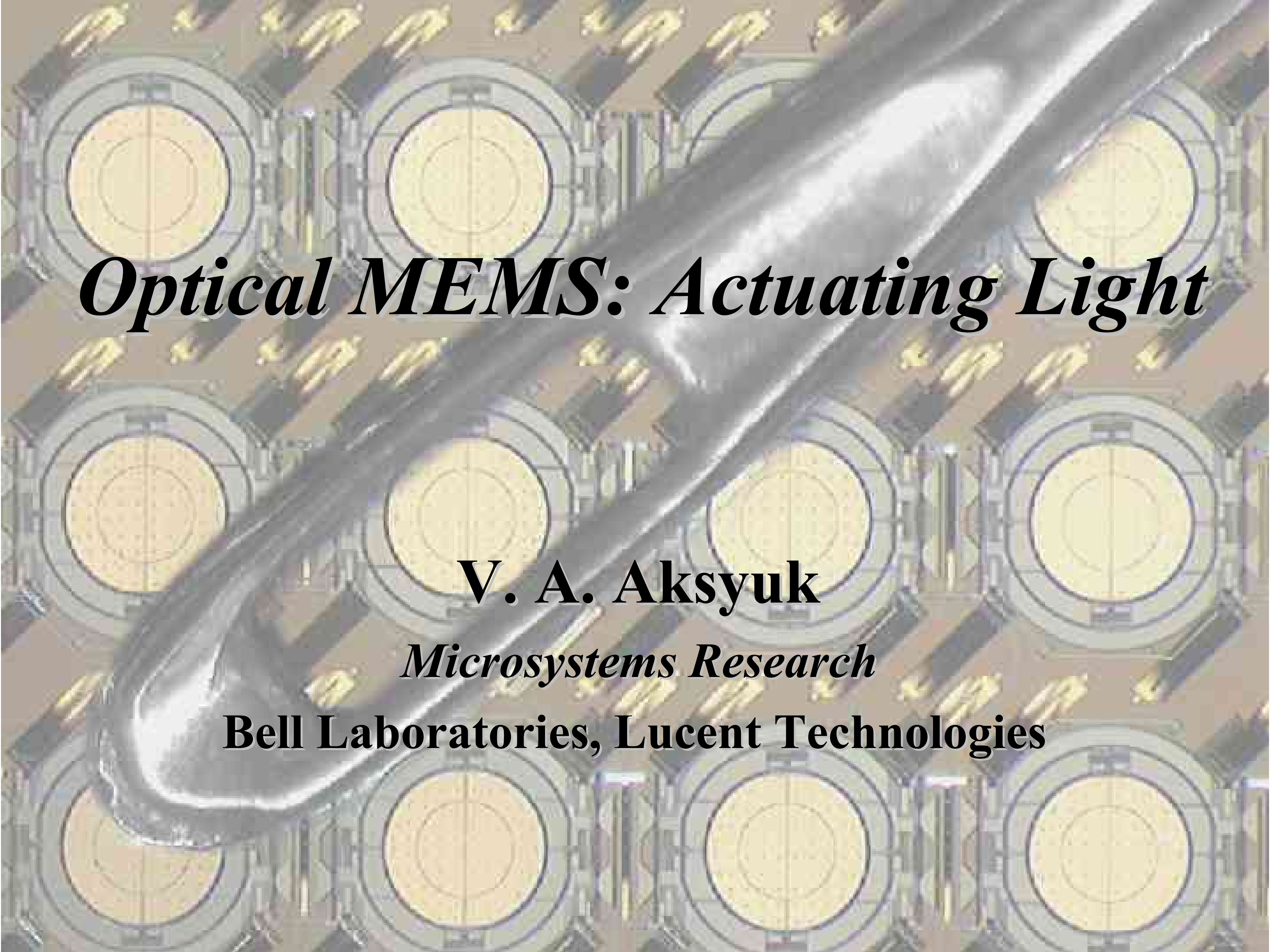


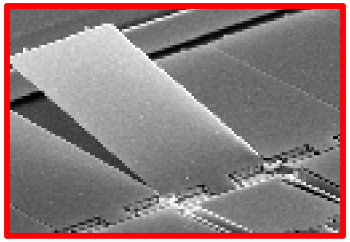
# *Optical MEMS: Actuating Light*

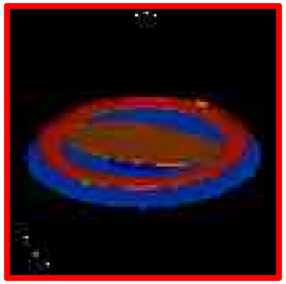
**V. A. Aksyuk**

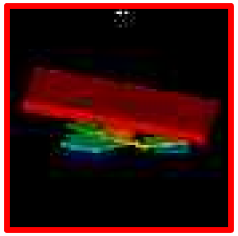
*Microsystems Research*

**Bell Laboratories, Lucent Technologies**

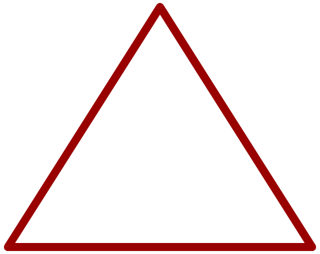
# Optical MEMS at Lucent





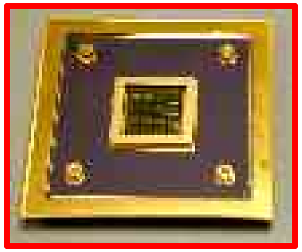


**Design**



**Fabrication**

**Microsystem Integration**



# Acknowledgements

MEMS devices: design, process, testing, reliability

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Subsystem and System: optics, packaging, physical design, electronics, software, training & test

N. Basavanhally, R. Boie, C. Doerr, J. Ford, R. Frahm, D. Fuchs, J. Gates, R. Giles, J. Kim, P. Kolodner, J.S. Kraus, B. Kumar, C. P. Lichtenwalner, D.F. Lieuwen, Y. Low, D. Marom, D.T. Neilson, C. Nijander, C. J. Nuzman, R. Pafcheck, A. R. Papazian, D. Ramsey, R. Ryf, R. Scotti, L. Stulz, H. Tang, A. Weiss, J. Weld

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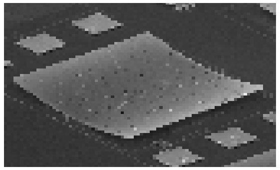
Leadership and support

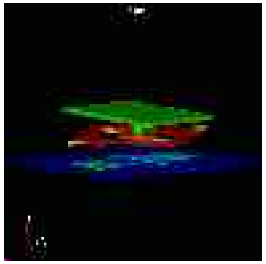
S. Arney, J. Gates, R. Giles, D. Bishop

# Optical MEMS at Lucent: Project Lineup

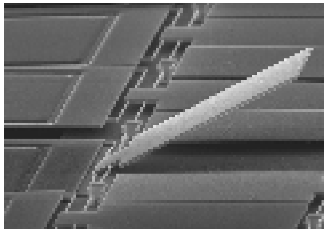
3 layer poly electrodes
bistable actuator
curvature mitigation
polarization controller
alternative flip-chip
control beyond snapdown
charging studies
dielectric leakage studies
MEMS reliability physics



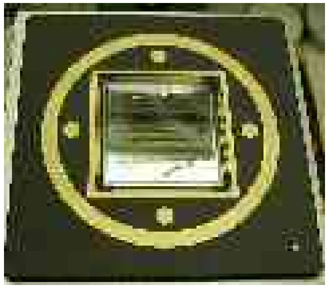
1xN switch
waveguide 1x2 WSS
2D WSS
1D tilt OXC
party-favor mirrors



Double-hinge WSS
Fringe-field WSS
Torsional WSS
Si microlens arrays
Flag switch/VOA



Torsional blocker
LR 1296



LR 256
Agere 64 OXC

### Research project

- idea demonstration
- approach verification
- numerical modeling
- process development
- basic reliability research

### Device concept

- functionality demonstration
- design verification
- performance assessment
- reliability assessment

### Device prototype

- subsystem demonstration
- detailed performance testing
- design optimization
- process optimization
- reliability testing

### Models

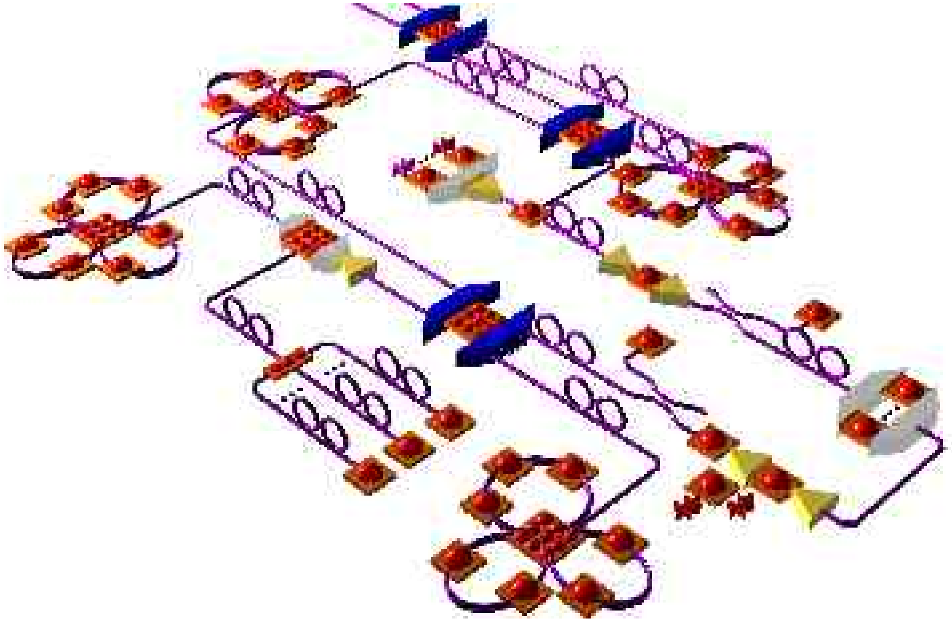
- subsystem optimization
- design optimization
- manufacturability & yield
- subsystem reliability

### Product

- performance improvement
- yield optimization
- cost cutting
- troubleshooting
- reliability enhancement

# Why Optical Micromachines ?

- Variable Attenuators
- Spectral Equalizers
- OLS Monitors
- Dispersion Compensators
- Data Modulators
- Protection Switches
- Add/Drop Multiplexers
- Crossconnects



**Excellent optical properties of opto-mechanical components**:
- low optical loss
- high contrast
- wavelength independent
- polarization independent
- data format independent

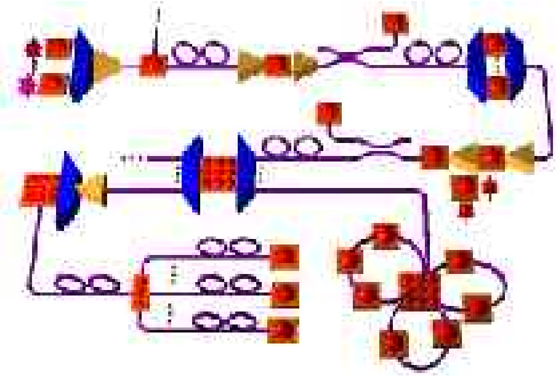
\+

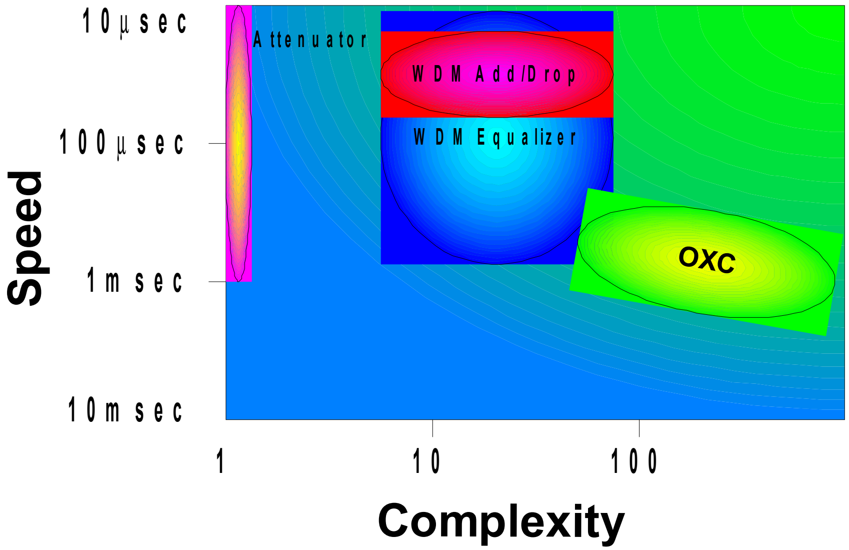
**Thousands of movable elements**
(degrees of freedom)
on a single Si chip

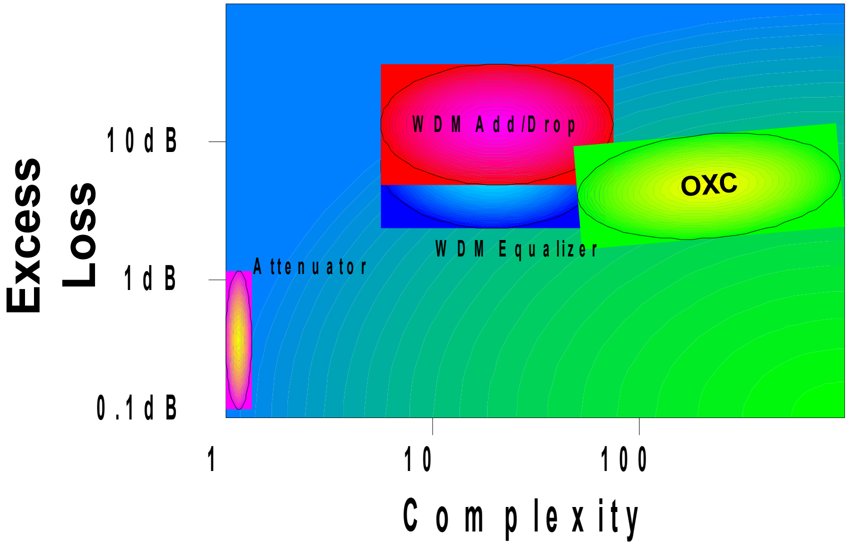
\+

**Fast**
**Small**
**Inexpensive**

# Optical MEMS Application Space





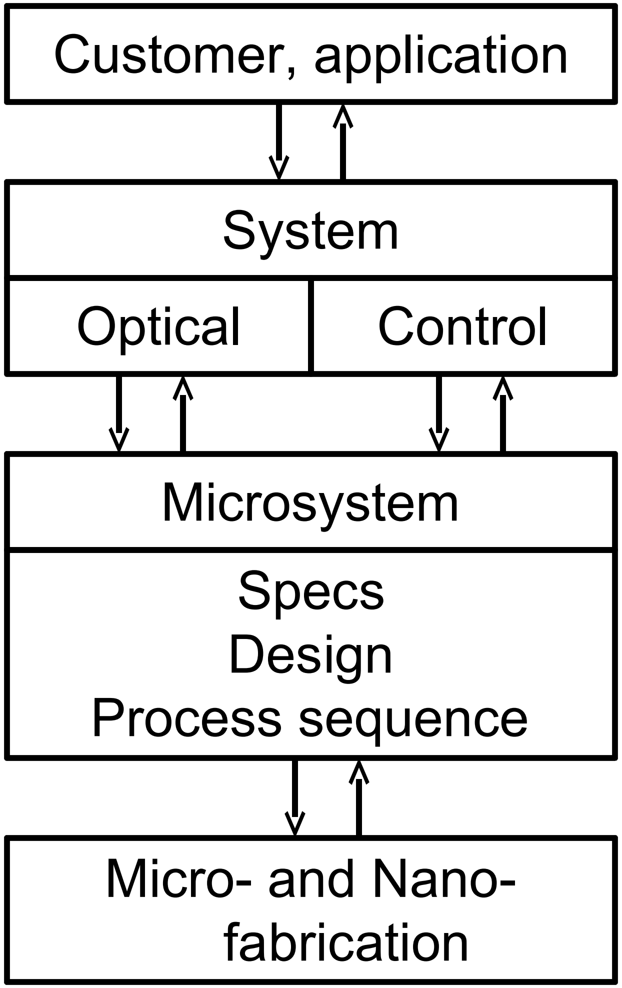


**High complexity devices - optical subsystems with *new functions*.**

**Low complexity devices - optical components with *enhanced performance and features*.**

Complexity is a measure of either function or number.

# Microsystems Enable Integrated Solutions



Customer, application

System

Optical

Control

Microsystem

Specs
Design
Process sequence

Micro- and Nano-
fabrication

**Expertise required:**

Application knowledge

System architecture

Optics

Electronics & Control

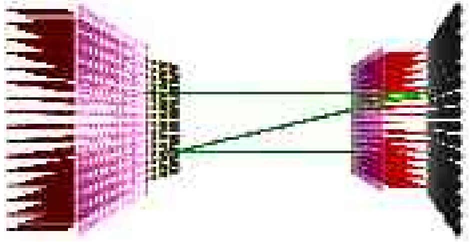
Packaging

Microsystems:

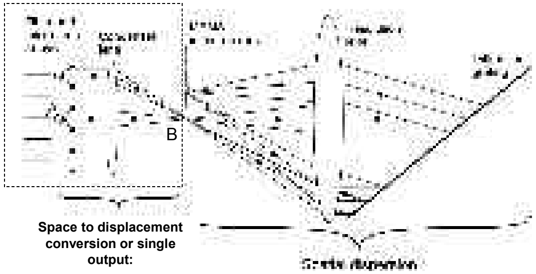
- Design
- Micro- Nano- fabrication
- Test and Characterization

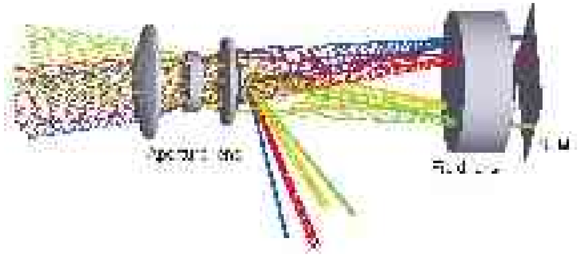
# Application Space

The GOAL is to realize Microsystems unique benefit – to combine a huge number of degrees of freedom in a single device, enabling <u>unprecedented degree of control over optical signal(s)</u>:



- 100’s of channels
- 100’s of wavelengths
- Millions of pixels
- Extremely complex wavefront manipulation
  - Point
  - Focus - multiple sources or targets
  - Track
  - Correct aberrations and distortions
  - Process information optically





# Addressable Application Space Diversity

- Optical switching
  - Distinct optical channels
  - Distinct wavelength
  - Dynamic DWDM filtering and dispersion compensation
- Free space optical
  - Communication
  - Imaging
  - Targeting
- Adaptive optics
  - Distortion correction for imaging
  - Metrolody
- Projection
  - (Deep) UV
  - Visible
  - IR
- Digital Holography
  - Optical data storage
  - Spectroscopy and imaging spectroscopy
  - Optical information processing
  - Optical tweezers and manipulation
  - Other imaging and metrology

TELECOM

- Optical Crossconnects
- Wavelength Selective Switches
- DWDM equalizing filters
- DWDM dispersion compensators

DARPA CCIT

Air Space Comm

Astronomy

Ophthalmology

Maskless Lithography

Military IR image projection

HDTV

Holographic Data Storage

Hyperspectral Imaging

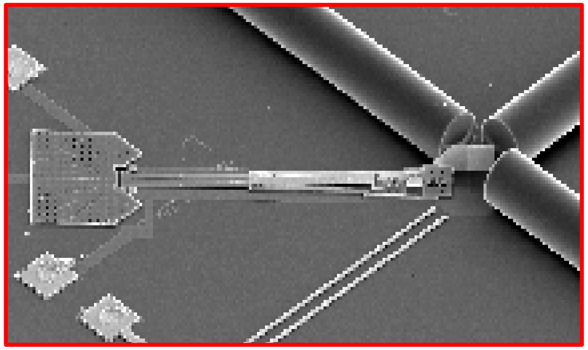
Biomedical Imaging

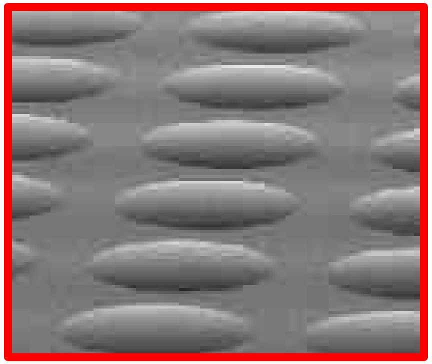
???

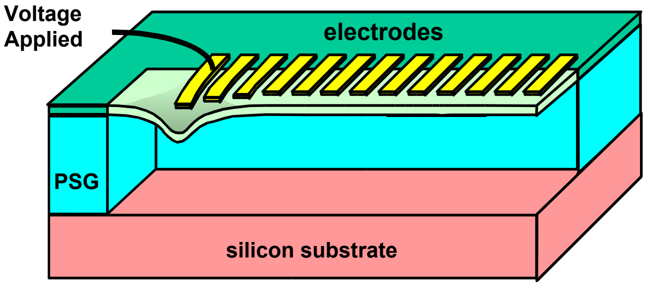
# Optical Microsystems Technologies: Examples

Large arrays of movable mirrors - **reflective**
Tunable reflectivity **interferometric** devices
Si microlens arrays - **refractive**
Variety of other devices (e.g. **diffractive**)

See e.g. J.Ford, Hilton Head 2004



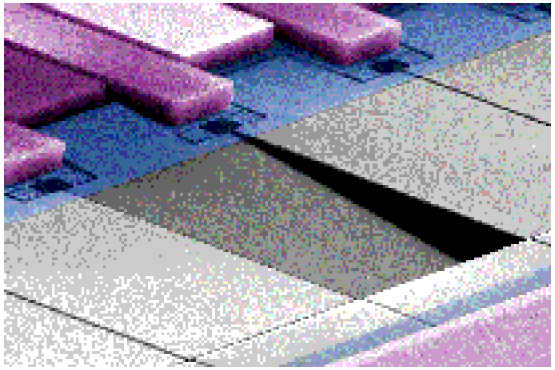


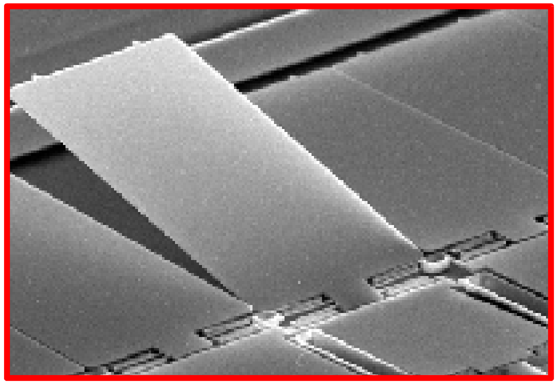


# Application example: Telecom

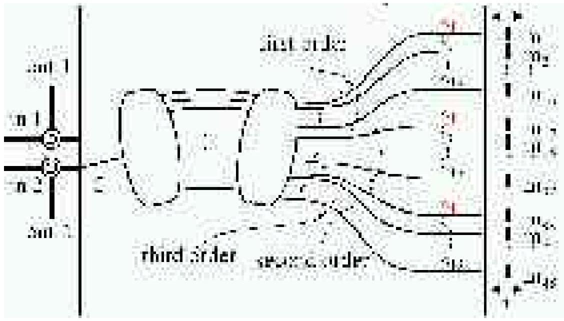
Lambda router

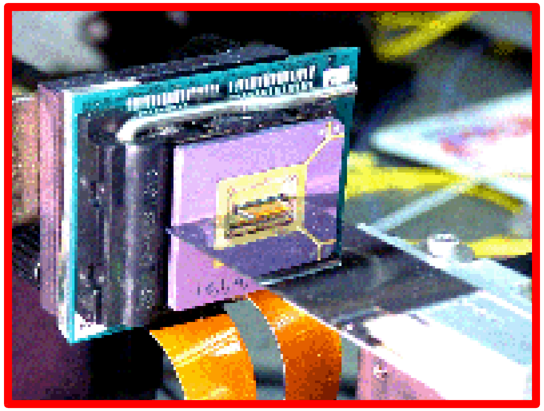
Wavelength selective switch



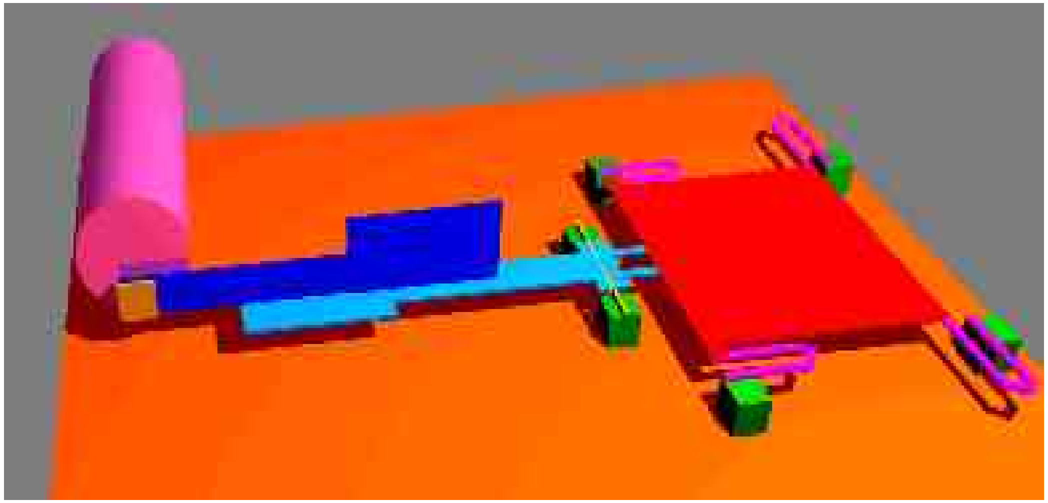


MEMS and Waveguides





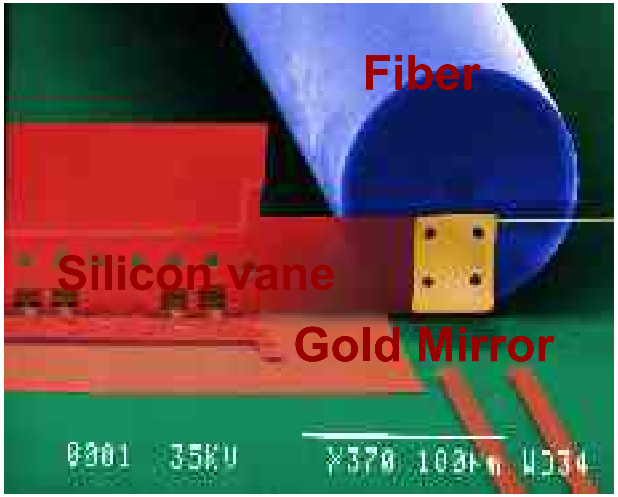
# Electrostatically Actuated MEMS Switch

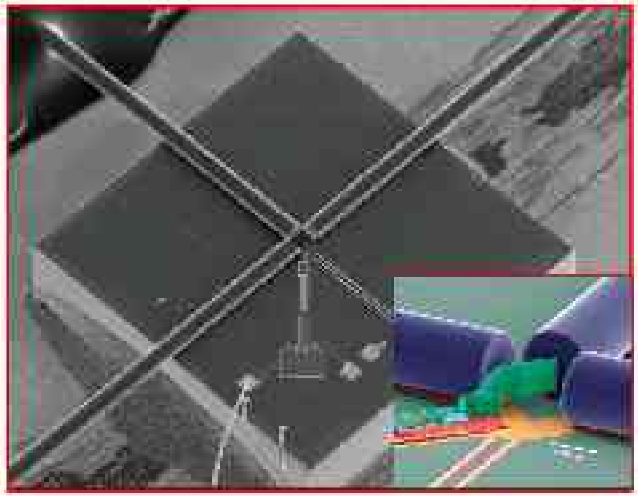


**Gold Reflector** enters **Optical Path**

**Spring-suspended capacitor plate**

- <70 µsec response
- 1.24-20V actuation (design dependent)
- supports attenuator function

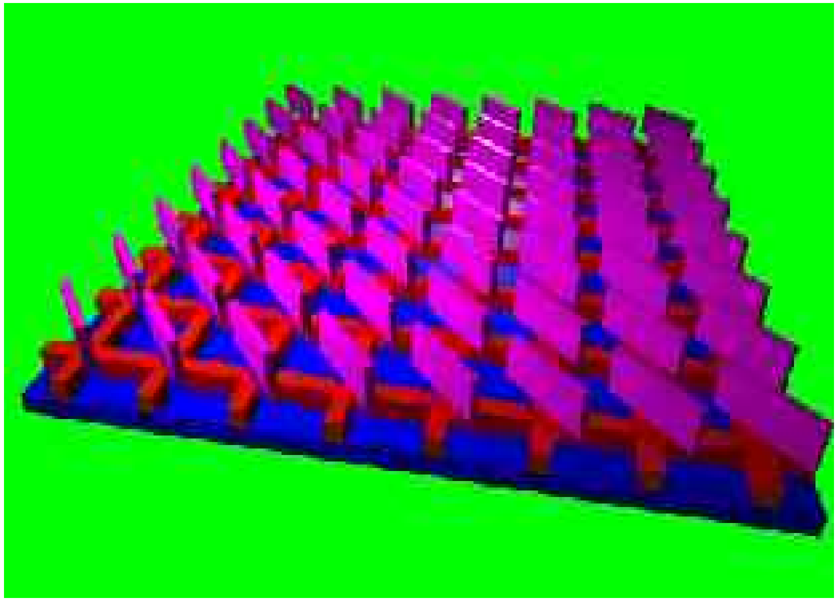


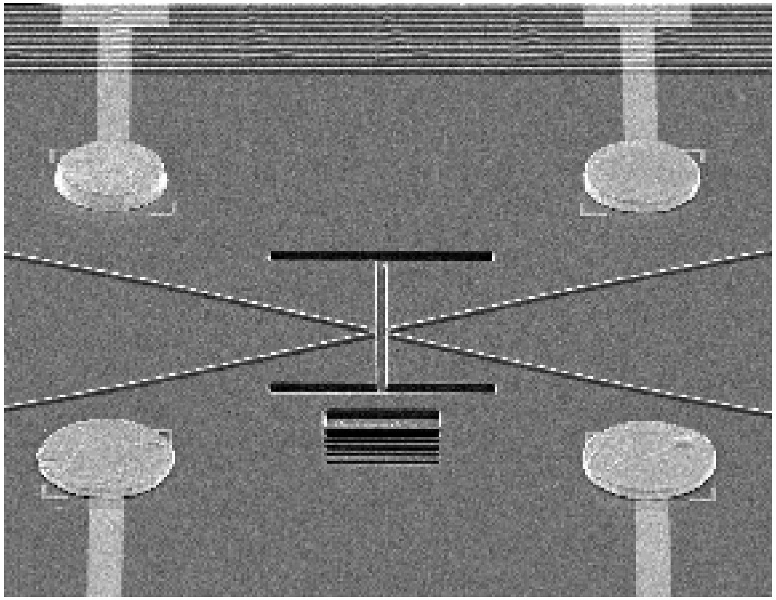


- 1x2 optical switch
- <1.5dB loss with passive alignment
- <1.0dB loss with active alignment

Lucent Technologies
Bell Labs Innovations

# Flag switch combined with waveguide technology





**Not practical for large single-stage optical crossconnect, but small switches and other *new subsystems* are possible.**

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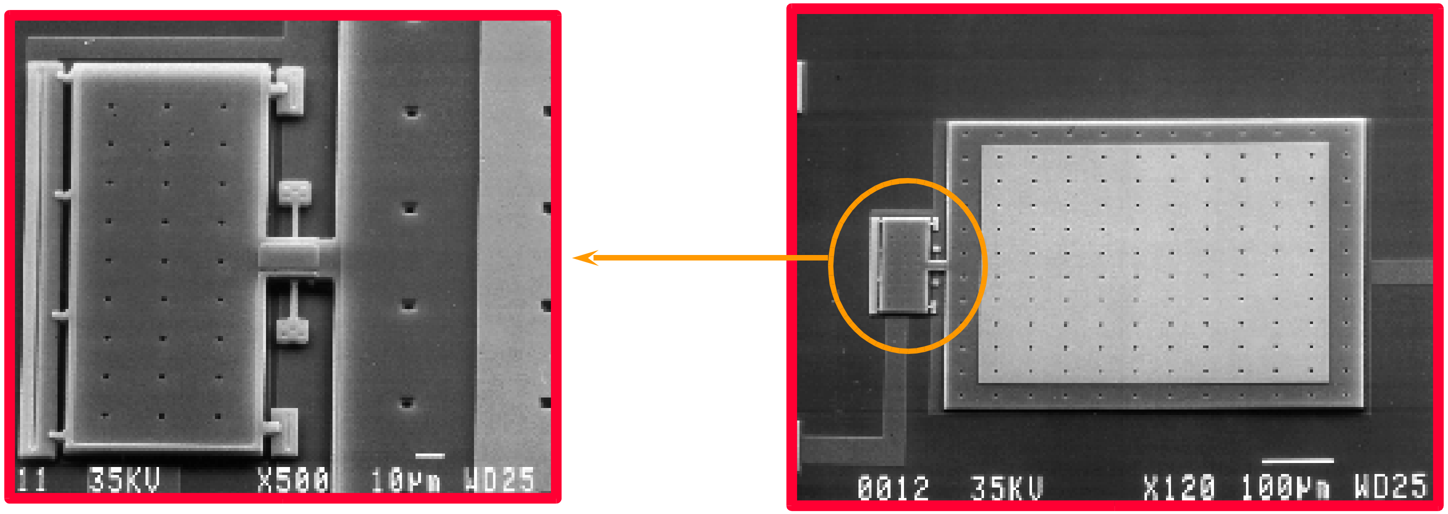
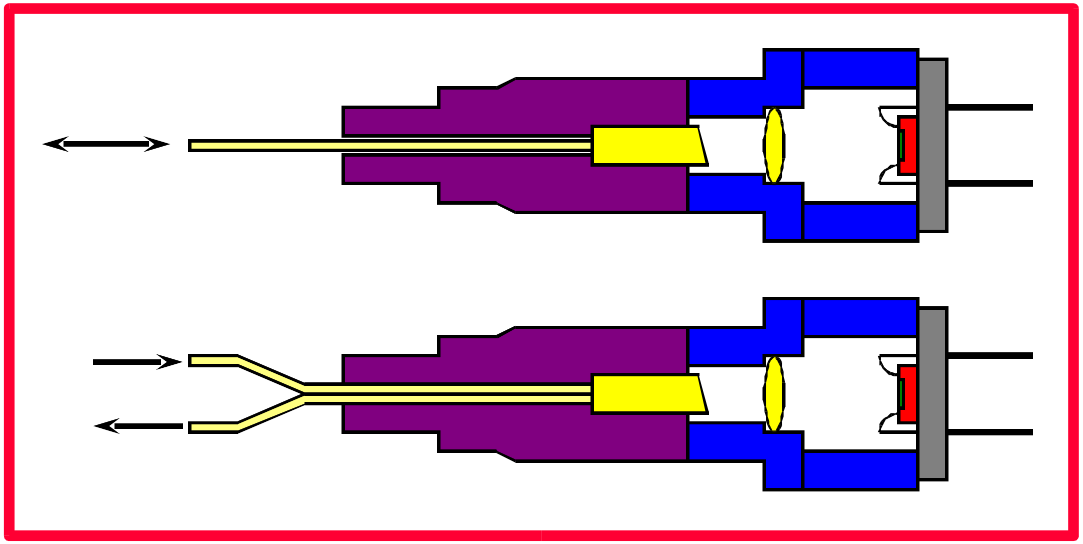
Bell Labs Innovations

# Tilt-Mirror Variable Attenuator

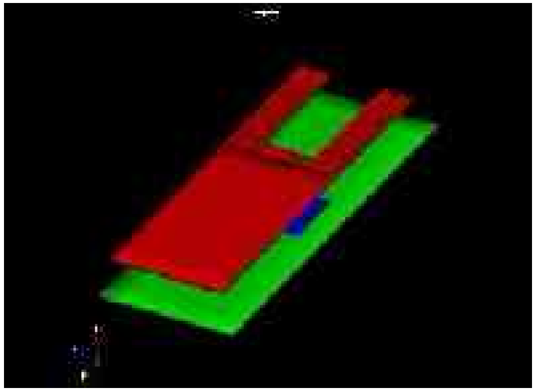


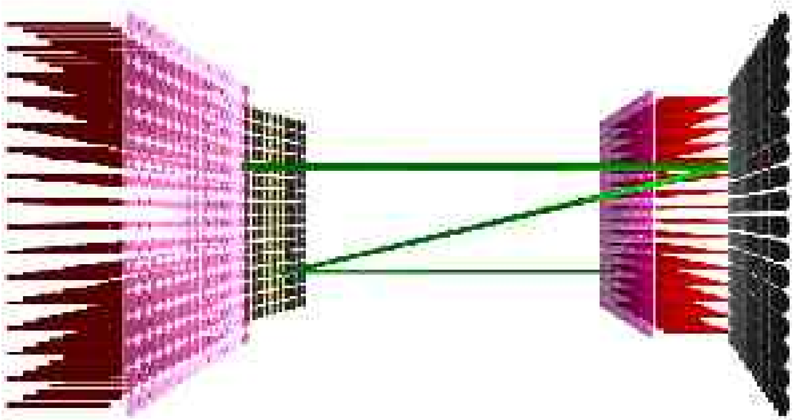


- operating power~1nW
- insertion loss~0.5dB
- PDL<0.1dB
- speed <1msec
- cost~low
- size 1x0.5x0.5 $\text{cm}^3$
- spectral flatness <0.2dB
- dynamic range~20dB

# Optical MEMS for Telecom:

- Quality optical elements
- Precision actuators
- Speed
- High reliability





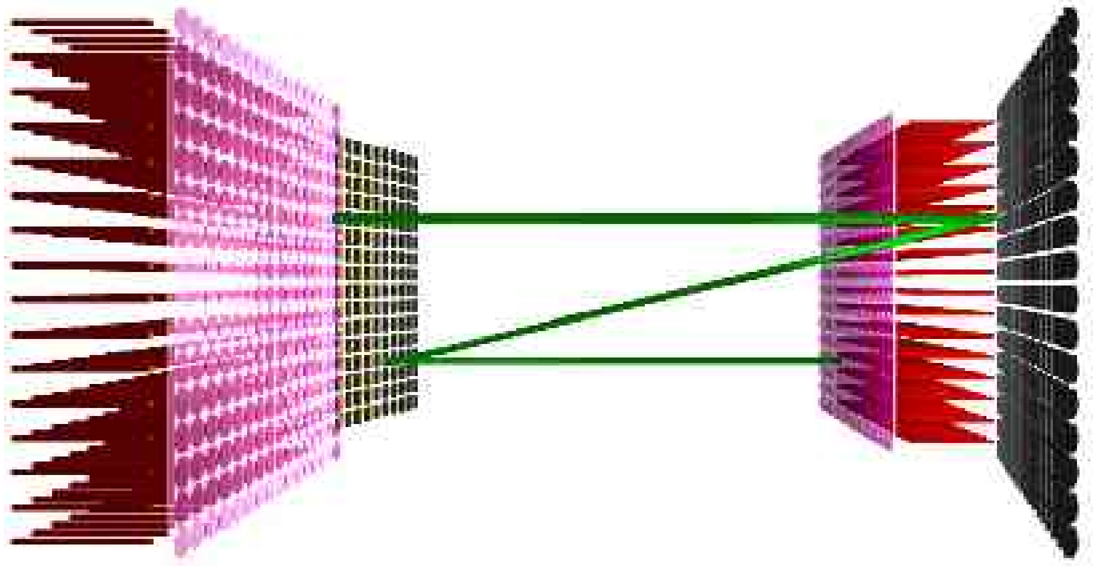
- Large number of elements
- High integration density

**Key design features:**

**compliant mechanisms, electrostatics, stress engineering**

***Nonlinear Effects - Numerical Modeling***

# MEMS OXC -- 3D Architecture

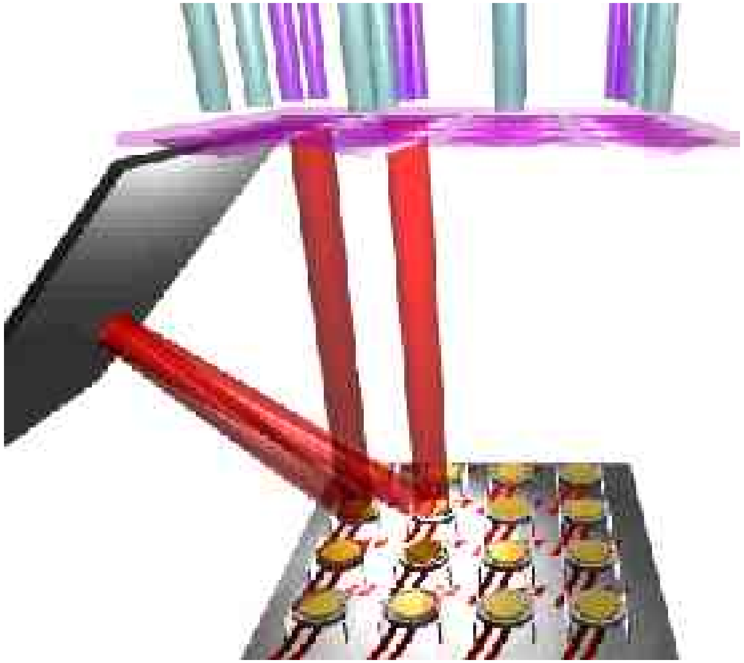


**Output Ports**

**Input Ports**

**MEMS Array**

**MEMS Array**



**512 MEMS mirrors in an 256x256 single-mode fiber optical crossconnect.**

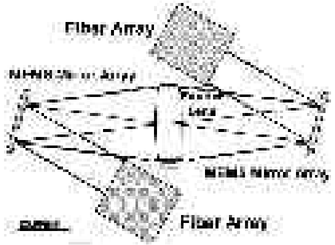
**16 mirrors in an 8x8 OXC Folded optical design**

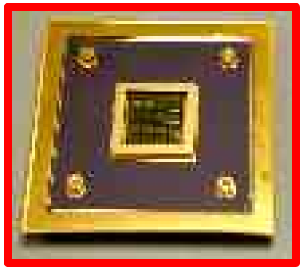
1.55 or 1.3 um single mode
Less then 5 msec switching
Low insertion loss

2N scaling
Non-blocking architecture
Single stage

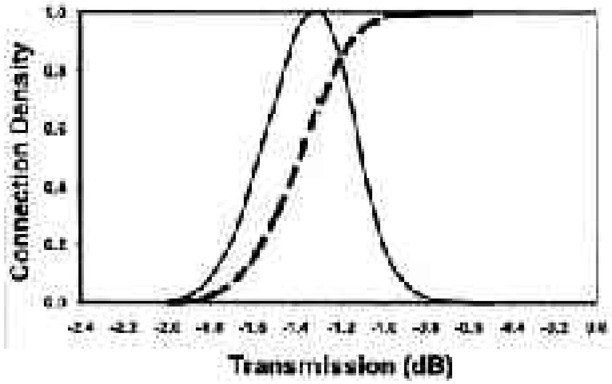
Lucent Technologies
Bell Labs Innovations

# MEMS OXCs – Big and Bigger





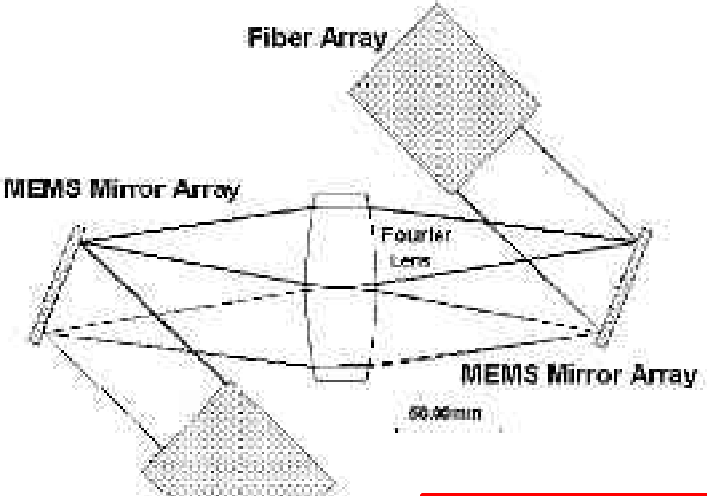
*256 mirrors*



**238x238 ports**

- **56,644 connections**
- **1.33 dB mean loss**
- **2.0 dB maximum loss**

V.A. Aksyuk et. al. PTL 2003

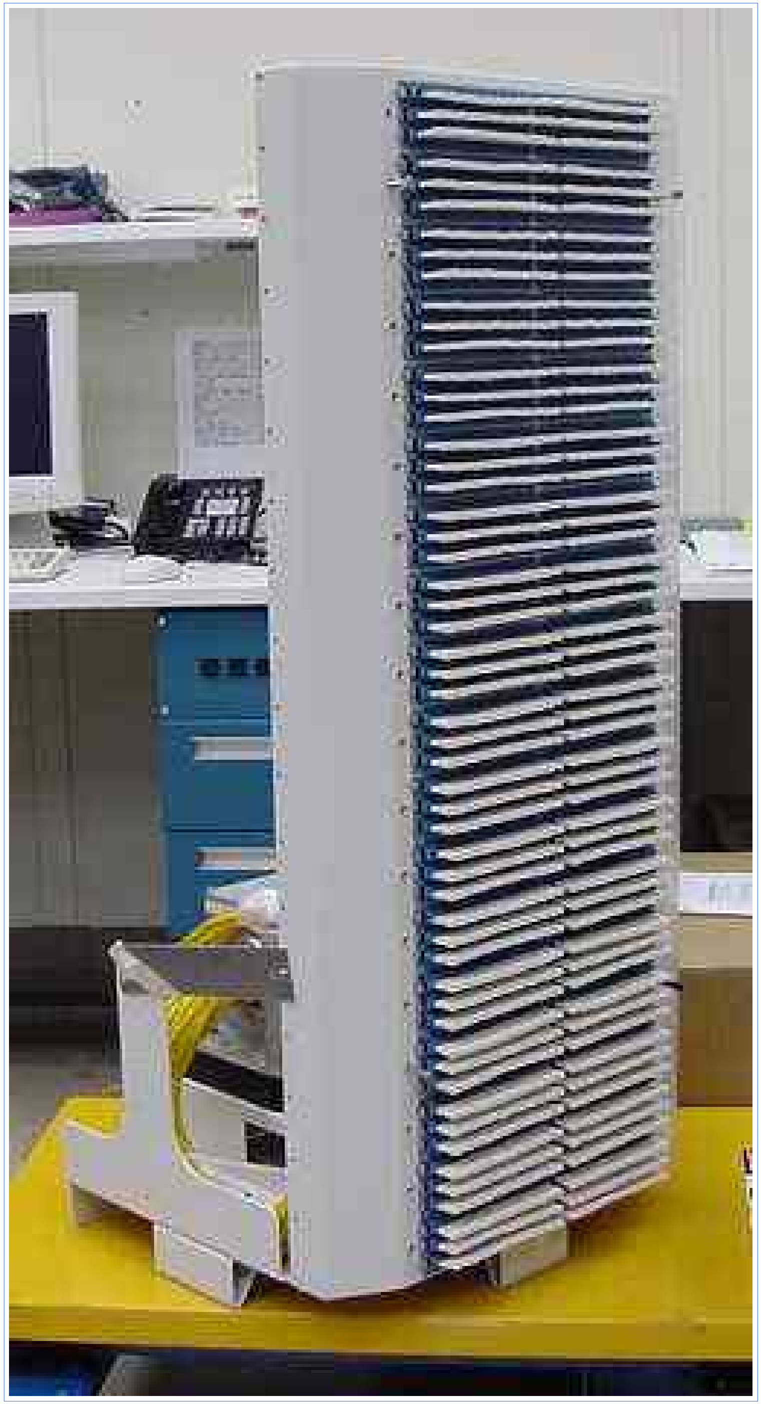


*1296 mirrors*

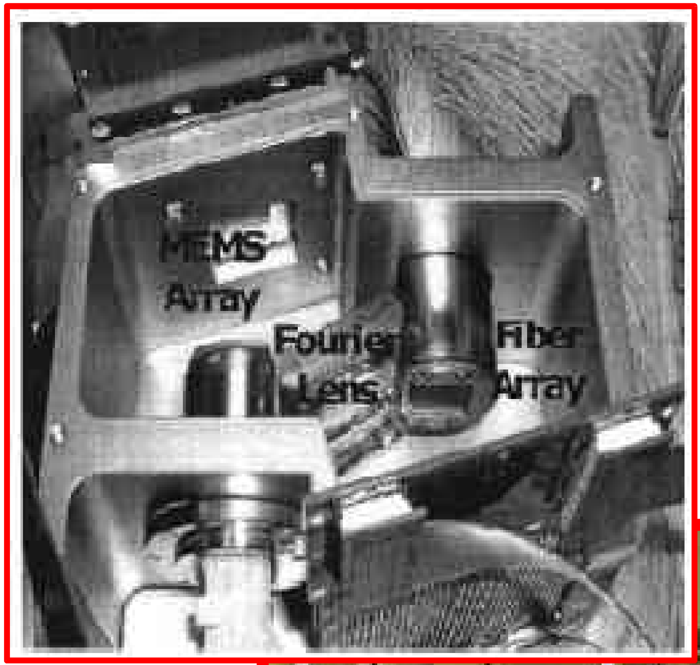
**1100x1100 ports**

- **1,210,000 connections**
- **2.1 dB mean loss**
- **4.0 dB maximum loss**

J. Kim et. al.



# Optical Switch Fabrics



# MEMS Device Requirements

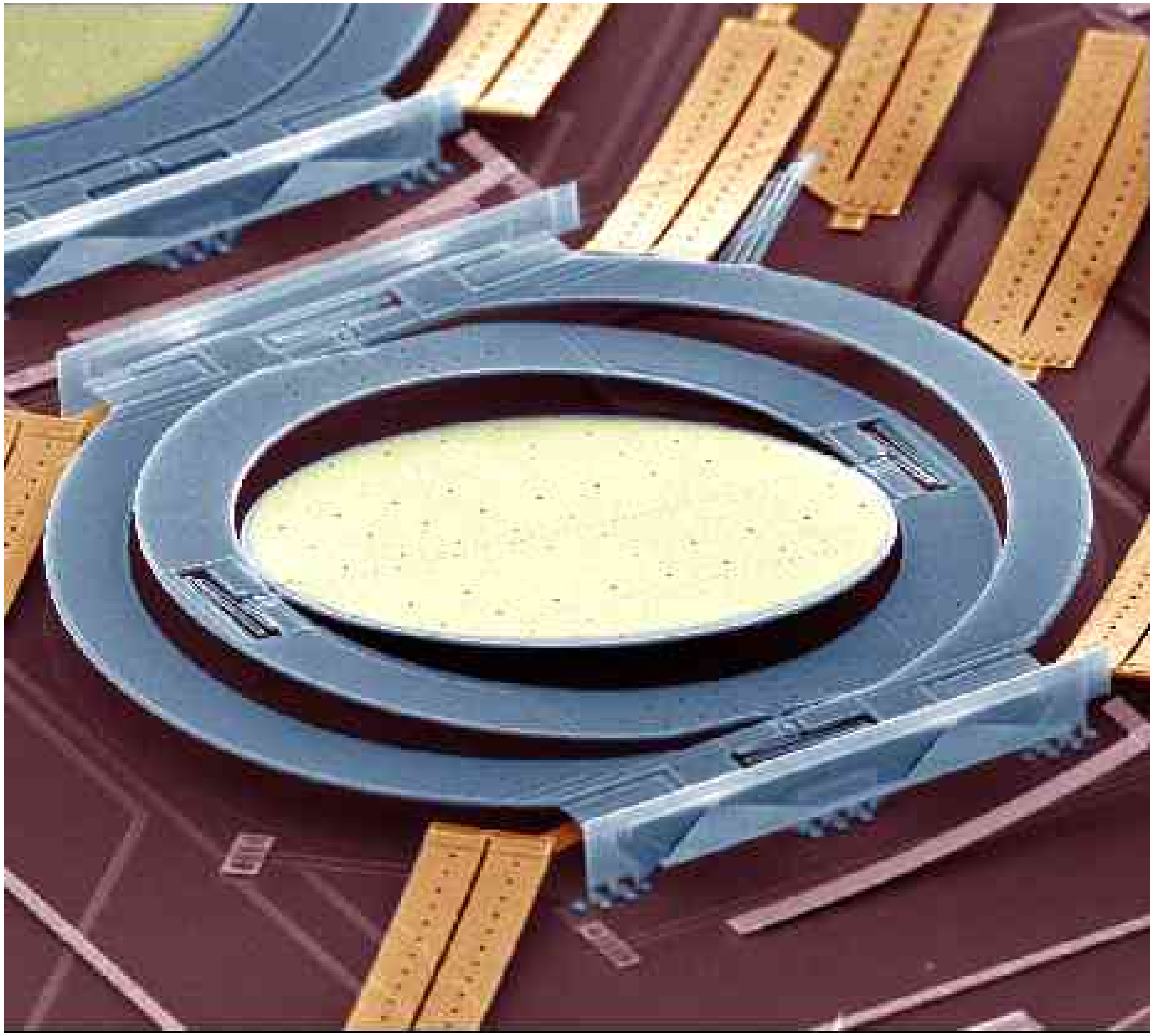
**Device:**
- 2-axis, large angular range
- continuous, controlled tilt
- high quality, large reflectors
- wavelength independent

**Technology:**
- scalable
- well-established
- manufacturable

# 2-axis Beam-Steering Surface-Micromachined Mirror

Lucent Technologies
Bell Labs Innovations

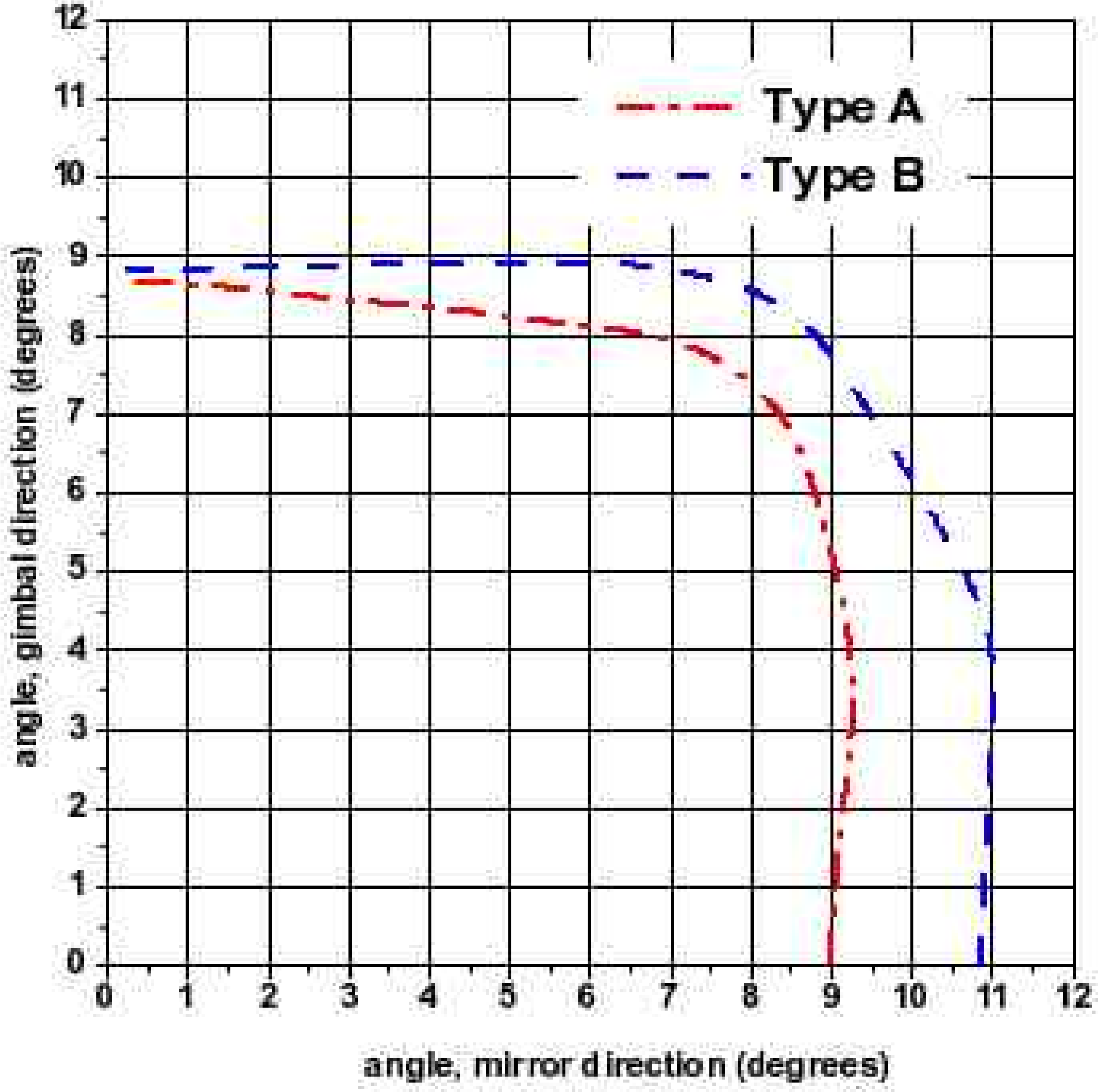
- raised frame for ±9° angles with 500um reflector
- self-assembly mechanism to lift and lock the frame
- gimbal mount with four serpentine springs
- electrostatic actuation with electrodes under device
- < 170V drive voltage to capacitive load
- < 5msec switching time
- gold reflector



V.A. Aksyuk et. al. Proc. SPIE v.4178 2000

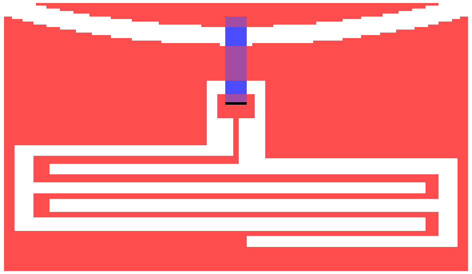
# Mirror Deflection Range

## 500um surface-micromachned mirror



**Type A**

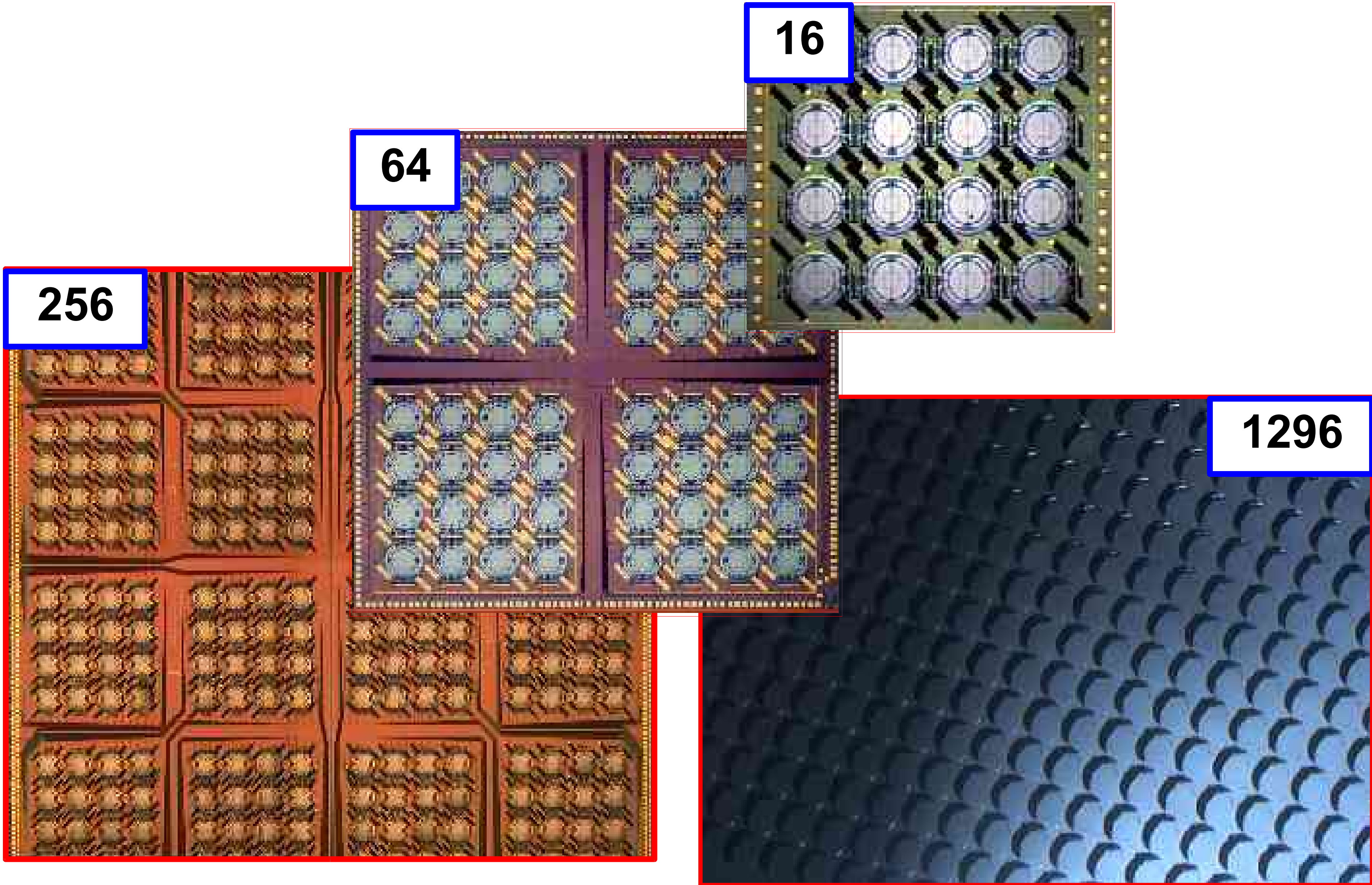
**Pure flexure, simple**



**Type B**

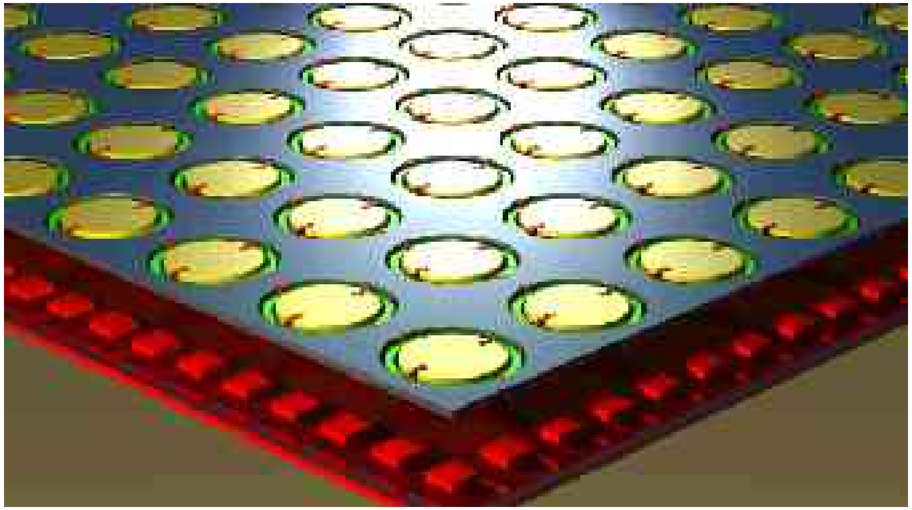
**Microbearing, greater range**

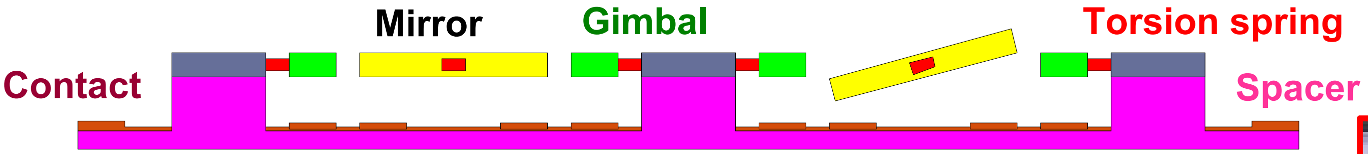
# Micromirror Arrays

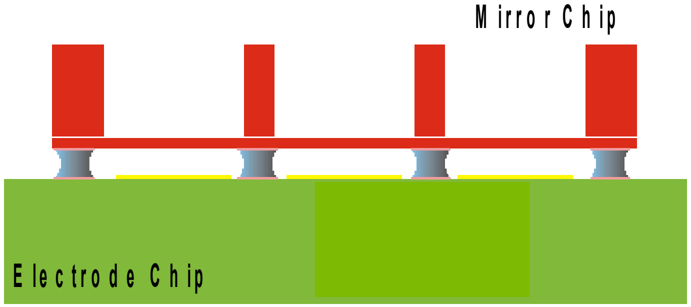


# Single-Crystal Silicon Micromirrors

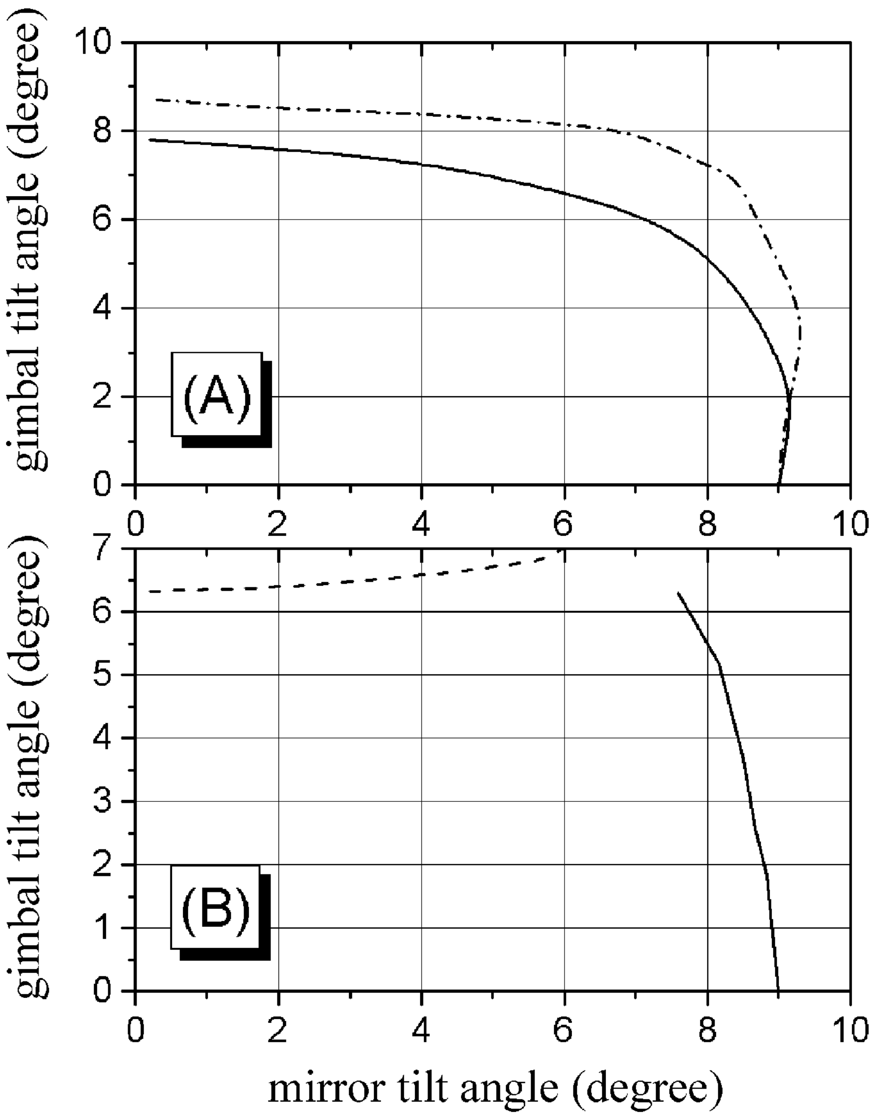
## 1296 mirror array (36x36)







# Mirror Deflection Range Comparison



**(A) Surface-micromachined mirrors (1 mm pitch):**

- **Solid curve – 500um reflector**
- **Dashed curve – 600um reflector**

**(B) SOI mirror (875um reflector, 1.25 mm pitch):**

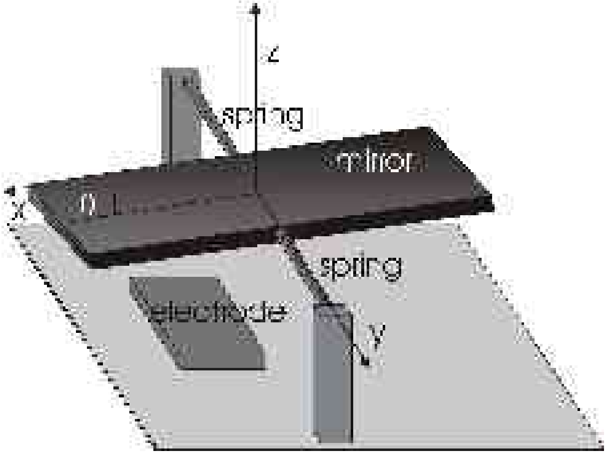
- **Solid curve – stability range**
- **Dashed curve – 200V range**

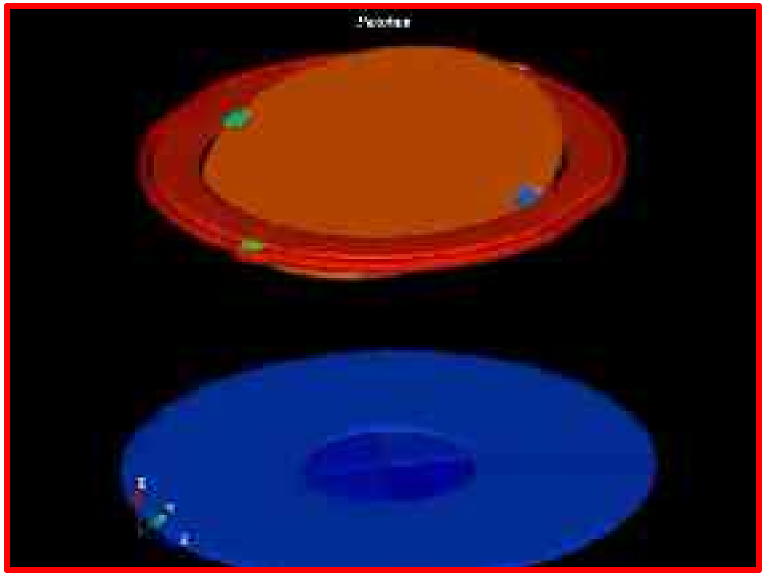
V.A. Aksyuk et. al. JLT 2003

# Beam-Steering Micromirror Design

## Design parameters:

- **Electrode size and shape**
- **Gap size**
- **Spring and gimbal geometry**
- Mirror thickness





## Device characteristics:

- **Angular range**
- **Mirror size**
- Mirror shape - flatness
- Integration density - fill factor - **no crosstalk**
- **Spring stiffness** - speed - vibration sensitivity
- **Drive voltage**, **angle vs. V curve** - control
- Stability and repeatability
- Reliability

# Electrostatics:

# Mechanics:

$E=\frac{1}{2}V_i V_j C_{ij};$ Torque: $T_l=\frac{\partial E}{\partial\ {}_l}$

$T_l=K_{lm}\ {}_m$

# Equilibrium:

$$K_{lm}\ {}_m=\frac{1}{2}V_i V_j\frac{\partial C_{ij}}{\partial\ {}_l}$$

Stiffness matrix linear, diagonal;
same springs for x and y: $K_{lm}=\tau\delta\ {}_{lm}$ $T\ {}_l=\frac{1}{2}V_i V_j\frac{\partial C_{ij}}{\partial\ {}_l}$

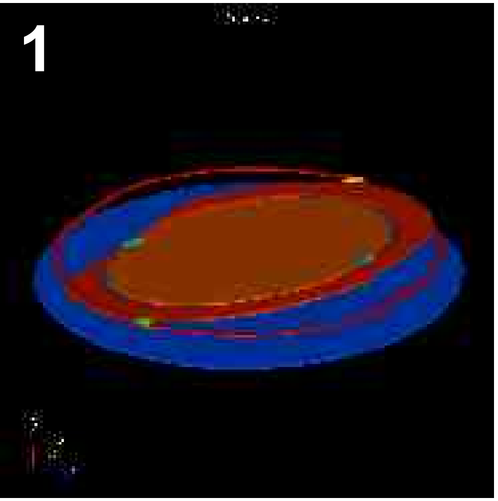
# Dynamics:

$I_{lm}\ \ddot{\ }_m=\frac{1}{2}V_i V_j\frac{\partial C_{ij}}{\partial\ {}_l}-T\ {}_l$

x, y collinear with main
axes of inertial tensor $I$: $I_{lm}=I_l\delta\ {}_{lm}$

$$for\ l=1,2\ (no\ summation\ in\ l):\ I_l\ \ddot{\ }_l=\frac{1}{2}V_i V_j\frac{\partial C_{ij}}{\partial\ {}_l}-T\ {}_l$$

# Resonance Modes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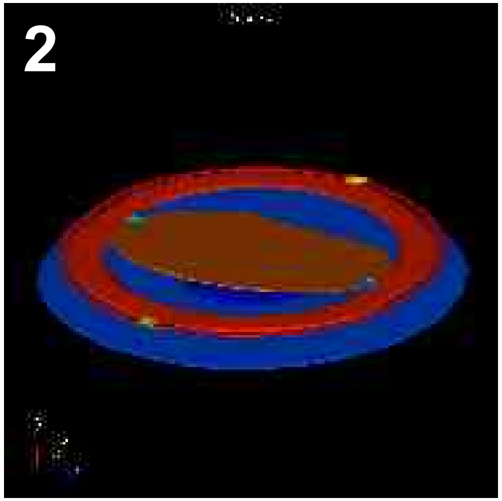
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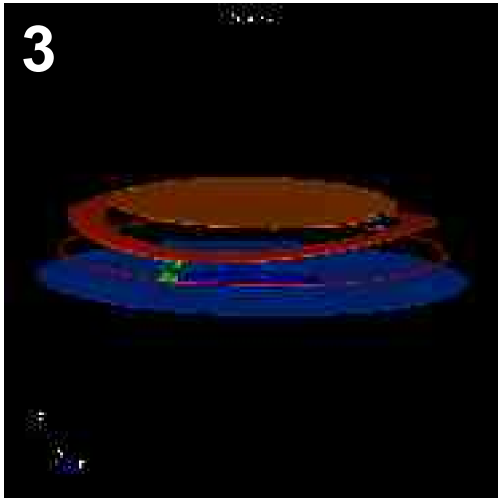
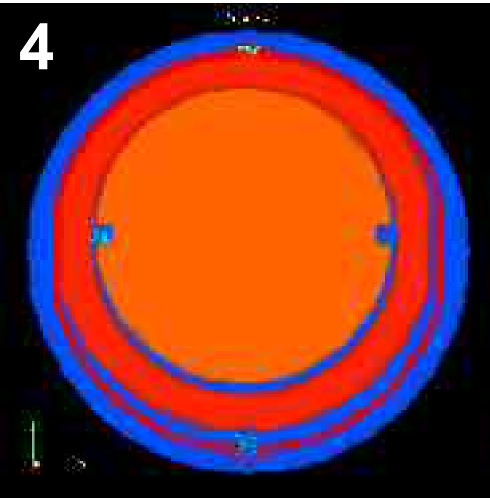

3

258 Hz 430 Hz 1786 Hz

2153 Hz 2345 Hz 3586 Hz 6869 Hz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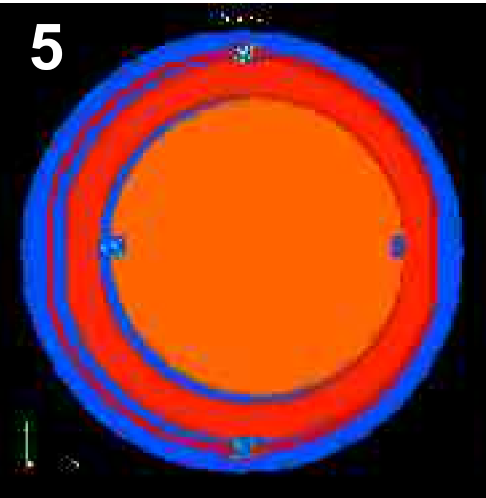
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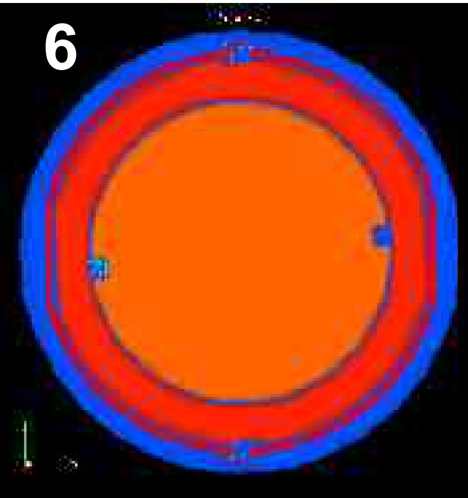
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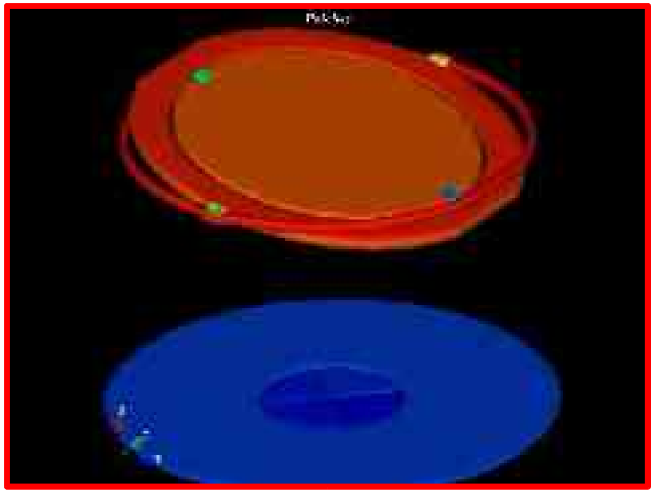
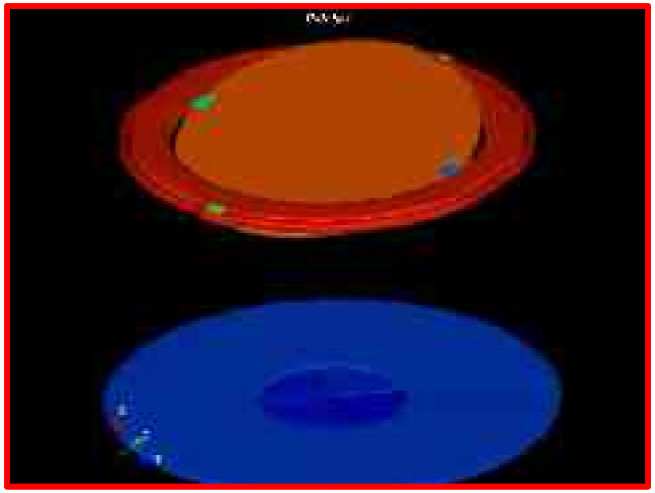
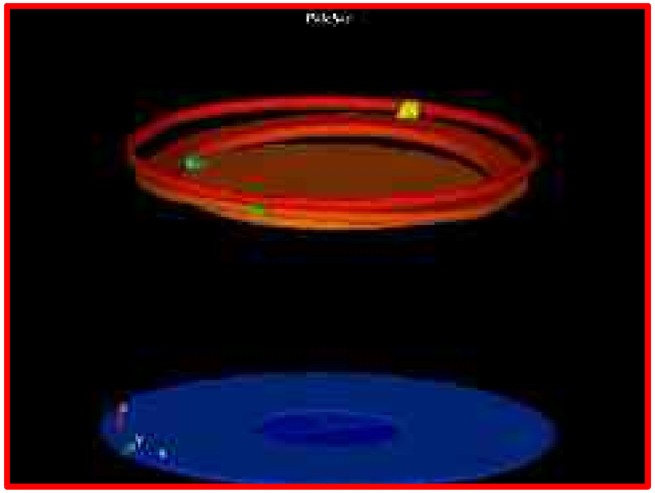
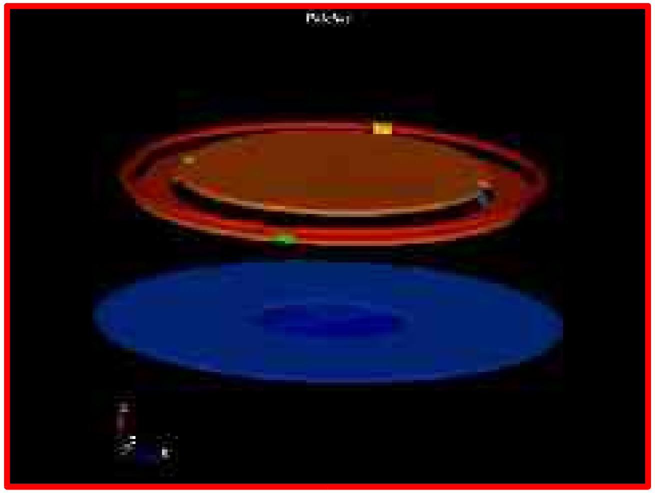








# Mode frequencies; crystalline direction dependence

| Mode # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 100 (45 degrees) | 258 | 430 | 1786 | 2153 | 2345 | 3586 | 6869 |
| 110 (90 degrees) | 286 | 477 | 1881 | 2409 | 2632 | 4048 | 7239 |
| 100 Experiment | 260 | 430 | 1700 | | | | 6900 |

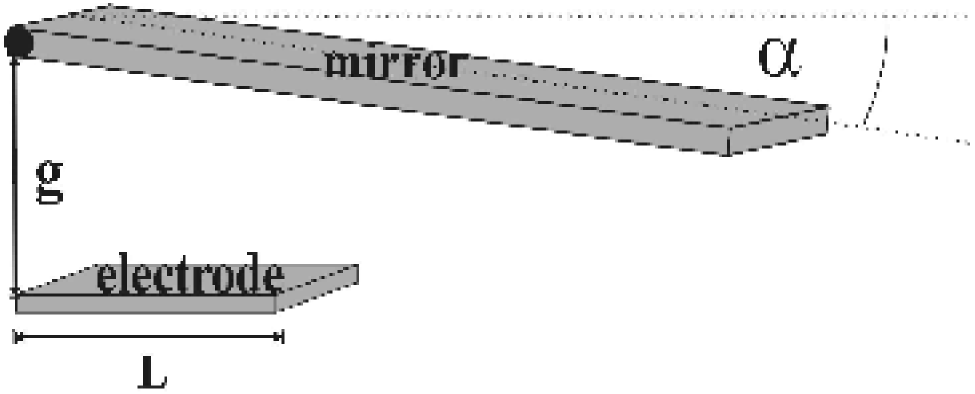
Approximation - beam X-section rectangular, w = (a+b)/2 =1.6um instead of real-life trapezoidal a =**1.4um**, b = 1.8 um.

Si elasticity tensor components:

$\lambda_{xxxx} = 165.5$ GPa, $\lambda_{xxyy} = 64.18$ GPa, $\lambda_{xyxy} = 79$ GPa

# Analytical

## Disregard Fringe Effects



$$T_{electrostatic} = \frac{\varepsilon}{2} V^2 \int_0^L \frac{xW(x)\,dx}{\left(\frac{g}{\sin\alpha} - x\right)^2 \alpha^2}$$

**Capacitance, $C(\alpha, L, g) = L\,F(L\tan(\alpha)/g)/g$**

Torque, $T = V^2/2\ dC/d\alpha \sim (L/g)^2\ dF/d\alpha$

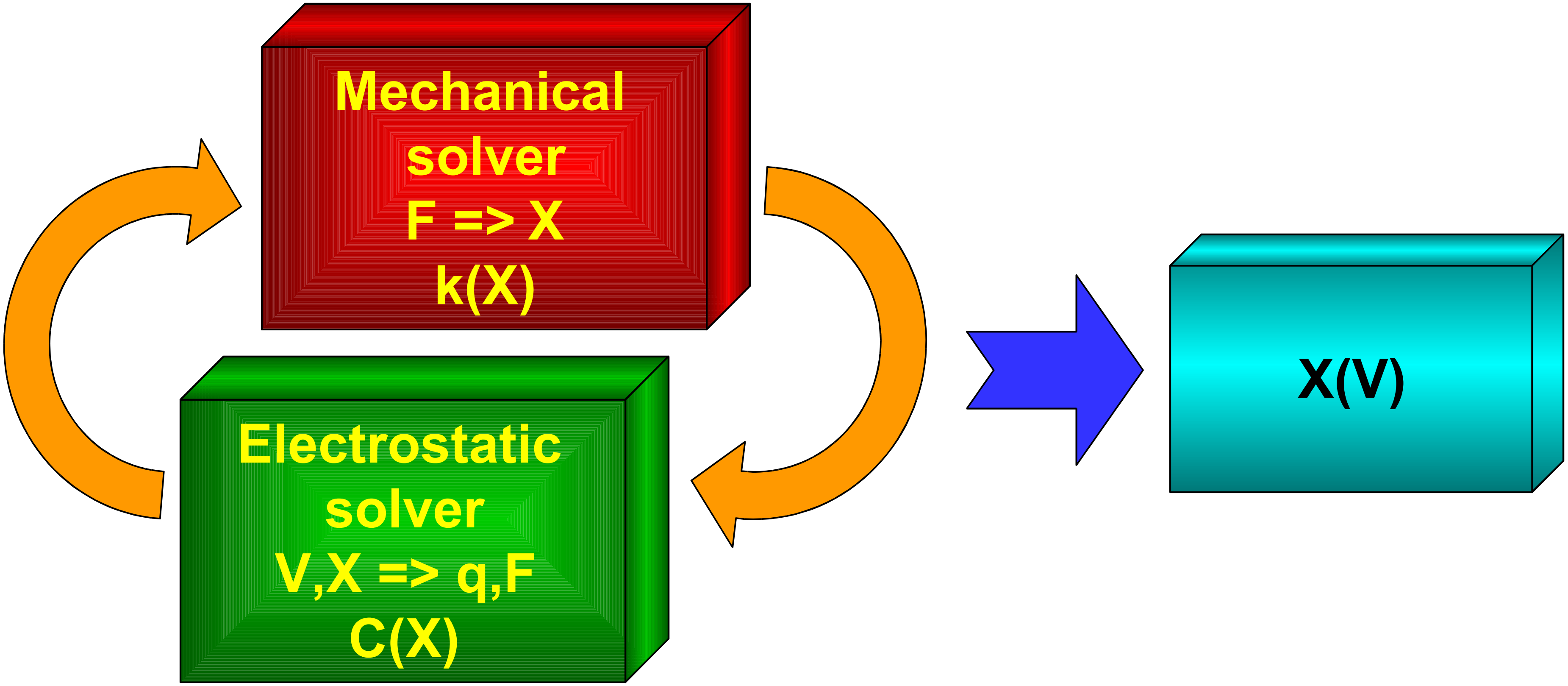
snap-down angle, $\alpha_{sd}$ scales as $g/L$

**As long as *g* << *L*, works for arbitrary electrode shape.**

**Analytical solution can be obtained for more than 1 DOF.**

**Does not work if edge effects are important, e.g. *g~L*.**

# Numerical Techniques: Iterative Solver


Mechanical solver
F => X
k(X)

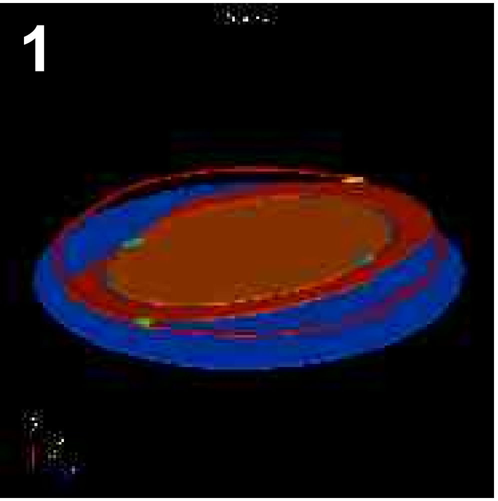
Electrostatic solver
V,X => q,F
C(X)

X(V)

**Exact calculations of mechanically deforming conductors**

**~ 10 cycles per device position, very time consuming for multiple trajectories.**

# Do we really need coupled analysis?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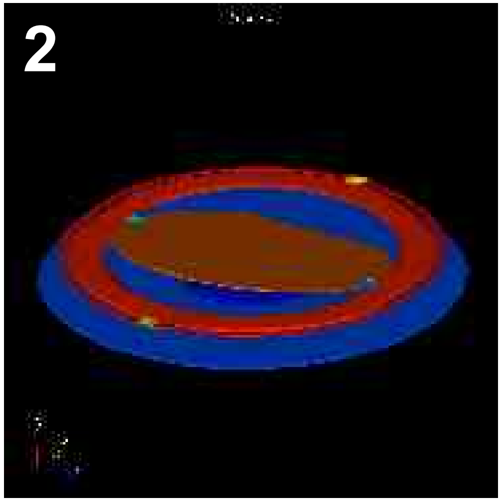
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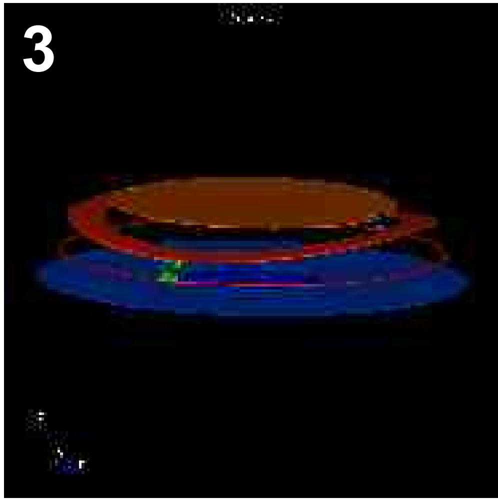
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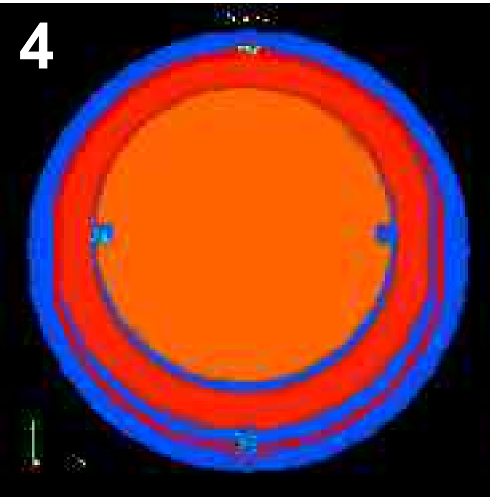
- This mirror moves as a collection of rigid bodies attached by springs
- Springs do not contribute to electrostatic force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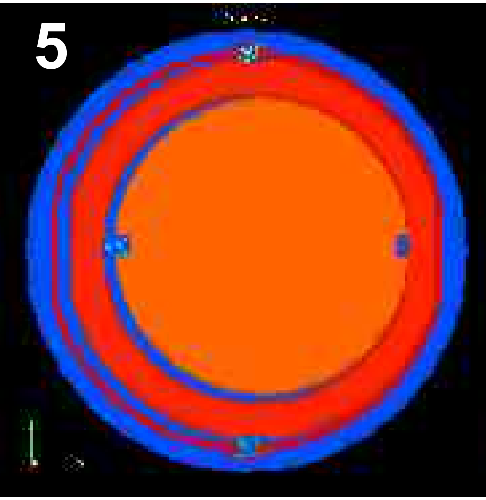
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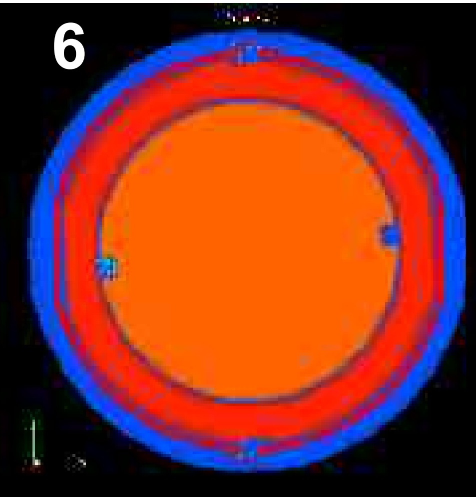
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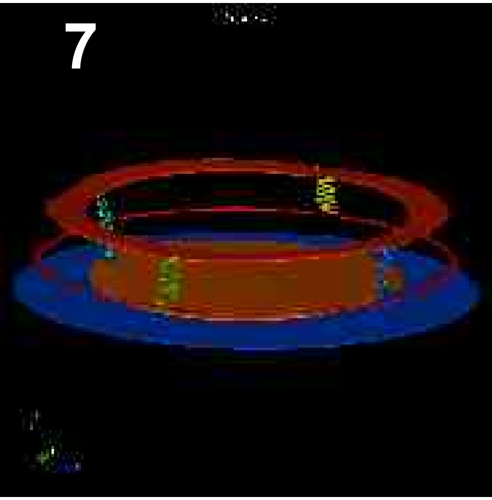
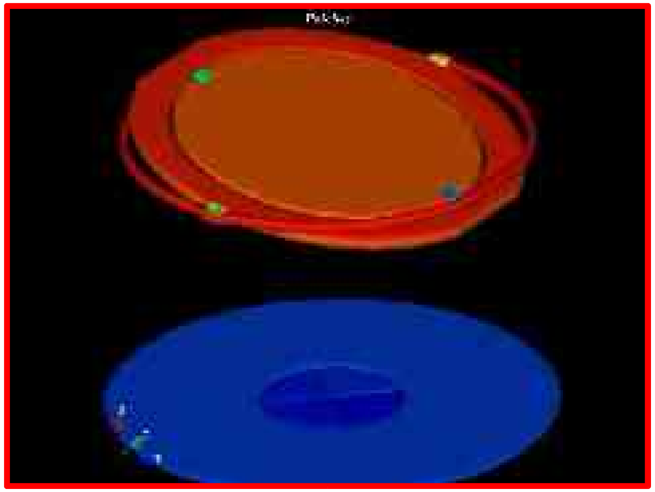

7

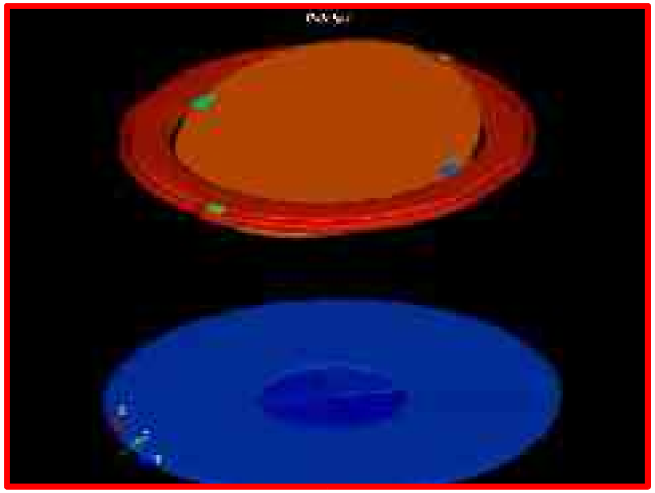
# Mirror Moves As Solid Body

## Tilts are the important DOF



$\Theta_x$

$\Theta_y$



**Mechanics:** $\vec{F} = \hat{K}(\vec{x}) \cdot \vec{x}$

**Electrostatics:** $E = \frac{1}{2} V_i V_j C_{ij}(\vec{x})$

Force or torque: $\vec{F} = \nabla E(\vec{x})$

---

**Equilibrium:** $\hat{K}(\vec{x}) \cdot \vec{x} = \frac{V_i V_j}{2} \nabla C_{ij}(\vec{x})$

E.g. 1D tilt case: $\tau\theta = \frac{1}{2} V^2 \frac{dC(\theta)}{d\theta}$

---

**No need to iterate:**

- **calculate $\tau$ once (Mechanical solver)**
- **calculate $C(\theta)$ for all $\theta$ once (Electrostatic solver)**
- **calculate $V(\theta)$ using the above equation**

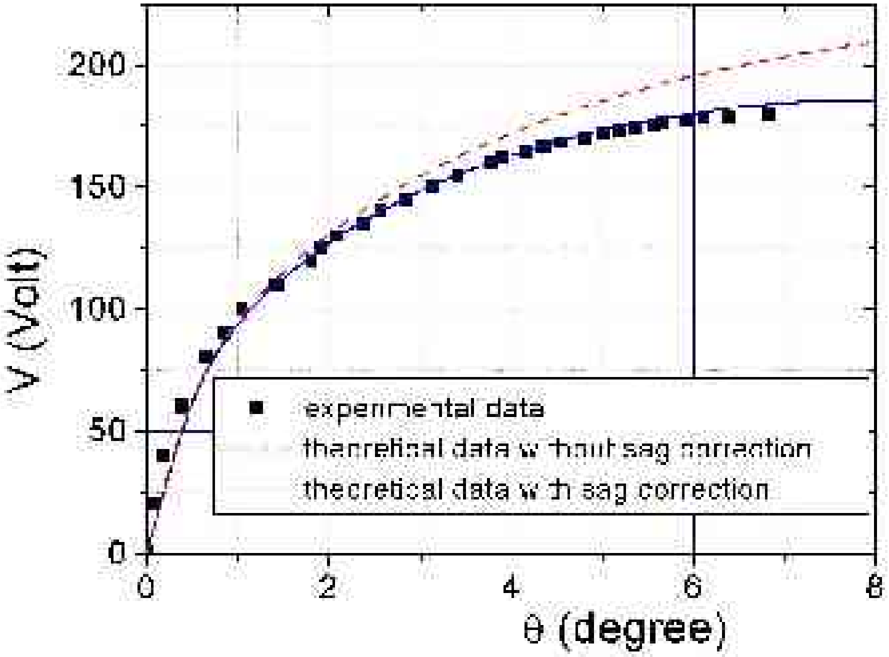
**Works for two tilt angles and voltages as well.**

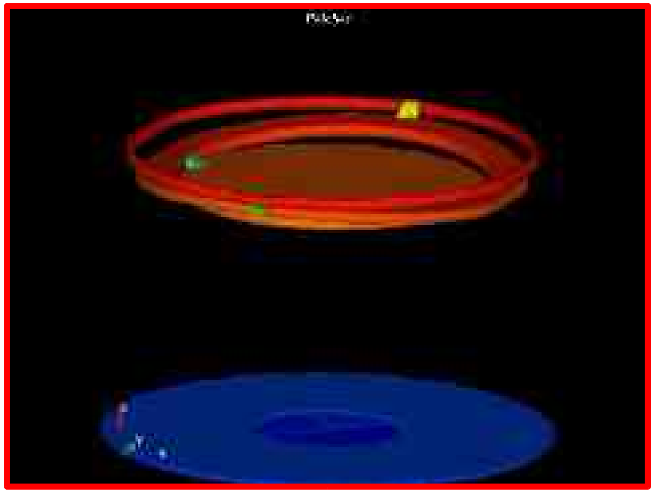
# More DOF - NO PROBLEM

## Treat Z sag as perturbation

$$\hat{K}(\vec{x})\cdot\vec{x}=\frac{V_i V_j}{2}\nabla C_{ij}(\vec{x})$$

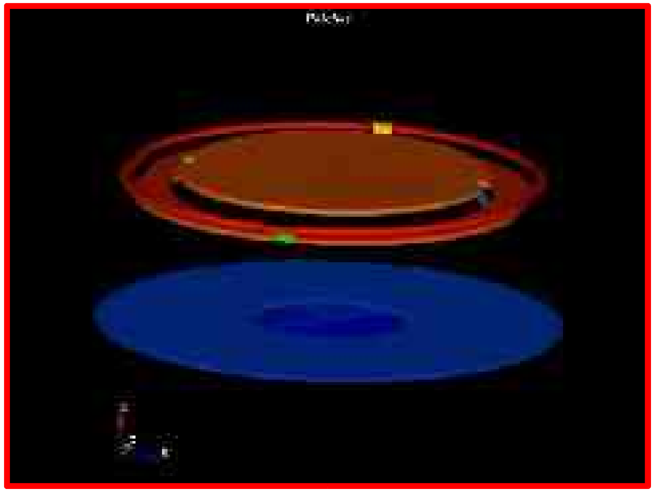
1. **Calculate** $V_0(\theta, z=0)$ **as before**
2. **Calculate** $z_1(\theta, V_0)$ **solving the same equation**
3. **Calculate new voltage** $V_1(\theta, z_1(\theta))$
4. **Iterate 2, 3**



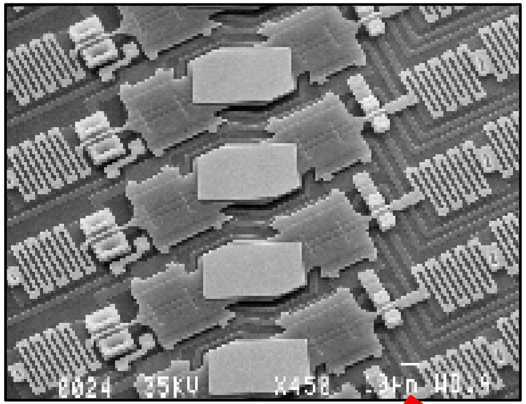


**$z_m + z_g$**

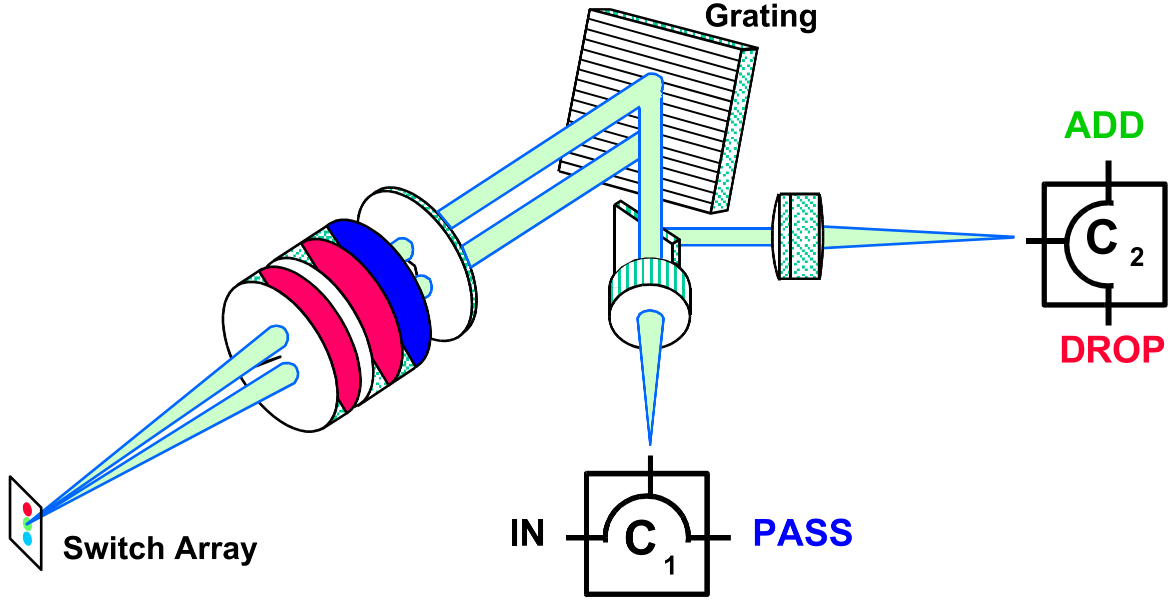
**$z_m - z_g$**

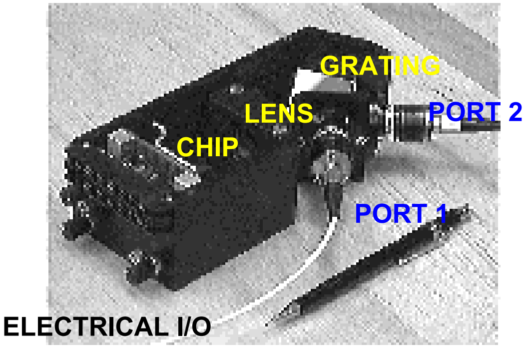


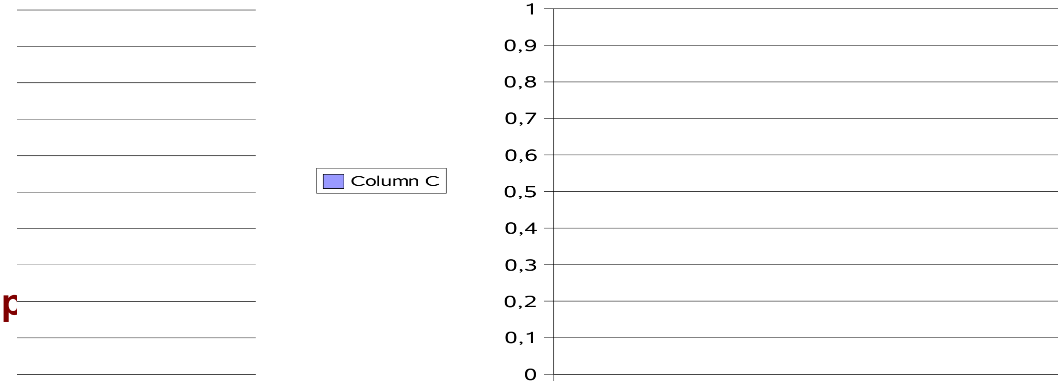
# Early MEMS Wavelength-Selective Add/Drop



Tilt-Mirror Switches



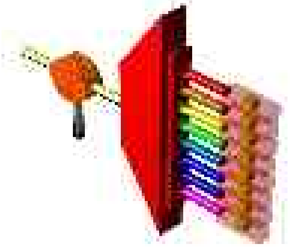


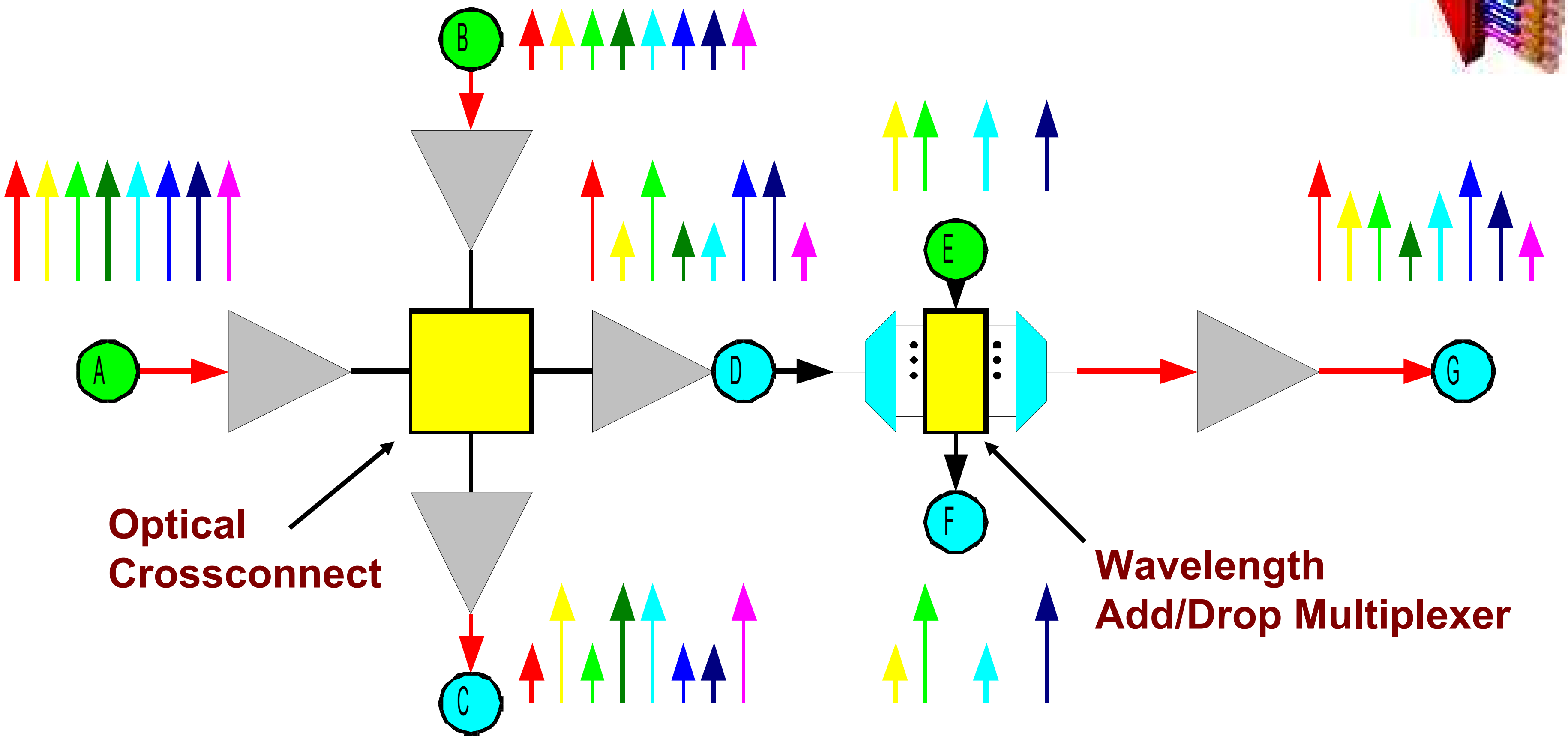


- 5 dB insertion loss (pass), 8 dB (drop
- > 30 dB switching contrast
- 20 µs switching of 16 λ's @ 200 GHz

J.E. Ford et. al. JLT 1999

# Equalization in Lightwave Networks





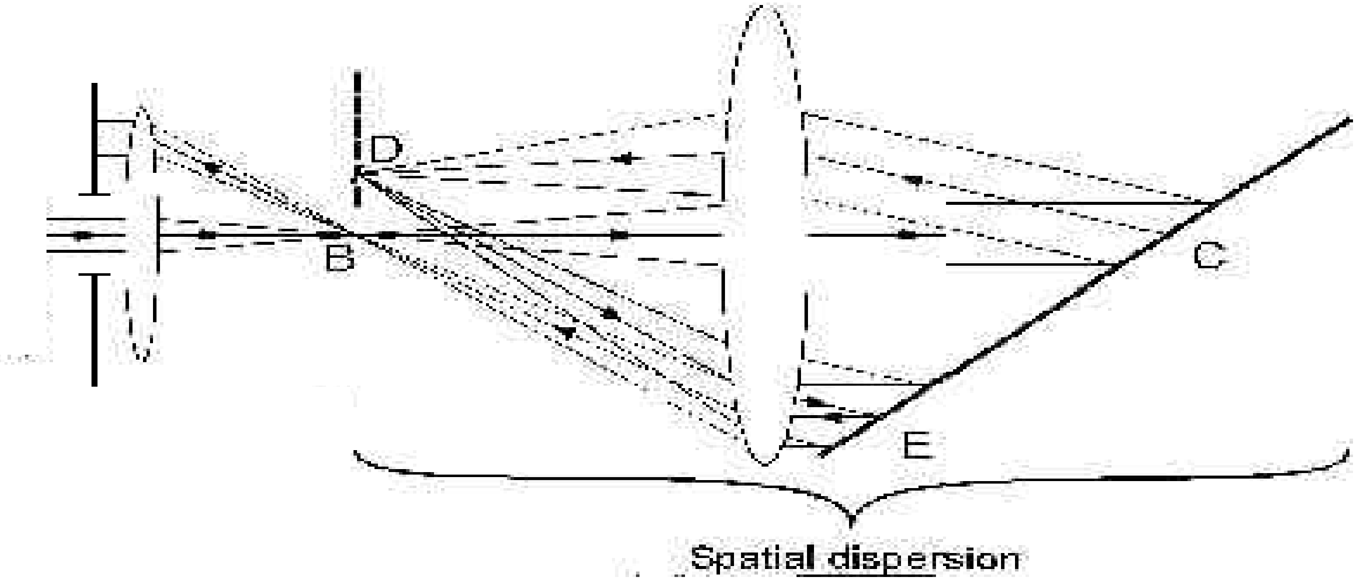
Optical Crossconnect

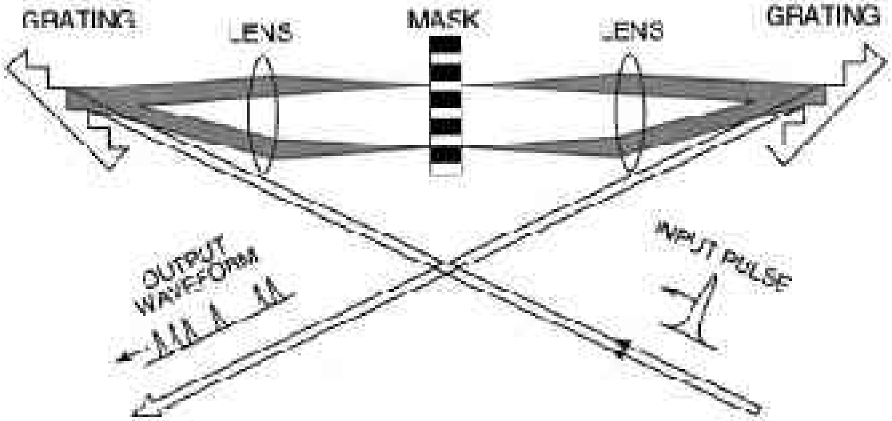
Wavelength Add/Drop Multiplexer

- Different line levels from **A** and **B** into crossconnect
- Different input and add levels from **D** and **E** into WADM
- Different channel losses through crossconnect and WADM
- Different channel gain and loss through optical amplifiers and fiber

# WSS for DWDM and Pulse Shaping

Phase-only SLM imparts amplitude change via spatial filtering

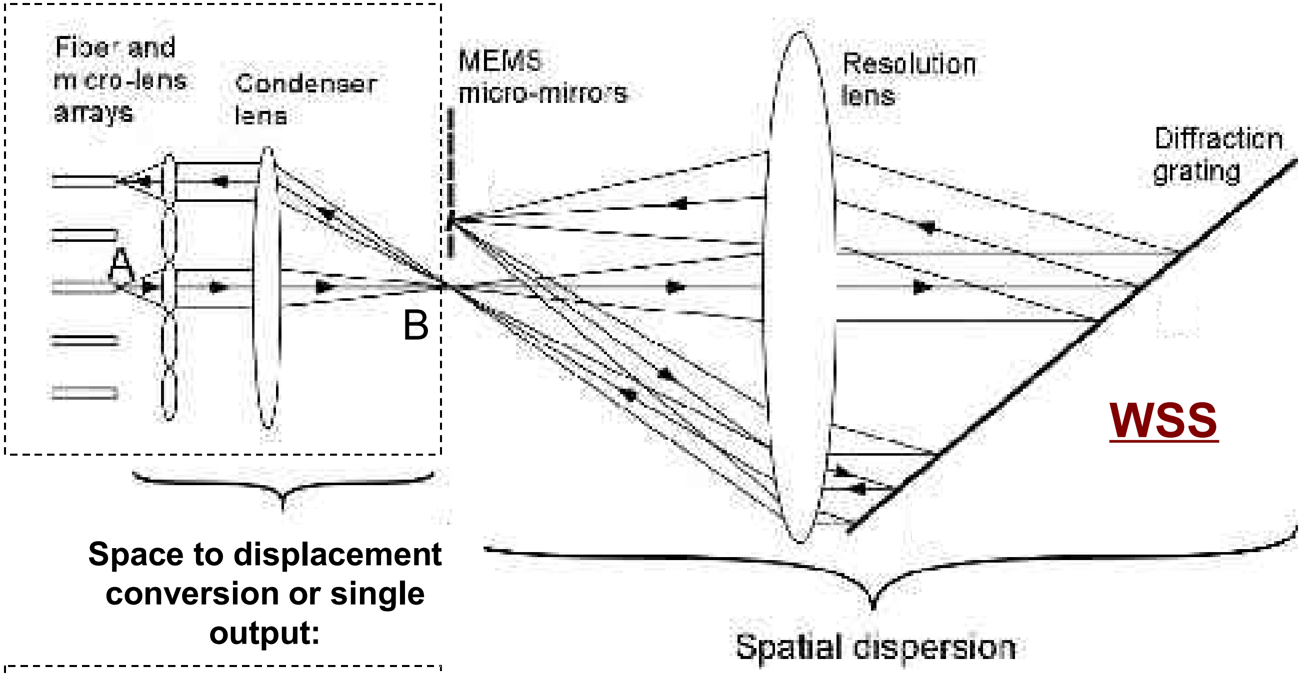




Basic layout for Fourier transform femtosecond pulse shaping.

A. M. Weiner, Rev. Sc. Instr. 2000

# Wavelength-Selective Switch and Dynamic Gain Equalizing Filter



**WSS**

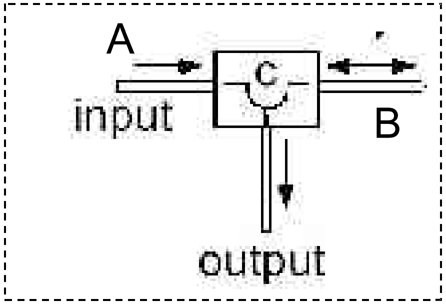
- >100 $\lambda$'s @ 100 GHz
- low loss, high contrast
- wide, flat passband

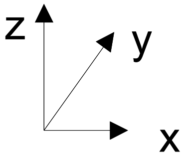
(high fill factor mirrors)

- variable attenuation

(analog tilt control)

**Space to displacement conversion or single output:**





**DGEF**

Tilt along or perpendicular to the dispersion direction.

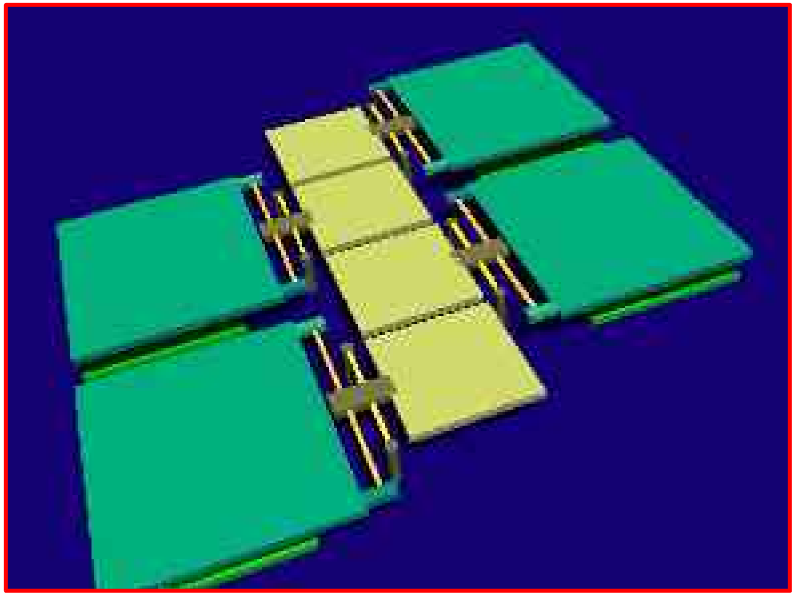
Similar to Femtosecond Pulse Shaping setup with MEMS mirror array as the SLM.

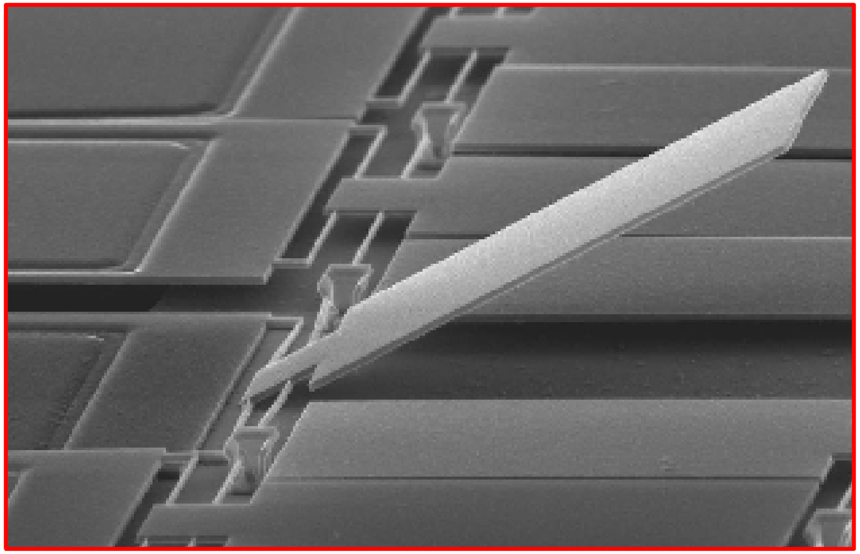
D.T. Neilson et. al. OFC2002 PostDeadline
D.M. Marom et.al. OFC2002 PostDeadline

# Double Hinge Tilting Mirror

- 10 degrees of continuous tilt
- 30 x 50 um mirrors
- moderate V < 100V
- high speed, f > 10kHz

- high fill factor (close-packed)
- no electromechanical crosstalk
- surface-micromachined





**Angle amplification enables a more efficient actuation regime**

**Micromechanical transmission mechanism**

# Angle Amplification

$$\sin(\theta) = \frac{L}{d}\sin(\alpha)$$

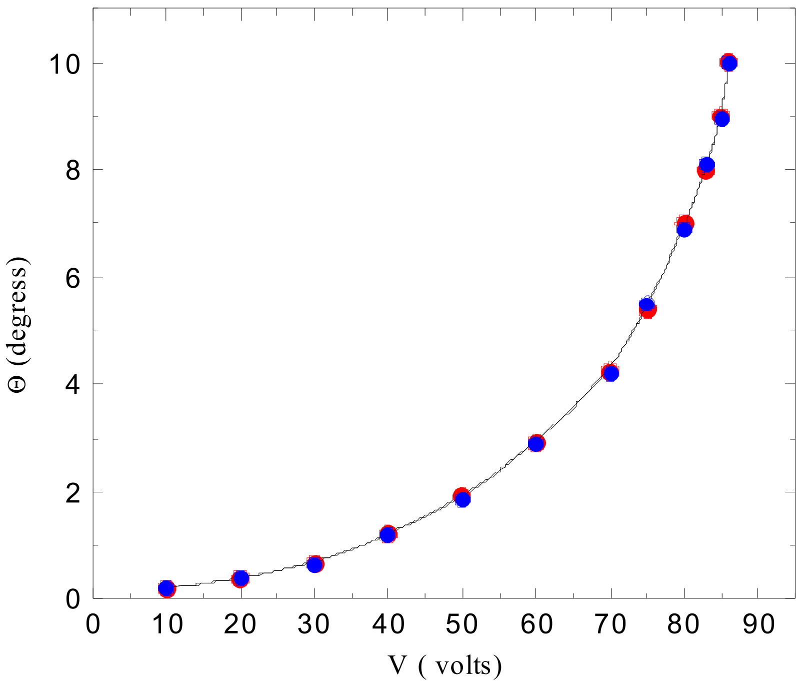
For an actuator consisting of plates, maximum output work is typically:

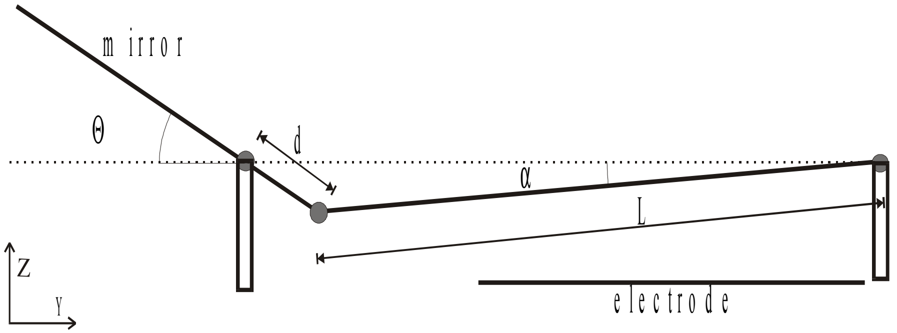
$$W_{\max} \propto \frac{A}{g} V^2$$

The *transmission mechanism* increases work produced by the actuator:

- larger area can be used
- actuator gap can be decreased,

while maintaining the required range of motion





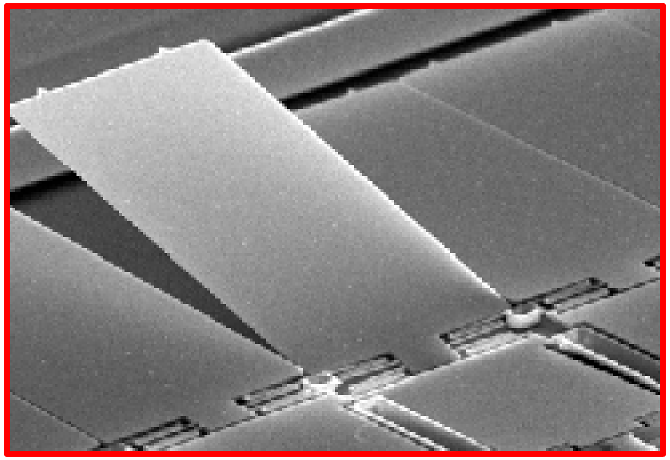
# Transmission Mechanism Efficiency

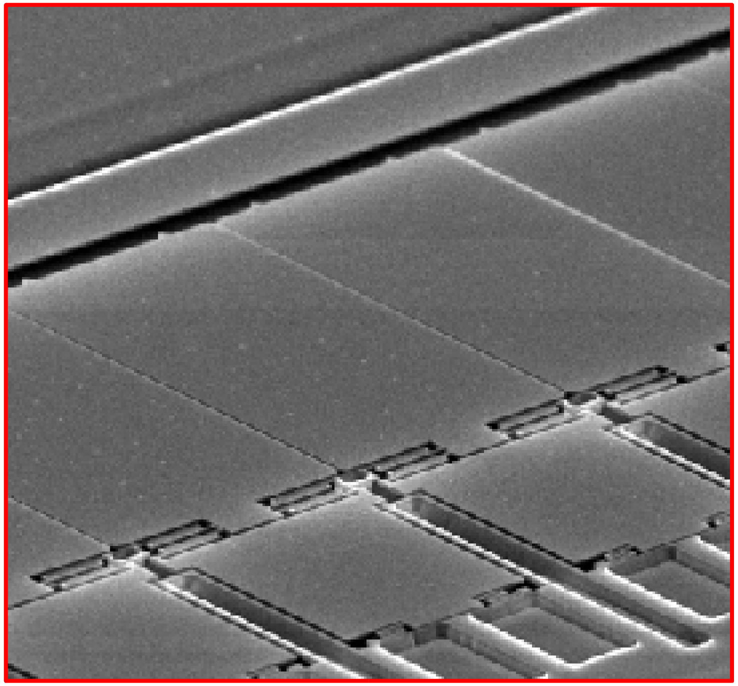
$$W_{electrostatic} = E^{required}_{mech} + E^{other}_{mech} = E^{torsional}_{mech} + E^{Z}_{mech}$$

$$E^{torsional}_{mech} = \frac{1}{2}\tau\theta \qquad {}^{2}$$

$$E^{Z}_{mech} = \frac{1}{2} K_Z \; z^2$$

$$\eta = \frac{E^{required}_{mech}}{W_{electrostatic}} \rightarrow \tau \qquad / \, d^2 \ll K_Z$$





**To maximize efficiency, need to increase stiffness to unwanted deformations:**

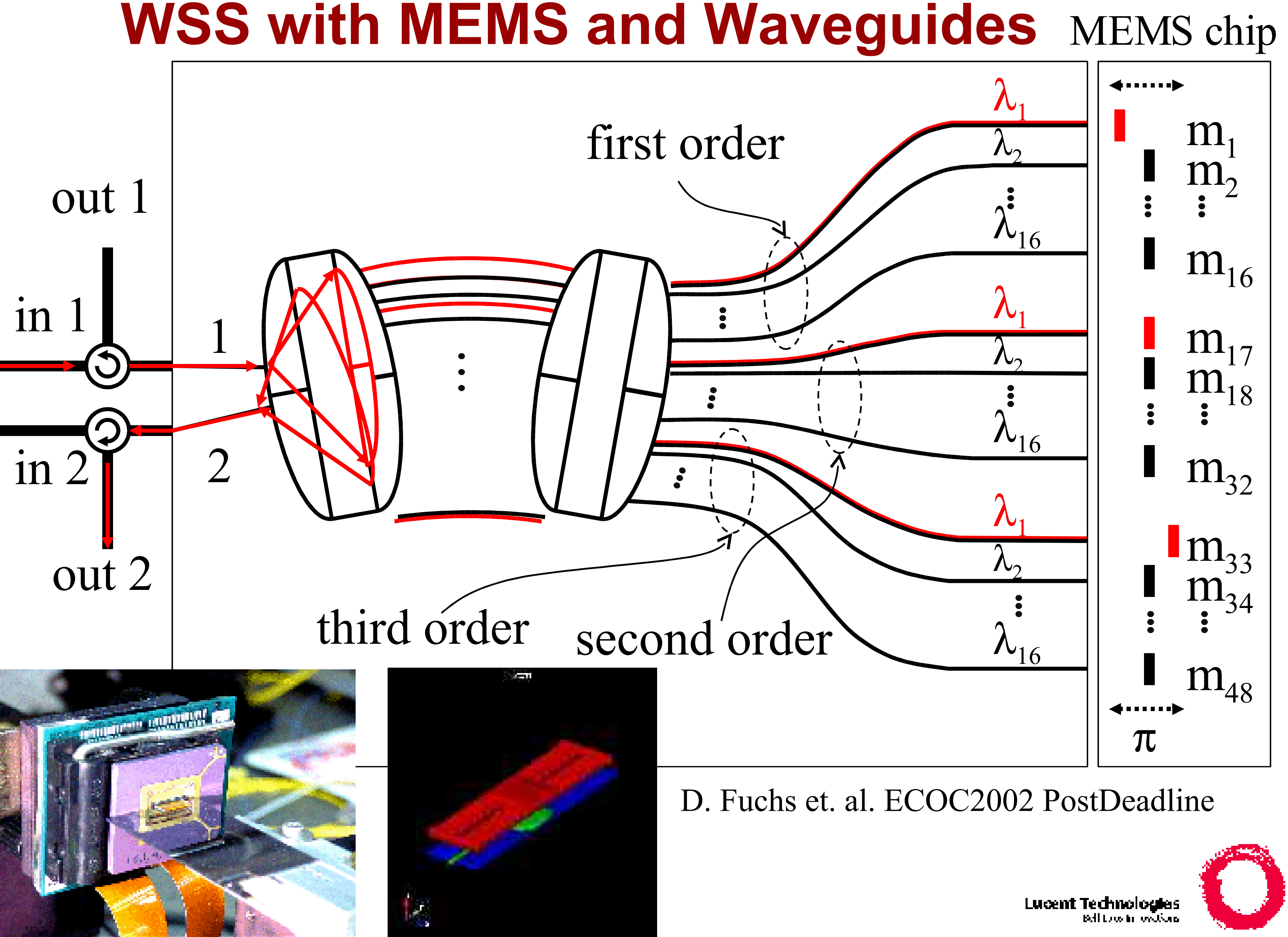
**<u>nonlinear</u> -**

- **mechanical contact - friction**
- **straight torsion rod - stress sensitivity**

**<u>linear</u> -**

- **high aspect ratio spring**
  - **- submicron lithography**

# WSS with MEMS and Waveguides



D. Fuchs et. al. ECOC2002 PostDeadline

Lucent Technologies
Bell Labs Innovations

# Complex Optical MEMS Components – What is next?

**Demonstrated applications:**

- Optical switches
- Displays (TI DMD)
- Adaptive optics
- Femtosecond pulse shapers
- Programmable correlation spectrometers

**MEMS devices:**

- mirrors arrays
- tilt or piston
- 1D or 2D
- 10um to 1mm
- 50% to 98% spatial fill factor

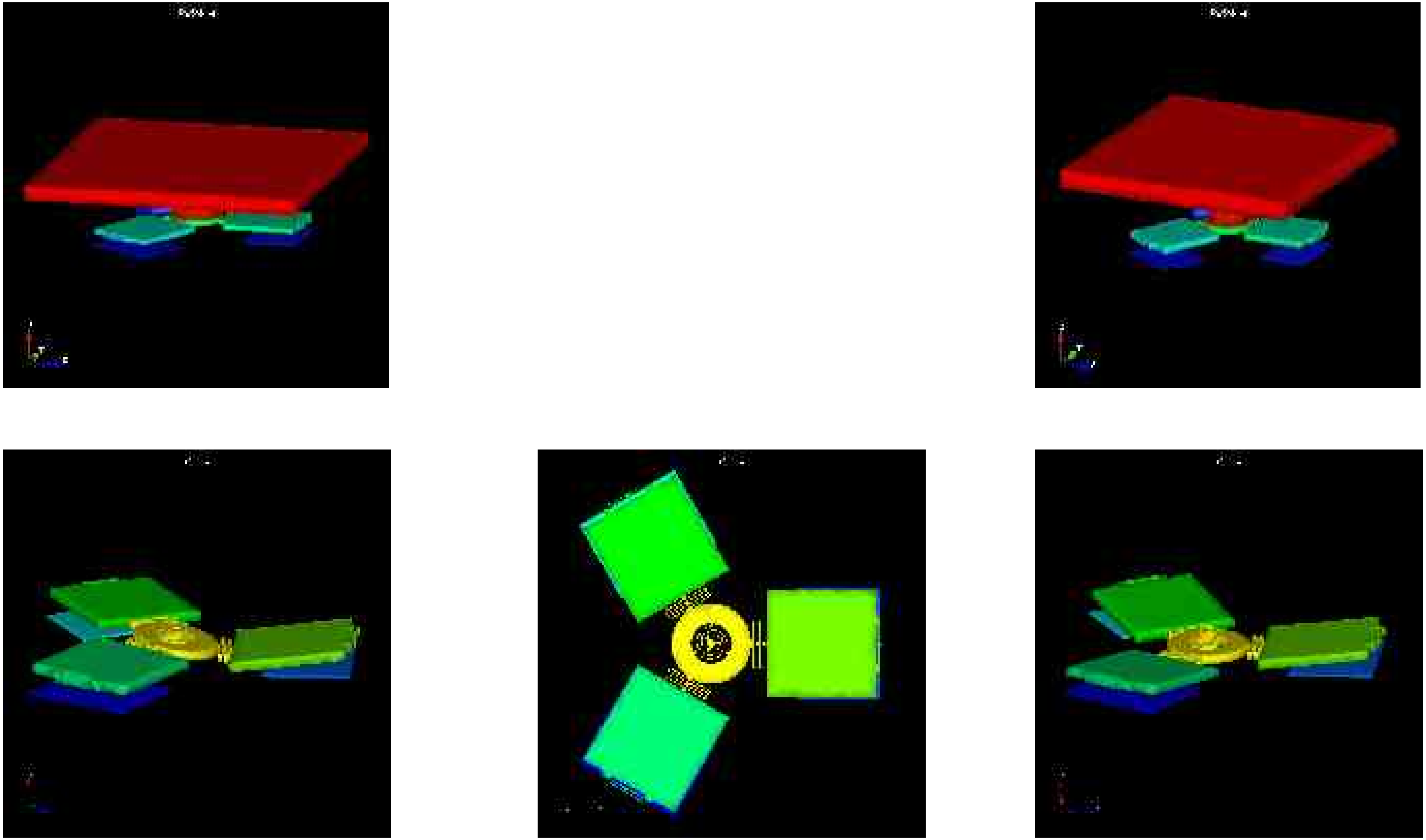
## Superset: *Programmable Reflective MEMS Spatial Light Modulator (SLM):*

- Combines Tilt and Piston motion
- High reflectivity
- High fill factor
- Small, fast elements
- 2D array scalable to 1M elements
- Programmable wavefront shape – Digitally controlled thin phase holograms

"Dial in" a compound optical element:

- variable curvature
- fast tracking
- optical information processing
- optical vortices
- holographic optical tweezers
- ………………

# Concept Tilt-Piston Mirror with Angle Amplification



# Some Current Research Directions for Optical MEMS at Lucent

<u>Micro- and Nano- fabrication</u>:

Processing for nanoscale mechanical features: combs, spring beams, vias, etc.

Electronics integration -

- Through Wafer Interconnect
- Ultra-dense chip- and wafer- scale bonding (millions of nano-bumps)
- New MEMS materials for monolithic integration with ICs

Low stress reflective micromirror coatings

Large clear aperture – processing large Si chips

. . .

<u>Microsystems Design:</u>

Lighter, stiffer, higher reflectivity mirror structures

Actuators-

- Higher power (fast, large amplitude, low voltage)
- Combining piston, tip and tilt

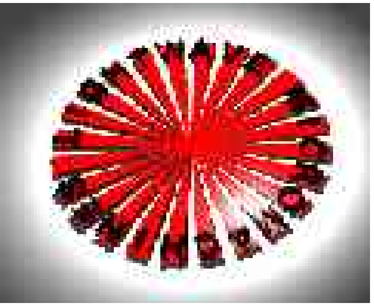
High fill factor 2D mirror arrays

Extreme high packing density, small pixel size, megapixels/chip

. . .

# Summary

- Microscopic optomechanical components retain excellent optical properties of their macro counterparts, but are *smaller, faster, cheaper*.
- Integration of multiple mechanisms enables *new system functions*: optical crossconnects, WDM add-drops, gain equalizers.
- Scale-specific design approaches result in the best performance: *compliant mechanisms, electrostatic actuation, stress engineering*.
- Large MEMS SLMs can now be built and are likely to enable *new and interesting optical systems.*



Optical MEMS is
an enabling technology
for optical systems