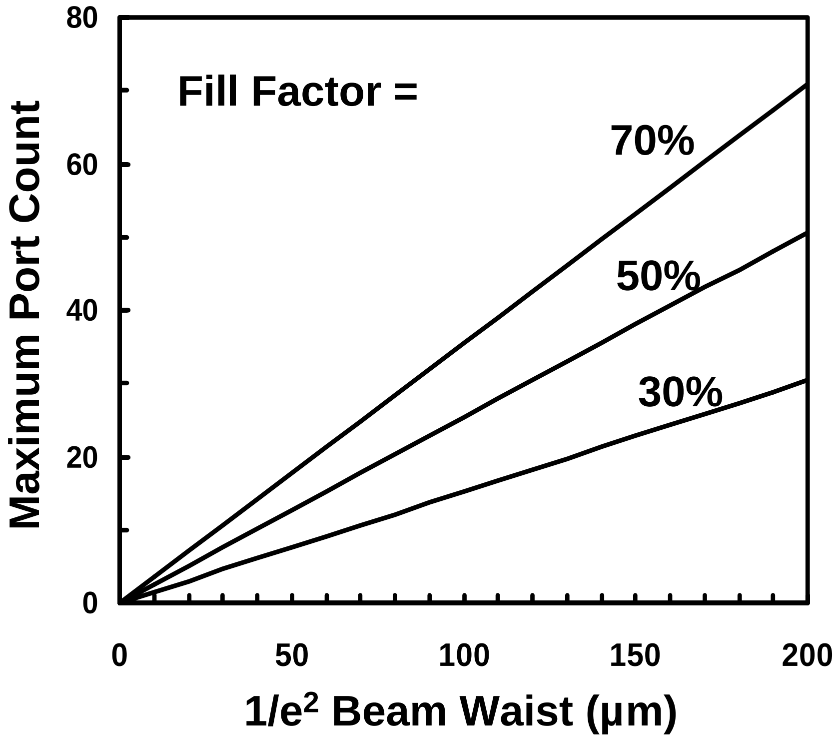
a ~ 2

$$\Rightarrow \boxed{N \approx \frac{\pi\eta}{a\lambda} w_0} \quad \boxed{L = \left(\frac{2a^2\lambda}{\pi\eta^2}\right) \cdot N^2}$$

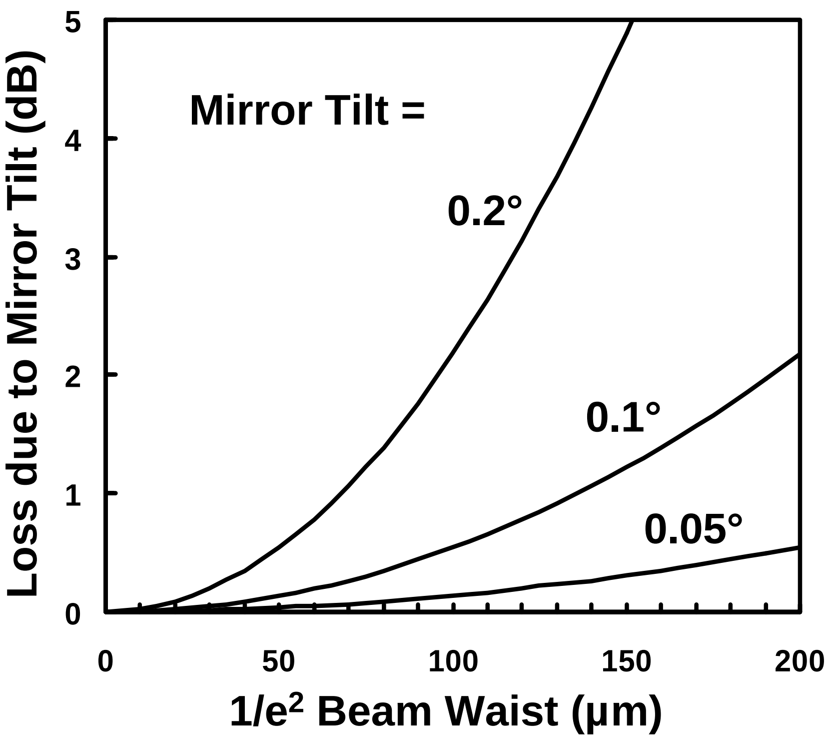


Port Count of 2D MEMS Switches

Port Count vs Beam Size



Loss Due to Mirror Tilt

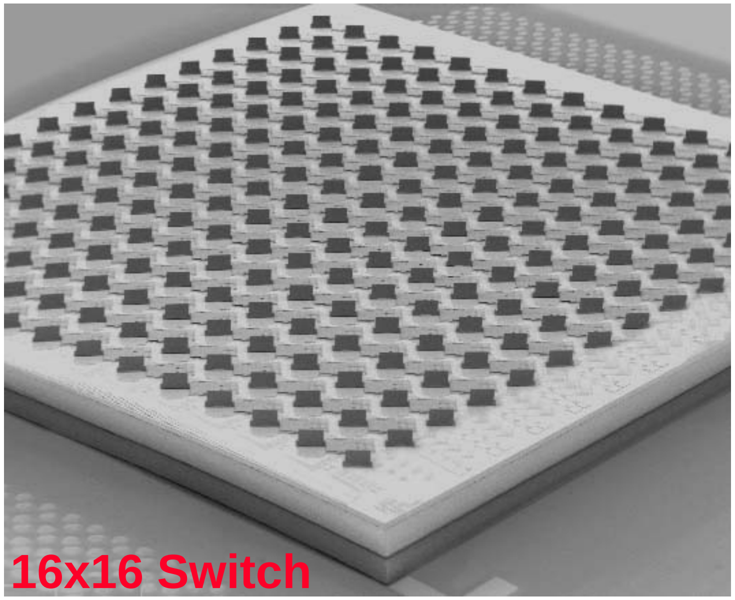


$$\text{Port Count:} \quad N \approx \frac{\pi\eta}{a\lambda} w_0$$

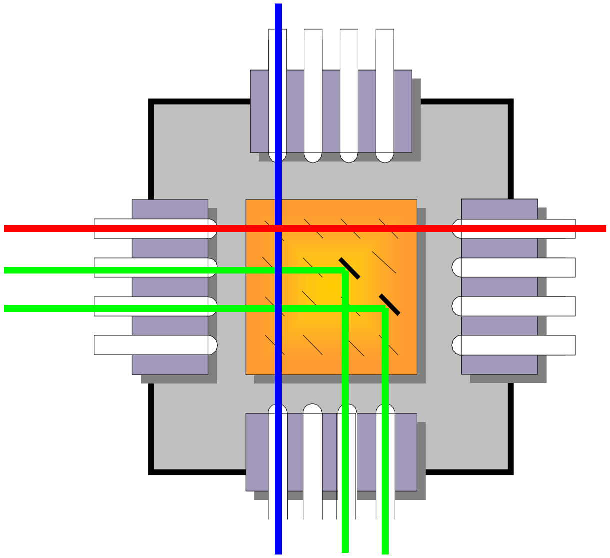
$$\text{Chip Size:} \quad L = \left(\frac{2a^2\lambda}{\pi\eta^2}\right) \cdot N^2$$

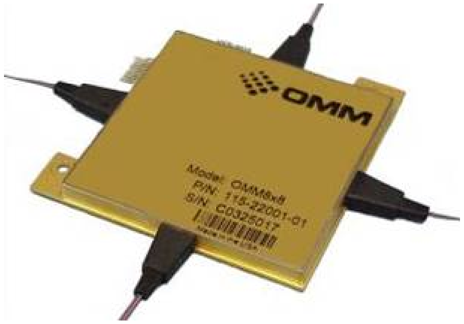
- **Accuracy and uniformity of mirror angles impose a loss penalty, which limit the maximum port count**

Surface-Micromachined
2D MEMS Optical Switches (16x16)



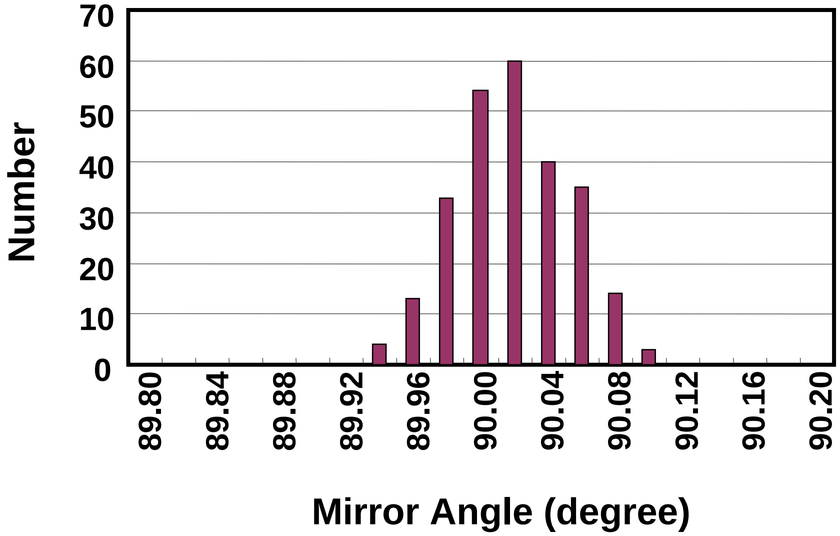
L. Fan, et al., OFC 2002

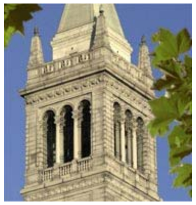




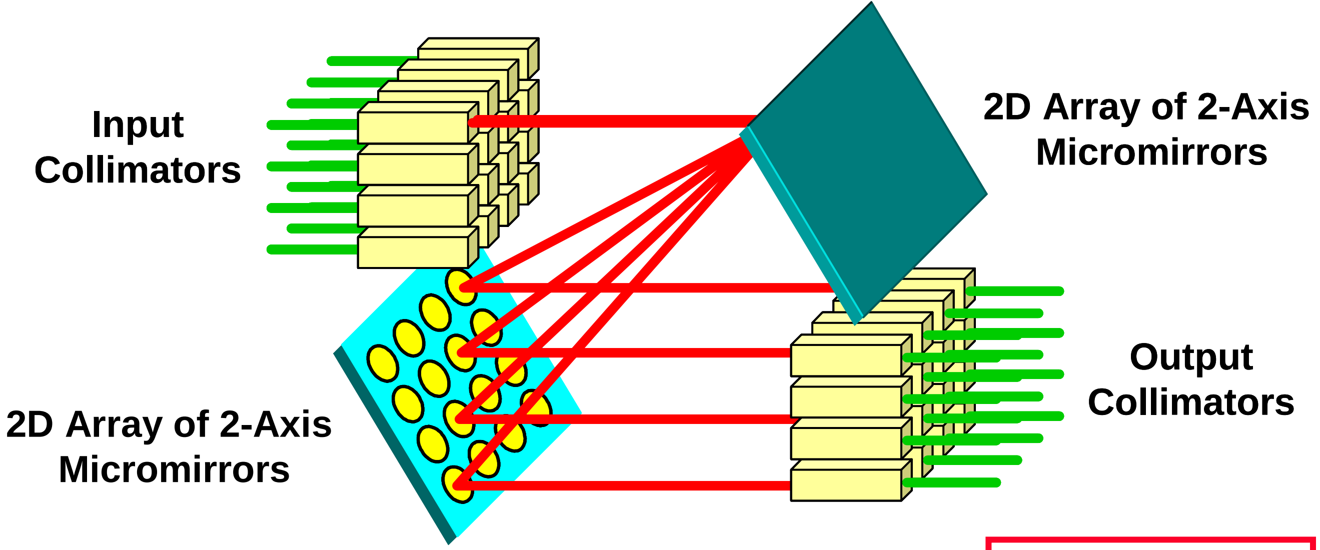
L. Fan, et al., OFC 2002

Absolute angular uniformity ~ ± 0.05°





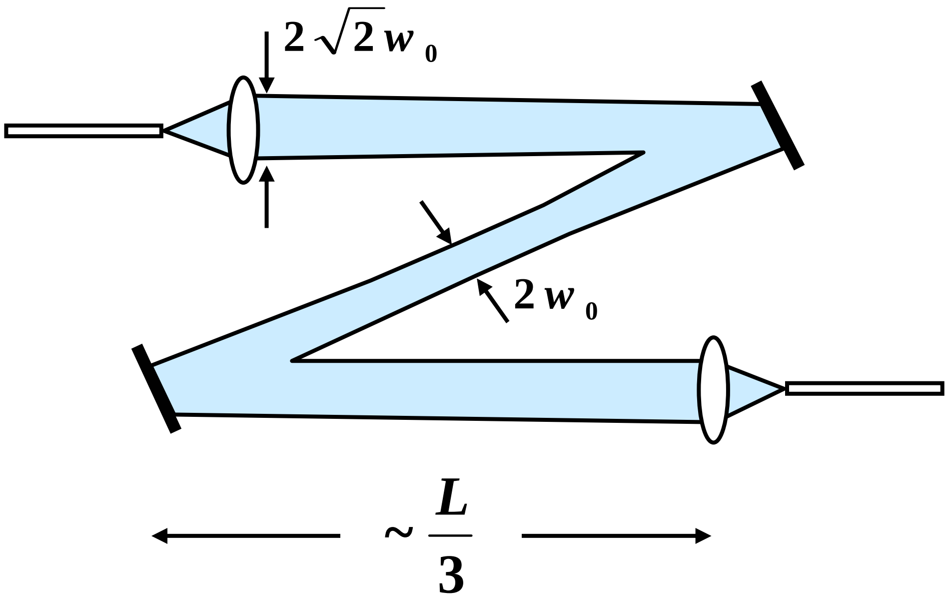
Scaling of 3D MEMS OXC



Port Count : $\boxed{N = \frac{\pi L(\Delta\theta)^2}{9a^2\lambda}}$

System size ~ $\boxed{\frac{L}{3} = \left(\frac{3a^2\lambda}{\pi(\Delta\theta)^2}\right)\cdot N}$

Optical Path Length : $L = 2b = \frac{2\pi w_0^2}{\lambda}$

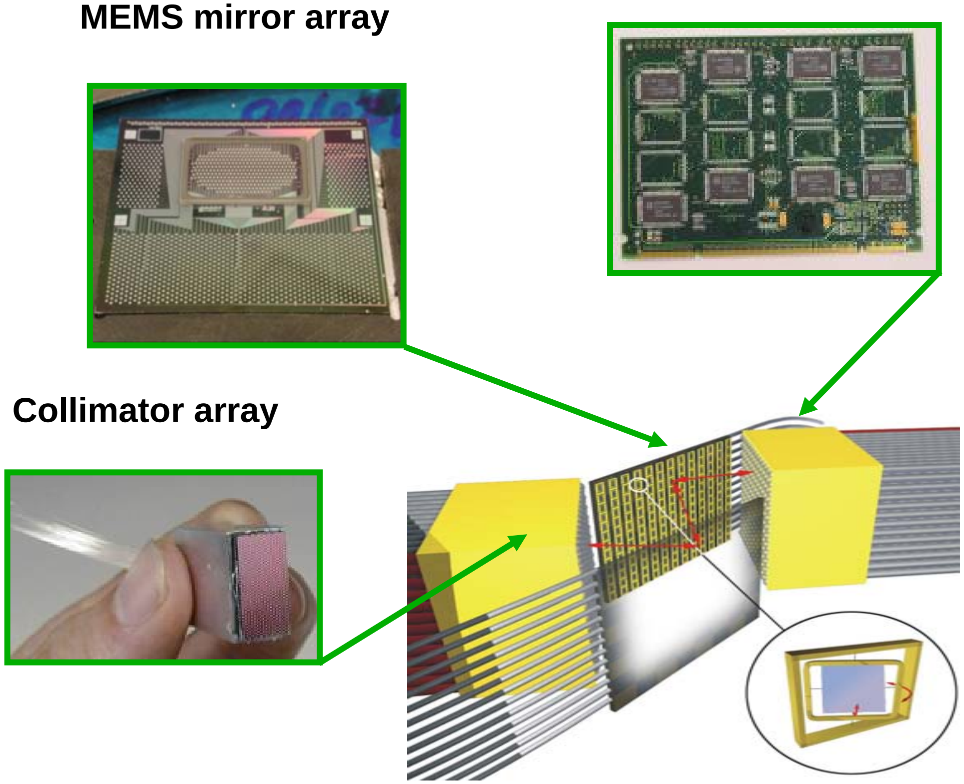


$\Delta\theta$: Mechanical Scan Angle

$R = aw_0$: Mirror Radius (a ~ 2)

w_0 : Beam Waist

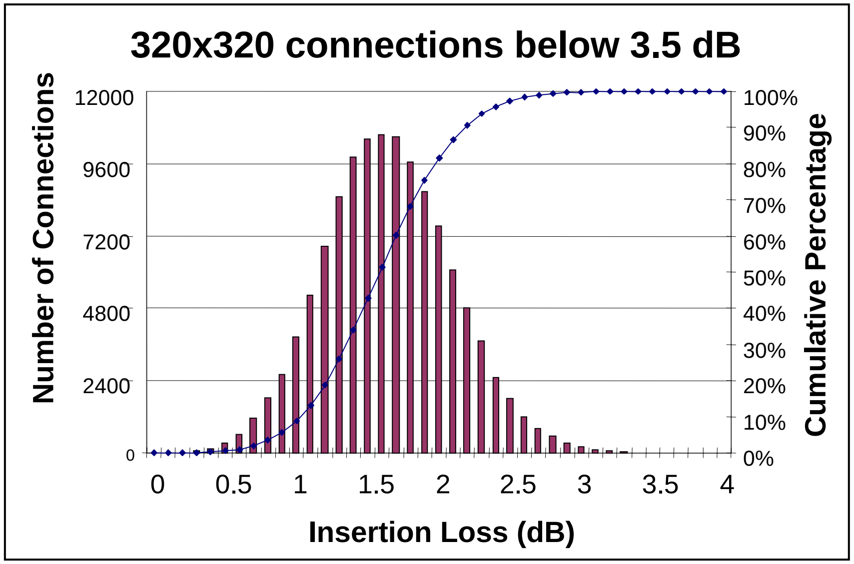
3D-MEMS Switching Technology



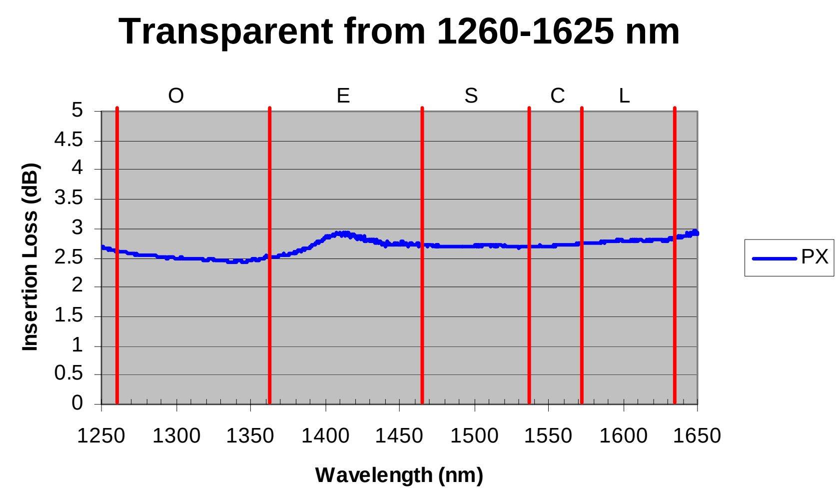
ASIC Voltage drivers

MEMS mirror array

Collimator array

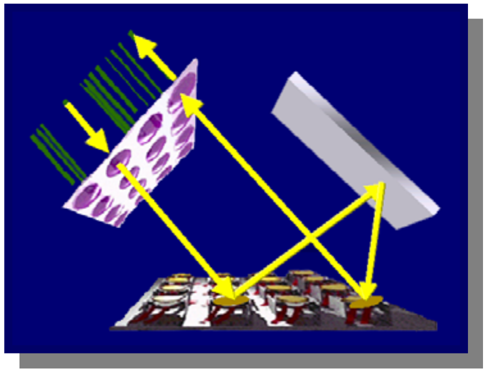


320x320 connections below 3.5 dB



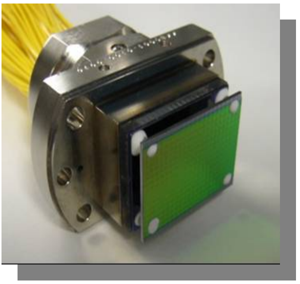
Transparent from 1260-1625 nm

Glimmerglass 3D-MEMS Switches



3D-MEMS Architecture

Collimator
Array



MEMS
Mirror Array

2” x 6” x 7”

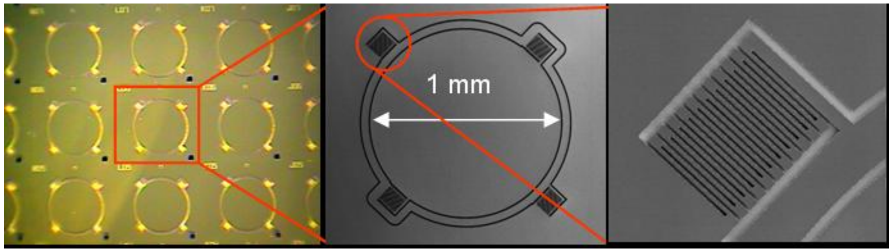
32x32 to 80x80 OEM Module

16x16 to 24x24 2U Chassis

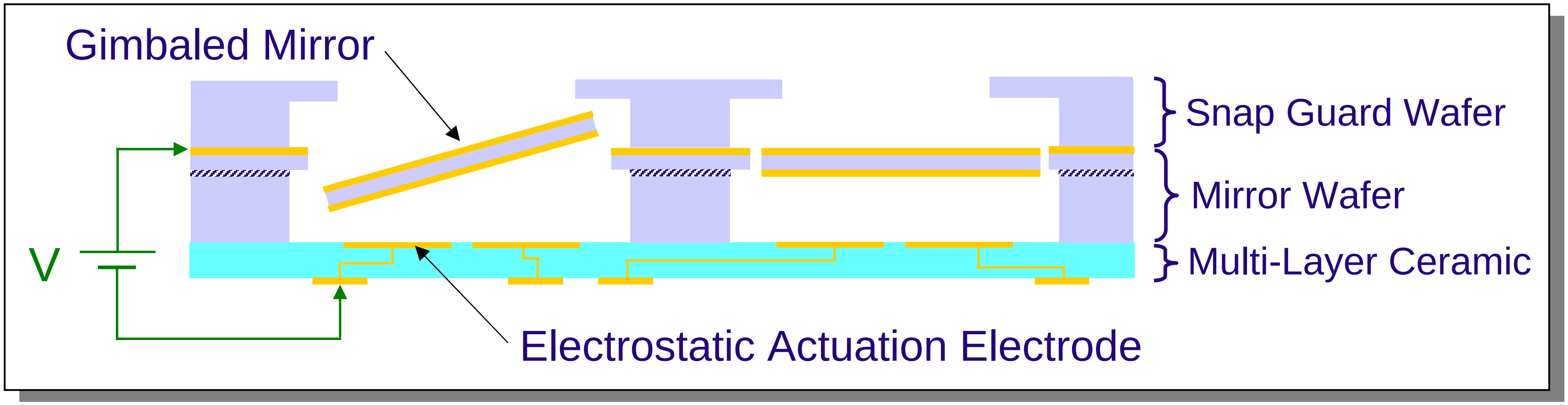
32x32 to 160x160 8U Chassis

Glimmerglass MEMS Module

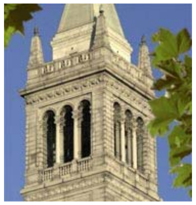
(Scan Angle ~ 3.5º @ ~ 200V)



SPIE Vol. 5604, pp. 208-217

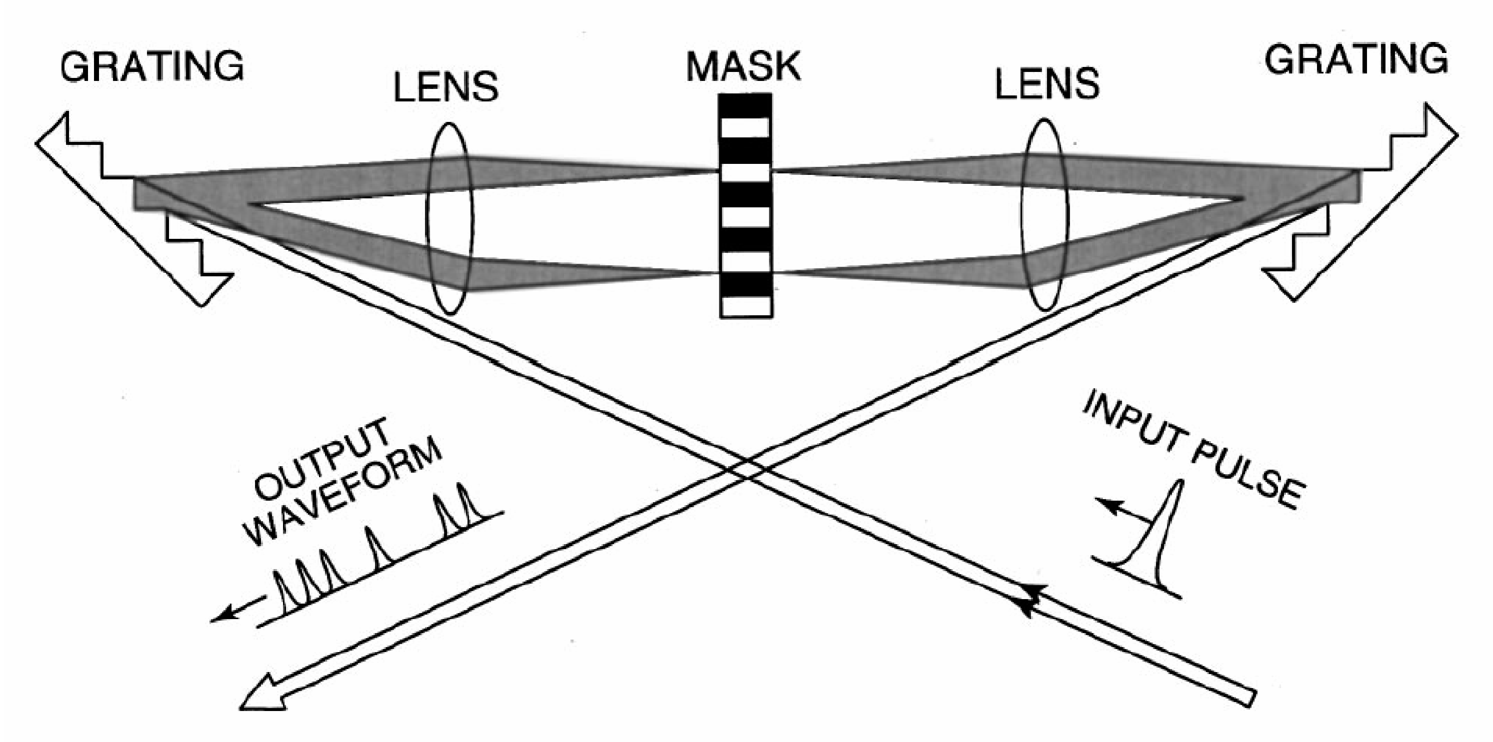


- **Snap Guard Prevents Electrostatic Snap-Down Failure**
- **Mirror Material Is Highly Reliable Single-Crystal Silicon on Insulator (SOI)**
- **Ceramic Substrate Contains Electrodes, Routing, And Hermetic Seal Ring**



Wavelength-Selective Switches (WSS)

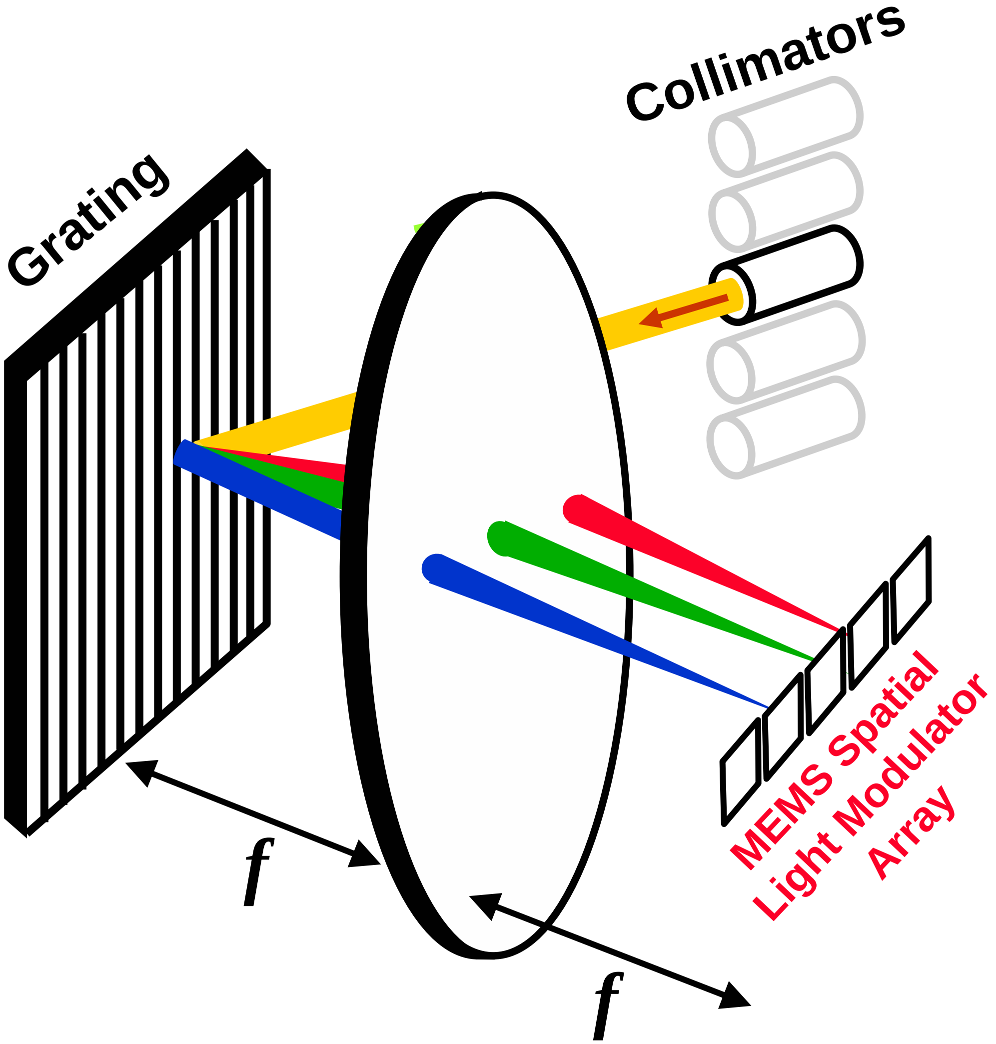
Fourier Transform Pulse Shaper



A. M. Weiner, J. P. Heritage, and E. M. Kirschner, J. Opt. Soc. Am. 1988

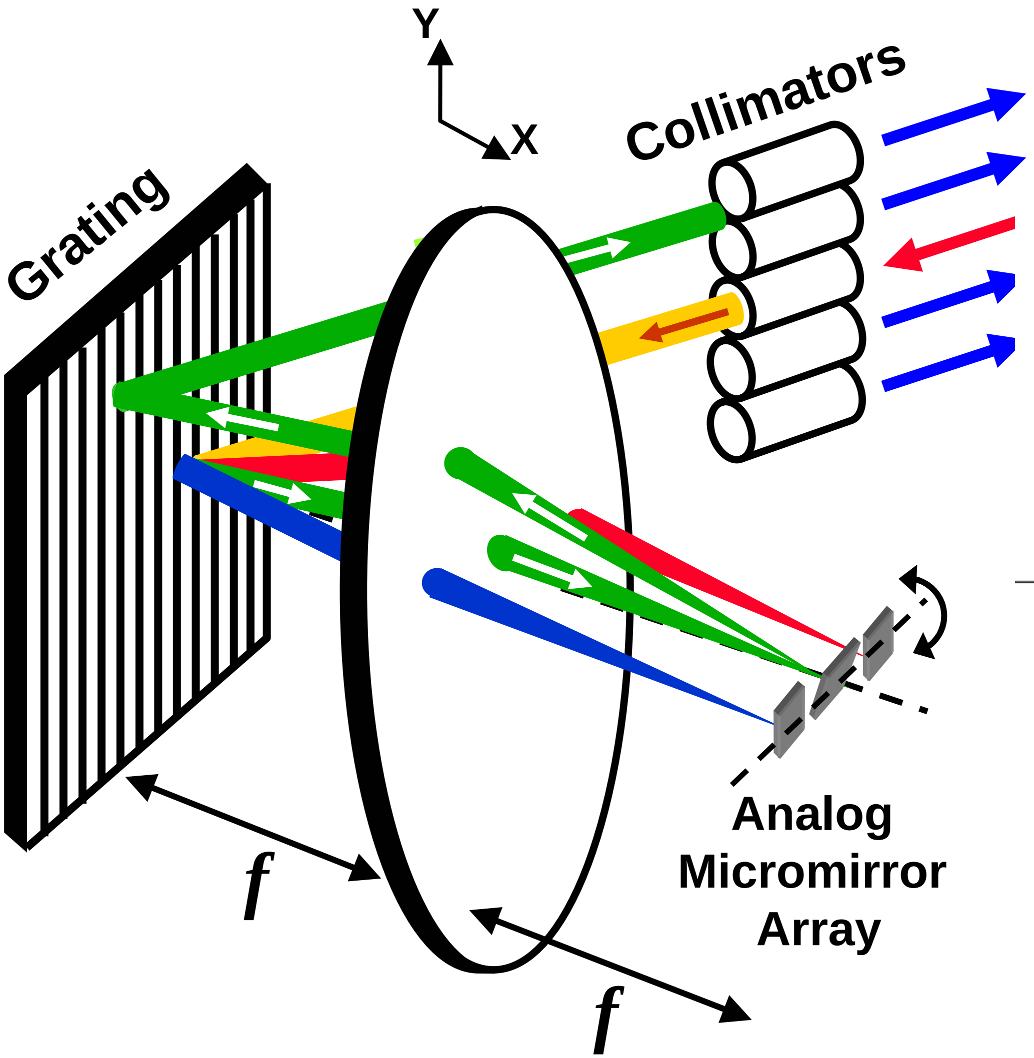
- **Shaping femtosecond pulses by modulating the phases and amplitudes of their spectral components**

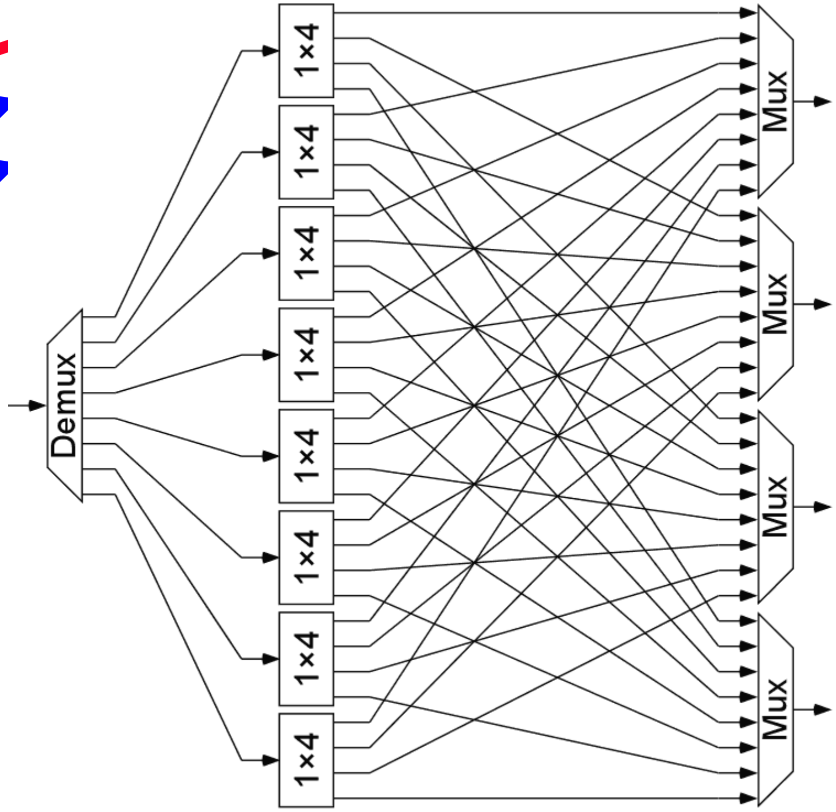
Dynamic WDM Functions



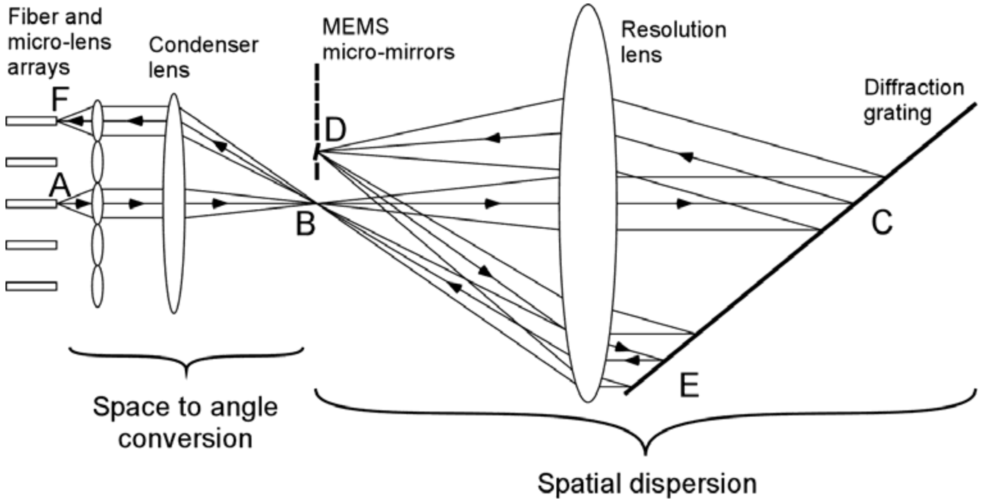
MEMS Spatial Light Modulator Array	Dynamic WDM Functions
Piston Mirrors	Femtosecond pulse shaper
ON-OFF reflectors	Wavelength blocker
Variable reflectivity mirror	Spectral (or gain) equalizer
1x2 Digital micromirrors	Optical add-drop multiplexer (OADM)
1xN analog micromirrors	Wavelength-Selective Switch (WSS)
Deformable mirrors	Tunable dispersion compensator

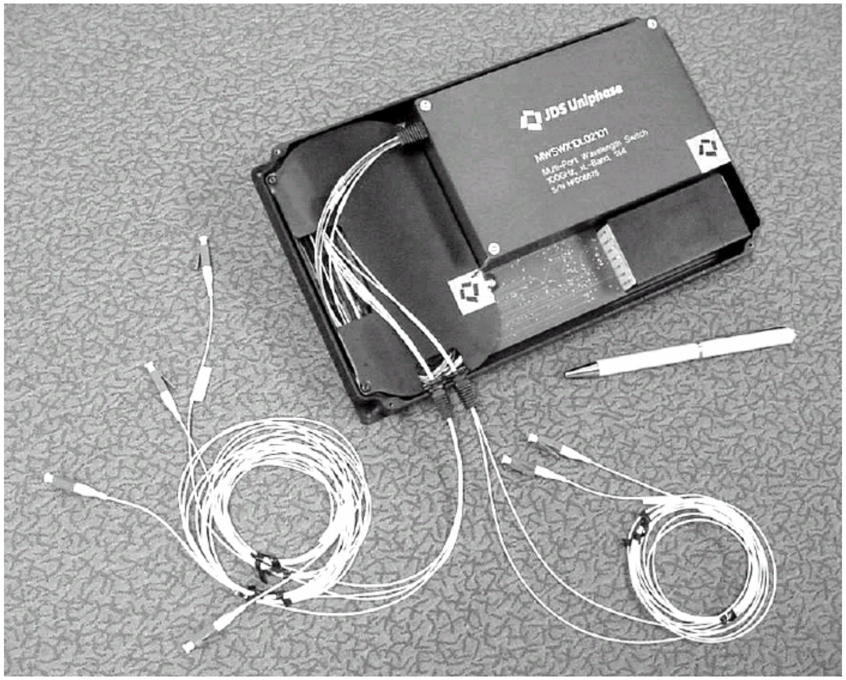
1x4 Wavelength-Selective Switch (WSS)





1x4 WSS



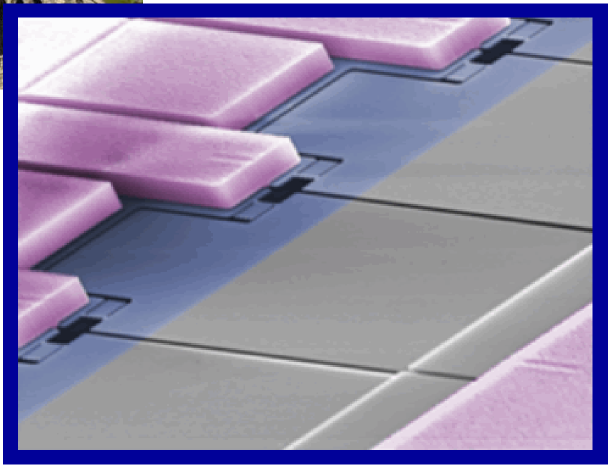


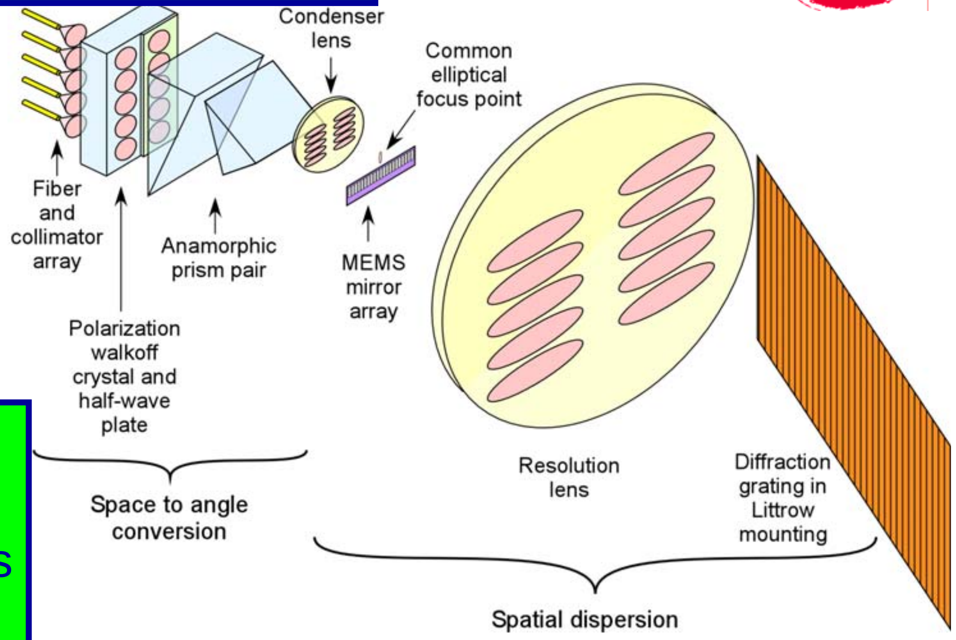
- **D. Marom et al. (Lucent), OFC 2002**
  - **1x4 WSS**
  - **Channel spacing: 50 or 100 GHz**
  - **MEMS performance: 12° (> 55 V)**
- **T. Ducellier et al. (JDS-U), ECOC 2002**
  - **1x4 WSS**
  - **Channel spacing: 100 GHz**
  - **MEMS performance: ±2°**

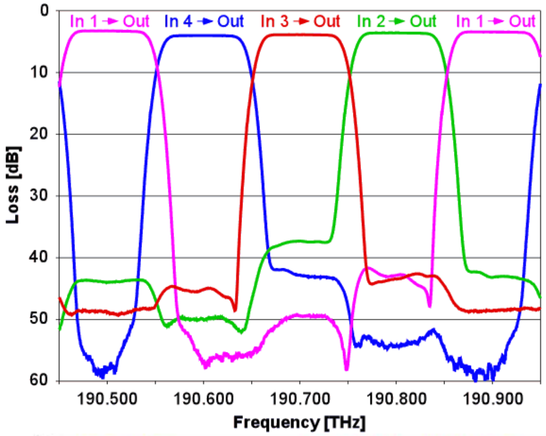
64 Channel, Wavelength-Selective 4×1 Switch (D. Marom)

Free-Space Implementation

Lucent Technologies
Bell Labs Innovations

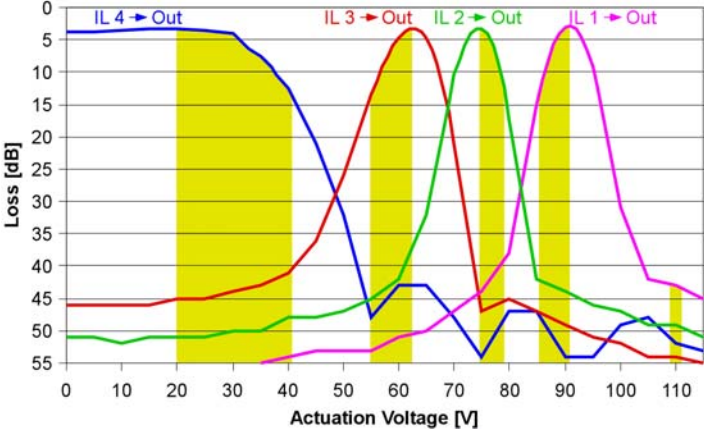




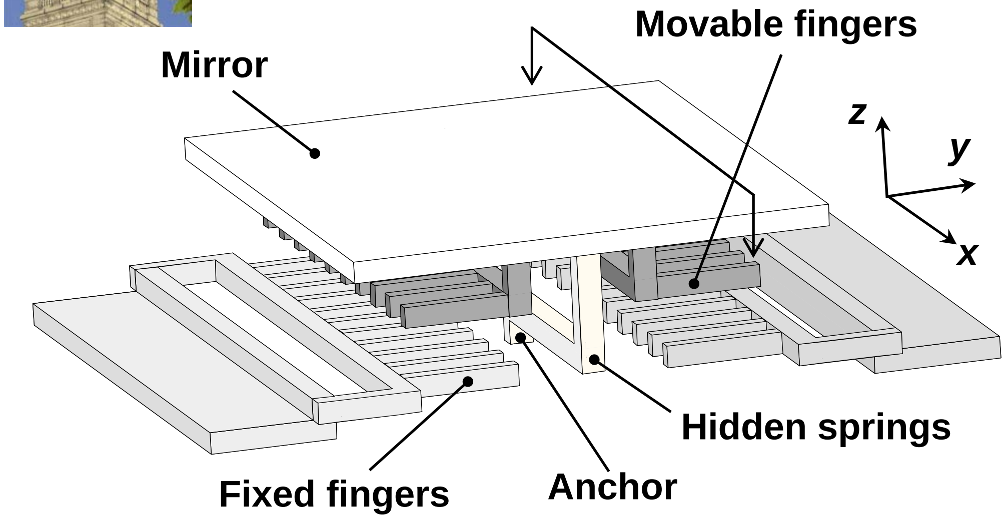


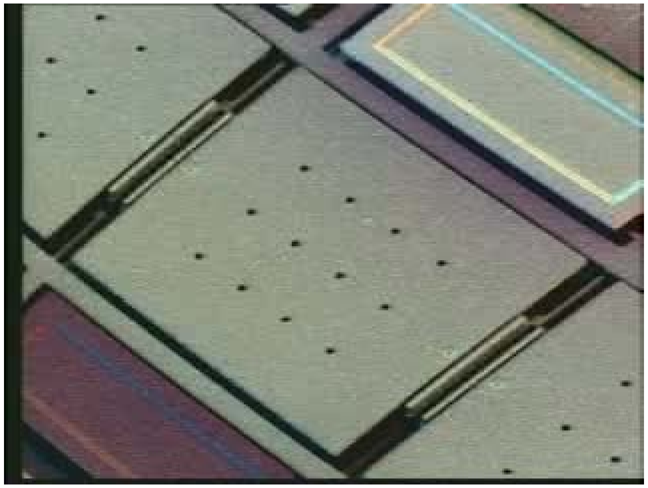
WSS provides:

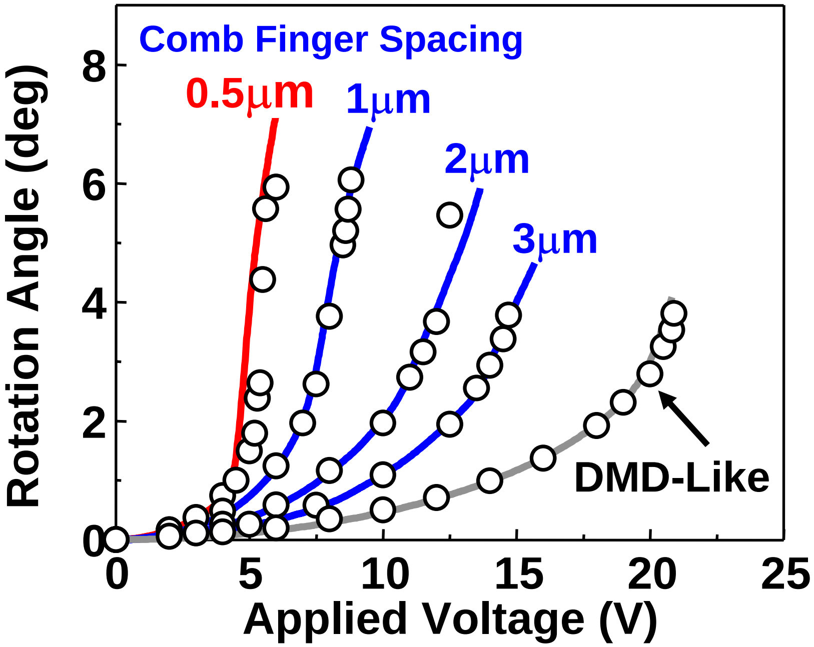
- Port switching
- Wide passbands
- 10 dB DSE
- Blocking
- Low insert loss
- Low PDL, DGD



Analog Micromirror Array (UCLA)



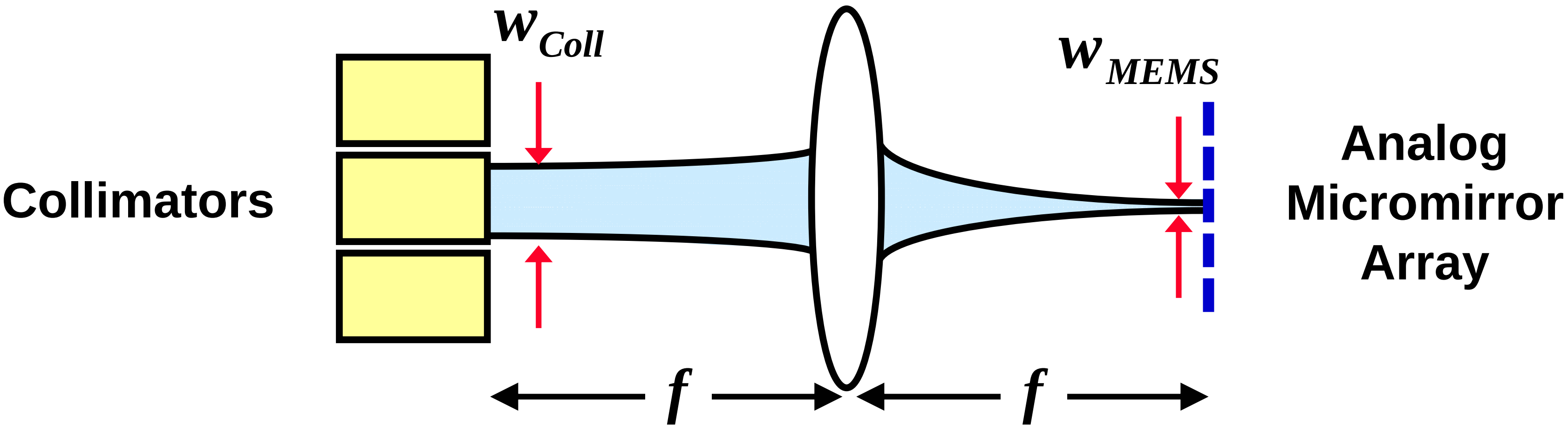




Scan Angles	+/- 6° (mechanical)
Voltage	6 V
Fill Factor	98%
Res. Freq.	3.4 kHz
Stability (3hr)	±0.00085°
System (3hr)	± 0.0035dB

- Hah, et al (UCLA) J. MEMS, 2004, p. 279
- Tsai, et al (UCLA) IEEE PTL 2004, p. 1041

Scaling of WSS



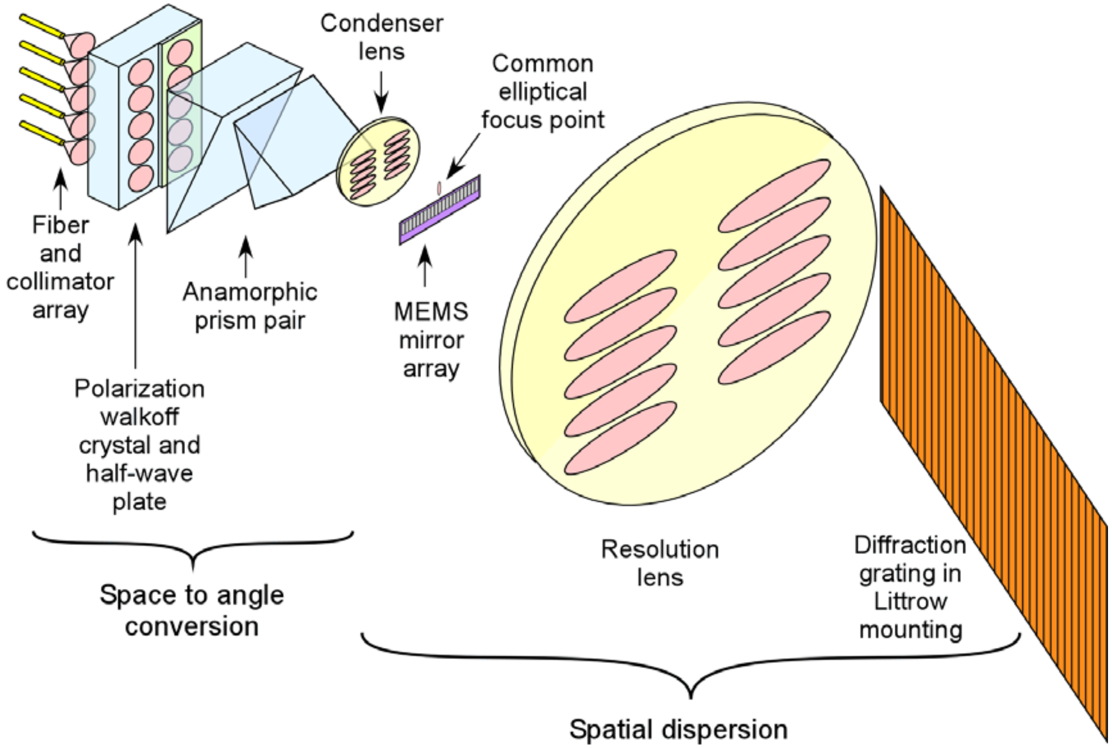
$$w_{MEMS} = \frac{\lambda \cdot f}{\pi \cdot w_{Coll}}$$

$$\frac{N_{\text{spatial}}}{\Delta\lambda} = \frac{\pi}{22\lambda} \frac{f}{f\#} \cdot \left(\frac{\partial\theta}{\partial\lambda}\right)_{\text{Grating}}$$

$$\boxed{N_{\text{spatial}} \cdot N_{\lambda} = \frac{\pi \cdot BW_{\lambda}}{22\lambda} \frac{f}{f\#} \cdot \left(\frac{\partial\theta}{\partial\lambda}\right)_{\text{Grating}}}$$

- **System size ~ 2 *f***
- **Total capacity ($N_{spatial}$ x N_{λ}) is constant**
  - **Proportional to *f***

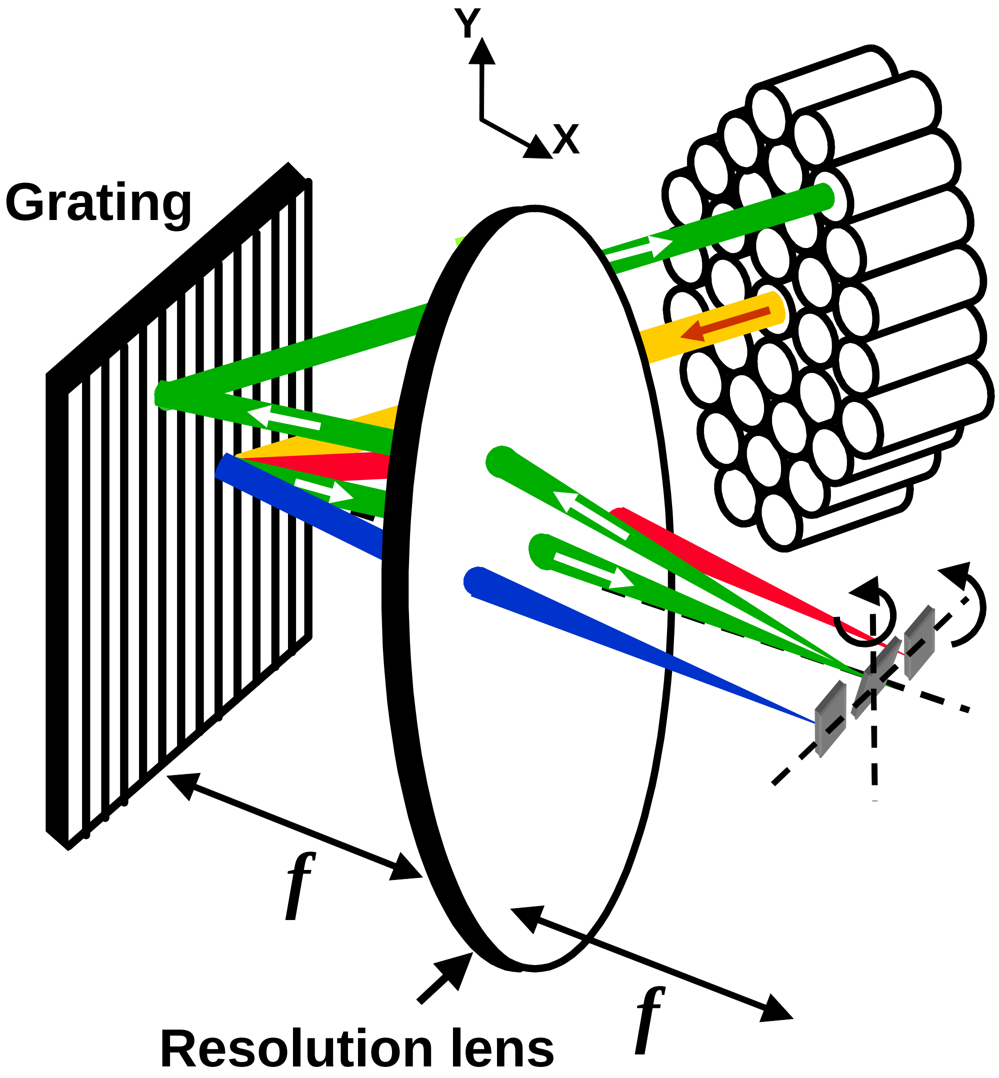
Approach for Increasing Port Count (1)



D. Marom (Lucent)

- Use anamorphic prism pair to compress lateral beam size on MEMS micromirrors
- Elliptical beams on MEMS mirrors → Rectangular micromirror

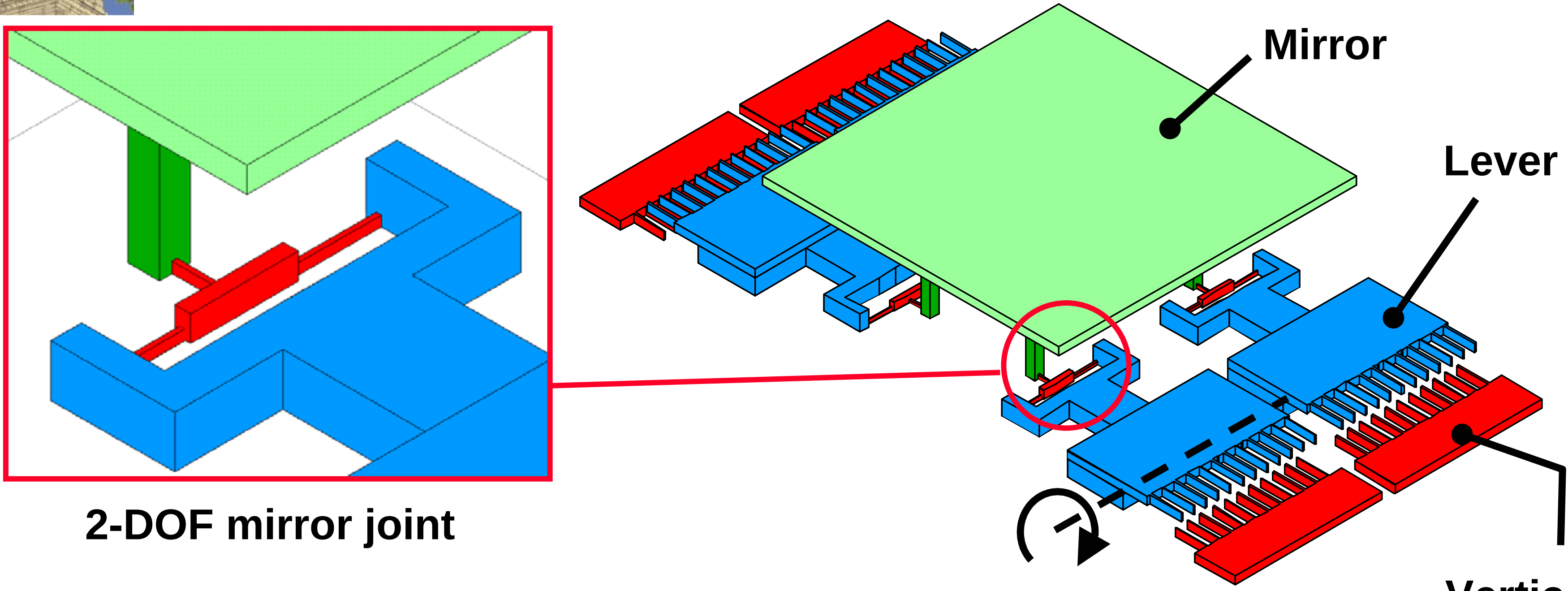
Approach for Increasing Port Count (2)



- $1\text{x}N^2$ WSS:
  - 2D collimator array
  - 1D array of 2-axis micromirror array
- Port count is increased from N to N^2
  - N is the diffraction-limited linear port count
- High port count WSS
  - 1x32 WSS has been demonstrated

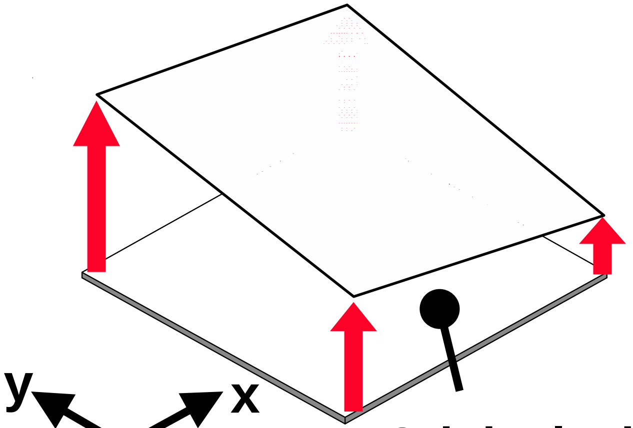
- J.-C. Tsai, et al., (UCLA) ECOC 2004, Paper Tu1.5.2

High-Fill Factor 2-Axis Micromirror Array



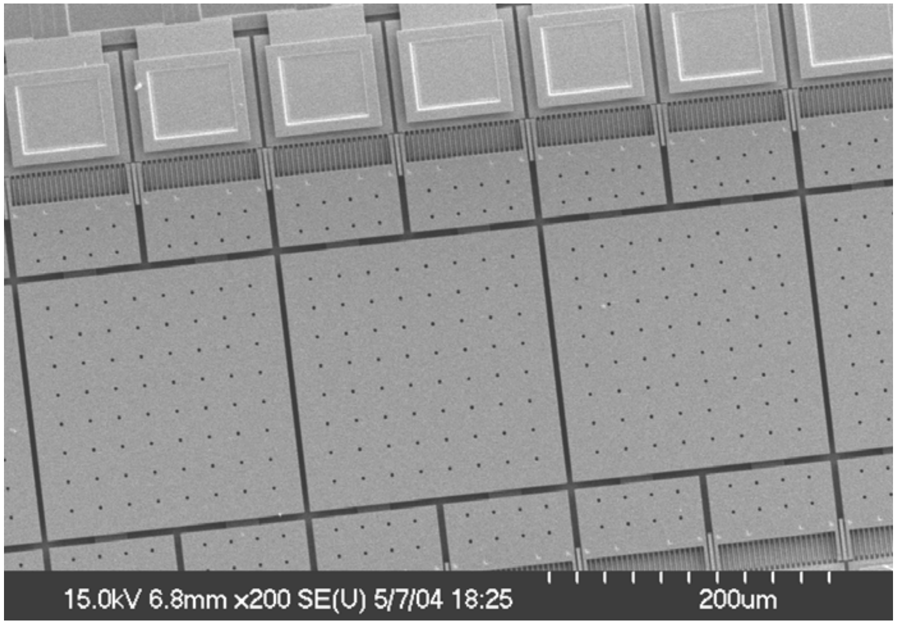
2-DOF mirror joint

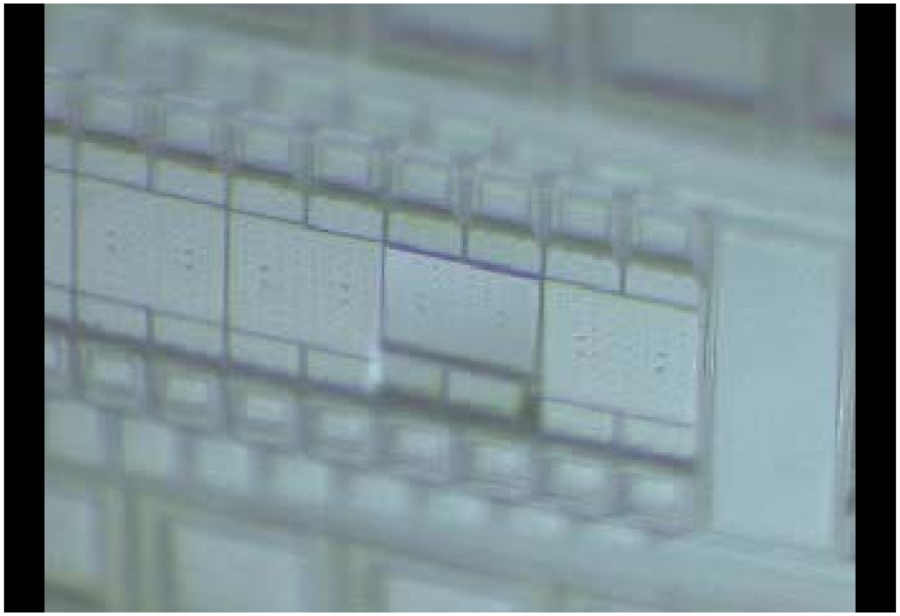
- Gimbal-less
  - High Fill factor (> 98%)
- Large scan angle
  - 3x leverage
  - Powerful vertical combdrive actuators



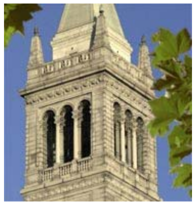
Tsai, Fan, Hah, Wu, Optical MEMS 2004

SEM of Gimbal-less 2-Axis Analog Micromirror Array

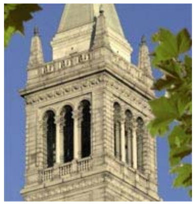




- SUMMiT-V 5-layer surface micromachining process
- Mirror pitch: 200 um
- Large scan angles: ±6.7º (mechanically) @ 75 V
- Fill factor: 98%
- Resonant frequency = 5.9 kHz



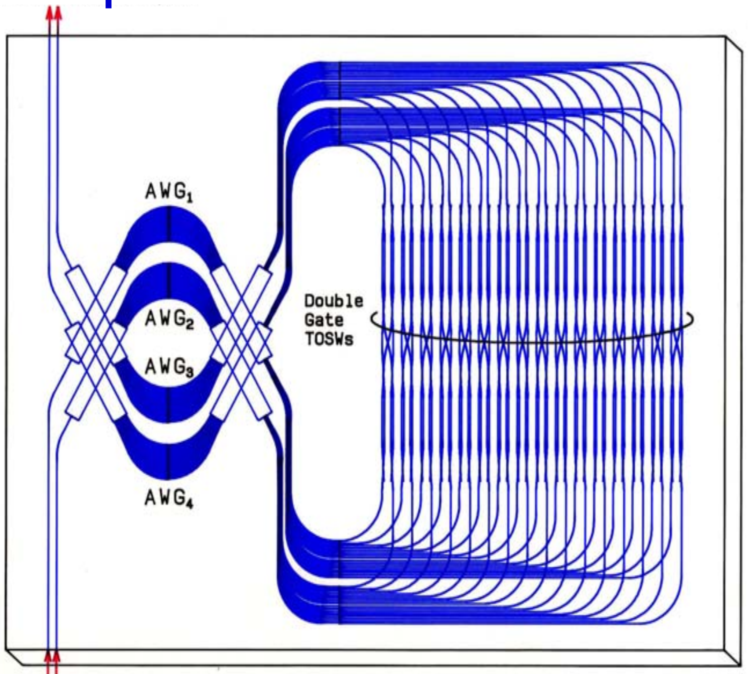
Planar Lightwave Circuit (PLC) MEMS



Reconfigurable Optical Add/Drop Multiplexer (ROADM)

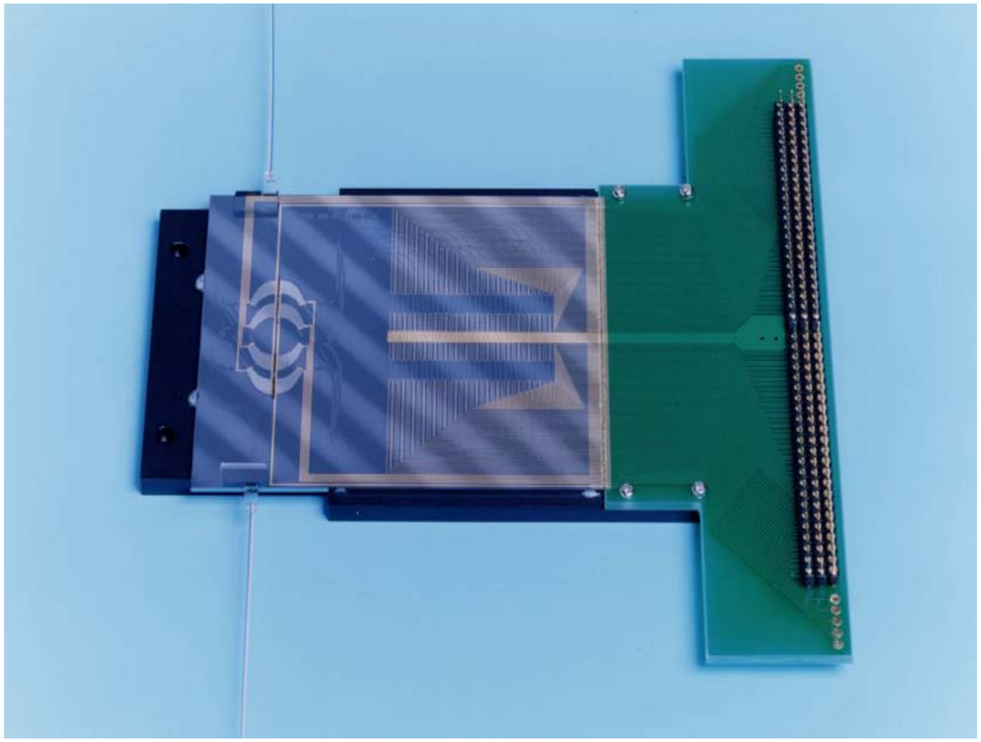
Drop port

Main output port



Main input port

Add port



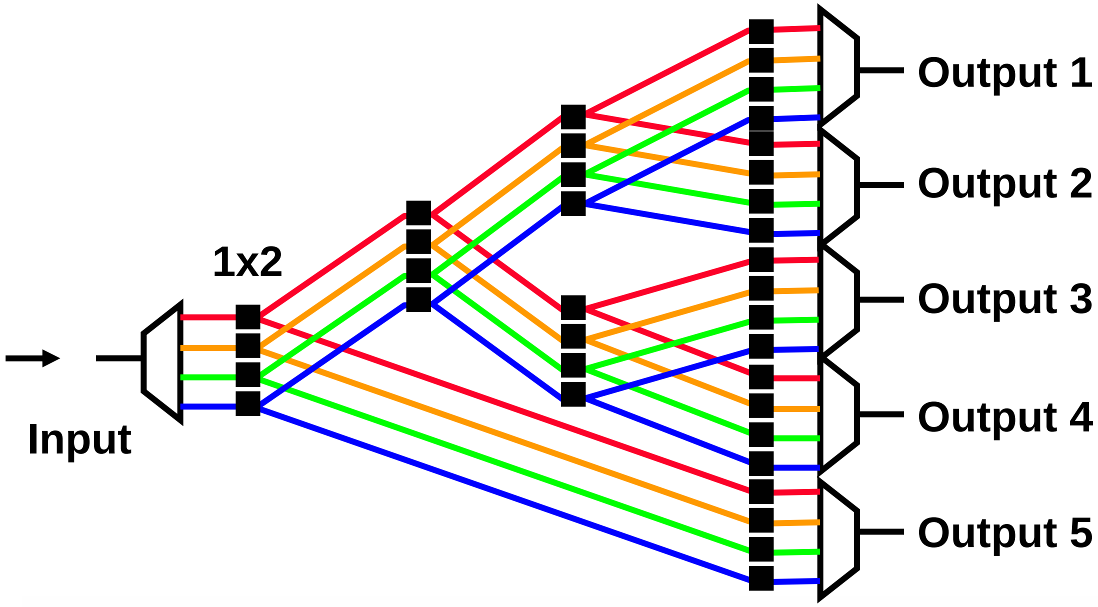
(a) Configuration of 16ch-100GHz OADM

(b) Photograph of OADM

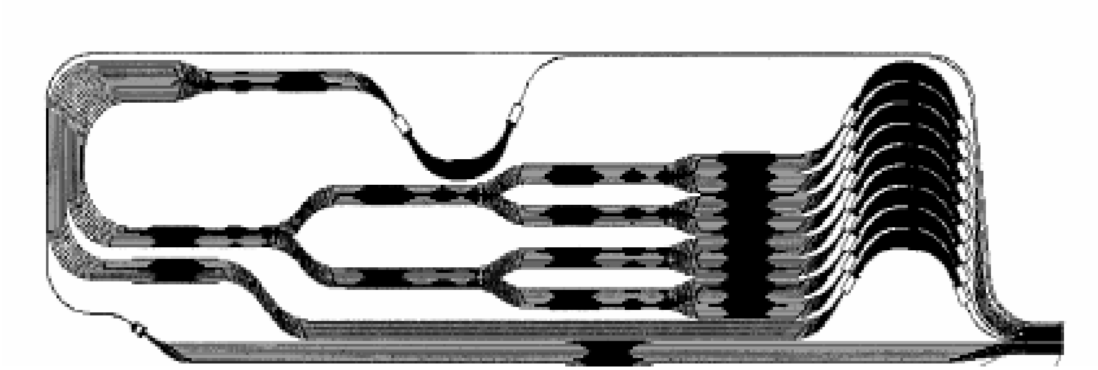
K. Okamoto et al., Electron. Lett., vol. 31, pp.723-724, 1995

(VG courtesy of K. Okamoto)

PLC 1x9 WSS

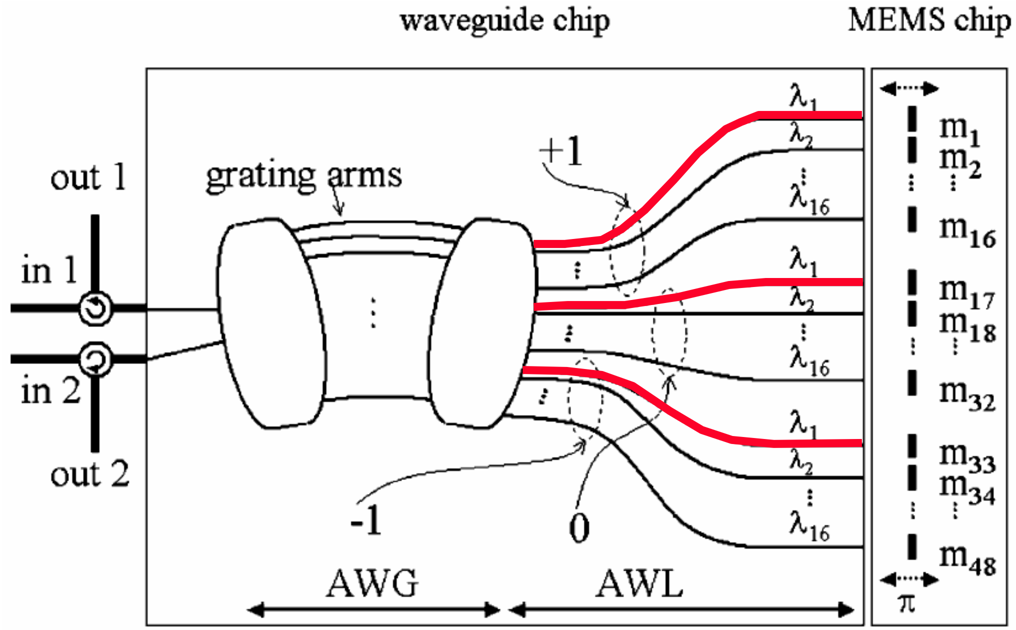


- 1x9 WSS
- Thermal optic switch
  - 450 mW / switch
  - Total power ~ 14W
- Loss ~ 5.4 dB
- Isolation > 46 dB



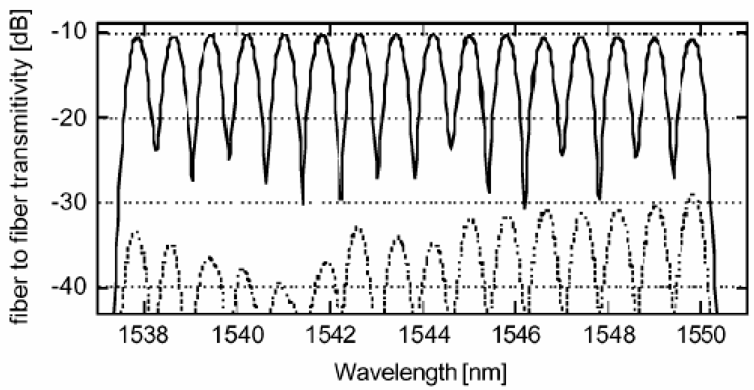
C.R. Doerr, et al. (Lucent), OFC 2002 Postdeadline Paper, FA3

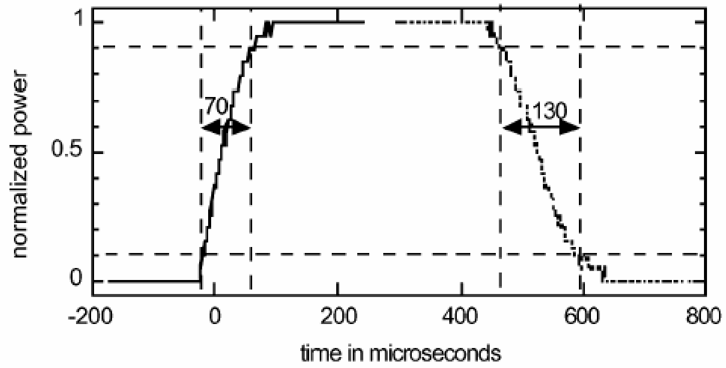
2x2 MEMS Waveguide WSXC



- **3 diffraction orders by AWG**
- **Optical phases of (+1, 0, -1) orders modulated by MEMS piston mirrors**
- **Chip ~ 5 x 9 mm^2**

D.T. Fuchs, et al (Lucent) IEEE PTL, Jan. 2004



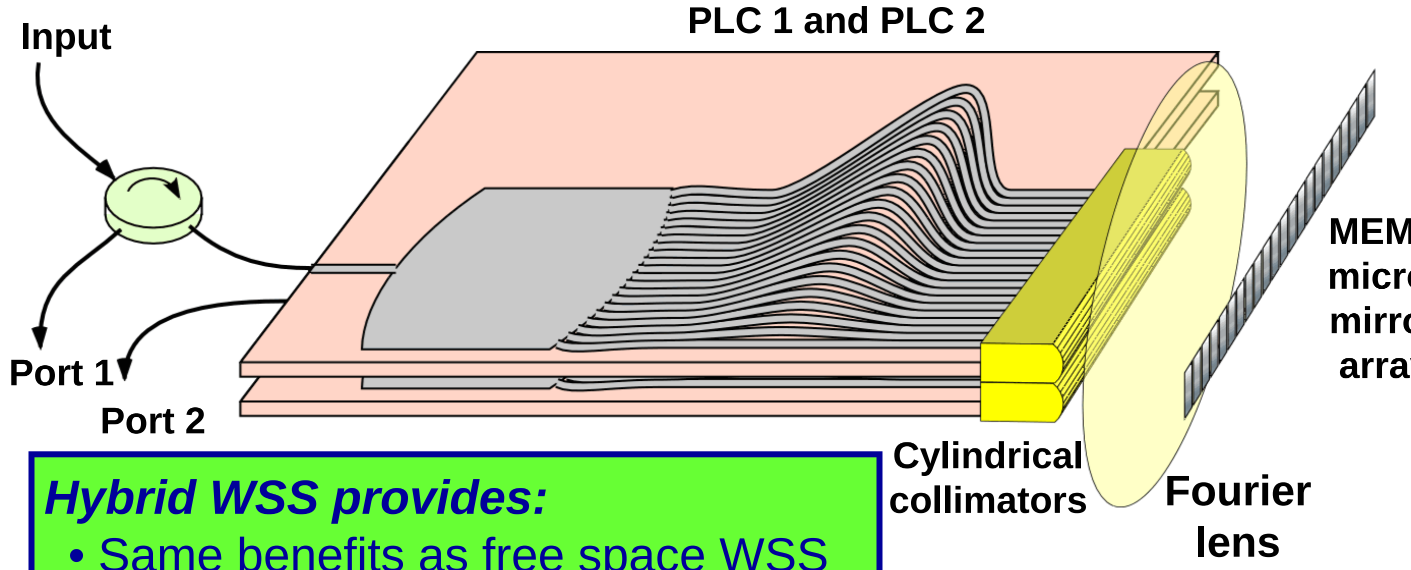


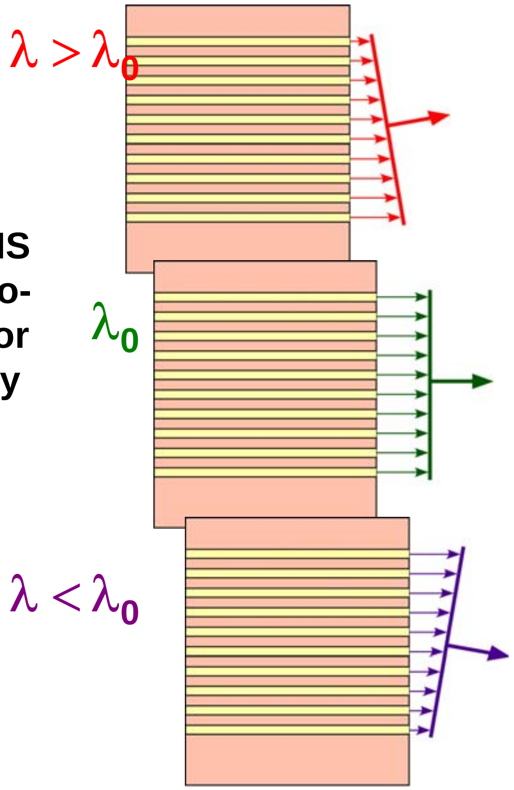
- **100 GHz channel spacing**
- **10.6 dB insertion loss**
- **20 dB extinction ratio**

40 Channel, Wavelength-Selective 1×2 Switch (D. Marom)

Lucent Technologies
Bell Labs Innovations

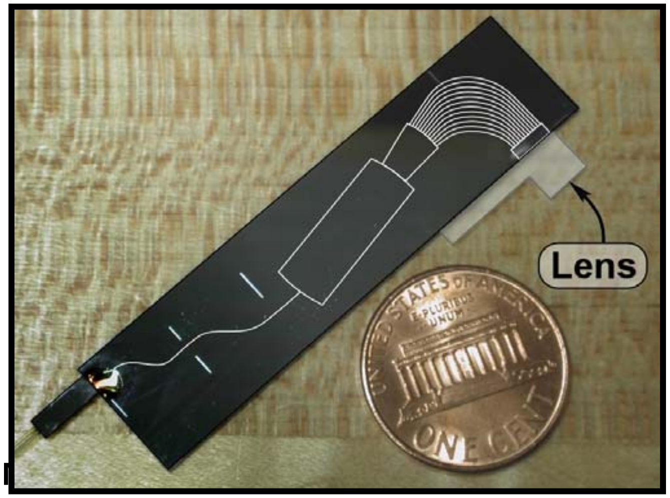
Hybrid PLC and Free-Space Implementation



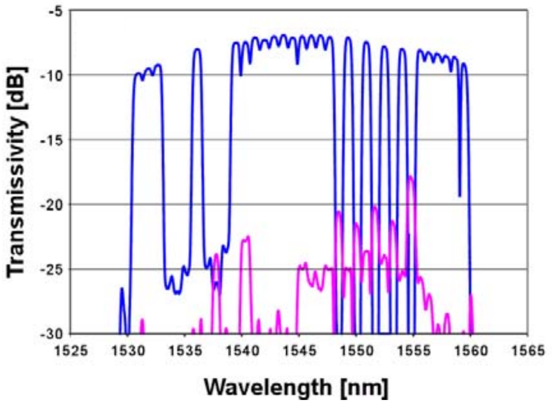


Hybrid WSS provides:

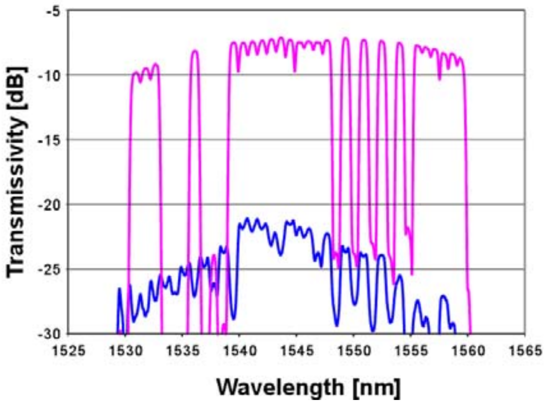
- Same benefits as free space WSS
- Compact implementation
- Integration of additional functionality



Switch to Port 1



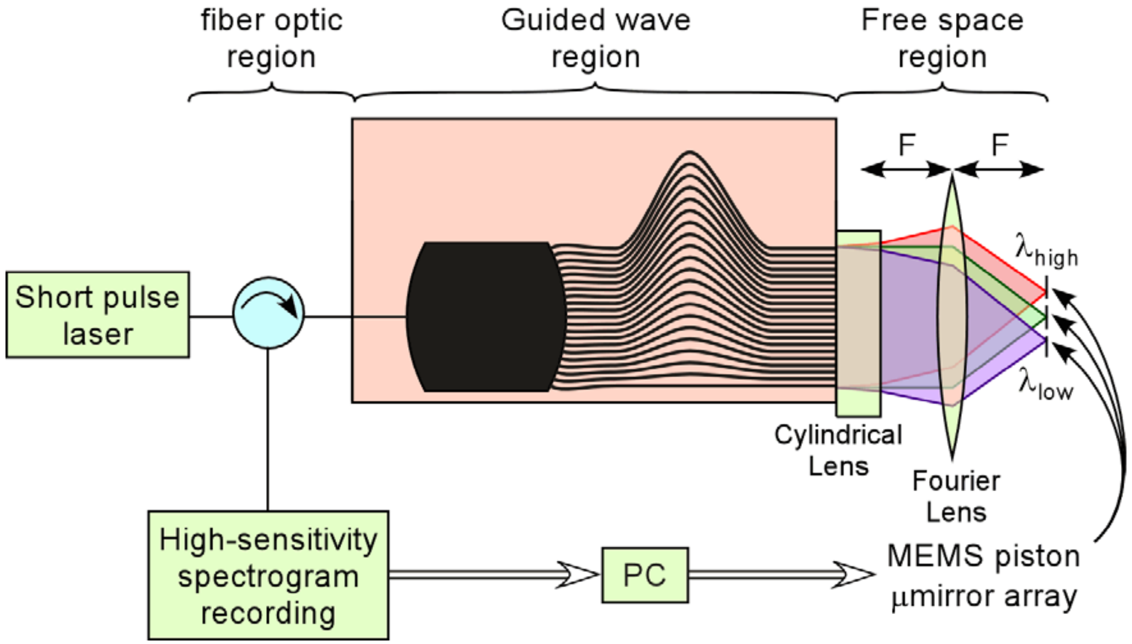
Switch to Port 2

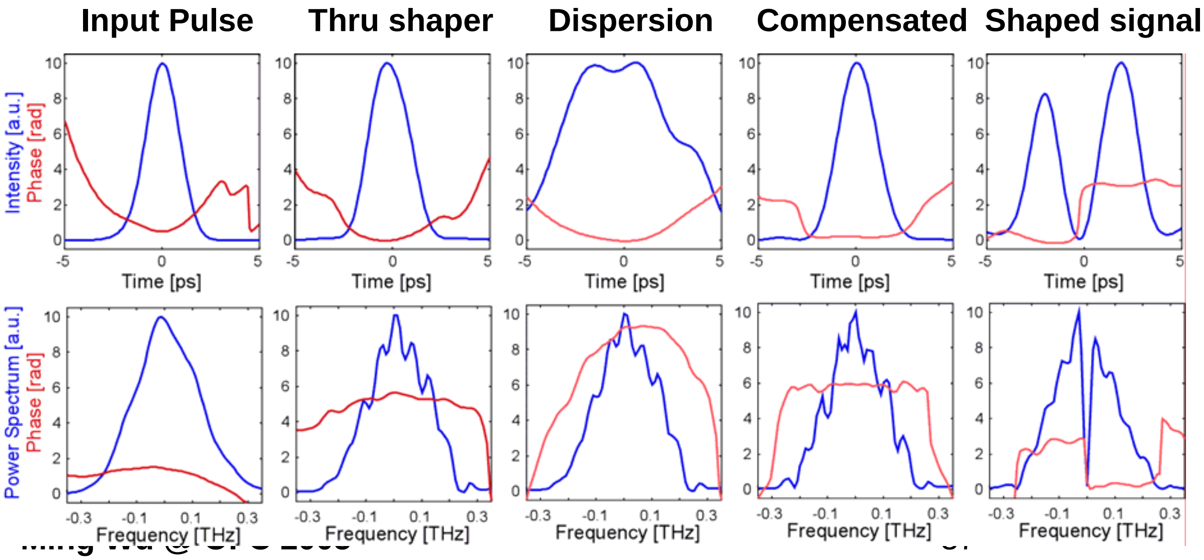


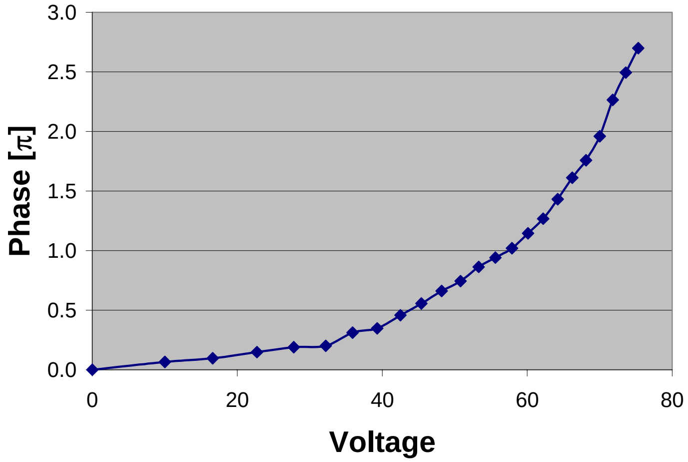
Compact Spectral Pulse Shaper (D. Marom)

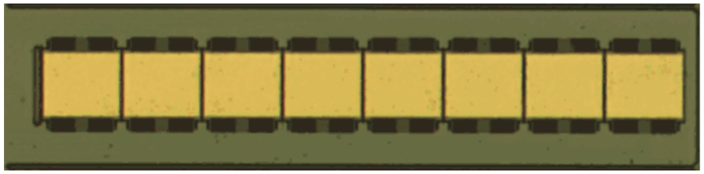
Lucent Technologies
Bell Labs Innovations

Hybrid PLC and Free-Space Implementation







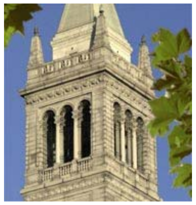


MEMS piston motion micromirror array

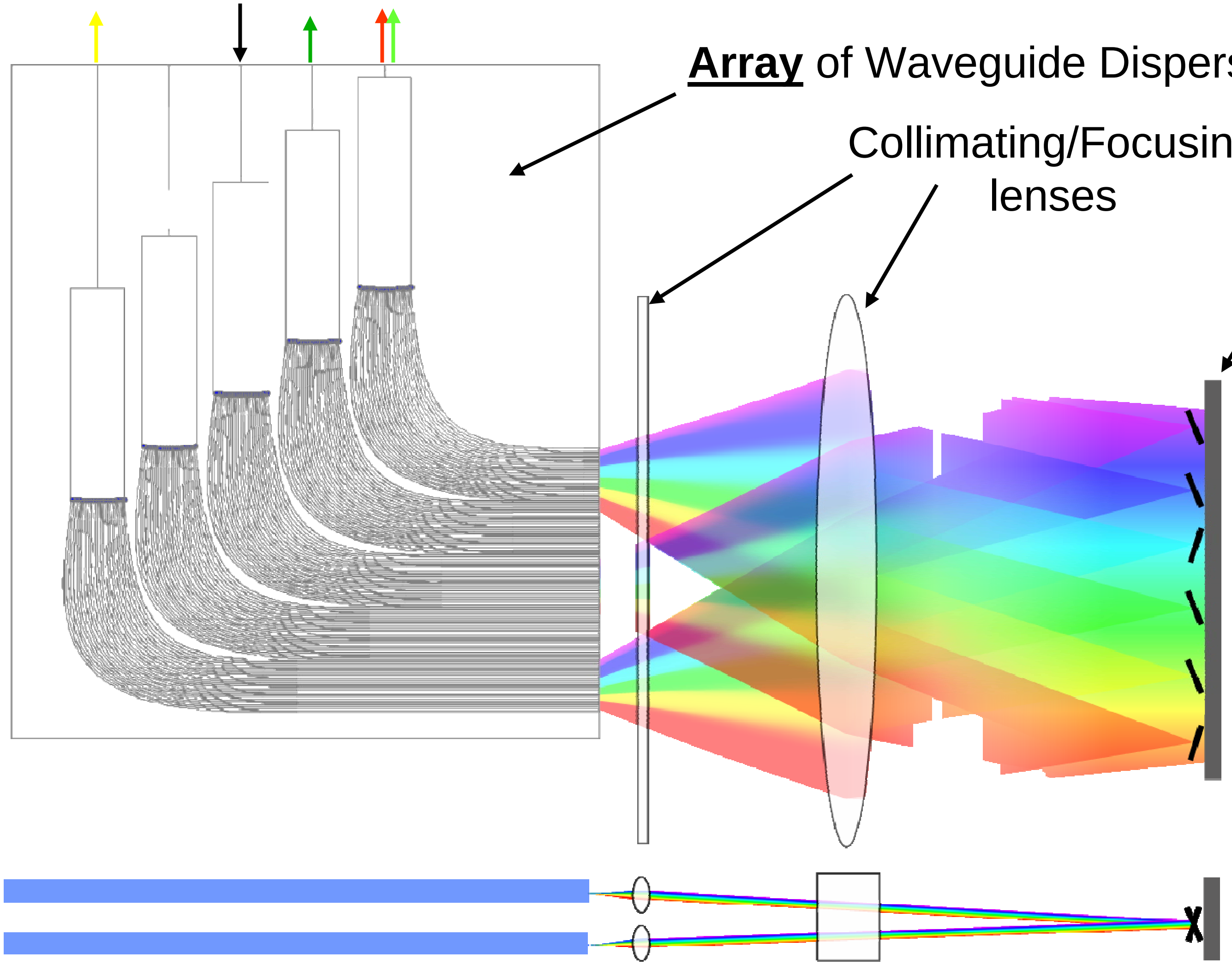
- >2π phase modulation
- Polarization insensitive

Pulse Shaper provides:

- Spectral domain processing
- Polarization independent
- Gateway to optical arbitrary waveform synthesis



2D arrangement of ports for scalable 1x9 WSS

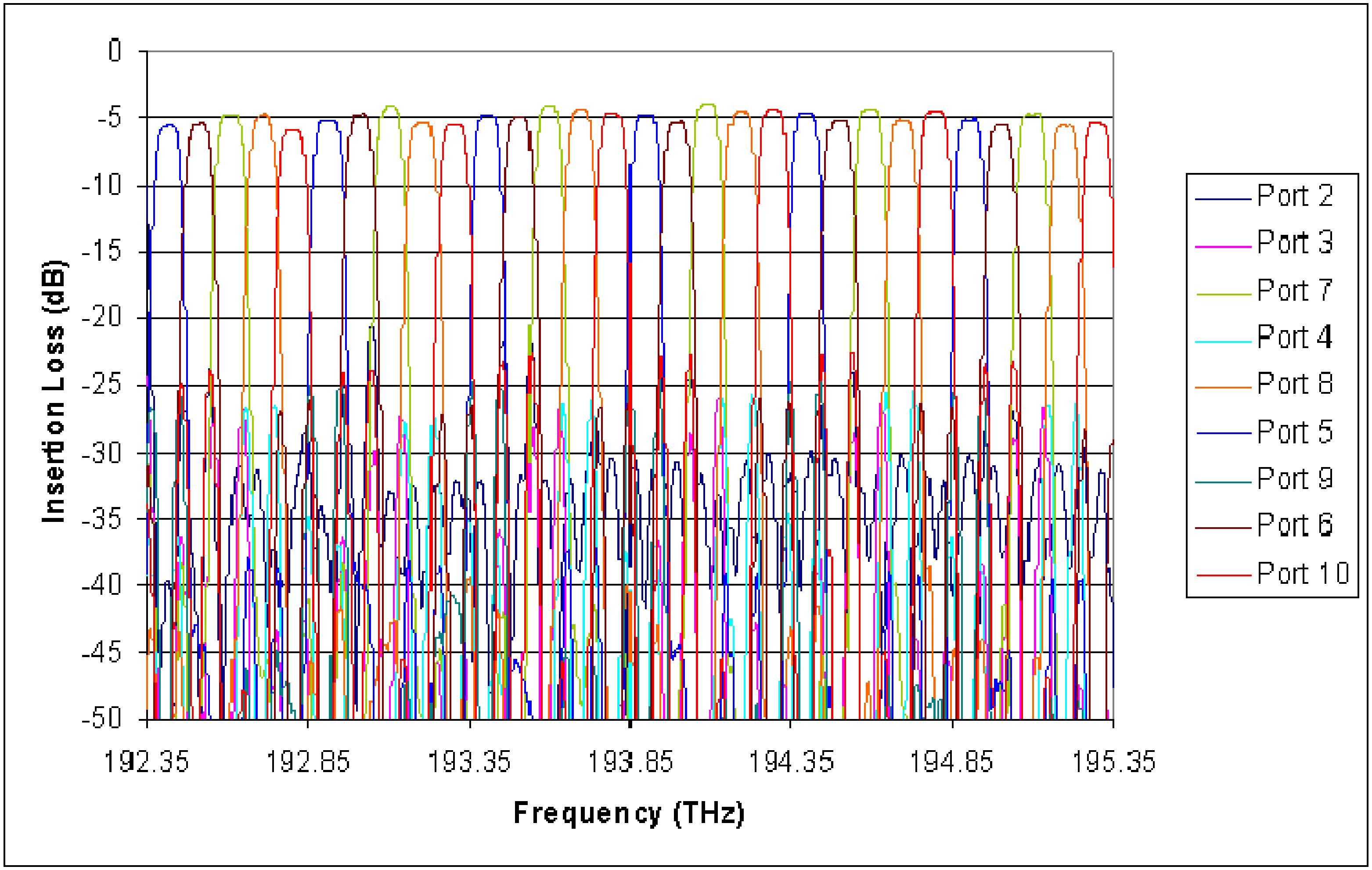


Array of Waveguide Dispersive Elements

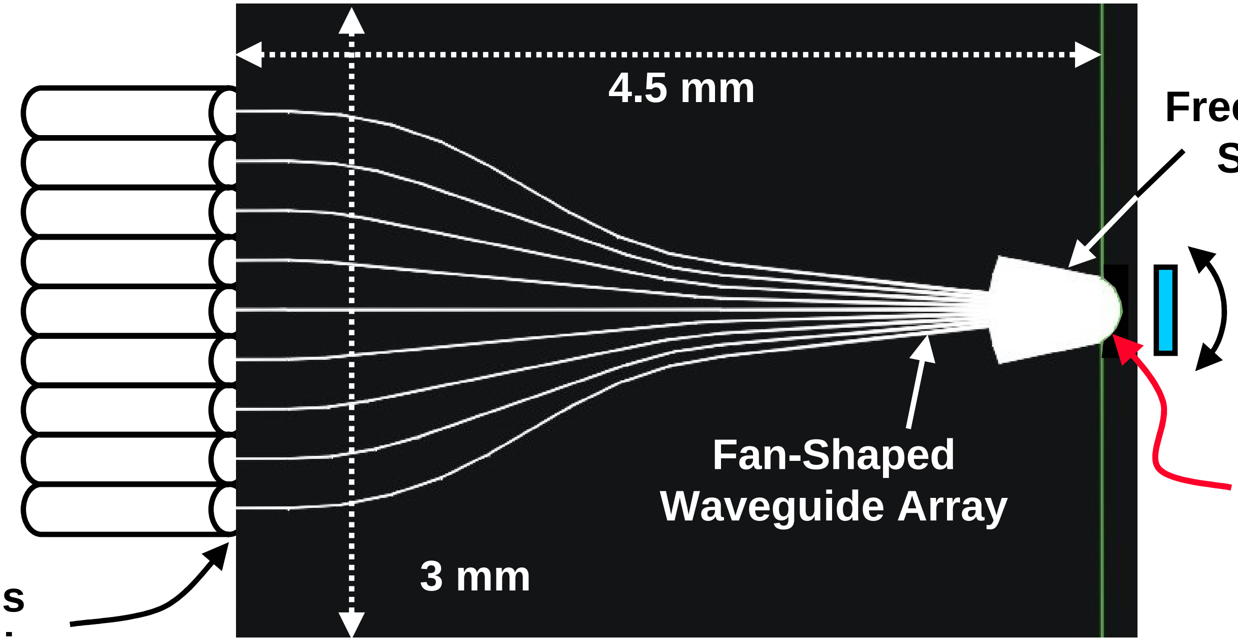
Collimating/Focusing lenses

MEMS mirror linear array

Interleaved spectrum switched to all output ports

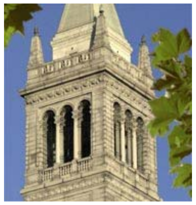


1x8 PLC MEMS Optical Switches

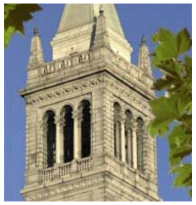


- **Theoretical loss ~ 0.5 dB, primarily due to vertical diffraction loss**
- **Compact, no bulk optical elements**

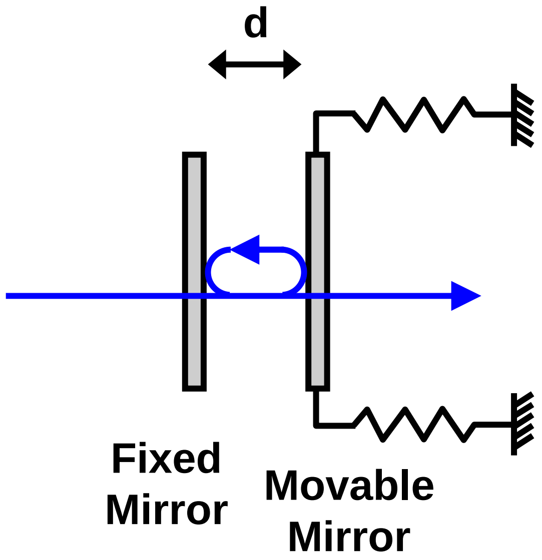
C.H. Chi, et al. (UCLA and Okamoto Lab), OFC 2004

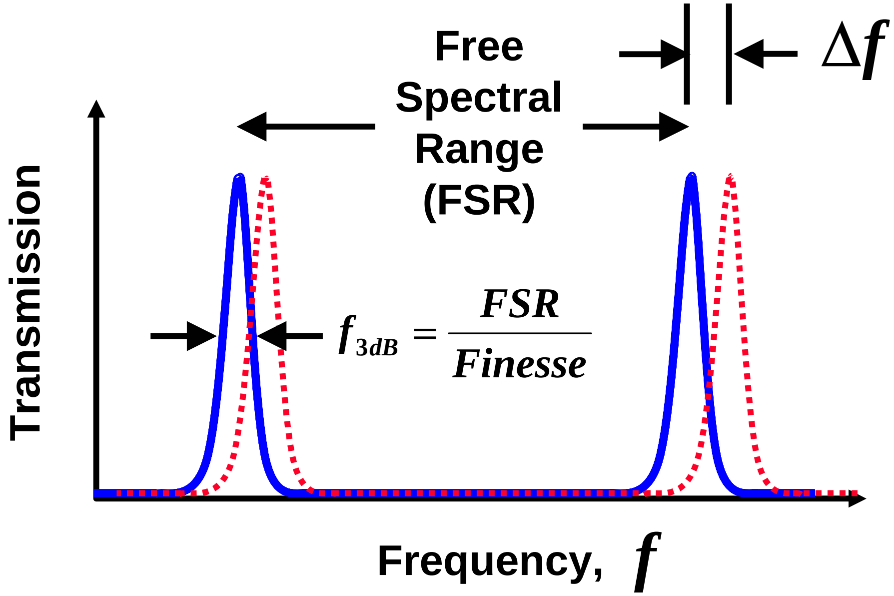


Tunable Fabry-Perot Filters



Tunable Fabry-Perot (FP) Filters





$$FSR = \frac{c}{2d} \text{ (in freq.)} = \frac{\lambda^2}{2d} \text{ (in wavelength)}$$

Resonance Condition:

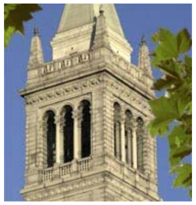
$$2kd = m \cdot 2\pi \Rightarrow 2\left(2\pi \frac{f}{c}\right) d = m \cdot 2\pi$$

$$\Rightarrow \boxed{\Delta f = \frac{f}{d}\Delta d = \frac{c}{\lambda d}\Delta d}$$

For d ~ 3λ

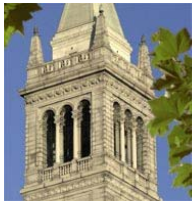
$FSR = 260$ nm $\Rightarrow$ Broadly Tunable

$\frac{\Delta f}{\Delta d} = 40 \frac{\text{GHz}}{\text{nm}}$ $\Rightarrow$ Efficient Tuning



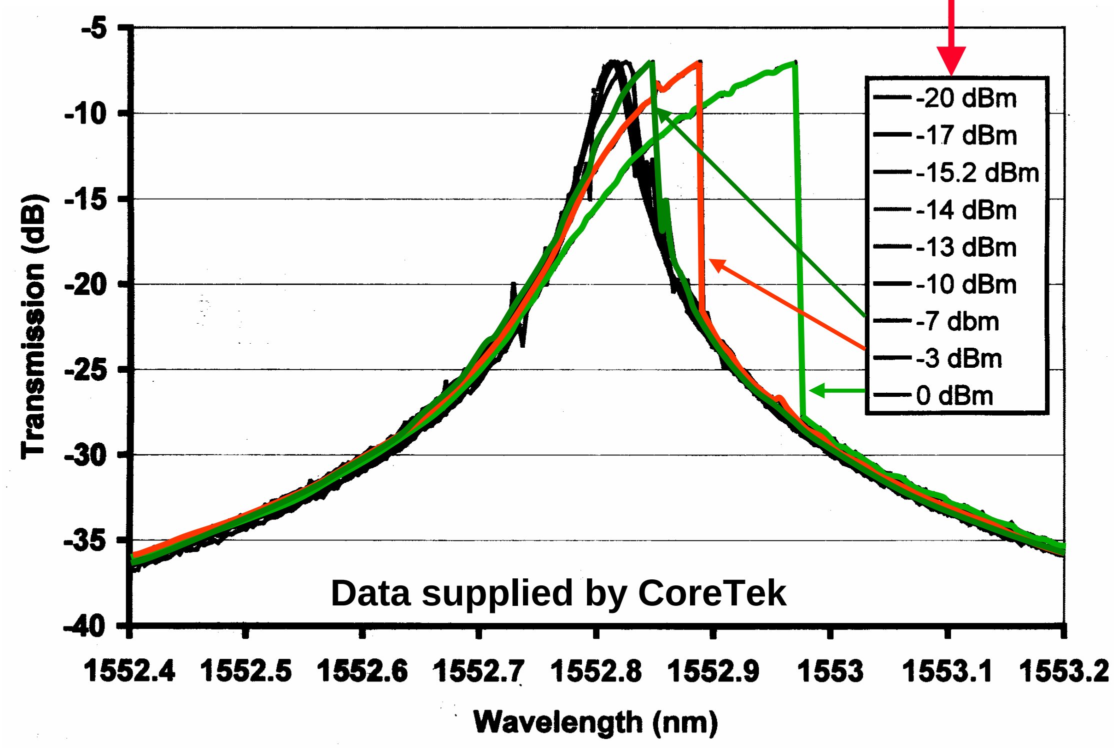
Tunable FP Filters

- Has been demonstrated in many material systems
    - III-V
    - Dielectric (e.g., Si/SiO_2)
    - Semiconductor – Air gap DBR
- Various actuation mechanisms
    - Electrostatic (parallel plate actuators)
    - Thermal actuators
    - Piezoelectric actuators



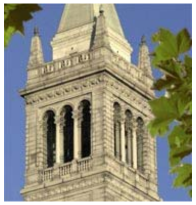
Nonlinear Optical Response

Optical Power

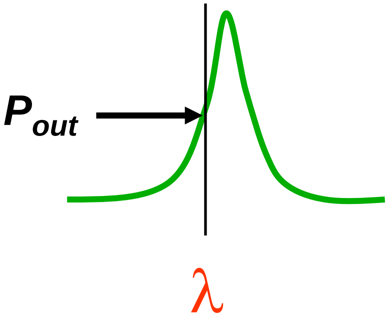


Data supplied by CoreTek

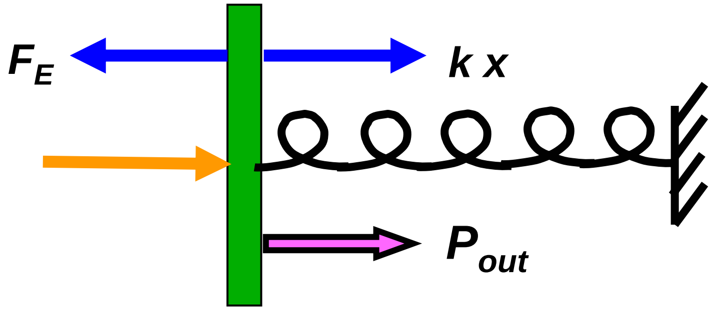
VG courtesy of Prof. Rod Tucker (Univ. Melbourne)



Effective Spring Constant due to Radiation Pressure

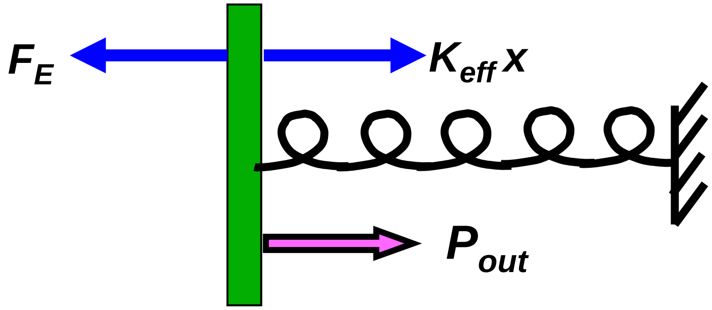


$$F_R = \frac{2P_{out}}{(1-R)c}$$

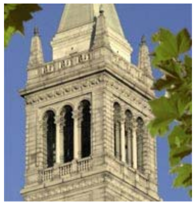


$$k_{eff} = k - \frac{4P_{in}FSR}{\lambda c(1-R)} \bullet \underbrace{\frac{dG}{df}}$$

Filter Response Slope



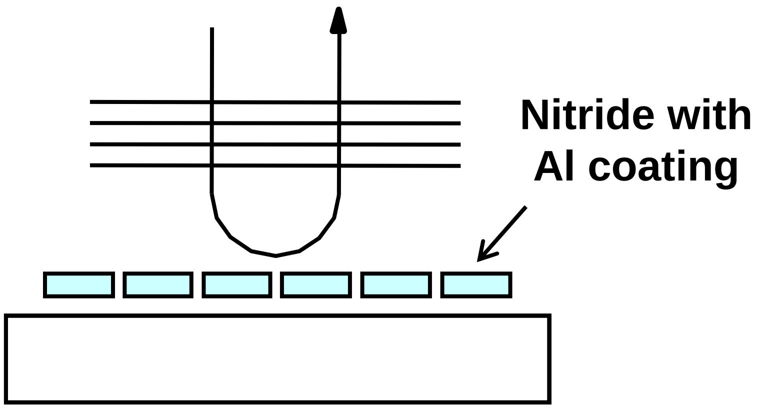
VG courtesy of Prof.
Rod Tucker (Univ. Melbourne)



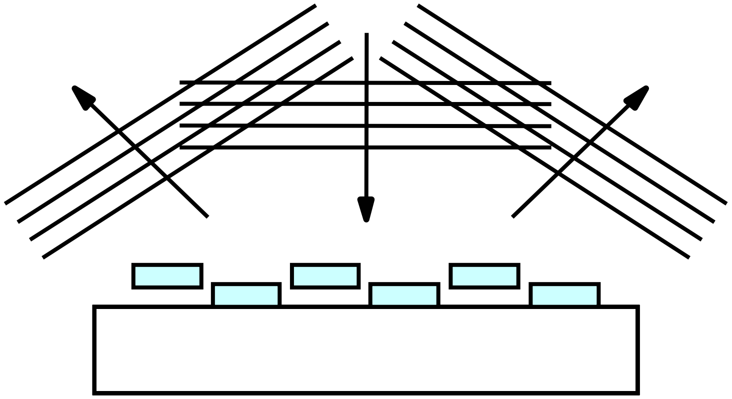
Diffractive Optical MEMS

Grating Light Valve

Incident Light Reflected

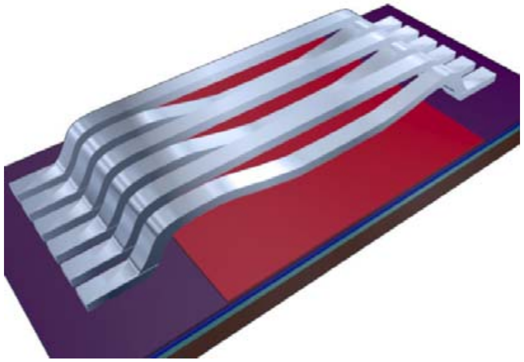


Incident Light Diffracted

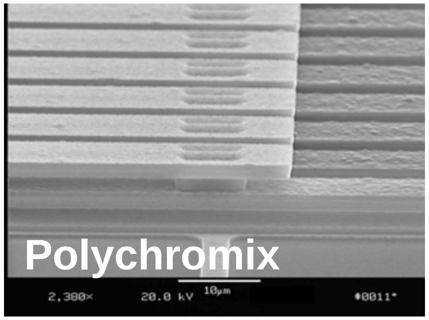


O. Solgaard, F. S. A. Sandejas, D. M. Bloom, "A deformable grating optical modulator", Optics Letters, vol. 17, no. 9, pp. 688-690, 1 May 1992.

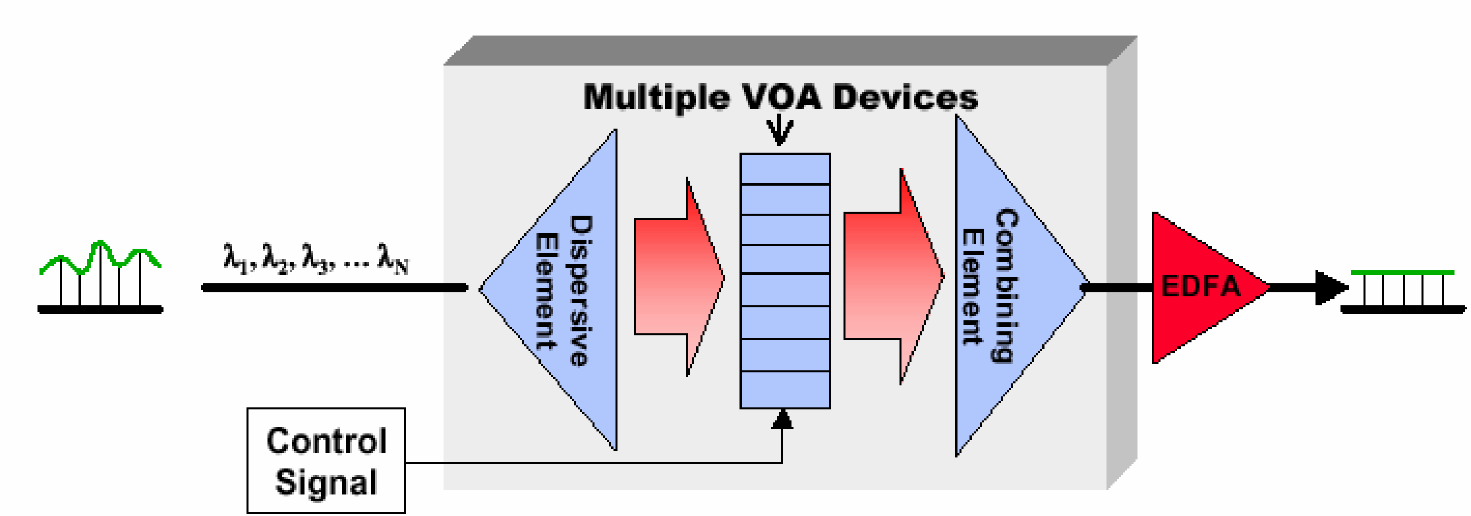
- **Applications**
  - **Projection display**
  - **Variable optical attenuators (VOA)**
  - **Gain equalizers**
  - **Wavelength blockers**
- **Companies**
  - **Silicon light machine (Cypress), Lightconnect, Polychromix, Kodak**



Silicon Light Machine

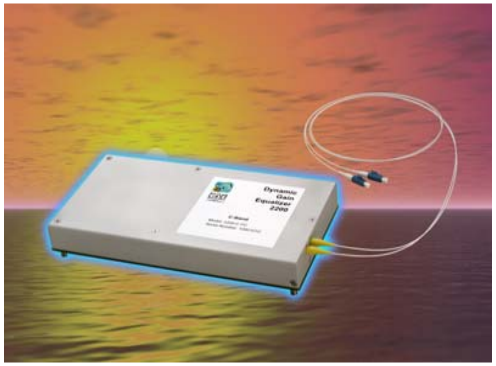


Telecommunications Applications



Dynamic Spectral Equalizer (DSE)

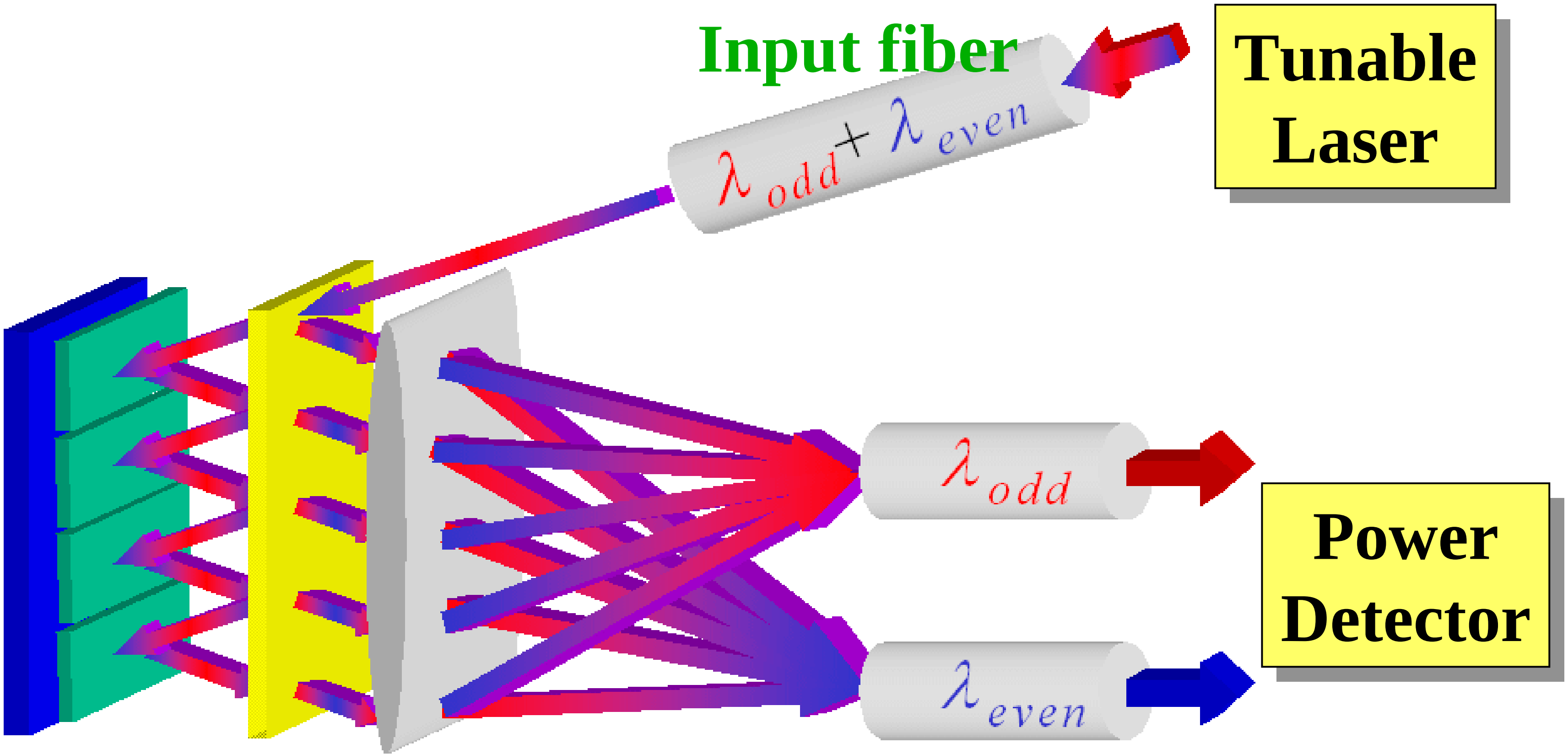
Reconfigurable Channel Blocking Filter



Dynamic Gain Equalizer

MEMS Switchable WDM Deinterleaver Based on Gires-Tournois Interferometer

Olav Solgaard, Stanford University



Input fiber

Tunable Laser

$\lambda_{odd} + \lambda_{even}$

λ_{odd}

λ_{even}

Power Detector

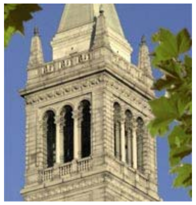
MEMS Mirror Array

Beam Splitter

Focusing Lens

Output Fiber Array

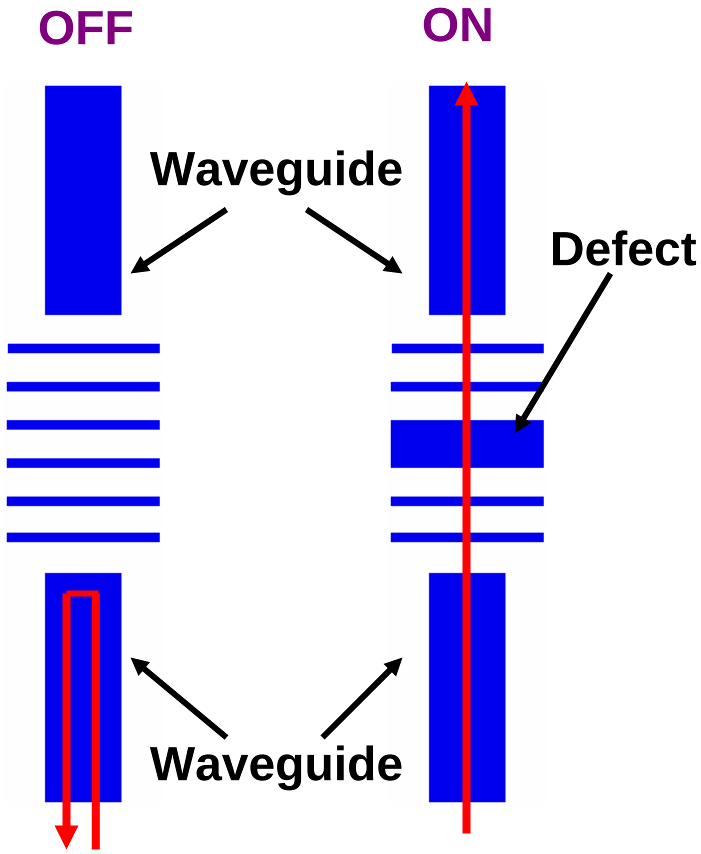
http://wdm.stanford.edu/snrc/kyoungsik12_10_01.ppt



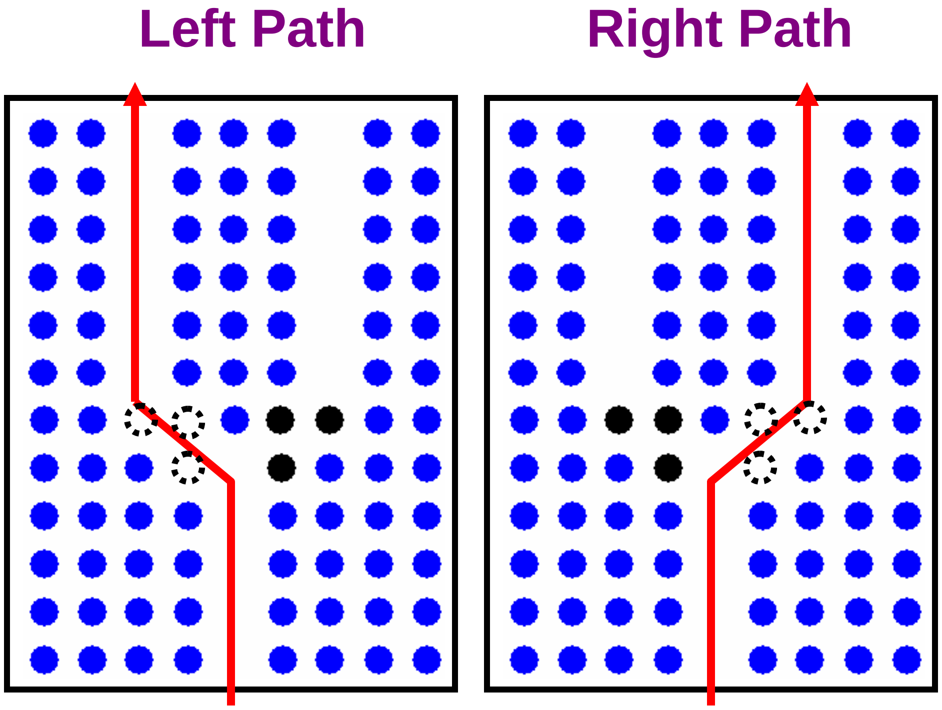
Nanophotonic MEMS

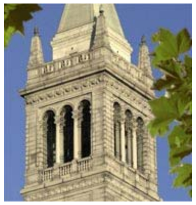
1D and 2D Photonic Crystal Switches

1D Photonic Crystal:
ON-OFF Switch



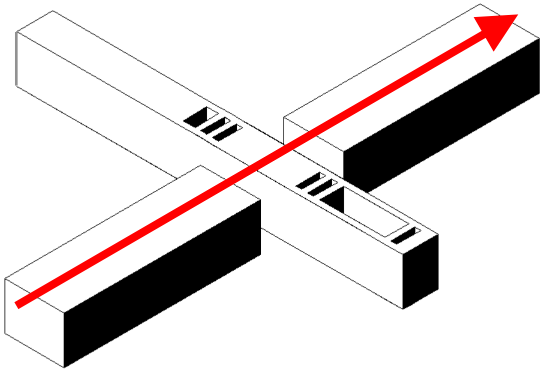
2D Photonic Crystal:
1x2 Switch
(→ NxN Switch)

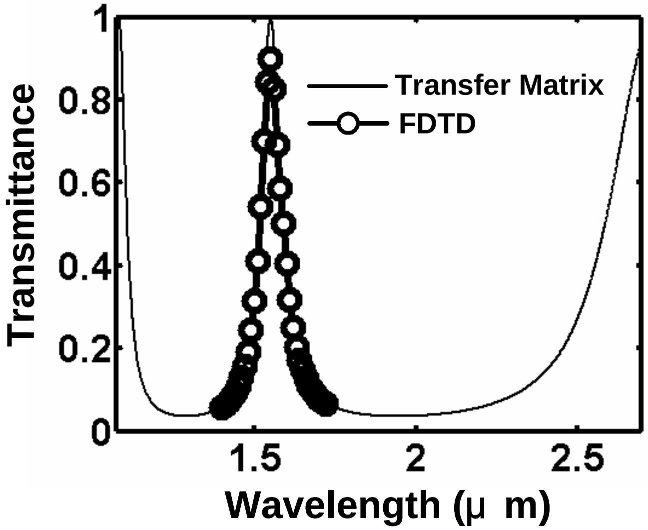




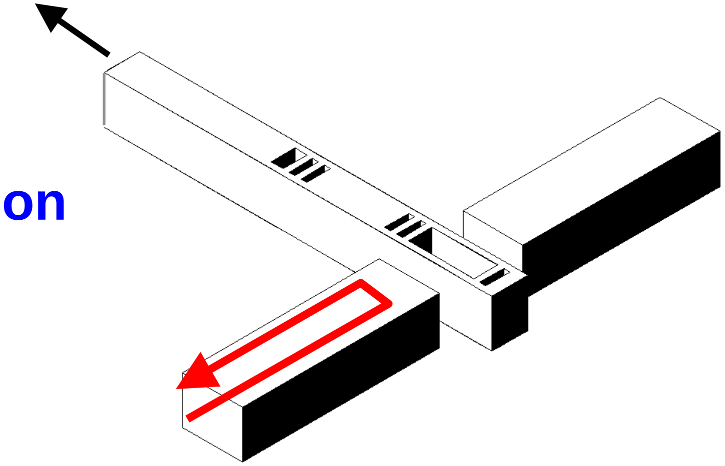
1D MEMS Photonic Switch

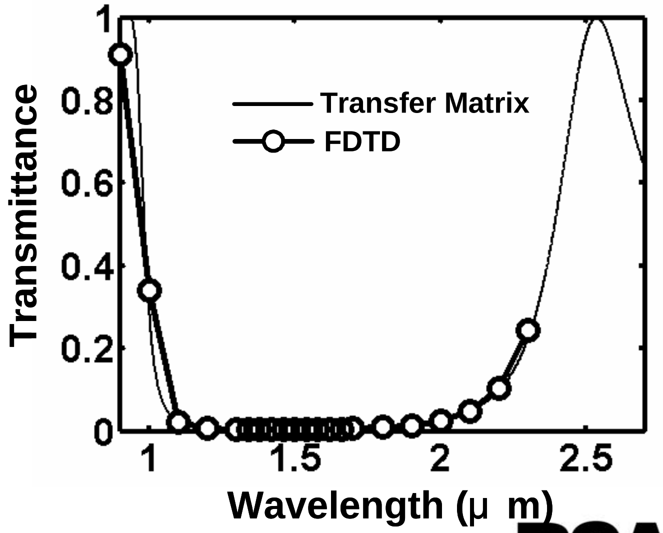
Reflection State



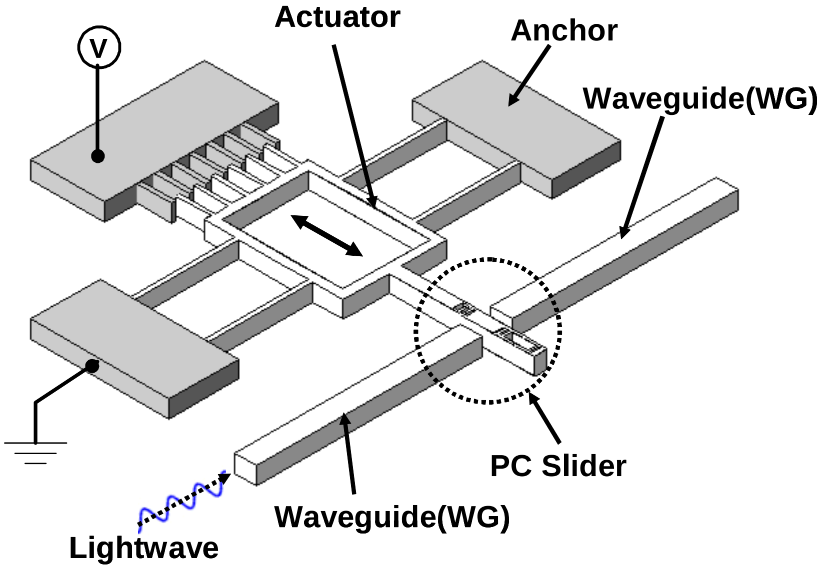


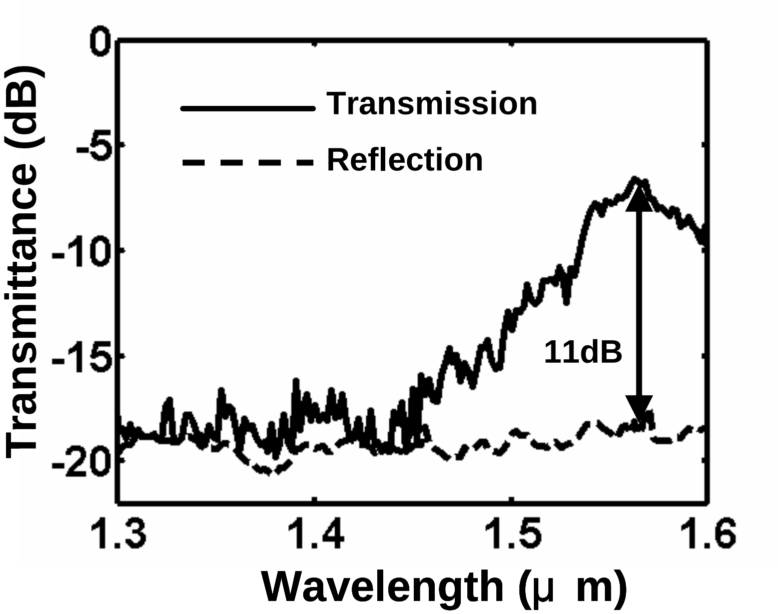
Transmission State

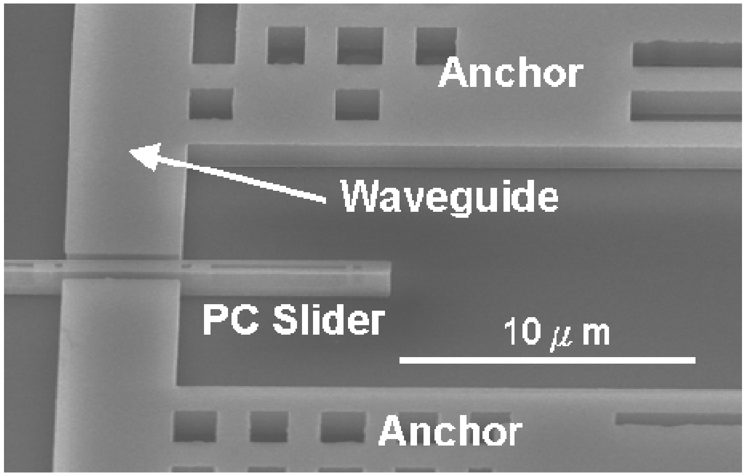




Experimental Results



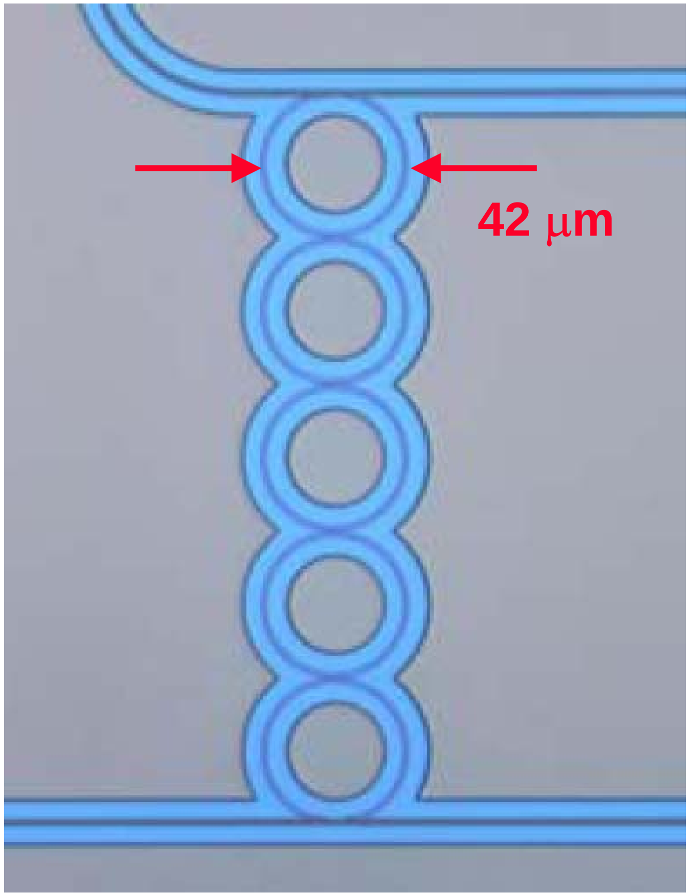


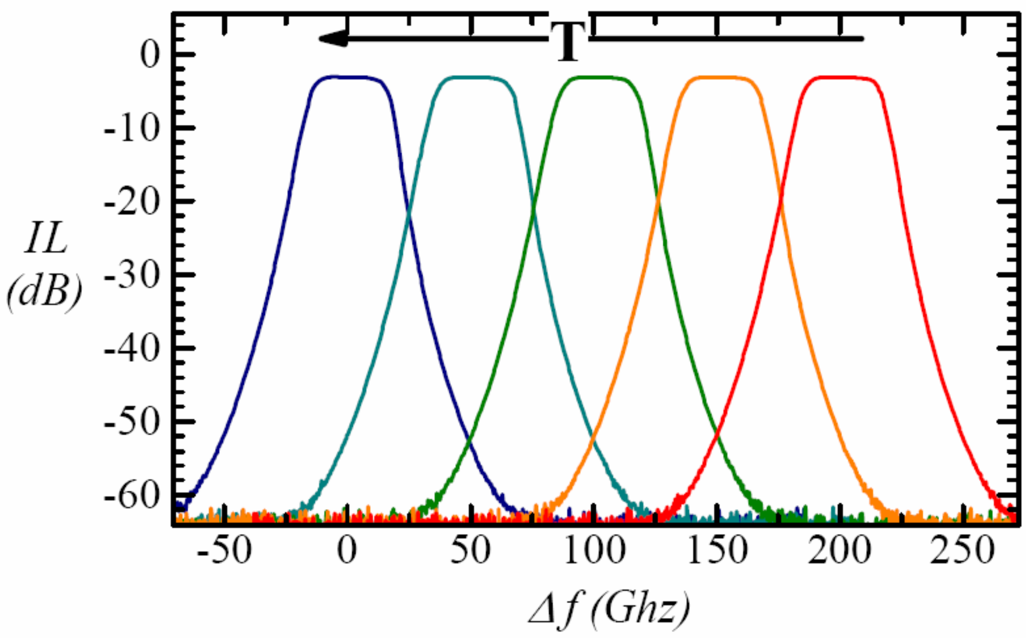


- **100-nm-wide beam with < 5 nm tolerance**
- **ON-OFF switching with 11 dB extinction ratio**
- **0.5 ms switching time**

M.C. Lee, et al (UCLA) OFC 2002

Microring Resonator-Based PIC



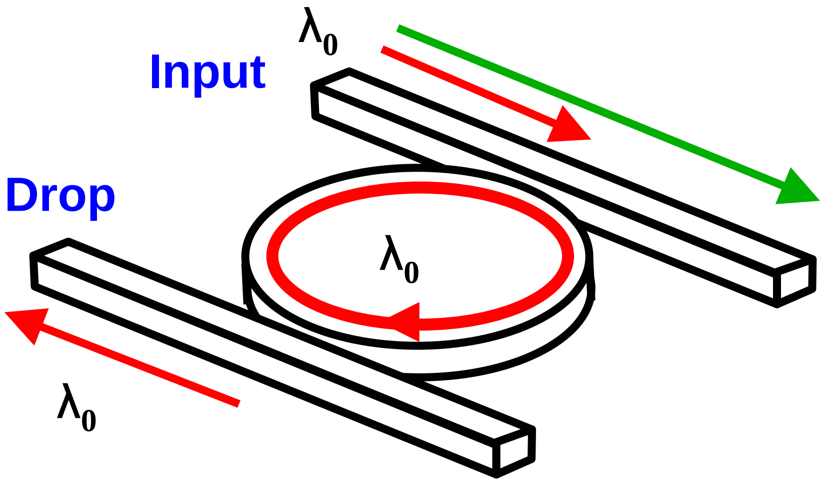


Thermally Tuned
with Vernier Architecture

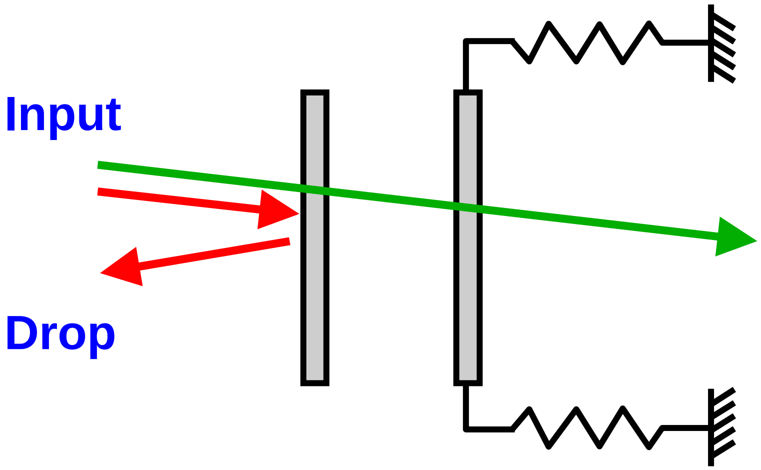
S. T. Chu, B. E. Little, V. Van, J. V. Hryniewicz, P. P. Absil, F. G. Johnson, D. Gill, O. King, F. Seiferth, M. Trakalo and J. Shanton (Little Optics) OFC 2004

MEMS Tunable Microresonators

Microdisk Resonators



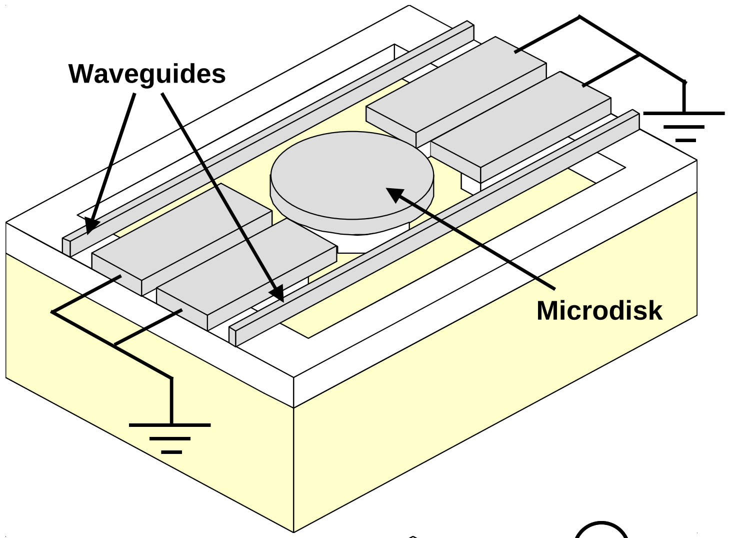
Fabry-Perot Resonators

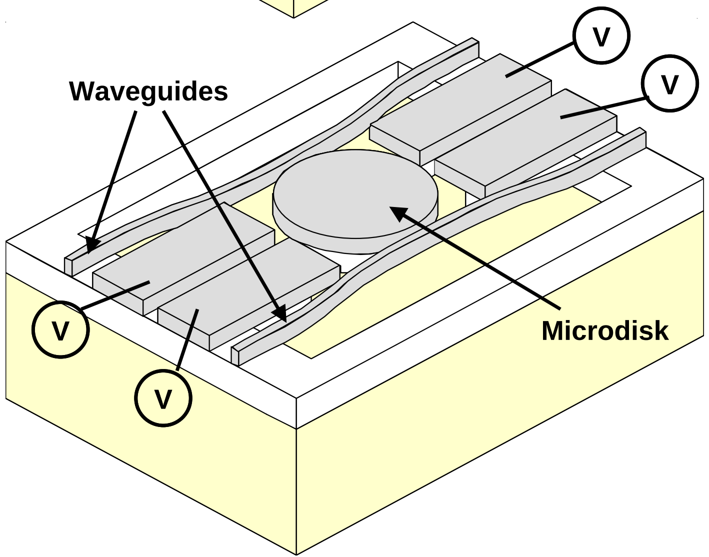


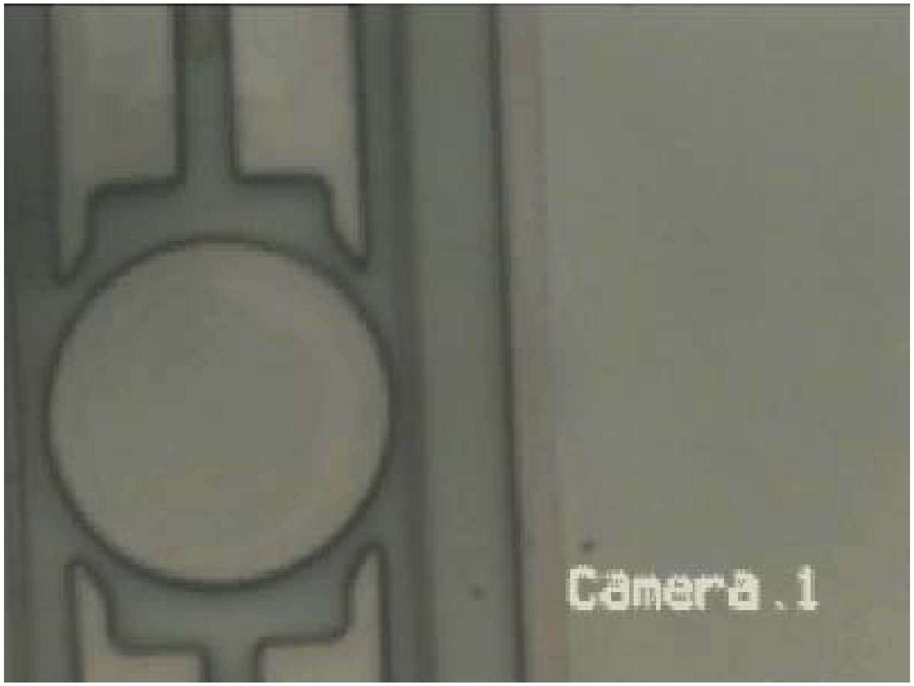
- Change resonant wavelength
  - Thermal tuning
  - Free-carrier injection
- Change effective Q
  - Increase cavity loss (e.g., electroabsorption)
  - Change waveguide-disk coupling

- Change resonant wavelength
  - Move mirror
- Change effective Q
  - Increase media loss
  - Tune mirror reflectivity (Hard)

Microdisk Resonator with MEMS Tunable Couplers

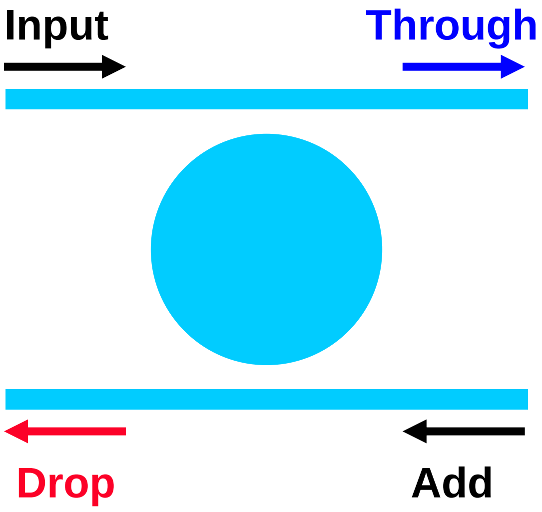


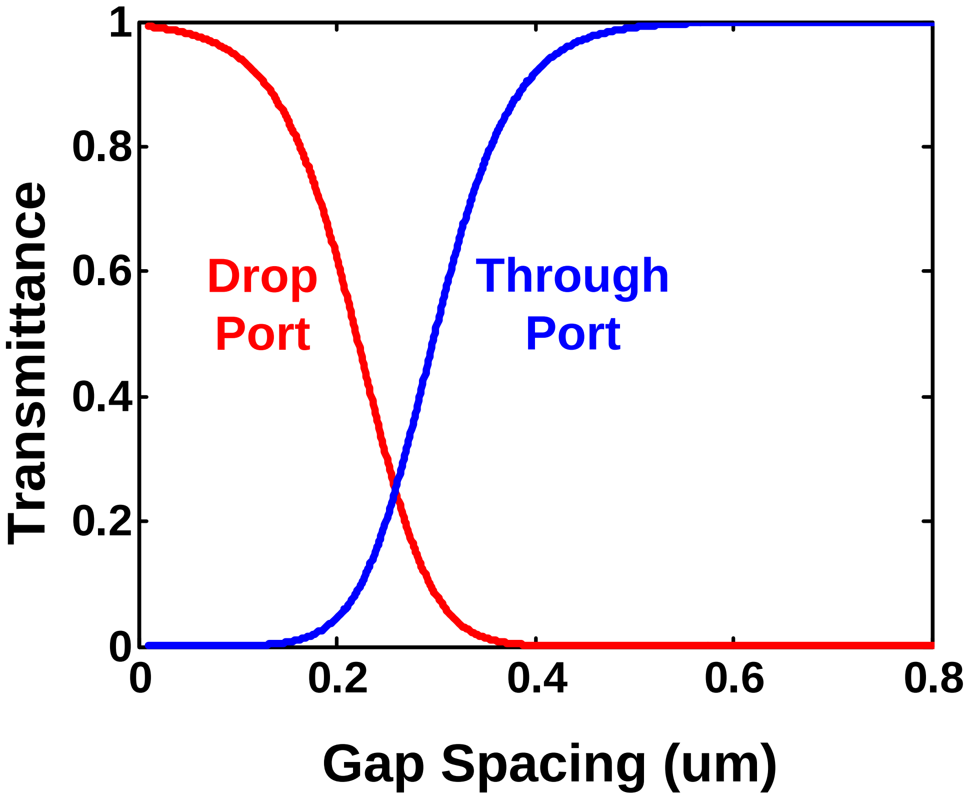


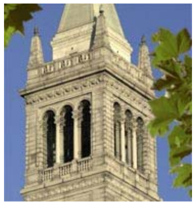


M.C.M. Lee and M.C. Wu, Optical MEMS 2003

Dynamic Optical Add-Drop Multiplexers

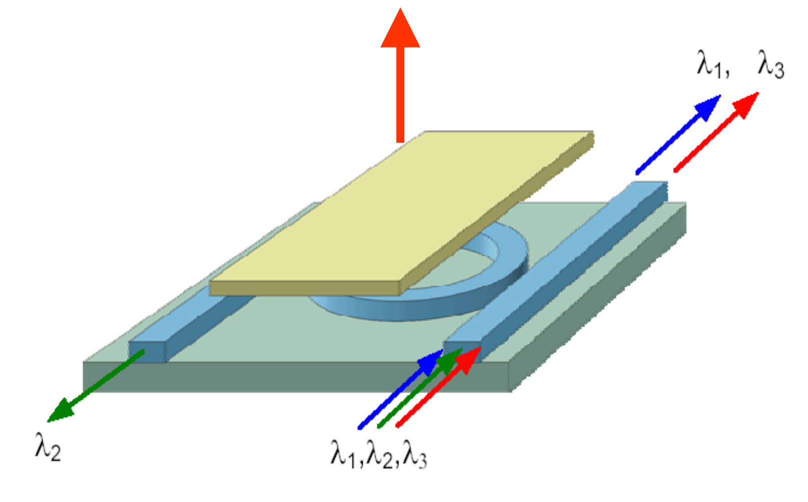




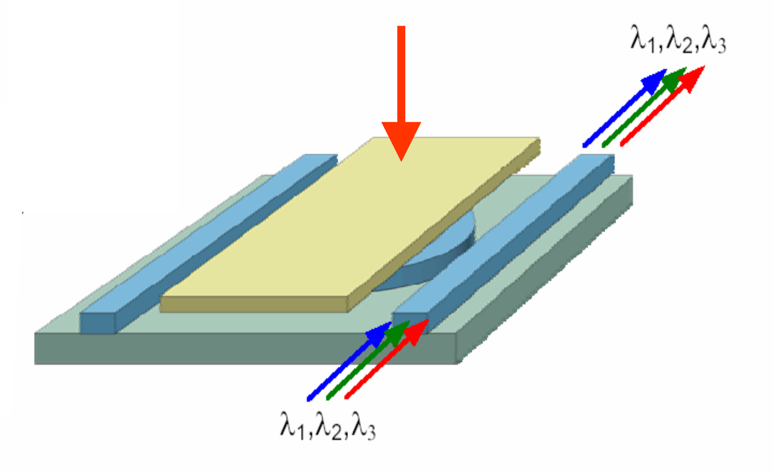


Spoiling Q by MEMS Metal Membrane

- **Use a metal membrane to spoil the Q of microring resonator**
  - **Low loss → resonant wavelength sent to "Drop" port**
  - **High loss → all wavelengths transmitted to "Through" port**

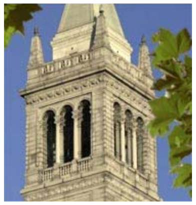


Enable resonance



Disabled resonance

Gregory N. Nielson, et al., (MIT) "MEMS based wavelength selective optical switching for integrated photonic circuits", CLEO 2004



SUMMARY

- Tremendous progresses have been made in
  - MEMS devices and manufacturing
  - Micro-optics
  - Packaging
  - Control
- New trends in Optical MEMS -- Integration
  - Higher level of integration, less free-space alignment
  - MEMS-PLC integration
  - MEMS-nanophotonics integration
  - Electronics integration
  - Single-chip optical MEMS system