Lecture for EE 233

Optical MEMS for Telecommunication Systems

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Acknowledgment

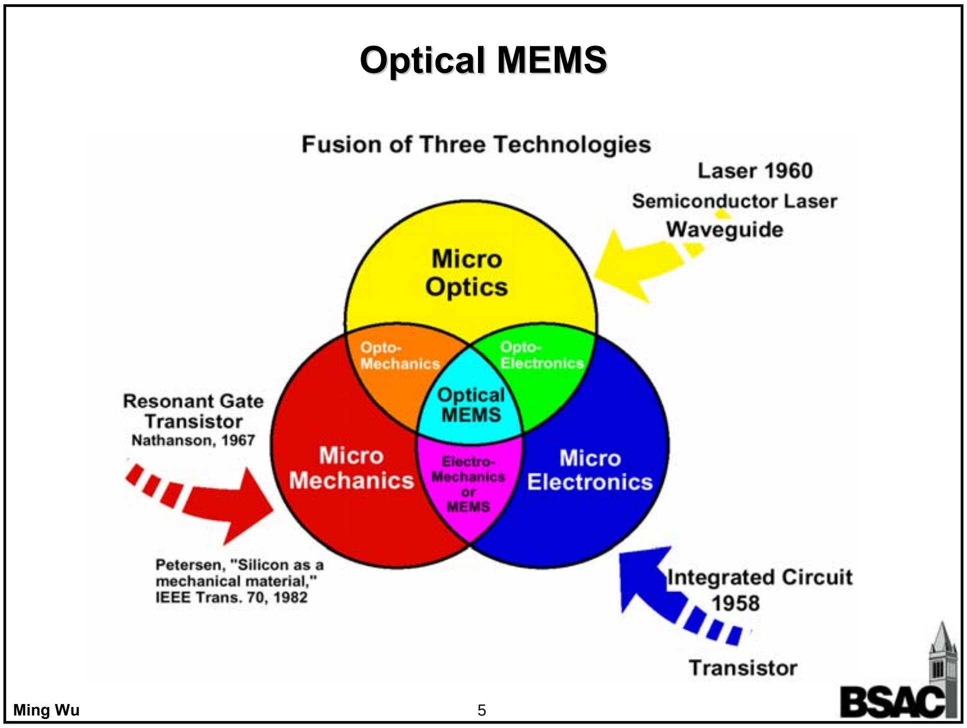
- Providing viewgraphs
  - Thomas Ducellier (Metconnex)
  - Dan Marom (Lucent)
  - Katsu Okamoto (Okamoto Lab)
  - Olav Solgaard (Stanford University)
  - Rod Tucker (Univ. Melborne)
- Graduate students and Postdocs at Berkeley and UCLA
  - Monolithic WSS: Josh C.H. Chi, Chenlu Hou, Chi-hung Lee
  - WSS: J.C. "Ted" Tsai, Dr. Li Fan, Dr. Dooyoung Hah, Sophia Huang
  - PLC switch: Josh C.H. Chi, Ted Tsai, in collaboration with Dr. Katsu Okamoto
  - PhC switch: M.C. "Mark" Lee
  - MEMS Microdisk: M.C. "Mark" Lee, Jin Yao, David Leuenberger
  - Si Photonics: Sagi Mathai, Joanna Lai, Xin Sun (Prof. Tsu-Jae King)

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

Why Optical MEMS ?

- Optical MEMS offers
  - Low optical insertion loss
  - Low crosstalk
  - Transparency (wavelength, polarization, bit rate, data format)
  - Low power consumption
- Why ?
  - The effect of moving optical elements is stronger than electro-optic, thermal-optic effects
  - Very efficient beam steering devices
- What
  - Switches
  - Tunable devices (delay, dispersion, wavelength, bandwidth, dynamic gain equalization, etc)


Optical MEMS
Fusion of Three Technologies
Laser 1960
Semiconductor Laser
Waveguide
Micro Optics
Opto-Mechanics
Opto-Electronics
Optical MEMS
Resonant Gate Transistor
Nathanson, 1967
Micro Mechanics
Electro-Mechanics or MEMS
Micro Electronics
Petersen, "Silicon as a mechanical material," IEEE Trans. 70, 1982
Integrated Circuit 1958
Transistor
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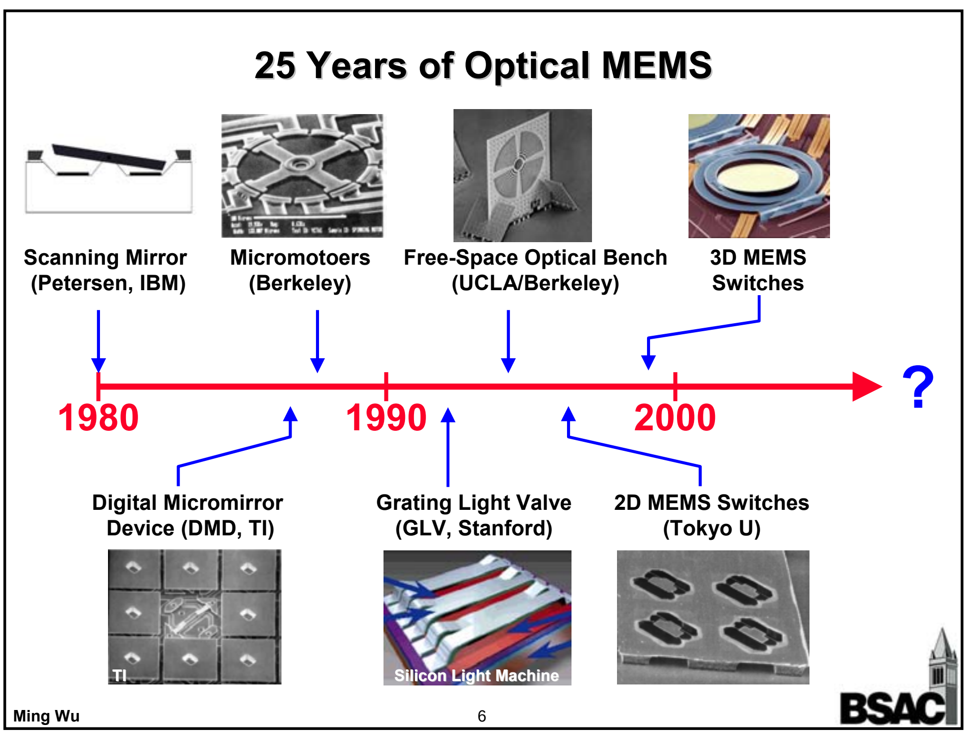
25 Years of Optical MEMS
Scanning Mirror (Petersen, IBM)
Micromotoers (Berkeley)
Free-Space Optical Bench (UCLA/Berkeley)
3D MEMS Switches
1980
1990
2000
?
Digital Micromirror Device (DMD, TI)
Grating Light Valve (GLV, Stanford)
2D MEMS Switches (Tokyo U)
TI
Silicon Light Machine
Ming Wu
6
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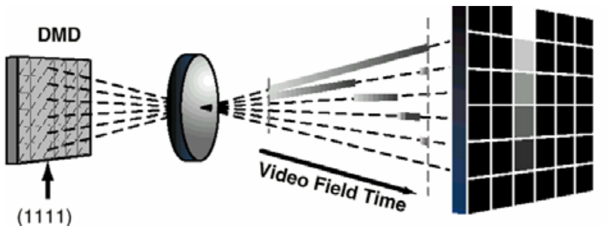
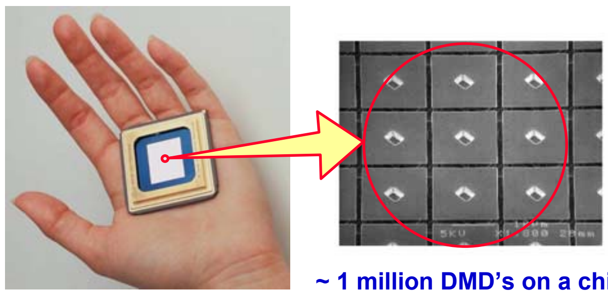
Digital Micromirror Devices (DMD)



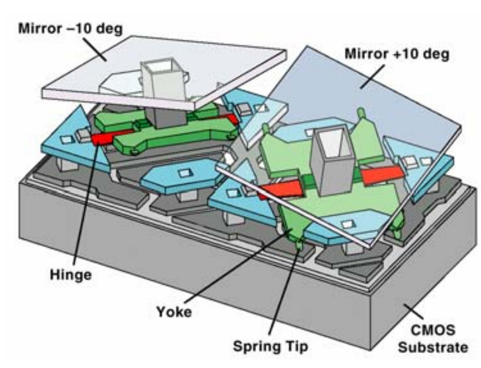


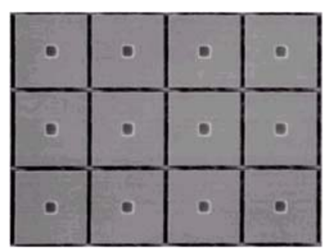
~ 1 million DMD's on a chip

http://www.dlp.com/dlp/resources/dmmd.asp

Digital Micromirror Device (DMD)

Texas Instruments

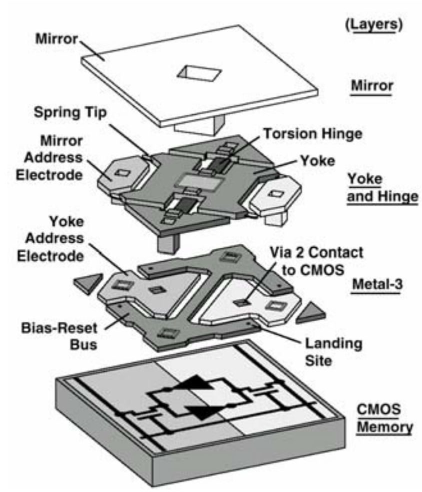




Top View of DMD

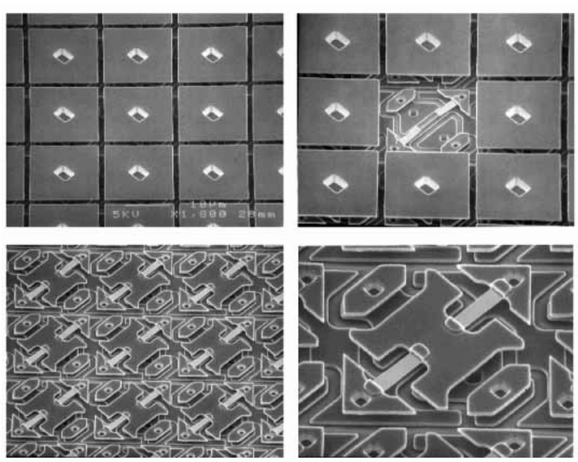
L. Hornbeck, Electronic Imaging, 1997

Detailed Layer Structure of DMD



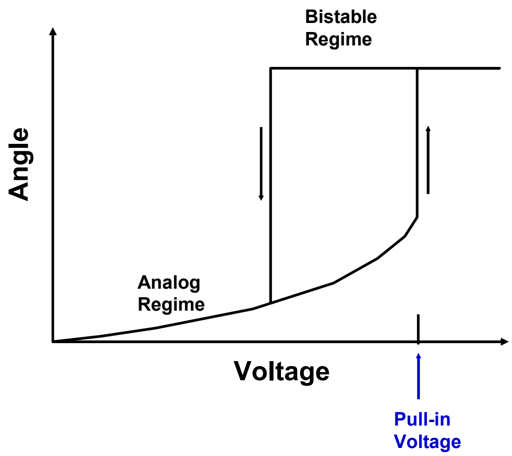
L. Hornbeck, Electronic Imaging, 1997

TI's Digital Micromirror Devices (DMD)



(Texas Instruments, Digital Micromirror Device™)

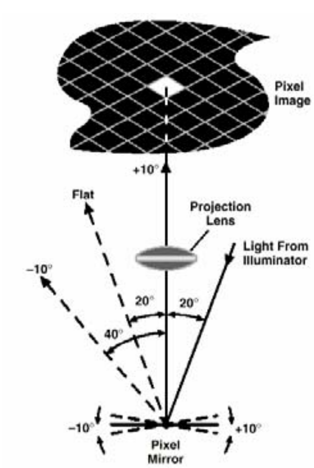
Transfer Characteristics of Torsion Mirrors

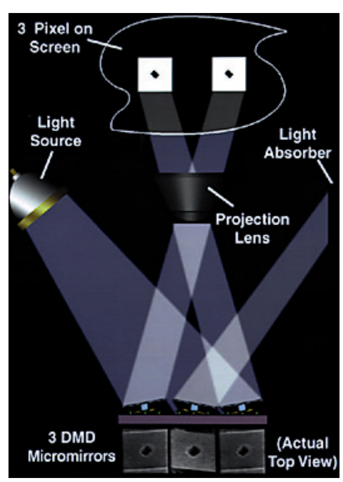


Pull-in voltage
(or Stiffness Voltage)

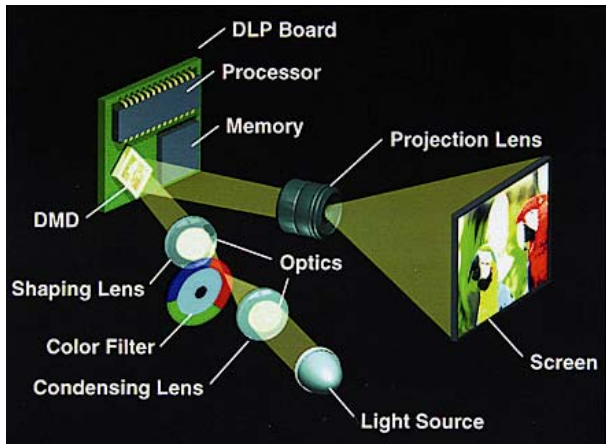
$$V_S = \sqrt{\frac{2 \cdot z_0^3}{\varepsilon W L^3 C}}$$

Principle of Projection System Using DMD



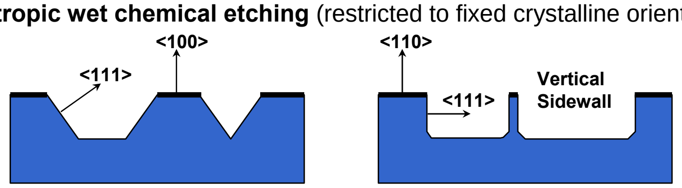


Projection Display Using Digital Micromirror Display (DMD)

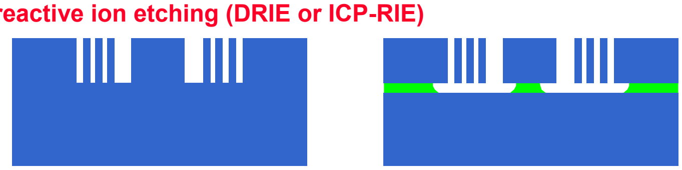


Bulk Micromachining

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



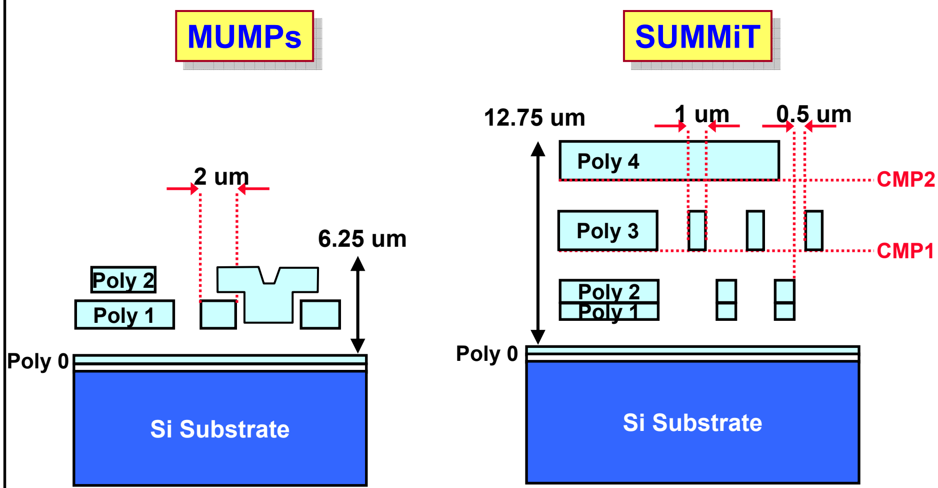
- **Deep reactive ion etching (DRIE or ICP-RIE)**



- **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**

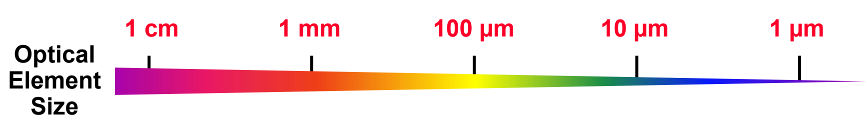
Surface-Micromachining: 2 "Standard" Foundry Process



- MEMSCAP

- Sandia National Lab
- Fairchild (SUMMiT-4)

MEMS Technologies and Optical Element Size

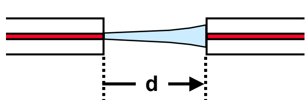


Applications	Scanning display / Imaging	Mirror-based VOA	OADM / WSS / Gain equalizer / Dispersion compensator	Projection display	Diffractive MEMS	Micro-resonators	
	3D-MEMS OXC	2D MEMS Switch		2x2 Switches / VOA		Photonic Crystals	
Main Fabrication Technologies	Bulk-Micromachining (Single Crystalline Si, DRIE, Wafer Bonding)	Surface-Micromachining (Poly-Si, Al)				Nano-Fabrication	
Main Actuation Mechanisms	Electromagnetic Actuation	Electrostatic Actuation					

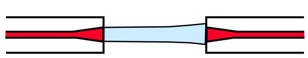
Optical Designs

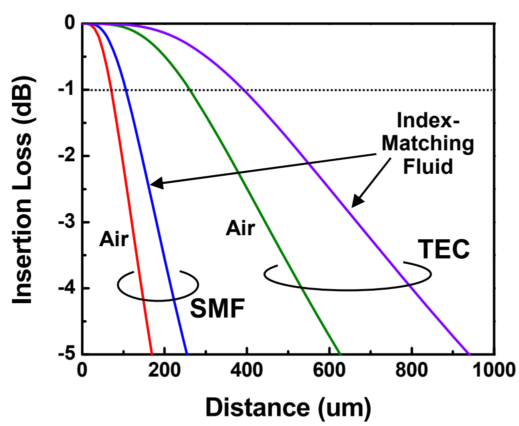
Direct Coupling Without Lenses

Single Mode Fiber (SMF)



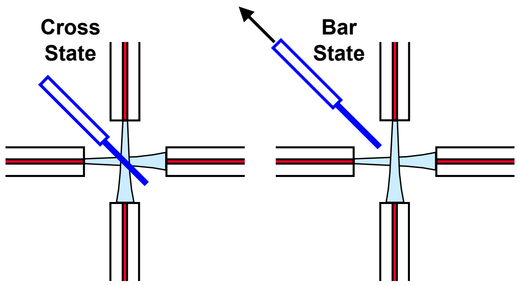
Thermally Expanded Core (TEC) Fiber

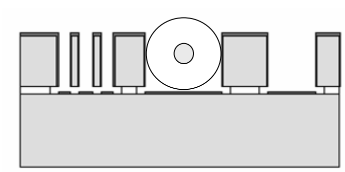


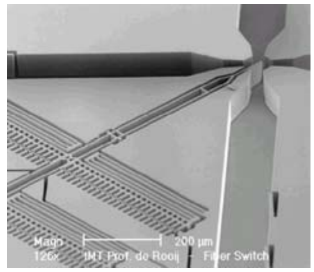


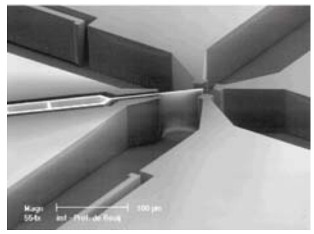
- Short propagation distance
- May be used for small switches or VOAs

Example: 2x2 Switch



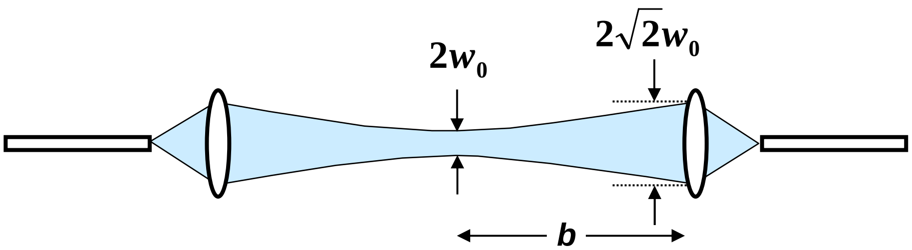






Marxer, et al., J-MEMS, vol.6, 1997. p.277-85.

Free-Space Optics: Gaussian Beam



$$w^2(z) = w_0^{\,2}\left[1+\left(\frac{z}{b}\right)^2\right] \qquad b = \frac{\pi w_0^2}{\lambda} \text{ (Confocal Parameter)}$$

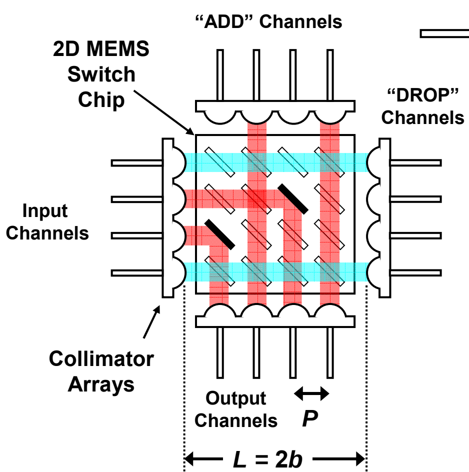
- **Larger beam waist → Long collimation length**
- **System size ~ 2*b***
- **Mirror diameter ~ 2aw_0, a ~ 1.5 to 2**

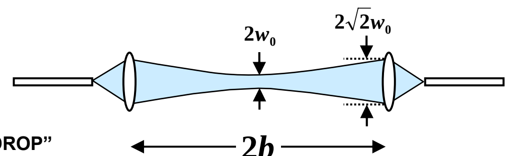
Space Division Switches:

(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

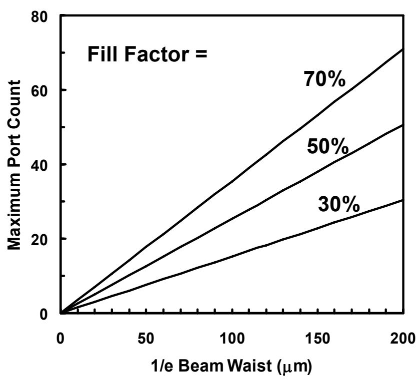
$\eta = \frac{2R}{P}$: Fill Factor of Micromirror

$R = aw_0$: Mirror Radius, a ~ 1.5 to 2

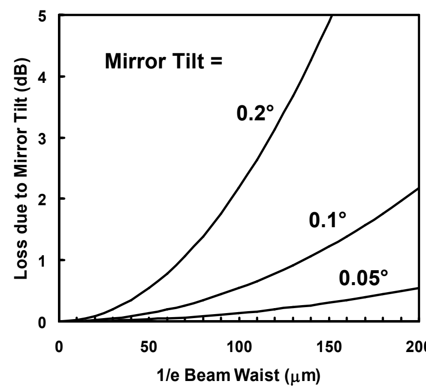
$\Rightarrow N \approx \frac{\pi\eta}{a\lambda} w_0$ $\quad L = \left(\frac{2a^2\lambda}{\pi\eta^2}\right) \cdot N^2$

Port Count of 2D MEMS Switches

Port Count vs Beam Size



Loss Due to Mirror Tilt

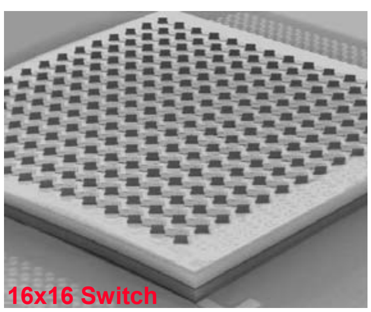


Port Count: $N \approx \frac{\pi\eta}{a\lambda} w_0$

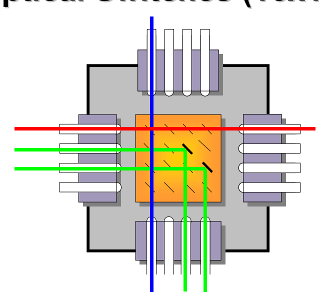
Chip Size: $L = \left(\frac{2a^2\lambda}{\pi\eta^2}\right) \cdot N^2$

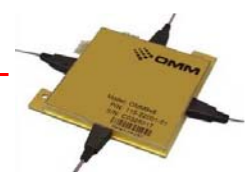
- **Accuracy and uniformity of mirror angles impose a loss penalty, which limit the maximum port count**

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



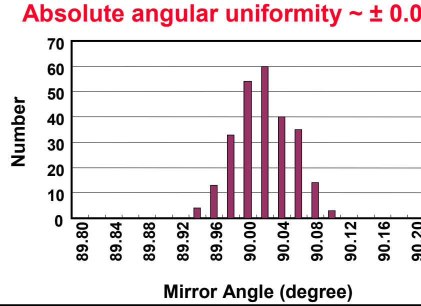
L. Fan, et al., OFC 2002



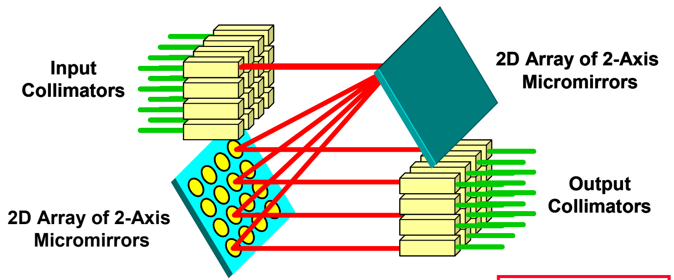


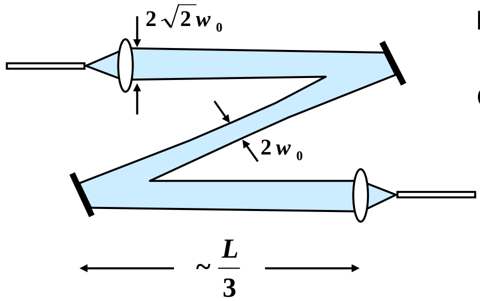
L. Fan, et al., OFC 2002

Absolute angular uniformity ~ ± 0.05°



Scaling of 3D MEMS OXC





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

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

$\Delta\theta$: Mechanical Scan Angle

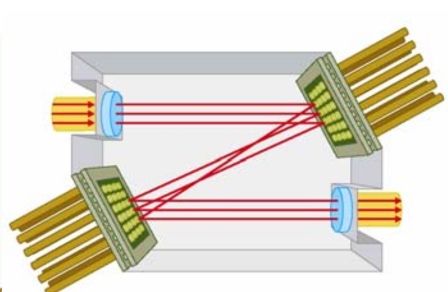
$R = aw_0$: Mirror Radius

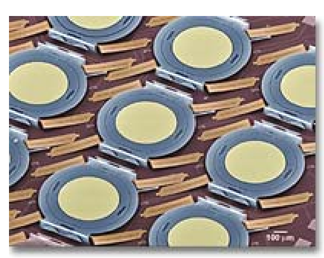
a ~ 1.5 to 2

w_0 : Beam Waist

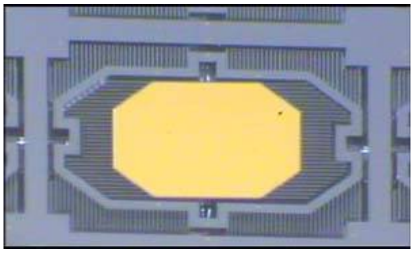
Lucent's Lambda Router

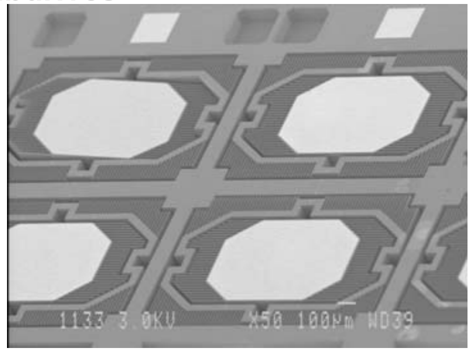
(Lucent Lambda Router)

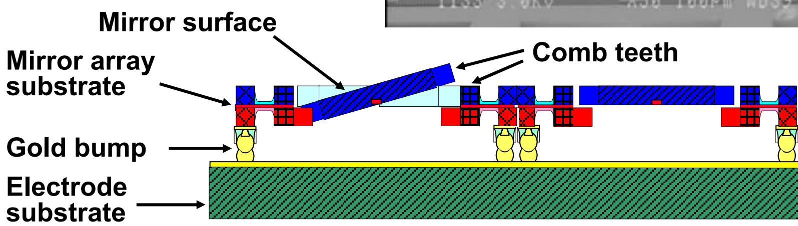




2D Scanners with Staggered Vertical Combdrives

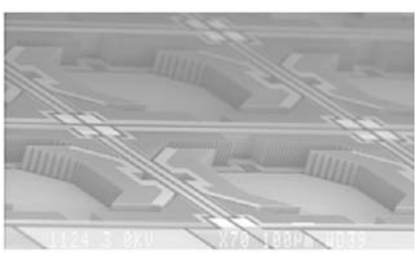




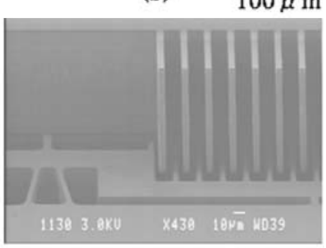


Fujitsu, 2002

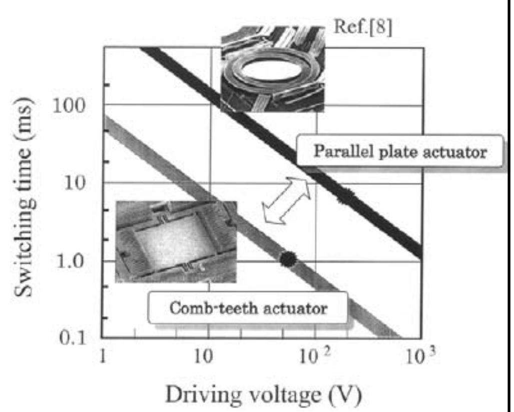
Fujitsu Micromirror for 3-D MEMS Optical Switch



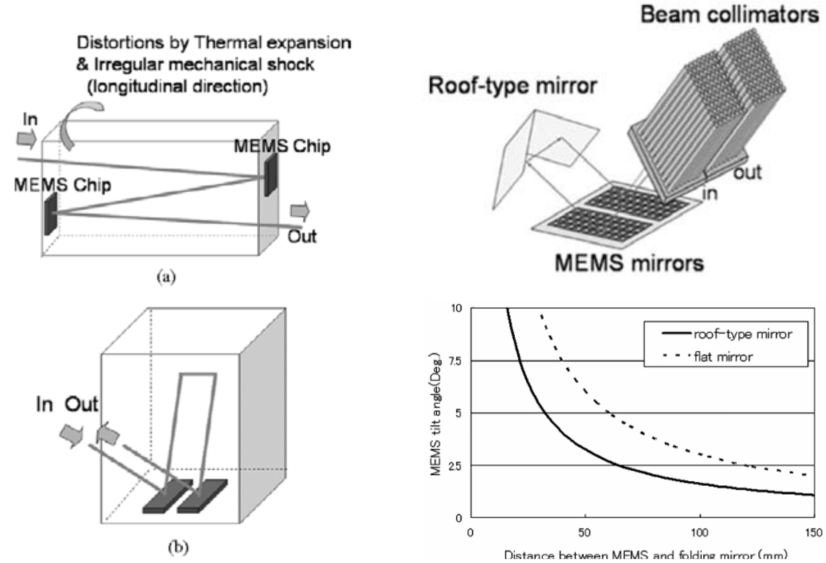
(b) 100 μm



(a) 10 μm

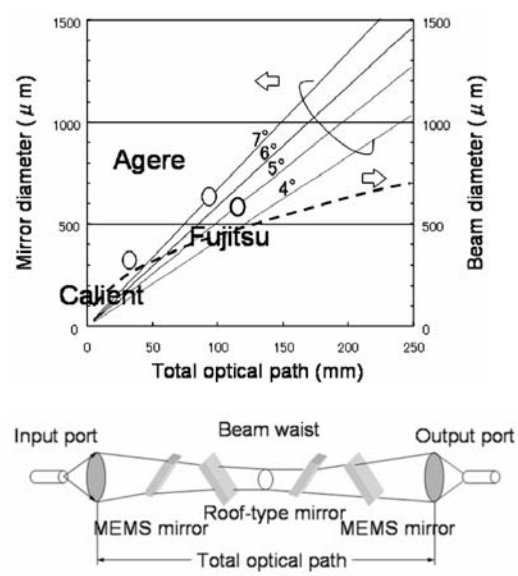


Fujitsu's 3-D MEMS Switch

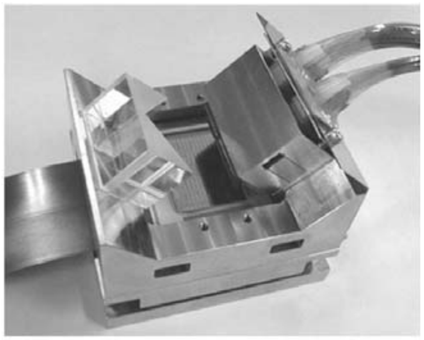


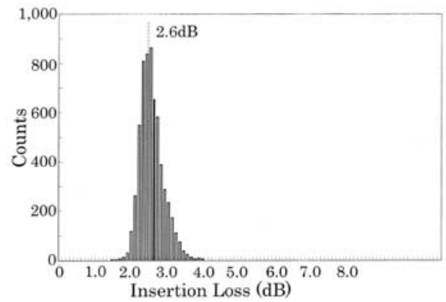
Mitsuhiro Yano, Fumio Yamagishi, and Toshitaka Tsuda, IEEE J. SELECTED TOPICS QUANTUM ELECTRONICS, VOL. 11, p. 383, MARCH/APRIL 2005

Fujitsu's 3-D MEMS Switch



Fujitsu's 3-D MEMS Switch





87x77x53 (mm^3)

Ming Wu 31

Wavelength-Selective Switches (WSS)

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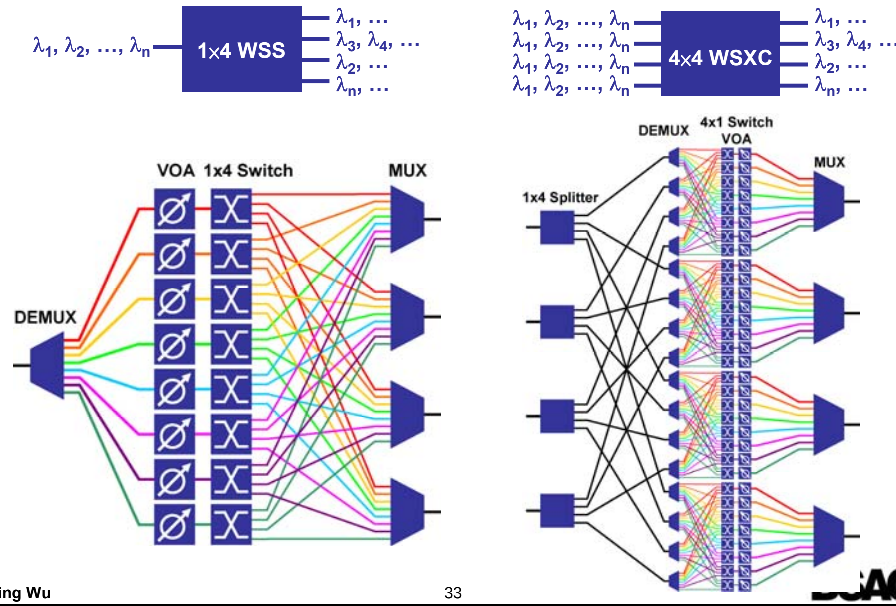
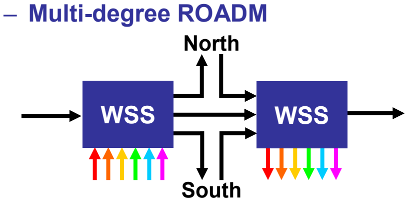
1xN Wavelength-Selective Switch & NxN Wavelength-Selective Cross Connect

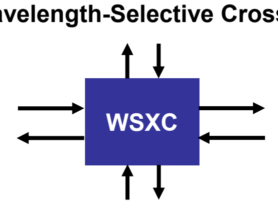


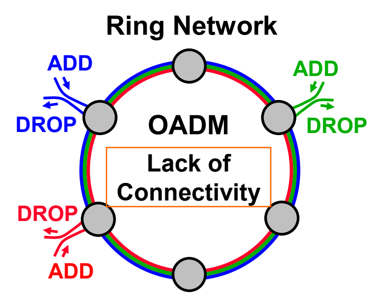
Optical Network Architecture

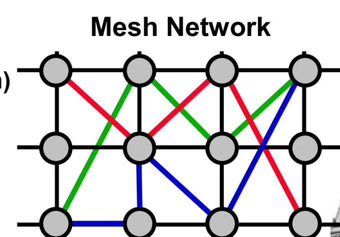
- OADM (Ring)
  - Add-Drop with fixed λ's
- ROADM (Ring)
  - Add-Drop with programmable λ's
- 1xN Wavelength-Selective Switch (Mesh)
  - Multi-degree ROADM



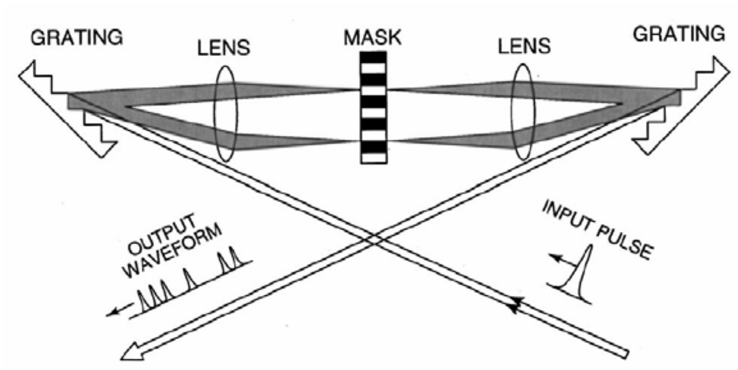
- NxN Wavelength-Selective Cross Connect (Mesh)







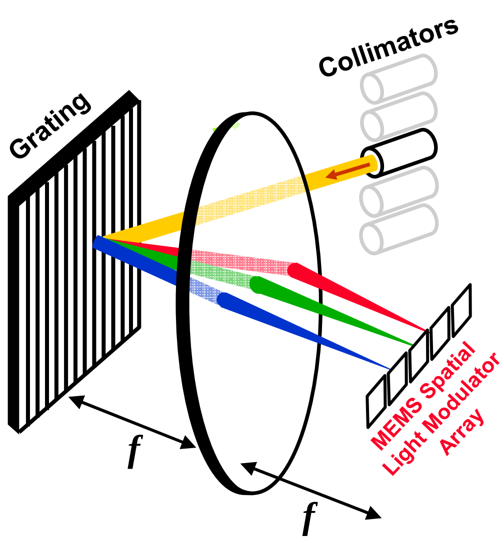
Fourier Transform Pulse Shaper



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

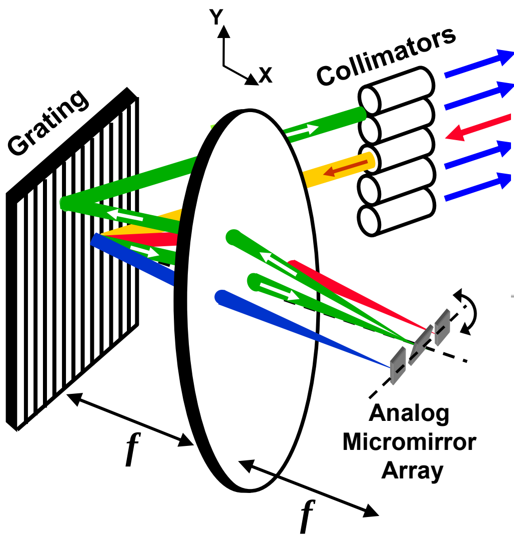
- **Shaping femtosecond pulses by modulating the phases and amplitudes of their spectral components**

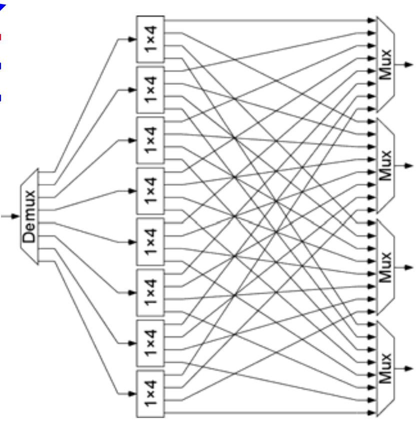
Dynamic WDM Functions



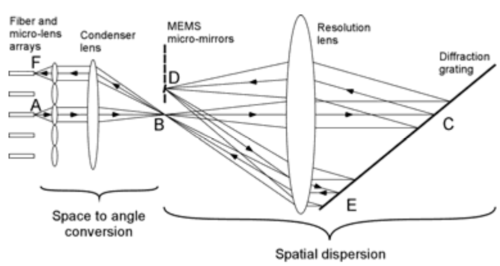
MEMS Spatial Light Modulator Array	Dynamic WDM Functions
Piston Mirrors	Femtosecond pulse shaper
ON-OFF reflectors	Wavelength blocker
Variable reflectivity mirror	Spectral (or gain) equalizer
1x2 Digital micromirrors	Optical add-drop multiplexer (OADM)
1xN analog micromirrors	Wavelength-Selective Switch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

1x4 Wavelength-Selective Switch (WSS)





1x4 WSS

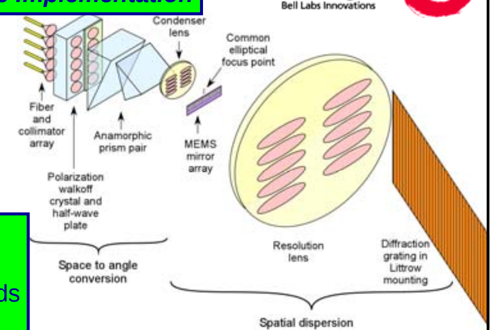


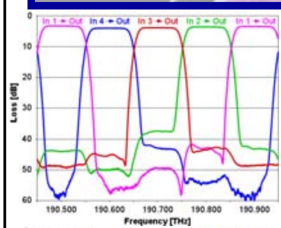
- D. Marom et al. (Lucent), OFC 2002
  - 1x4 WSS
  - Channel spacing: 50 or 100 GHz
  - MEMS performance: 12˚ (> 55 V)
- T. Ducellier et al. (JDS-U), ECOC 2002
  - 1x4 WSS
  - Channel spacing: 100 GHz
  - MEMS performance: ±2˚

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

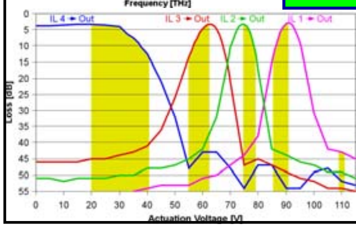
Free-Space Implementation

Lucent Technologies
Bell Labs Innovations

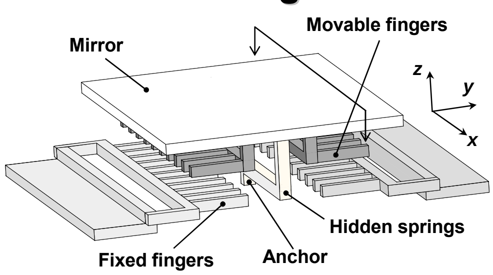


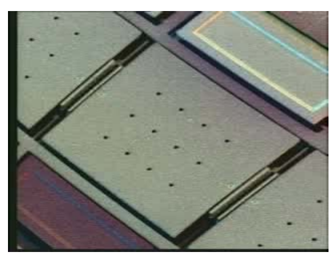


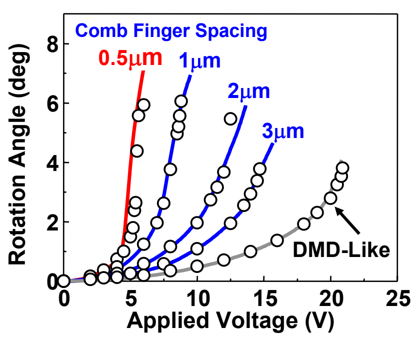
WSS provides:
- Port switching
- Wide passbands
- 10 dB DSE
- Blocking
- Low insert loss
- Low PDL, DGD



Analog Micromirror Array (UCLA)



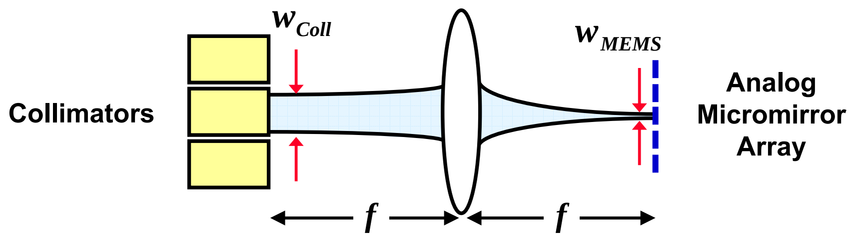




Scan Angles	+/- 6° (mechanical)
Voltage	6 V
Fill Factor	98%
Res. Freq.	3.4 kHz
Stability (3hr)	±0.00085˚
System (3hr)	± 0.0035dB

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

Scaling of WSS



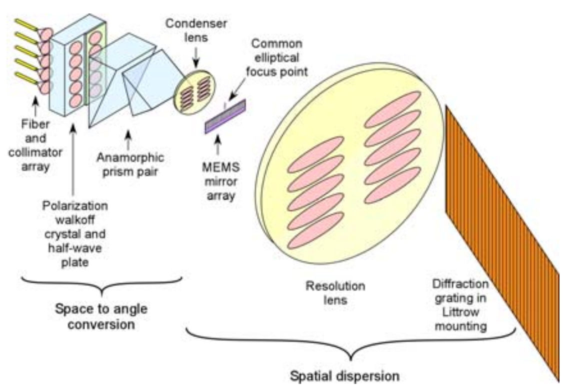
$$w_{MEMS} = \frac{\lambda \cdot f}{\pi \cdot w_{Coll}}$$

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

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

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

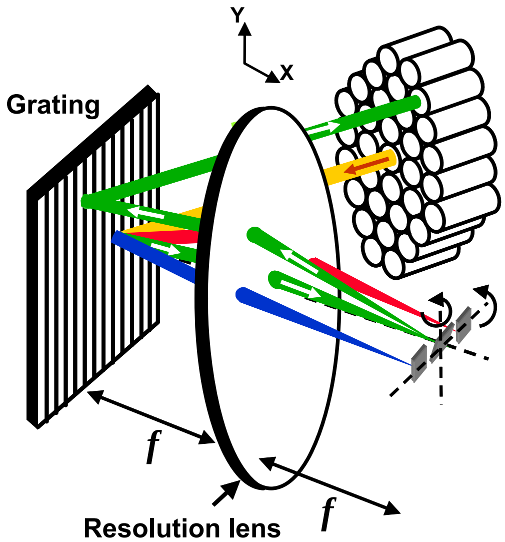
Approach for Increasing Port Count (1)



D. Marom (Lucent)

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

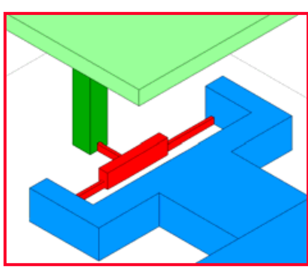
Approach for Increasing Port Count (2)



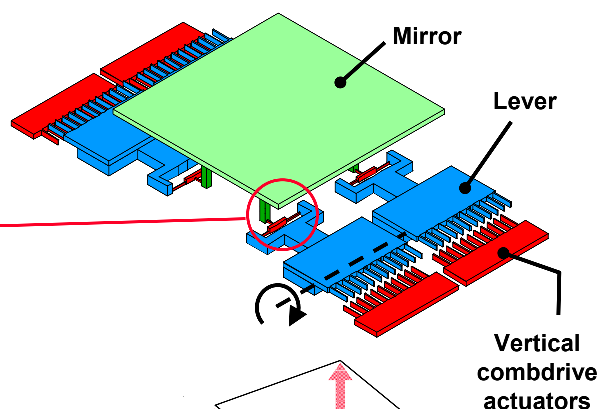
- $1xN^2$ WSS:
  - 2D collimator array
  - 1D array of 2-axis micromirror array
- Port count is increased from N to N^2
  - N is the diffraction-limited linear port count
- High port count WSS
  - 1x32 WSS has been demonstrated

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

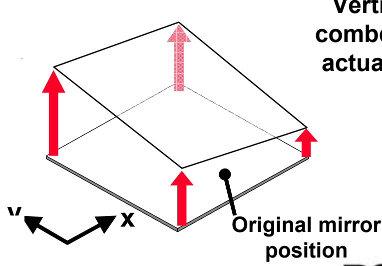
High-Fill Factor 2-Axis Micromirror Array



2-DOF mirror joint

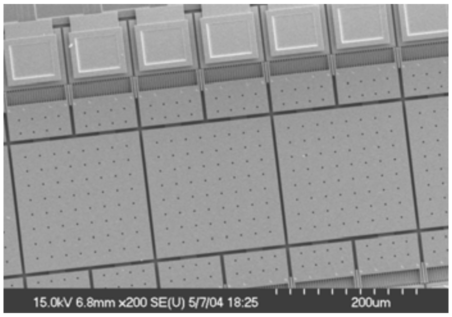


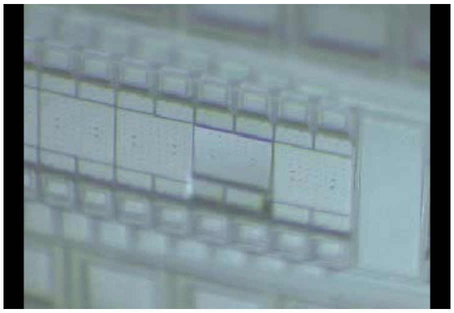
- Gimbal-less
  - High Fill factor (> 98%)
- Large scan angle
  - 3x angle amplification by leverage
- Low voltage
  - Powerful vertical combdrive actuators



J.C. Tsai, L. Fan, D. Hah, and M.C. Wu, IEEE LEOS International Conference on Optical MEMS 2004

SEM of Gimbal-less 2-Axis Analog Micromirror Array



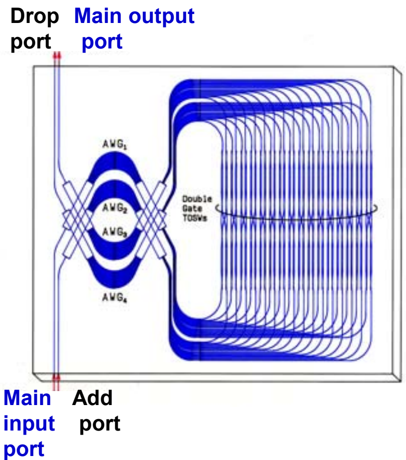


- SUMMiT-V 5-layer surface micromachining process
- Mirror pitch: 200 um
- Large scan angles: ±6.7º (mechanically) @ 75 V
- Fill factor: 98%
- Resonant frequency = 5.9 kHz

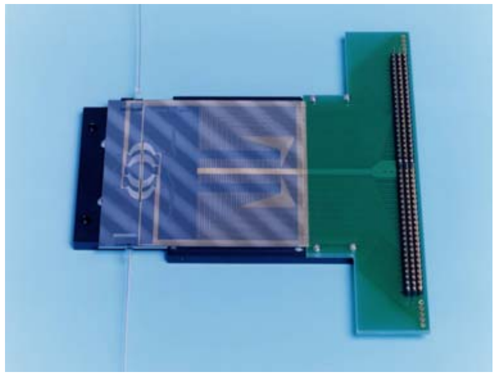
J.C. Tsai, L. Fan, D. Hah, and M.C. Wu, IEEE LEOS International Conference on Optical MEMS 2004

Planar Lightwave Circuit (PLC) MEMS

Reconfigurable Optical Add/Drop Multiplexer (ROADM)



(a) Configuration of 16ch-100GHz OADM

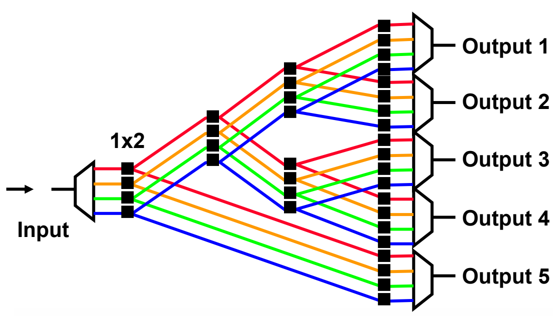


(b) Photograph of OADM

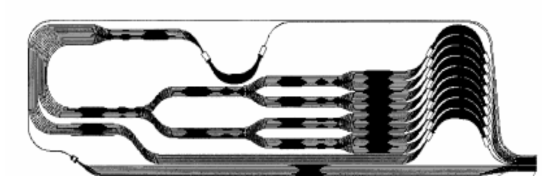
K. Okamoto et al., Electron. Lett., vol. 31, pp.723-724, 1995

(VG courtesy of K. Okamoto)

PLC 1x9 WSS

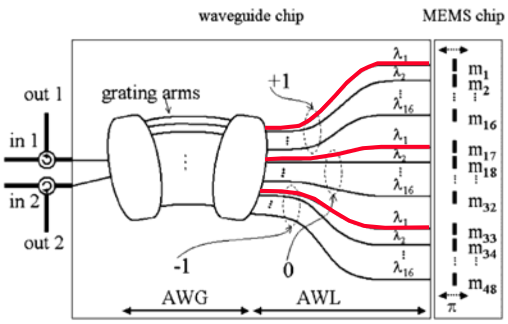


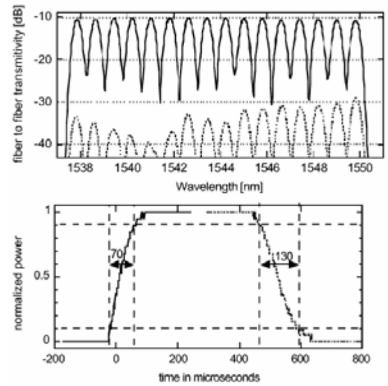
- 1x9 WSS
- Thermal optic switch
  - 450 mW / switch
  - Total power ~ 14W
- Loss ~ 5.4 dB
- Isolation > 46 dB



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 mm²

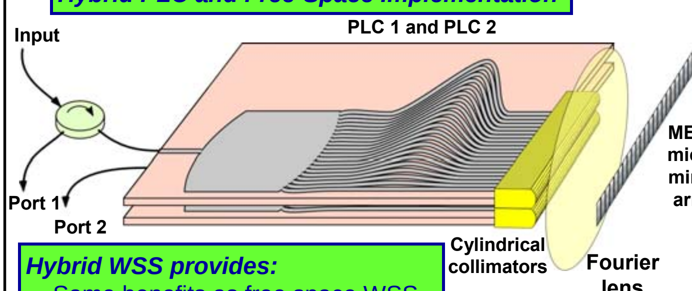
D.T. Fuchs, et al (Lucent) IEEE PTL, Jan. 2004

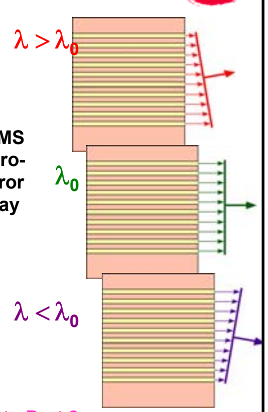
- 100 GHz channel spacing
- 10.6 dB insertion loss
- 20 dB extinction ratio

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

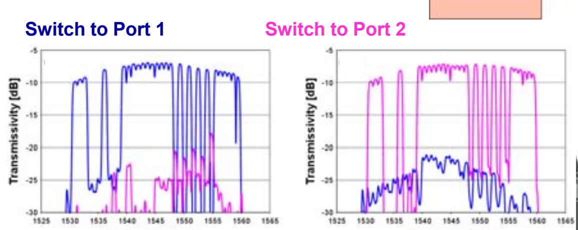
Lucent Technologies
Bell Labs Innovations

Hybrid PLC and Free-Space Implementation





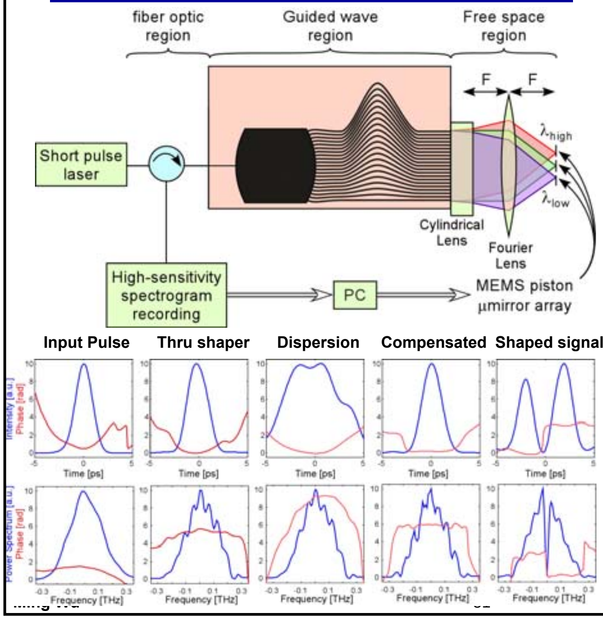
Hybrid WSS provides:
- Same benefits as free space WSS
- Compact implementation
- Integration of additional functionality

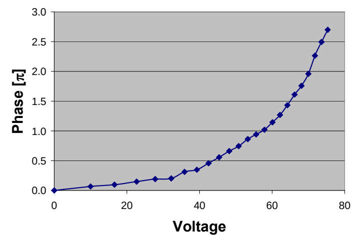


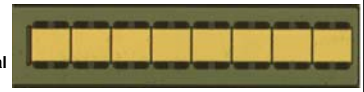
Compact Spectral Pulse Shaper (D. Marom)

Lucent Technologies
Bell Labs Innovations

Hybrid PLC and Free-Space Implementation



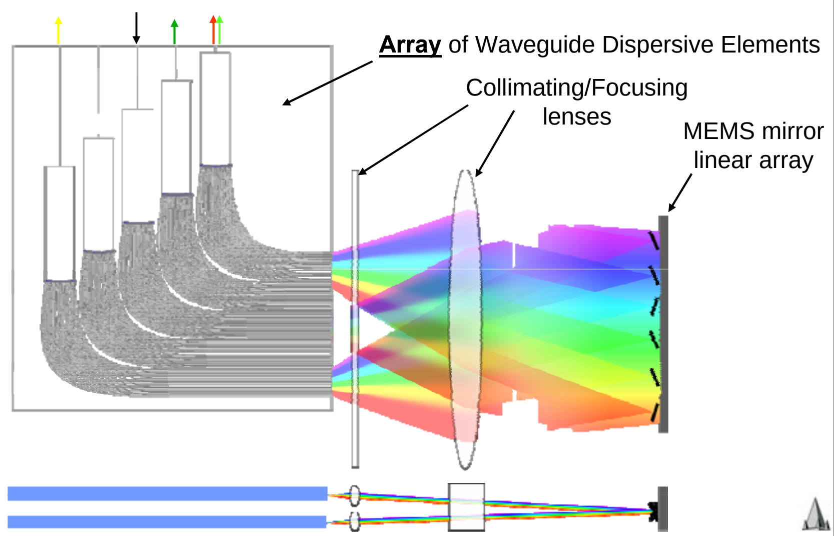




MEMS piston motion micromirror array
- $>2\pi$ phase modulation
- Polarization insensitive

Pulse Shaper provides:
- Spectral domain processing
- Polarization independent
- Gateway to optical arbitrary waveform synthesis

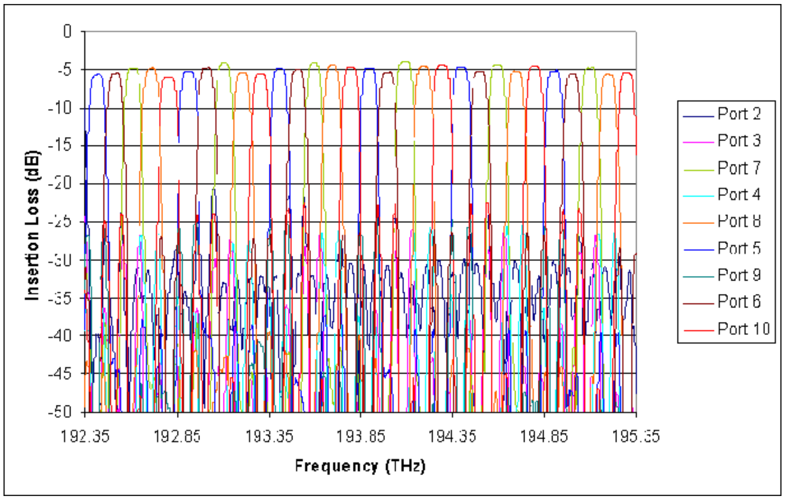
2D arrangement of ports for scalable 1x9 WSS



metconnex

ALCATEL

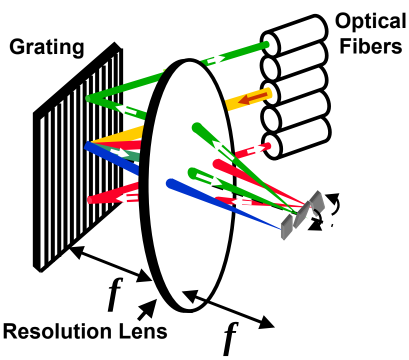
Interleaved spectrum switched to all output ports



metconnex ALCATEL

Free-Space and Hybrid Integrated 1xN WSS

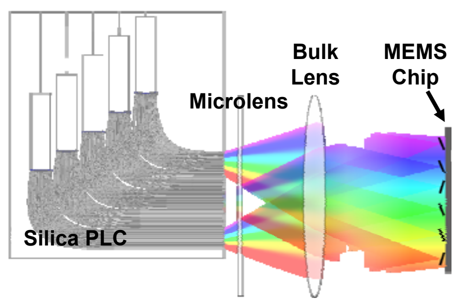
Free-Space 1xN WSS



- Large space
- Complicated alignment

D. Marom, et al. (Lucent), OFC 2002.
T. Ducellier, et al. (JDS-U), ECOC 2002.
S. Huang, et al. (UCLA), O-MEMS 2002.

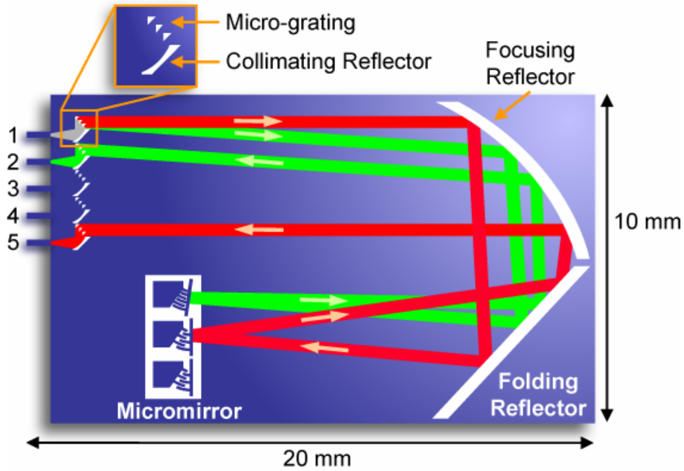
Hybrid 1xN WSS



- Silica PLC has low insertion loss
- Hybrid integration requires external collimator and lens

T. Ducellier et al. (Metconnex), ECOC, 2004
D.M. Marom et al. (Lucent), OMEMS 2004
D.M. Marom et al. (Lucent), ECOC 2005

Silicon-Based Monolithic 1x4 Wavelength-Selective Switch

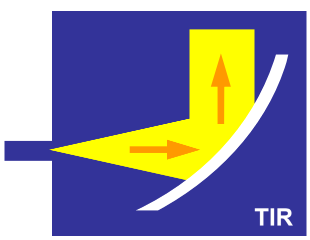


- **Silicon PLC is compatible with SOI-MEMS technologies**
- **Excess Insertion loss can be reduced with AR coating and smoothed sidewall (e.g. hydrogen annealing)**

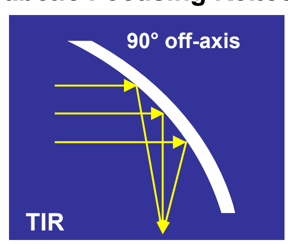
C.H. Chi et al., CLEO 2005

Integrated Optical Components

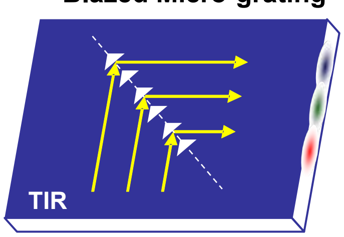
Parabolic Collimator



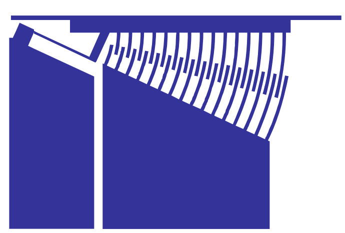
Parabolic Focusing Reflector



Blazed Micro-grating

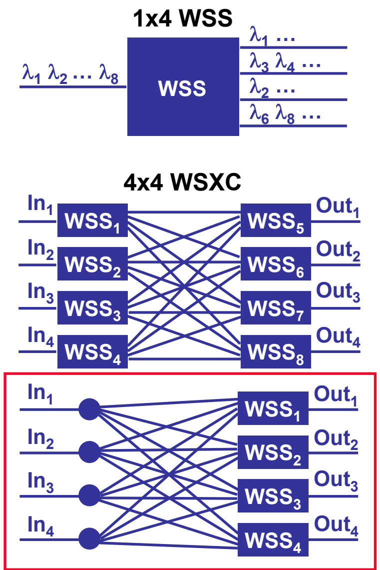


Electrostatic Micromirror



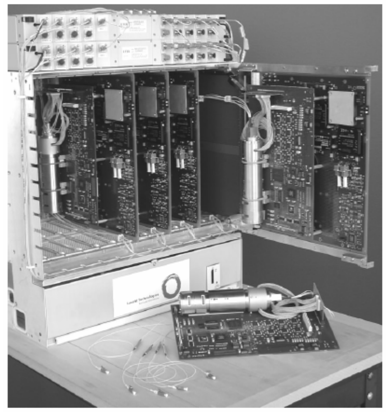
C.H. Chi et al., OFC 2006

4x4 Wavelength-Selective Cross Connect



C.H. Chi et al., OFC 2006

Free-Space WSXC

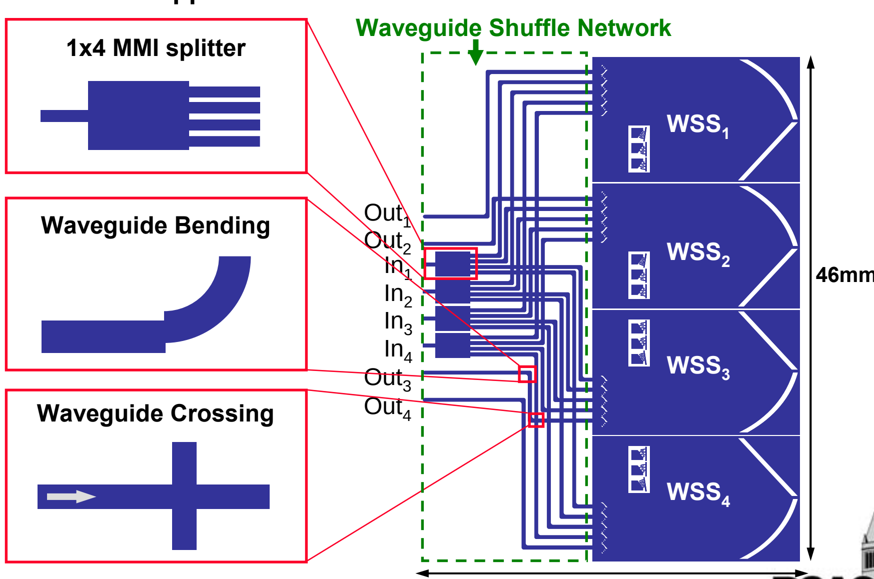


D. M. Marom et al. (Lucent), ECOC 2003

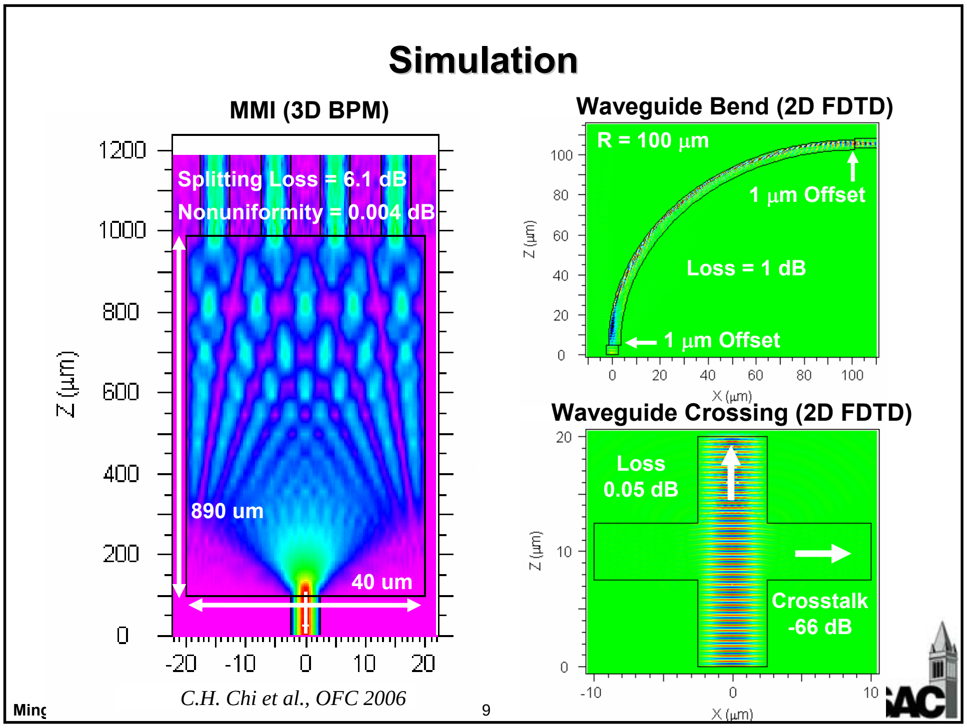
- **Four passive 1x4 splitters (6.5 dB loss)**
- **Four 4x1 WSS (4 dB loss)**

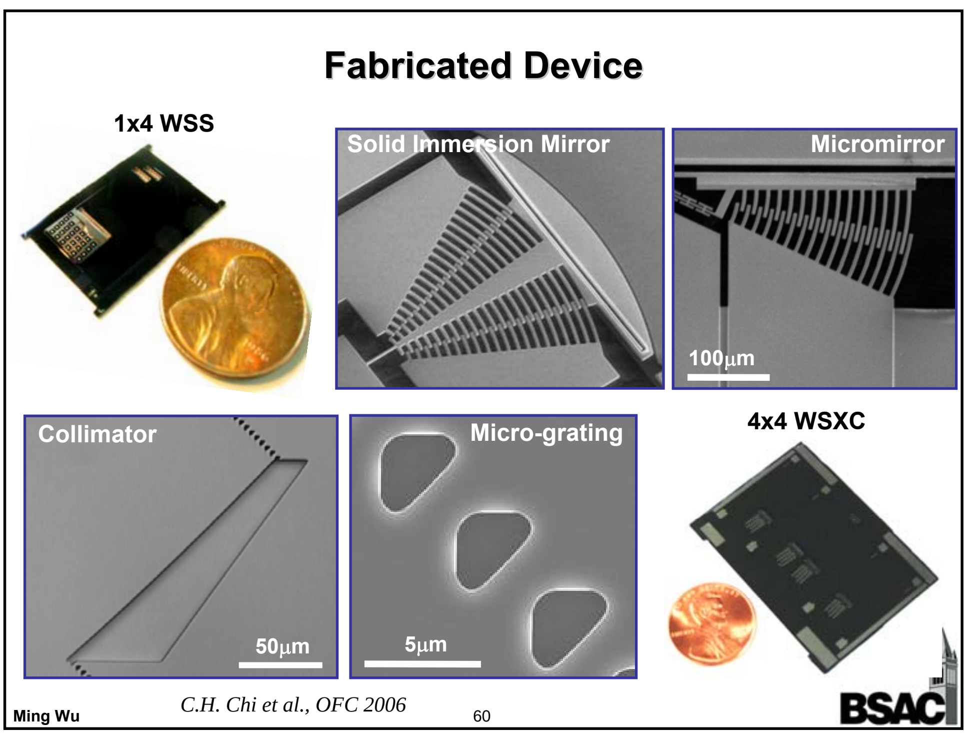
Monolithic 4x4 WSXC – Planar Integration

Support Broadcast and Multicast Functions

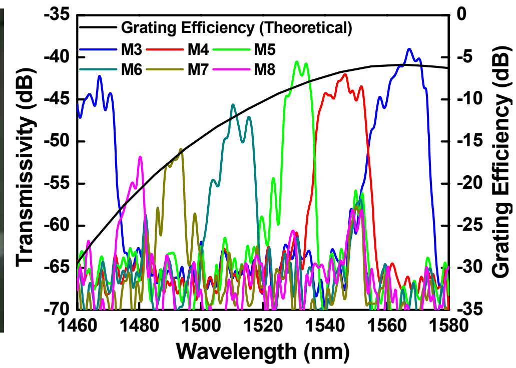


C.H. Chi et al., OFC 2006


Simulation
MMI (3D BPM)
Splitting Loss = 6.1 dB
Nonuniformity = 0.004 dB
890 um
40 um
Z (µm)
1200
1000
800
600
400
200
0
-20 -10 0 10 20
Waveguide Bend (2D FDTD)
R = 100 µm
1 µm Offset
Loss = 1 dB
1 µm Offset
Z (µm)
X (µm)
Waveguide Crossing (2D FDTD)
Loss
0.05 dB
Crosstalk
-66 dB
Z (µm)
X (µm)
C.H. Chi et al., OFC 2006
9


Fabricated Device
1x4 WSS
Solid Immersion Mirror
Micromirror
100µm
Collimator
50µm
Micro-grating
5µm
4x4 WSXC
Ming Wu
C.H. Chi et al., OFC 2006
60
BSAC

Spectral Response of 4x4 WSXC

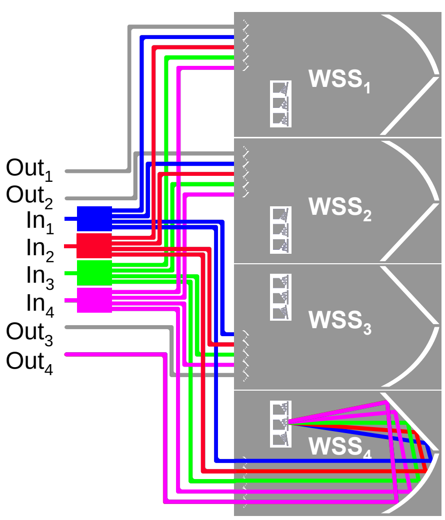


- Six micromirrors tested with available tuning range: 1460-1580 nm
- 3 dB passbands:
  - 1477-1482 nm, 1488-1494 nm, 1507-1517 nm
  - 1527-1535 nm, 1539-1553 nm, 1561-1573 nm
- Additional passband from adjacent grating order

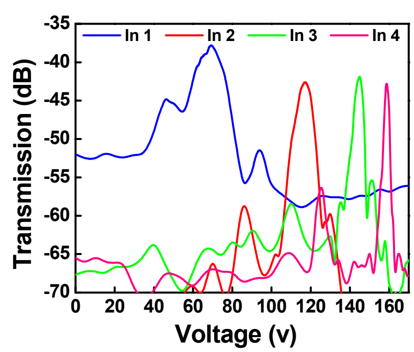
Ming Wu *C.H. Chi et al., OFC 2006* 61

BSAC

Transfer Curve of 4x4 WSXC



- Signals are selected from each input port and transported to the designated output port
- Extinction ratio from In_1 is lower due to imperfect AR coating

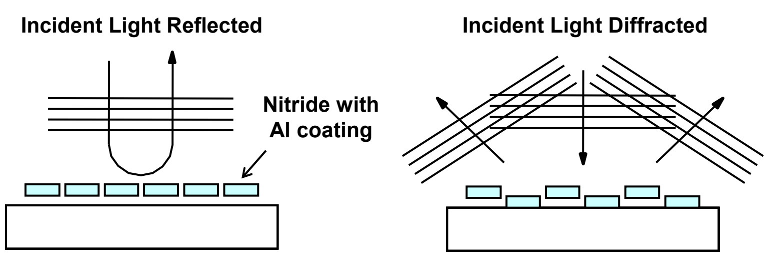


Ming Wu *C.H. Chi et al., OFC 2006* 62

BSAC

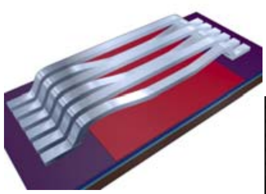
Diffractive Optical MEMS

Grating Light Valve

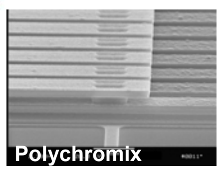


O. Solgaard, F. S. A. Sandejas, D. M. Bloom, "A deformable grating optical modulator", Optics Letters, vol. 17, no. 9, pp. 688-690, 1 May 1992.

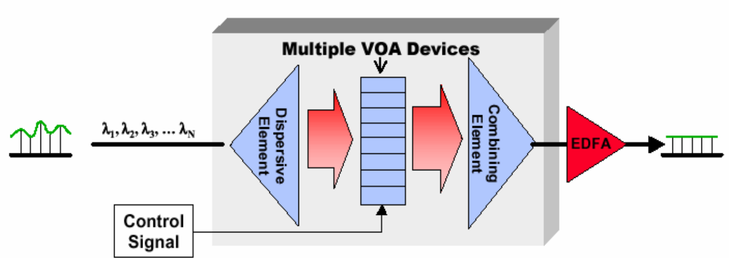
- **Applications**
  - Projection display
  - Variable optical attenuators (VOA)
  - Gain equalizers
  - Wavelength blockers
- **Companies**
  - Silicon light machine (Cypress), Lightconnect, Polychromix, Kodak



Silicon Light Machine

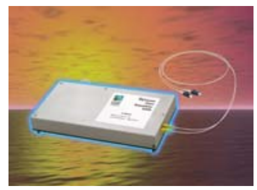


Telecommunications Applications



Dynamic Spectral Equalizer (DSE)

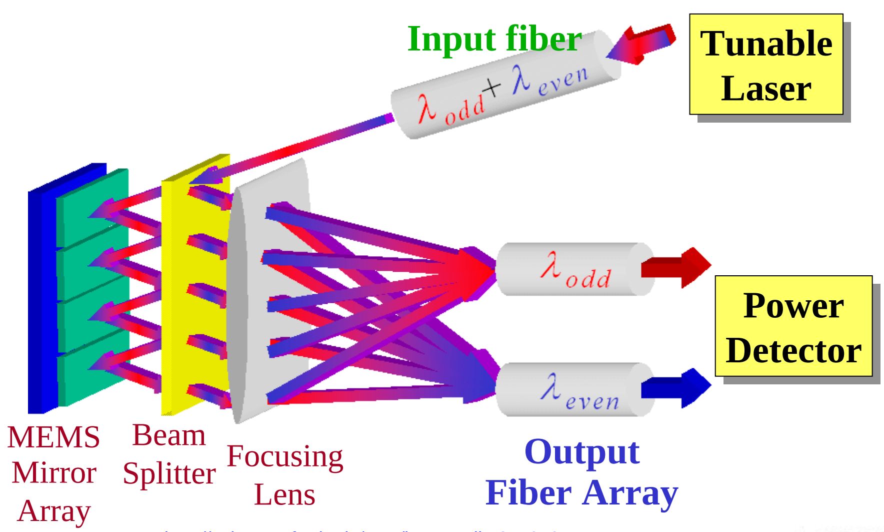
Reconfigurable Channel Blocking Filter



Dynamic Gain Equalizer

MEMS Switchable WDM Deinterleaver Based on Gires-Tournois Interferometer

Olav Solgaard, Stanford University

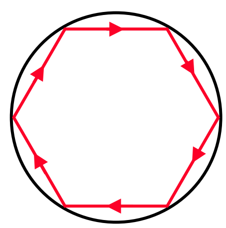


http://wdm.stanford.edu/snrc/kyoungsik12_10_01.ppt

Nanophotonic MEMS

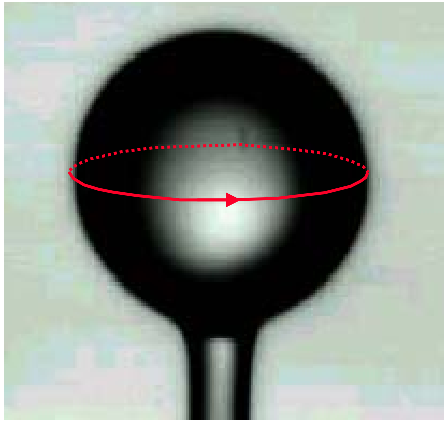
Whispering Gallery Mode (WGM)

St Paul's Cathedral, London



- WGM first explained by Lord Rayleigh in 1910
- Used in
  - Acoustic waves
  - Microwaves
  - Optical waves

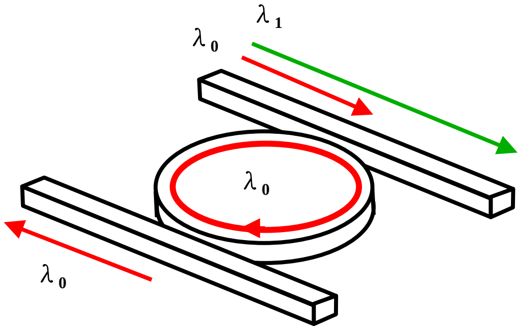
WGM in Silica Microsphere



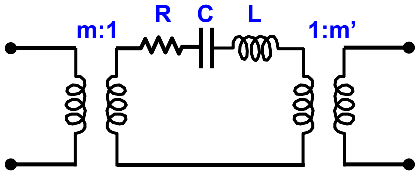
- Made by melting a fiber tip
- First demonstrated by Braginsky, et al, 1989
- Extremely high Q ~ 2×10^{10}
  - Maleki, et al, (JPL) 2004

BSAC

Optical Microresonators



Equivalent Circuit

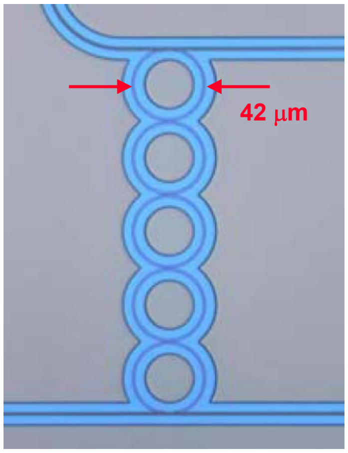


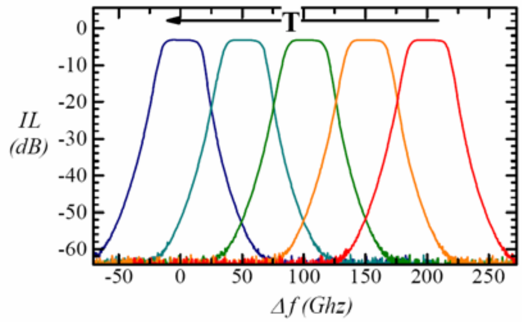
- Filter proposed by Marcatili (Bell Labs), 1969
- Channel dropping filter
- Needs high Q > 10^5

→ Surface roughness < 1 nm

BSAC

Microring Resonator-Based PIC

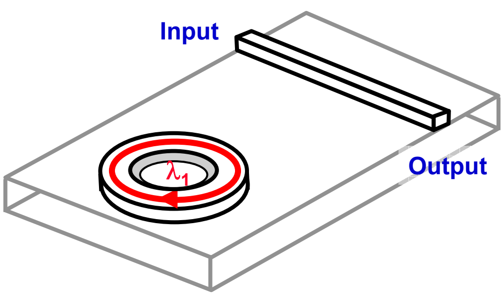


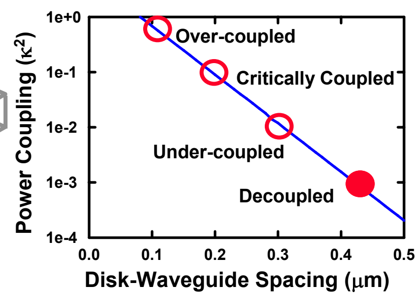


Thermally Tuned with Vernier Architecture

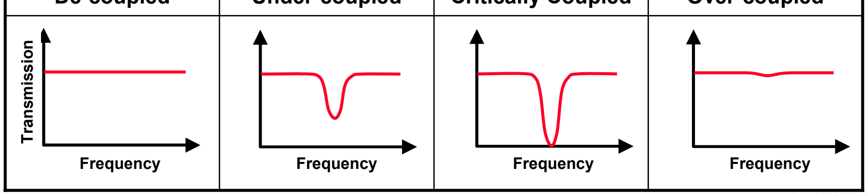
S. T. Chu, B. E. Little, V. Van, J. V. Hryniewicz, P. P. Absil, F. G. Johnson, D. Gill, O. King, F. Seiferth, M. Trakalo and J. Shanton (Little Optics) OFC 2004

Variable Quality Factor



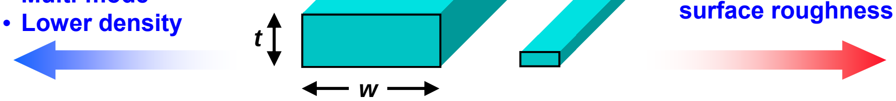


De-coupled	Under-coupled	Critically Coupled	Over-coupled



Scaling of Optical Wires

- Insensitive to surface roughness
- Multi-mode
- Lower density



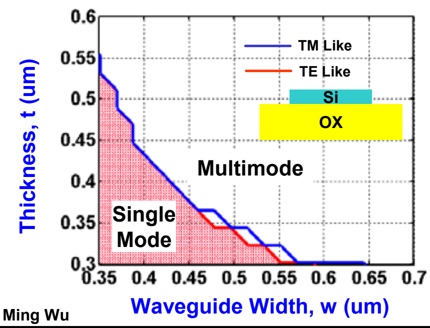
- Higher density
- Very sensitive to surface roughness

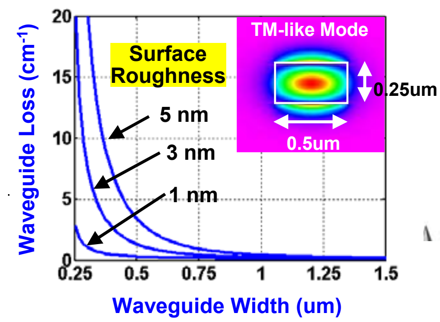
Single Mode

$w \times t \leq 0.18\ \mu m^2$

Surface Roughness

$\delta_{rms} \leq 1$ nm





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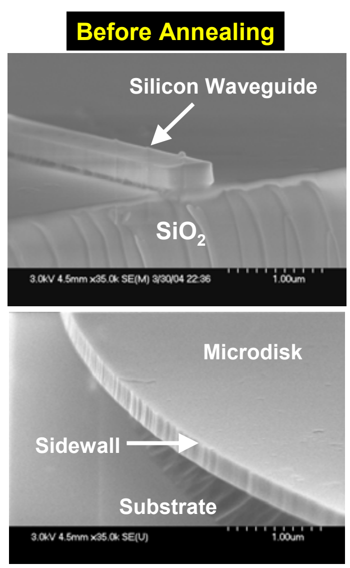
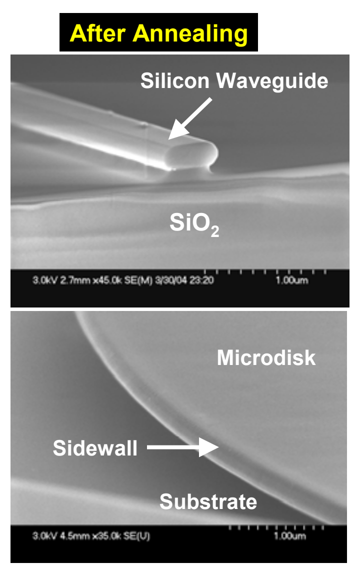
< 0.25-nm Surface Roughness by H_2 Annealing





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Surface Roughness < 0.25 nm

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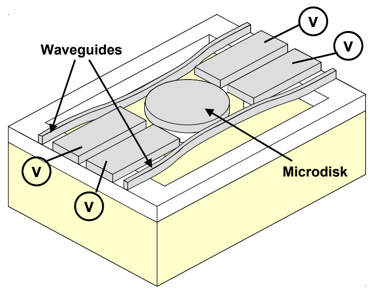
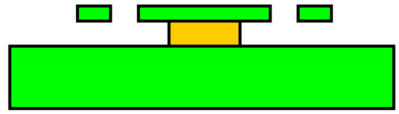
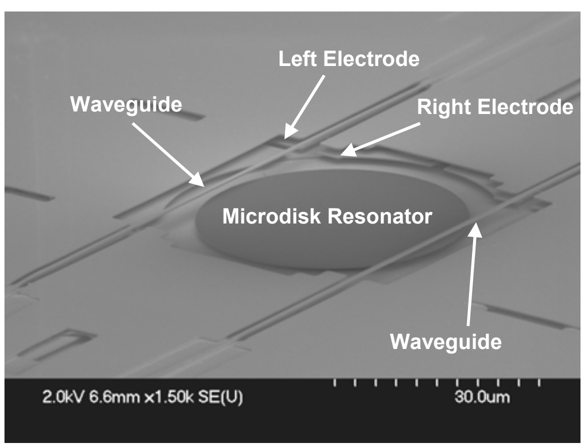
Microdisk Resonator with MEMS Tunable Coupler (First Generation Device)



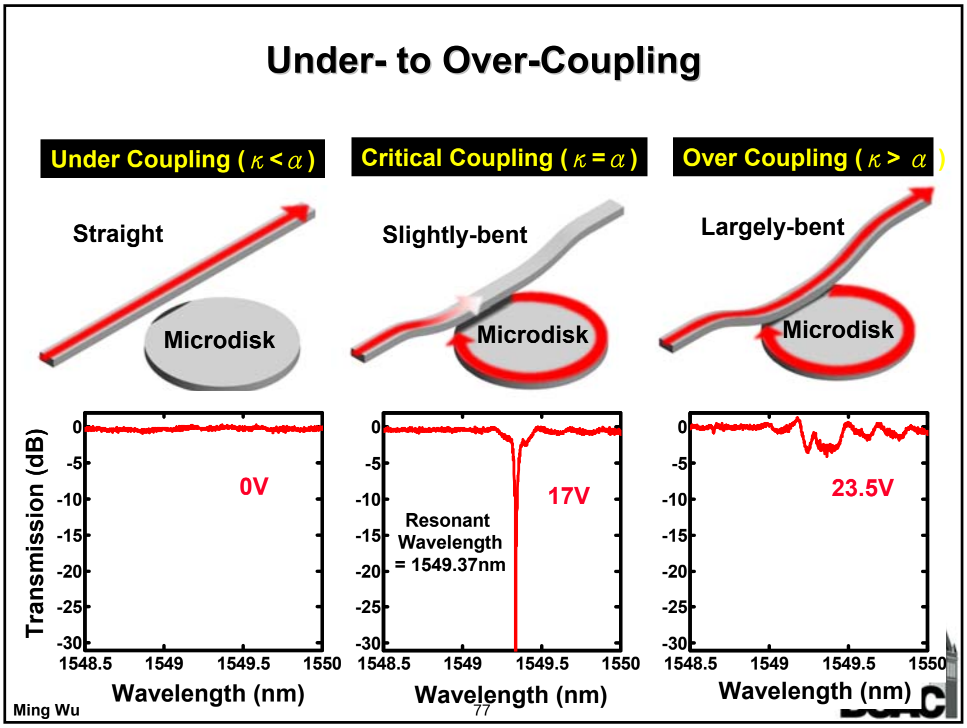


- Successfully demonstrated
  - Switchable notch filter (O-MEMS ’03)
  - Tunable dispersion, 0 ~ 400 ps/nm (CLEO ’04)
- Q ~ 10,000 due to vertical offset

Second-Generation MEMS Microdisk Resonator



- Microdisk
  - Radius: 20 μm
  - Thickness : 0.25 μm
- **Suspended deformable waveguides**
  - Width: 800 nm
  - Thickness: 250 nm
  - Length: 100 μm
- Initial gap spacing
  - WG/Disk: 1 μm


Under- to Over-Coupling
Under Coupling (κ < α)
Critical Coupling (κ = α)
Over Coupling (κ > α)
Straight
Slightly-bent
Largely-bent
Microdisk
Microdisk
Microdisk
Transmission (dB)
0V
17V
23.5V
Resonant Wavelength = 1549.37nm
Wavelength (nm)
Wavelength (nm)
Wavelength (nm)
Ming Wu
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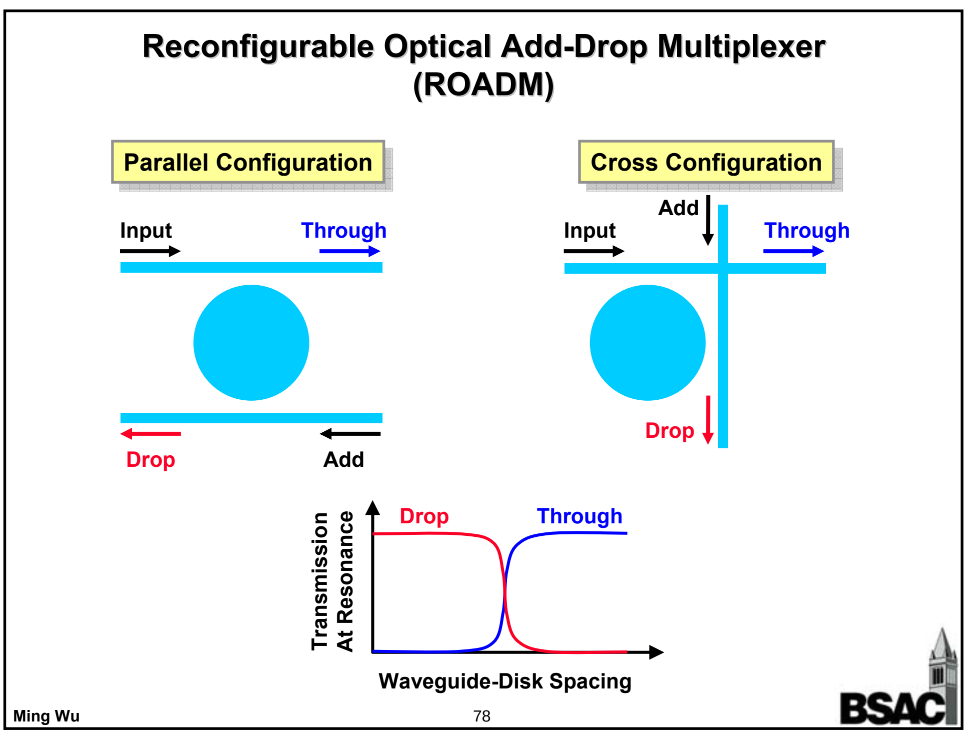
Reconfigurable Optical Add-Drop Multiplexer (ROADM)
Parallel Configuration
Cross Configuration
Input
Through
Drop
Add
Input
Add
Through
Drop
Drop
Through
Transmission At Resonance
Waveguide-Disk Spacing
Ming Wu
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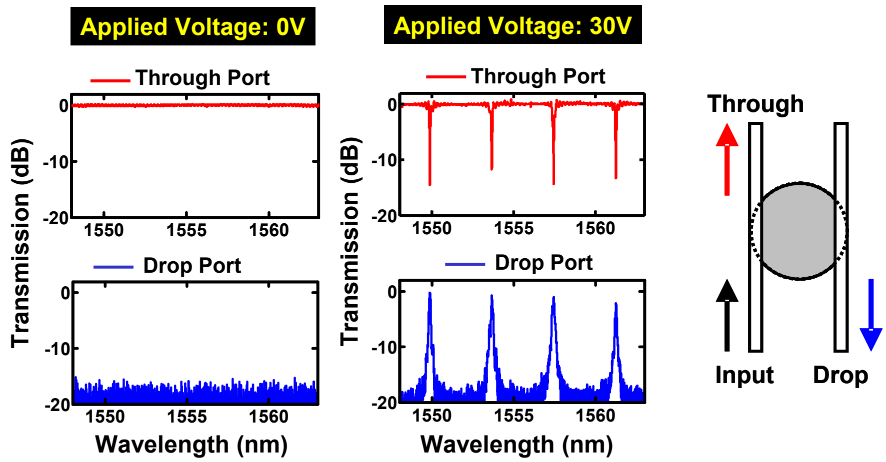
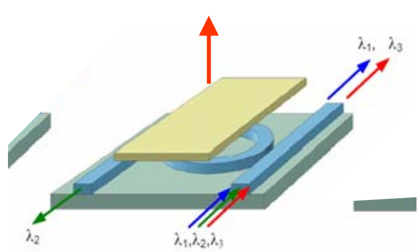
Dynamic Wavelength Add-Drop



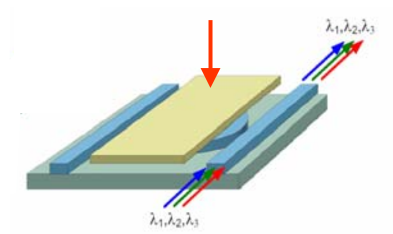
- Cascadable, hitless operation
- Almost 0 dB insertion loss is observed without bias

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