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OPTICAL MICRO-ELECTRO-MECHANICAL SYSTEMS (O-MEMS)

J. S. Harris, Jr.

Stanford University

Outline

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- **Overview**
  - **Advantages**
  - **Fundamentals**
- **Mechanical O-MEMS**
  - **Optical Communications Network Switches**
  - **Optical Bench**
  - **Displays**
    - **Torsional Mirror**
    - **Grating Light Valve**
- **Semiconductor Optical Device O-MEMS**
  - **Tunable Laser**
  - **Tunable Detector**
  - **Modeling**
- **MEMS Systems Examples**
- **Summary**

What is O-MEMS

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l **A Marriage of Three Technologies**

- **Optics**
  - **Reflective**
  - **Refractive**
  - **Diffractive**
  - **Waveguiding**
- **Semiconductor Devices**
  - **Optoelectronic III-V Devices**
  - **Si-CMOS Processing and Control Electronics**
- **Semiconductor Based Micromachining**
  - **Lithography**
  - **Deposition**
  - **Epitaxy**
  - **Etching**

The Past Millennium

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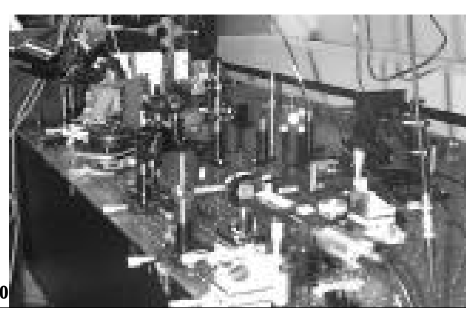
Palomar Telescope

Tunable Laser



Optical Table

The New Millenium

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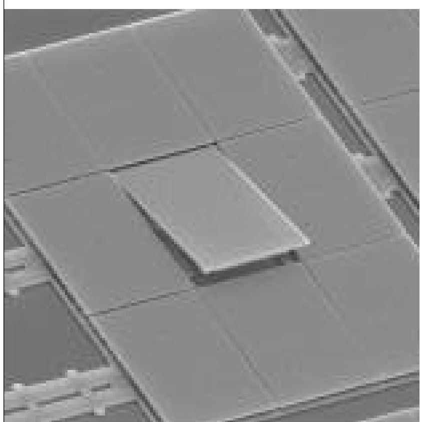
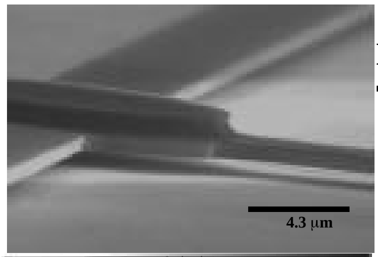
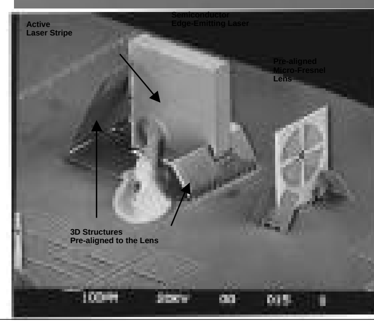
NASA Space Telescope





Monolithic Tunable µ Laser



µ Optical Table

Integration
System on a chip

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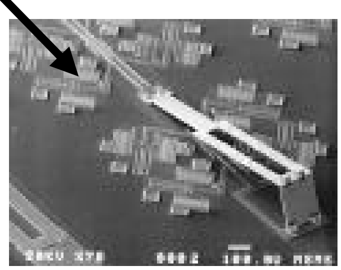
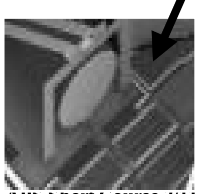
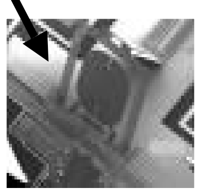
Laser-to-fiber coupling

Micropositioners for mirrors and gratings



High-resolution raster scanner





The Major Driving Force: Communications Link Capacity

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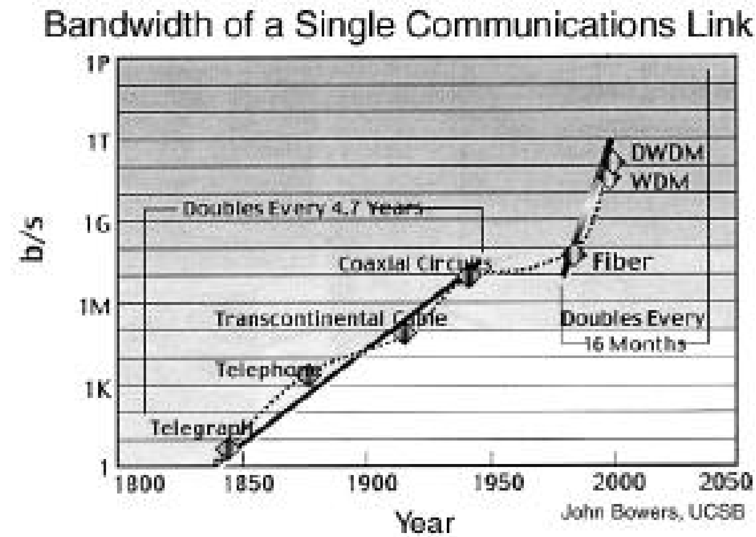

Advantages of O-MEMS "A Marriage of Technologies"

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- **Small force required - Photons have zero mass**
- **Very small displacements required - $\lambda/4$**
- **Precision displacement possible**
- **Based upon compatible semiconductor processing**
  - **Mass, low cost production**
  - **Added functionality thru integration**
- **Reduced size, weight, and cost**
- **Physically robust**
- **Reduced physical alignment - Photolithography**
- **High resonant frequencies**
- **Speed of light (no RC limitation)**

O-MEMS: an Enabling Technology

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- Communications: Fiber Switches. Femtosecond Lasers, Pulse Shaping, Modulators, Tunable Optical Devices
- Optical Interconnects
- Optical Data Storage
- Displays: Projection, Head Mounted - Virtual Reality
- Repro-graphics: Printing, Scanners
- Adaptive Optics
- Optical Transducers and Sensors
- Optical Spectroscopy and Instrumentation

Fundamental Optical Functions

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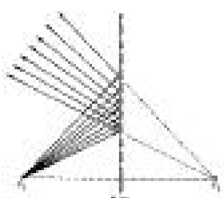
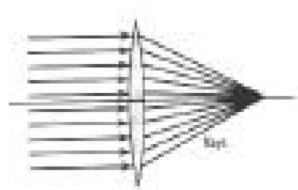
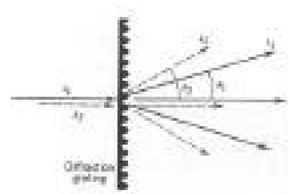
Reflection



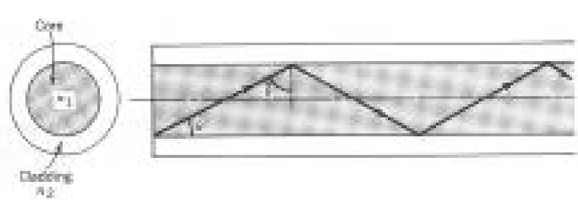
Refraction



Diffraction



Guiding



Active Device Functions

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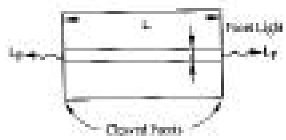
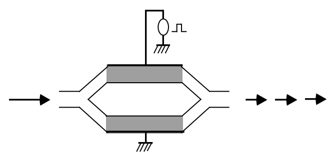
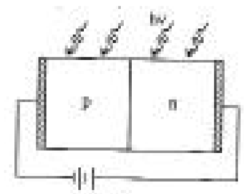
Generation	Modulation	Detection
Laser	Mach-Zehnder	Photodiode







O-MEMS Active Devices

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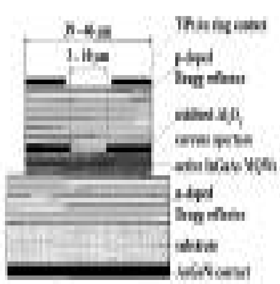
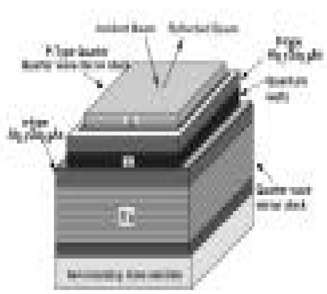
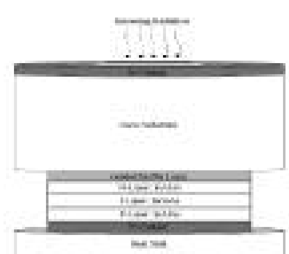
Generation	Modulation	Detection
VCSELs	QCSE Modulator	Photodiode







All Active Devices are Surface Normal

Technologically Available Optoelectronic Materials

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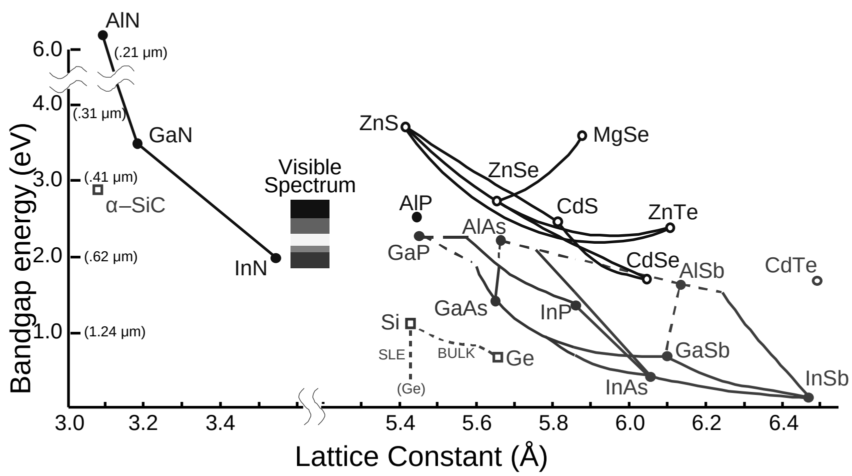

Optical Communications Material Choices

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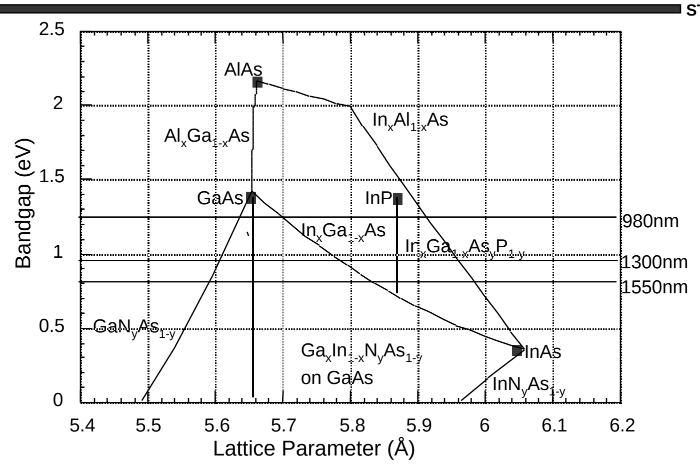
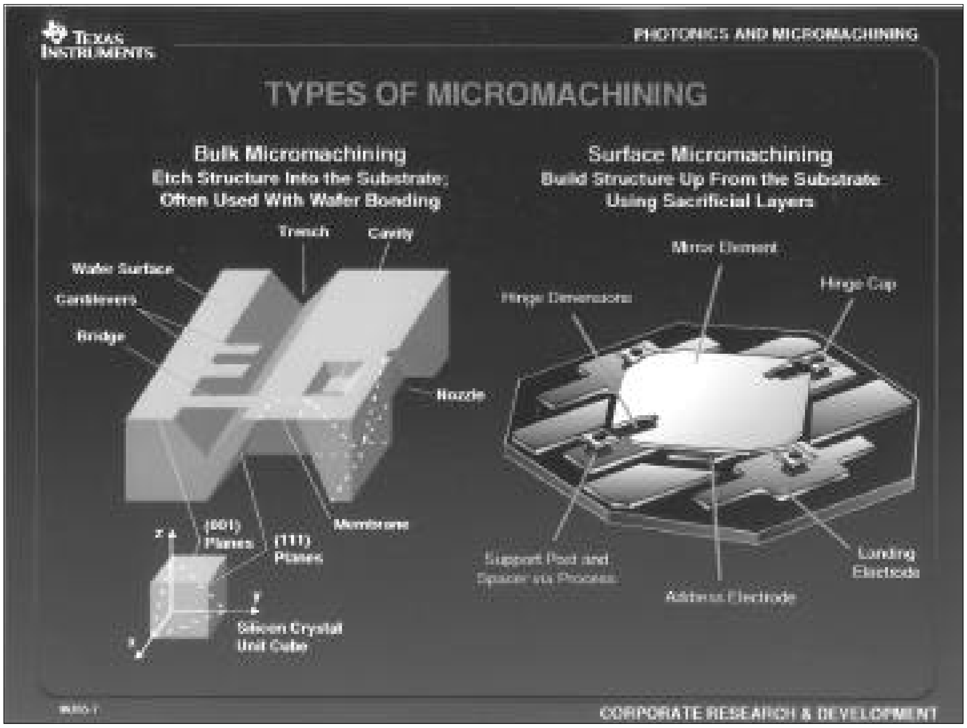
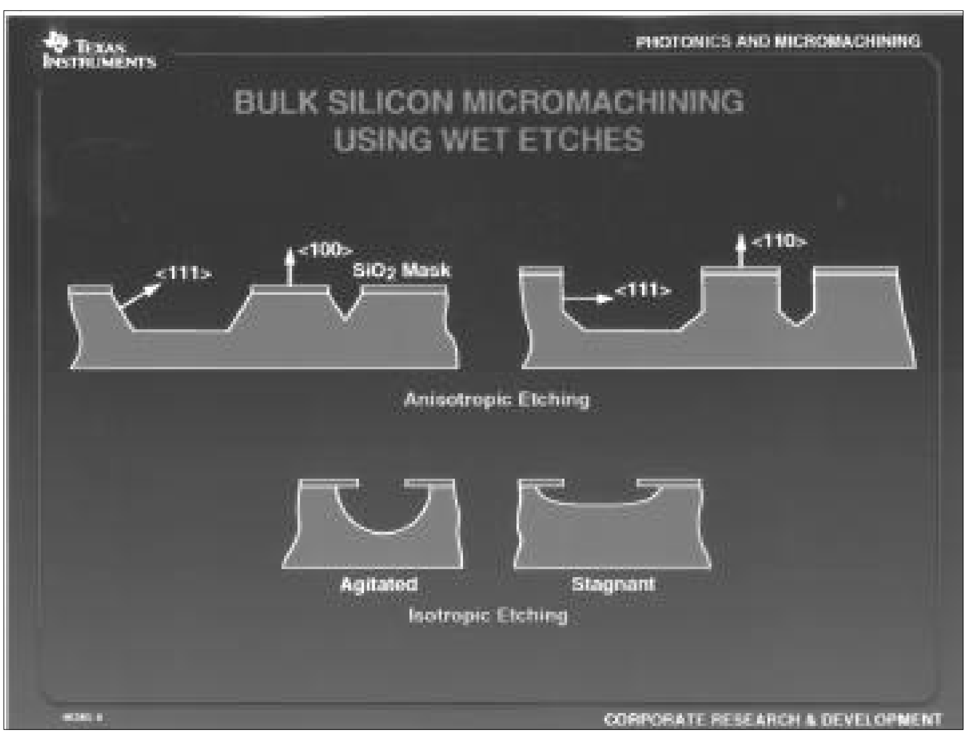


- **GaNAs and GaInNAs have large bandgap bowing**
  - **Long wavelength material lattice matched to GaAs**


TEXAS INSTRUMENTS
PHOTONICS AND MICROMACHINING
TYPES OF MICROMACHINING
Bulk Micromachining
Etch Structure Into the Substrate;
Often Used With Wafer Bonding
Surface Micromachining
Build Structure Up From the Substrate
Using Sacrificial Layers
Trench
Cavity
Wafer Surface
Cantilevers
Bridge
Nozzle
Membrane
(001) Planes
(111) Planes
Silicon Crystal Unit Cube
Mirror Element
Hinge Dimensions
Hinge Cap
Support Post and Spacer via Process
Address Electrode
Landing Electrode
CORPORATE RESEARCH & DEVELOPMENT


TEXAS INSTRUMENTS
PHOTONICS AND MICROMACHINING
BULK SILICON MICROMACHINING
USING WET ETCHES
<111>
<100>
SiO2 Mask
<110>
<111>
Anisotropic Etching
Agitated
Stagnant
Isotropic Etching
CORPORATE RESEARCH & DEVELOPMENT

Surface Micromachining

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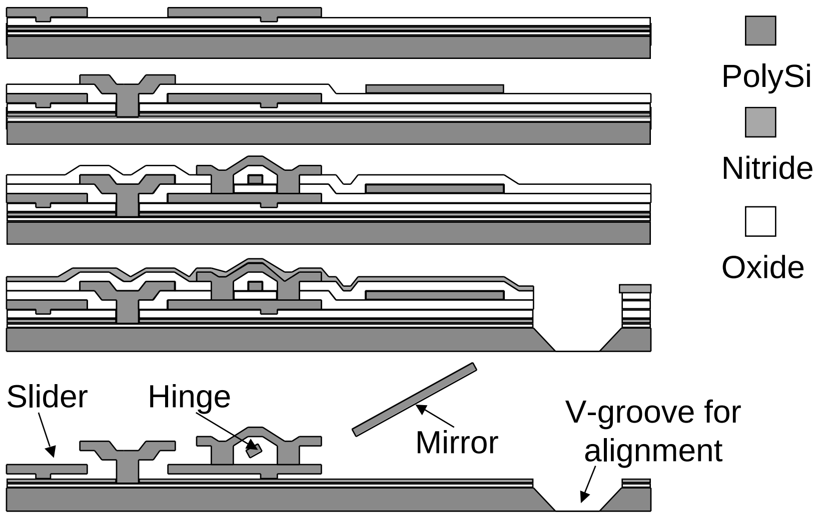

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Principle of Operation

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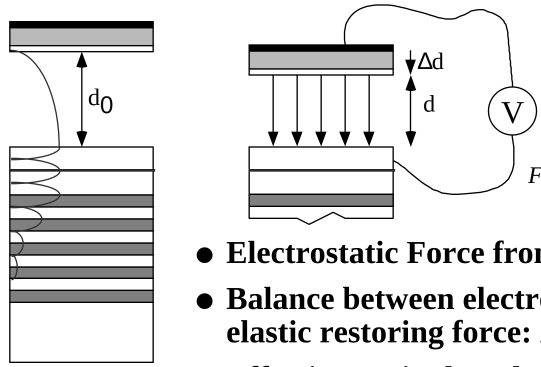
- **Coupled Cavity: Air Gap + Semiconductor Cavity**



$$F = \frac{\partial W}{\partial z} = \frac{\partial}{\partial z}\left(\frac{1}{2}CV^2\right) = \frac{\varepsilon_0 A V^2}{2d^2}$$

- **Electrostatic Force from applied voltage**
- **Balance between electrostatic and elastic restoring force: $\Delta d \sim V^2/d^2$**
- **Effective cavity length: $\Delta\lambda/\lambda_0 = \gamma\ \Delta d/d_0$**
- **Light emission restricted to cavity modes**

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Design Issues: Mechanical Actuation Limit

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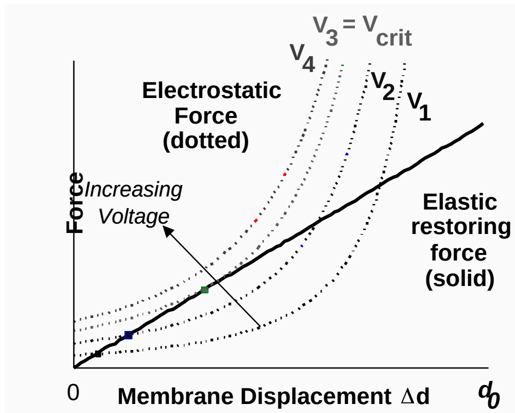

- **Nonlinear nature of Electrostatic Force**
- **Stable solutions: displacement less than ~L_{g0} / 3**

μMIRRORS

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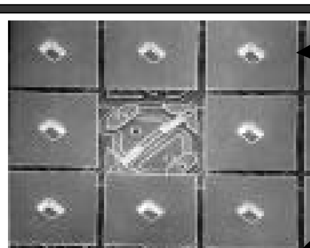
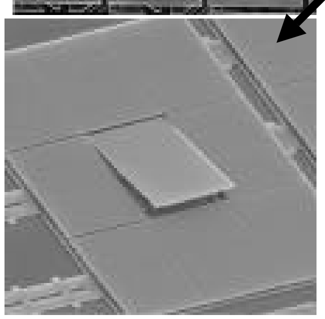
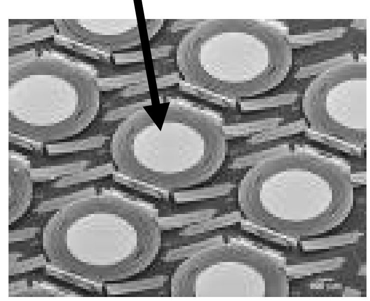


Texas Instrument's DMD

NASA's Next Generation Space Telescope (2008) with 4M micromirrors by Sandia NL



Lucent's Optical X-Connect



Electrostatic-combdrive

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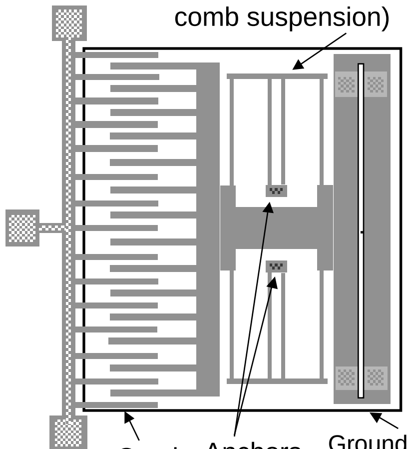

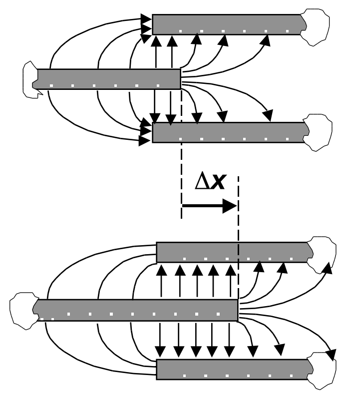

Electric field distribution in comb-finger gaps

μactuators – Electrostatic Combdrives

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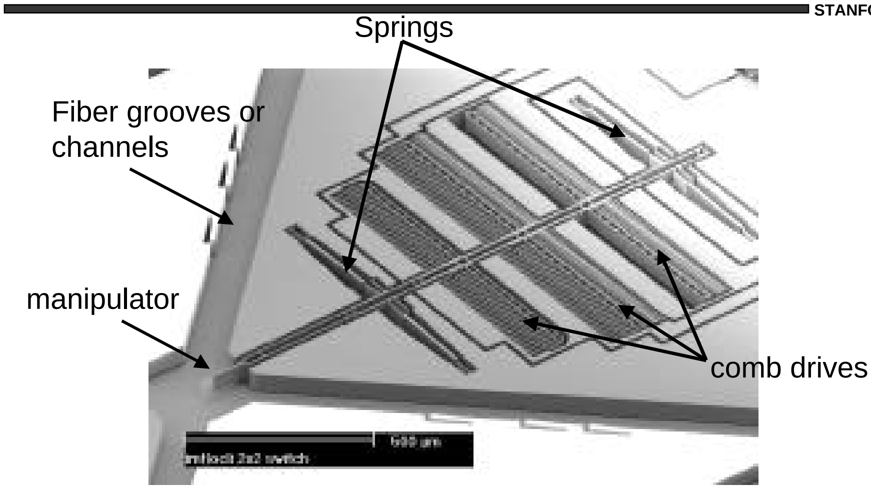

Bryant Hichwa etal, OCLI/JDS Uniphase, "A Unique Latching 2x2 MEMS Fiber Optics Switch", Optical MEMS 2000, Kauai, August 21-24th, 2000.

Wavelength Switching Speed

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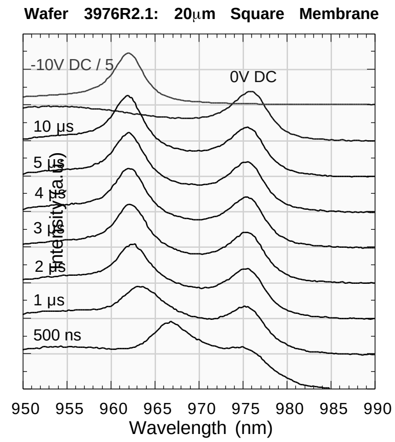

- Bias conditions:
  - Constant 10mA Diode Current
  - Membrane driven by square pulse, 500ns to 10μs variable pulse width, 10V Amplitude, 20% duty cycle
- Time-averaged Spectrum:
  - 90% of average λ shift in 1 μs

Micromirror Reliability

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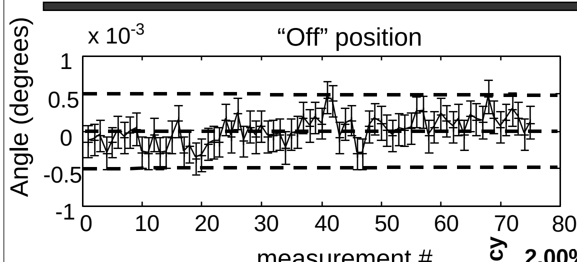

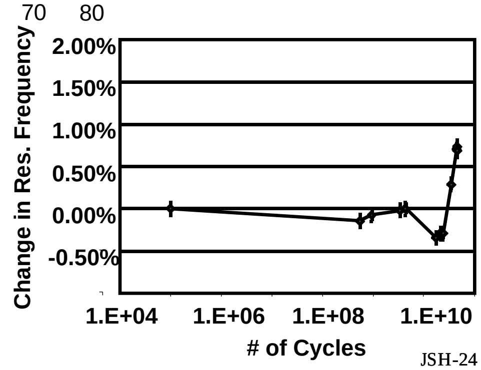

Outline

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- Overview
  - Advantages
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- Mechanical O-MEMS
  - Optical Communications Network Switches
  - Optical Bench
  - Displays
    - Torsional Mirror
    - Grating Light Valve
- Semiconductor Optical Device O-MEMS
  - Tunable Laser
  - Tunable Detector
  - Modeling
- MEMS Systems Examples
- Summary

WDM Crossbar Switch

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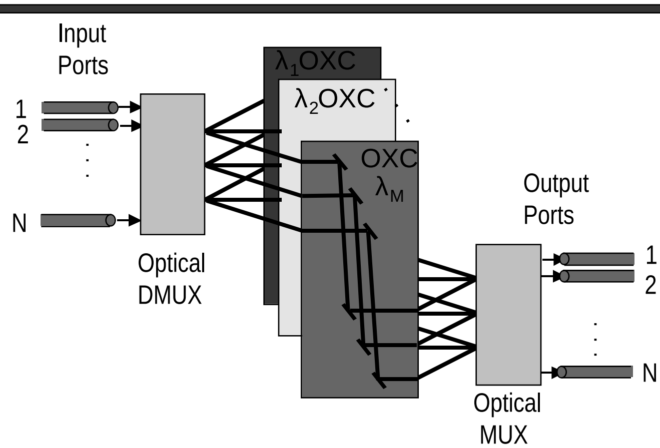

Architecture of WDM Switch
The optical input signals are demultiplexed, and each wavelength is routed to an independent *NxN* spatial cross-connect

O-MEMS Modulation Means

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Properties of Light:

- **Intensity, Wavelength, Polarization, and Phase**

  Each of these can be modulated, although intensity is the most common mode

Modulation Means:

- **Linear Motion**
- **Deflection**
- **Reflection**
- **Diffraction**
- **Interference**

2 x 2 fiber-optic switch

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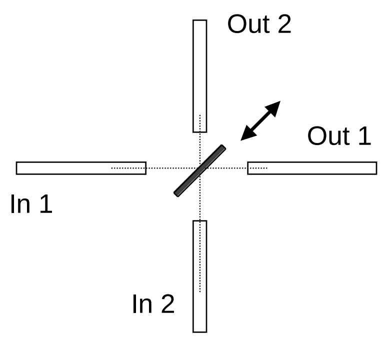

- **Compact design**
- **One-mask fabrication using DRIE on SOI**
- **Integration of fibers, lenses, and micromirrors**
- **2 by 1 operation**
- **By-pass switch**
- **AT&T, JDSU.......**

1 x 2 Matrix Switch

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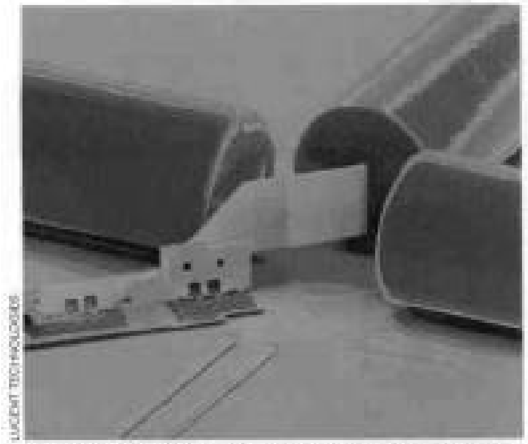

FIGURE 1. This 1 × 2 MEMS optical switch can route light from the input fiber to one of two output fibers.

MEMS-based OXC switches

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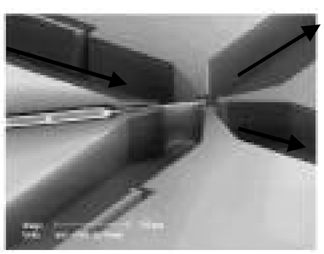
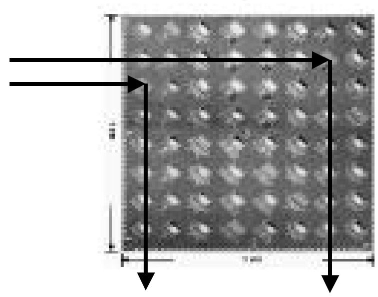
2X2 Fiber-optic switch [1]



8x8 Fiber-optic switch [2]



- ***Some issues:***
  - **Switch scalability with minimum insertion loss**
  - **Large device count**
  - **Non-standard fabrication processes**
  - **Actuator reliability problems**

[1] C. Marxer, N.F. de Rooij, Jrnl of Lightwave Tech., Vol. 17, No. 1, Jan 1999
[2] L.Y. Lin, E.L. Goldstein, R.W. Tkach, Jrnl of selected topics in Quantum Electronics, Vol. 5, No. 1, Jan 1999

NxN Matrix OXC

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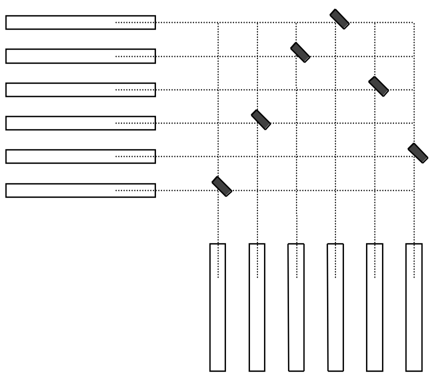

- **Simple 1 by 2 cross-points**
- **Digital mirrors**
- **N^2 scaling**
- **Large motion**
- **Reliability??**
- **OMM, Onix, AT&T, Agilent.....**

Beam Steering Optical Switch

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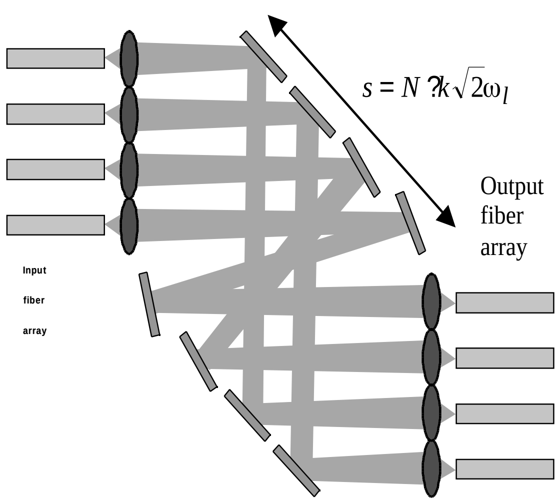

- Analog mirrors
- 2N scaling
- Accuracy?
- Lucent, C-speed, Xros(NT),.....

2x2 Beam Steering Switch*

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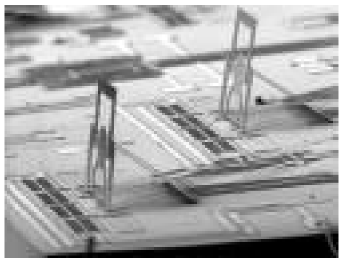
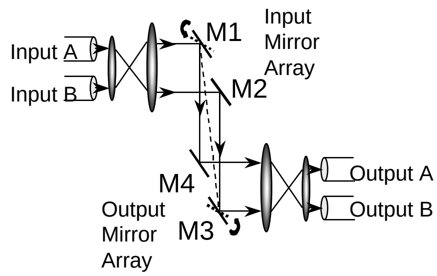
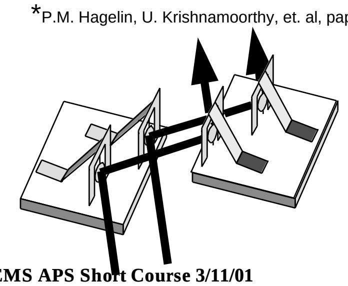




*P.M. Hagelin, U. Krishnamoorthy, et. al, paper published in ***Photonics Technology Letters***, July 2000.



- **Silicon micromachined v-grooves**
- **1.55μm diode laser source**
- **Comb-drive actuated mirrors**
- **Bulk optics for optical field scaling**
- **-4.2 dB measured insertion loss**
- **-54 dB measured cross-talk**

Switching Characteristics

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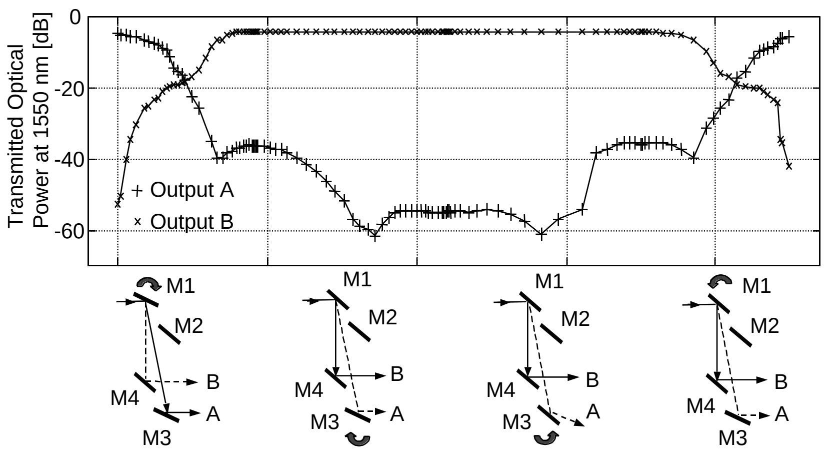
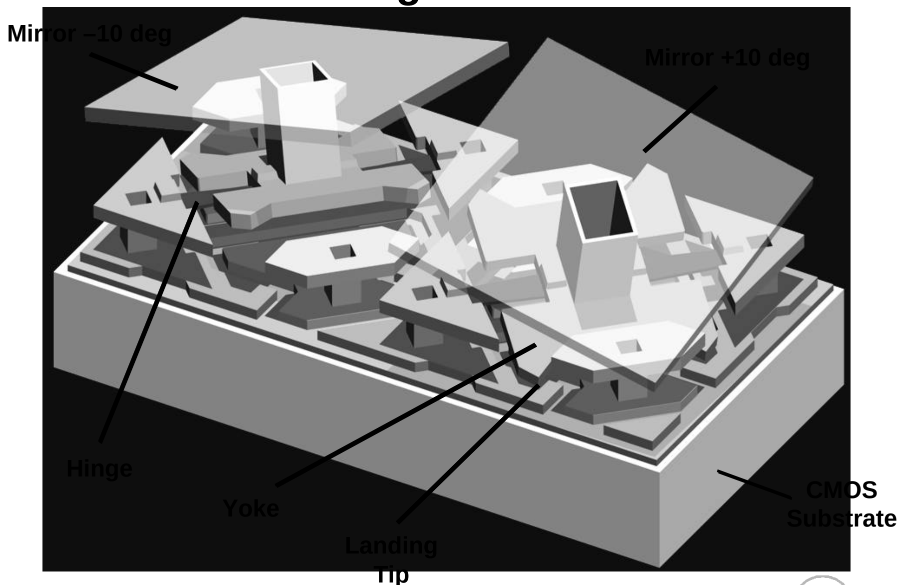
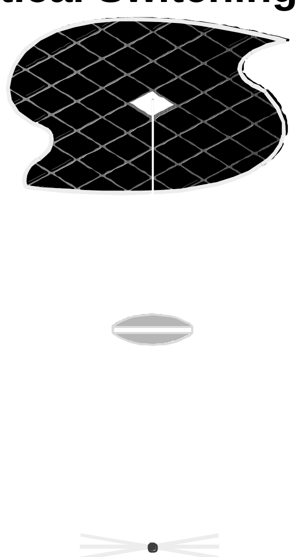


M1: 21.65V to 0V	M1: 0V	M1: 0 V	M1: 0V to 22.24V
M3: 25.52V	M3: 25.52Vto 0V	M3: 0Vto 25.52V	M3: 25.52V

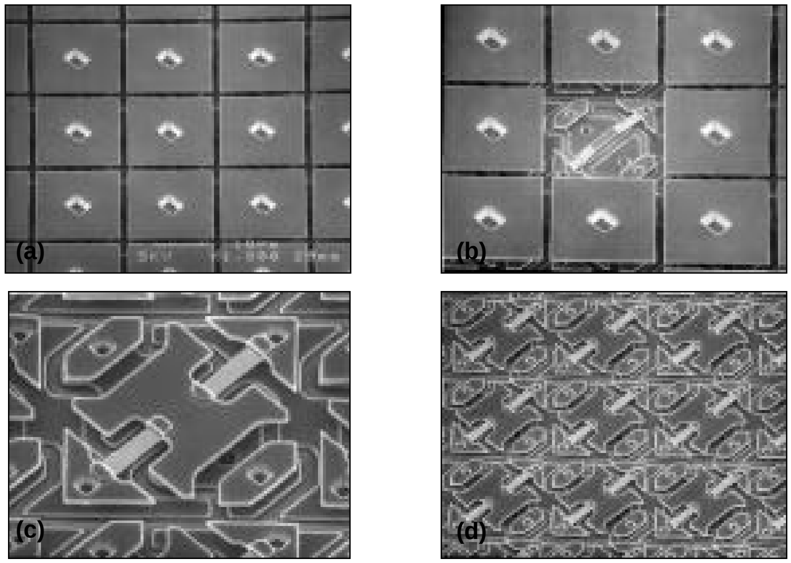
DMD Light Switches



DMD Optical Switching Principle



SEM Photomicrographs of DMD Chips



Grating Light Modulator

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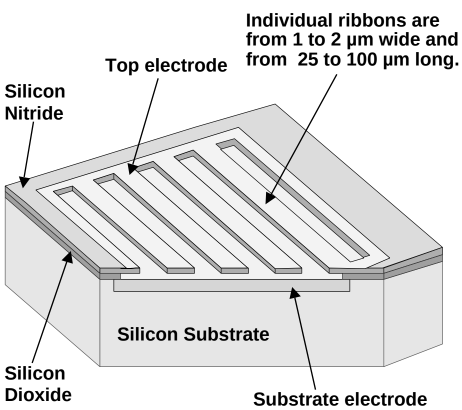

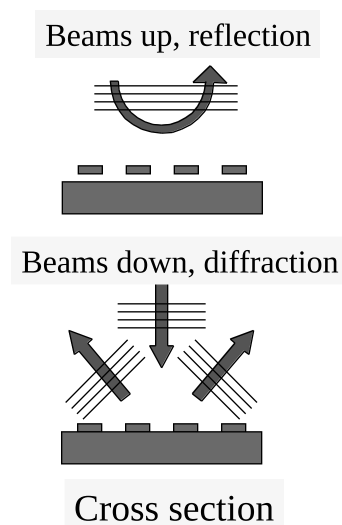

Grating Light Valve Projector

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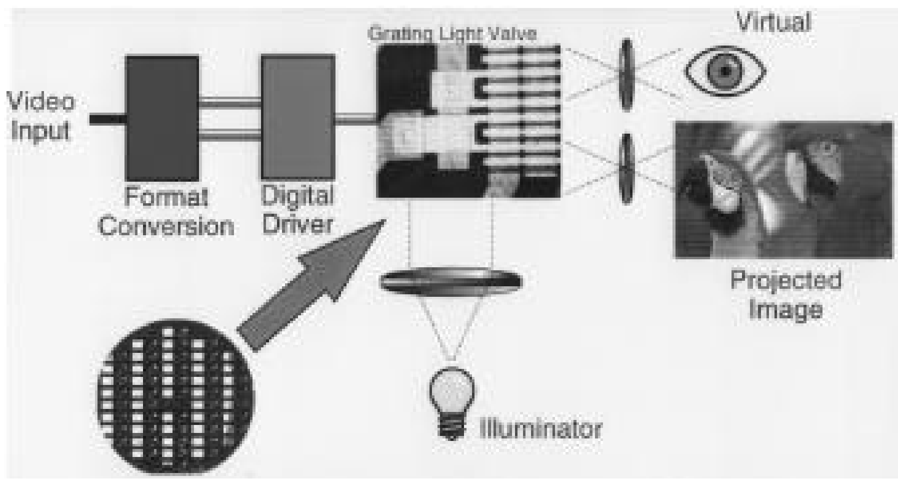

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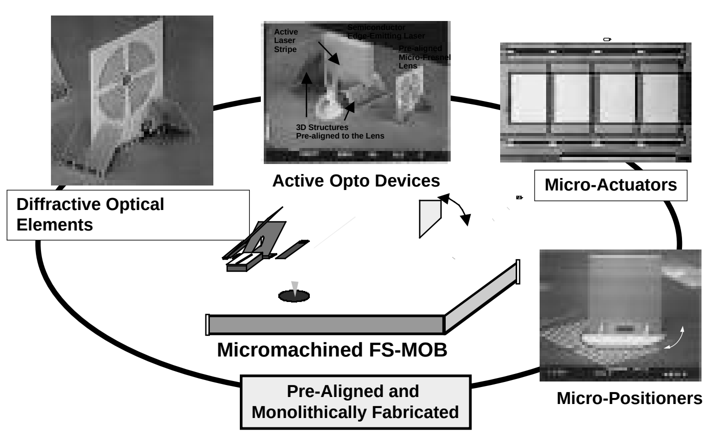
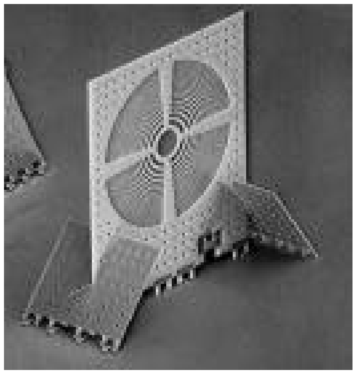
Micromachined Free-Space Micro-Optical Bench (FS-MOB)



M. C. Wu

Out-of-Plane micro-Fresnel lens

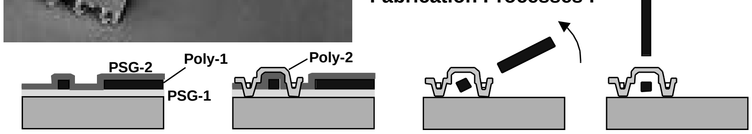


- Low cost, batch processing technique to fabricate free-space micro-optical system.
- All optical elements fabricated at the same time by photolithography.

→ The optical system can be pre-aligned.

- Greatly reduce the size, weight, and volume of free-space micro-optical systems

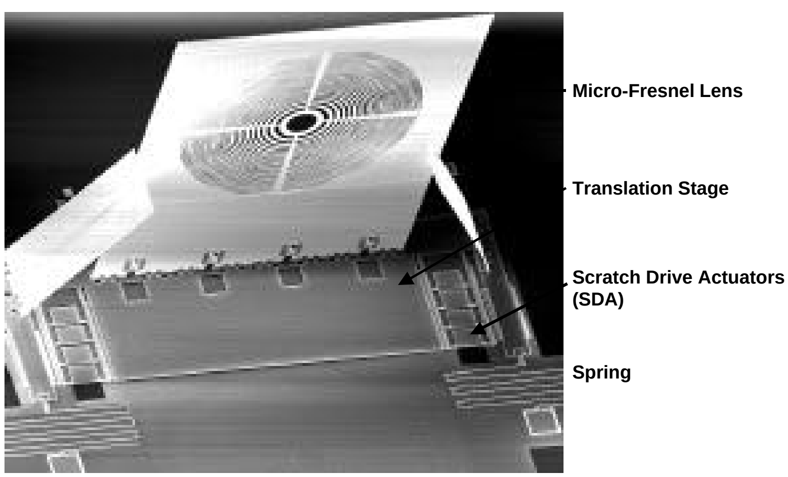
Fabrication Processes :



Si or GaAs

- Ref: Lin, Lee, Pister, and Wu, *Electronics Letters*, v.30, p.448, March 1994.

Micro-Fresnel Lens with Integrated Scratch Drive Actuators (SDA)



Outline

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- Overview
  - Advantages
  - Fundamentals
- Mechanical O-MEMS
  - Optical Communications Network Switches
  - Optical Bench
  - Displays
    - Torsional Mirror
    - Grating Light Valve
- **Semiconductor Optical Device O-MEMS**
  - **Tunable Laser**
  - **Tunable Detector**
  - **Modeling**
- MEMS Systems Examples
- Summary

Need for Tunable Devices

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- Wavelength division multiplexing (WDM):
  - tunable vertical cavity lasers
  - tunable photodiodes
  - tunable phototransistors
- Optical Routing and Switching:
  - Beam steering
- Spectroscopy:
  - Gas sensing
  - Laser spectroscopy
  - Cavity ring-down spectroscopy
  - Intracavity laser absorption spectroscopy
- Adaptive Optics:
  - Tunable mirror arrays

Ar Ion Pumped Ti:Sapphire Tunable Laser

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Laser Background

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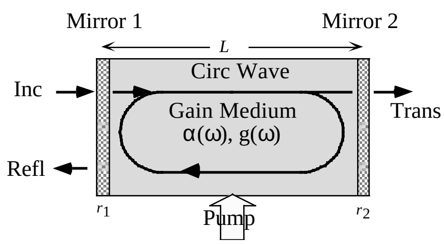

- **Laser: Gain + Feedback**

  (Mirrors)

- **Oscillation/Lasing**
  - **Gain > Loss (internal + mirror)**
  - **Resonance condition**

    $2\omega nL/c = 2\pi m$ *or* $nL = m\lambda/2$

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Laser Background

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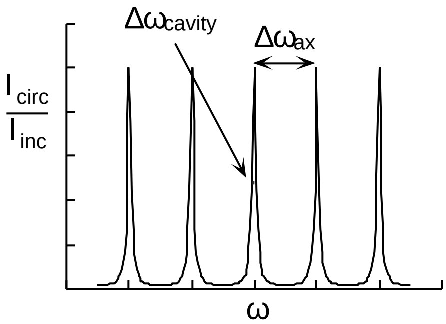

- **Resonance**

$$\omega = \frac{\pi c}{nL} m \quad \text{, where } m = 1, 2, \ldots$$

- **Axial Mode Spacing**

$$\Delta\omega_{axial} = \frac{\pi c}{nL}$$

- **Cavity Finesse**

$$F \equiv \frac{\pi\sqrt{g_{rt}}}{1 - g_{rt}} \approx \frac{\Delta\omega_{axial}}{\Delta\omega_{cavity}}$$

Semiconductor Lasers: In-Plane vs. Vertical-Cavity

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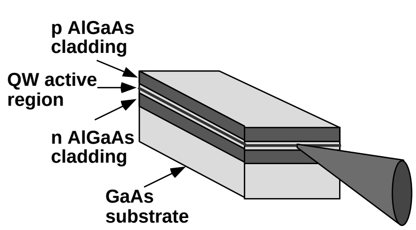
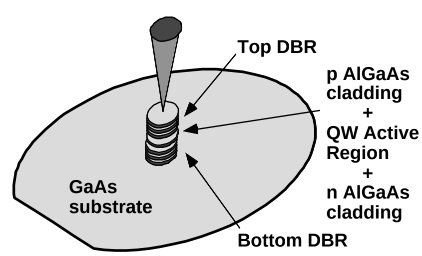
In-Plane Edge-Emitting Laser



- **Cavity length ~ 100-400 µm**
- **High gain (2gL), low reflectance mirror is sufficient for lasing**
- **Mirrors usually formed by cleaving ~ 30% reflectance**
- **Small emission aperature produces highly astigmatic beam**

Vertical-Cavity Surface-Emitting Laser



- **Cavity length (λ) ~ 0.25 µm**
- **Low gain (2gL), high reflectance mirror (> 99%) needed for lasing**
- **Mirrors are made of 1/4 λ alternating low and high index materials such as: AlAs/GaAs**
- **Circular beam**

Why Vertical Cavity Devices?

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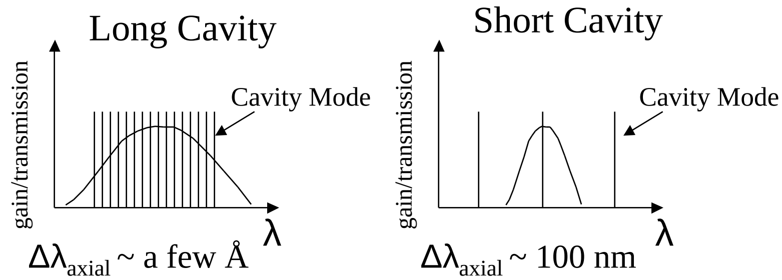

- Axial mode spacing is inversely proportional to cavity length: $\Delta\omega_{ax} = \pi c/nL$
- Wide axial mode spacing in vertical cavities possibility for broad and continuous wavelength tuning ($\Delta\lambda < \Delta\lambda_{axial}$, ~100 nm or ~10%)

Wavelength Tuning in VCSELs

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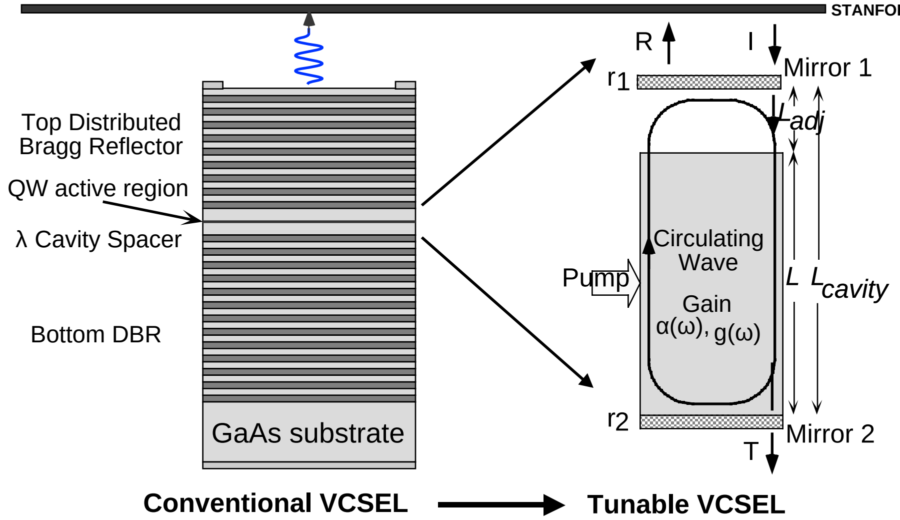

$nL = m\lambda/2$ → $nL + L_{adj} = m\lambda/2$

Hybrid Dielectric DBR Tunable VCSEL Structure

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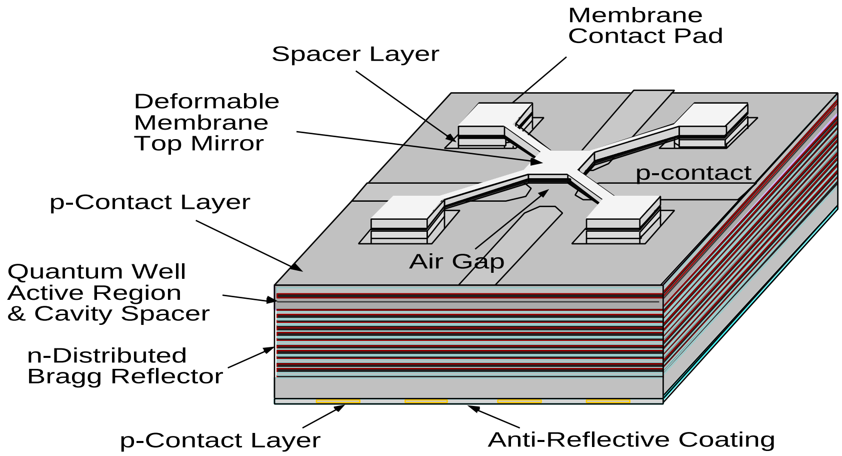

Dielectric Mirror Deposition & Current Aperture Formation

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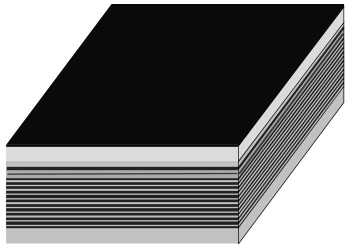
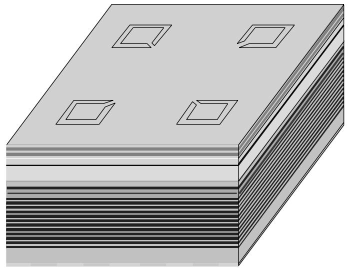


- **Grow epitaxial layers using MBE**



- **Deposit backside anti-reflective coating & ohmic contact**
- **Deposit Si_3N_4 mechanical layer & Si_3N_4/SiO_2 dielectric DBR**
- **Pattern/Etch to high Al content AlGaAs current confinement layer**
- **Wet Thermal oxidation of AlGaAs to form current aperture**

Top Mirror Formation

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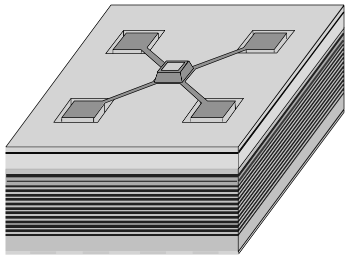
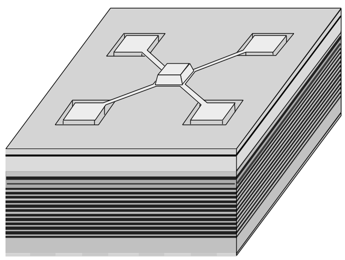


- Pattern/Etch dielectric DBR to form central reflector region
- Evaporate/Liftoff Ti-Au adhesion layer



- Evaporate/Liftoff Au mirror layer

Intracavity Contact

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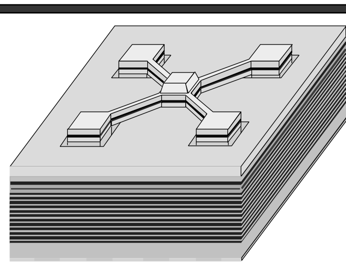
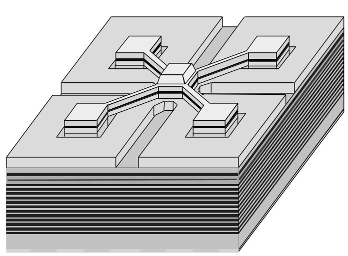


- Plasma etch mechanical nitride layer to form membrane
- Recess etch $Al_{0.85}Ga_{0.15}As$ sacrificial layer



- Wet Etch sacrificial layer for intracavity contact
- Evaporate/Liftoff Ti-Au intracavity contact

Membrane Release

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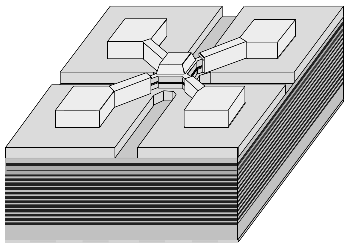
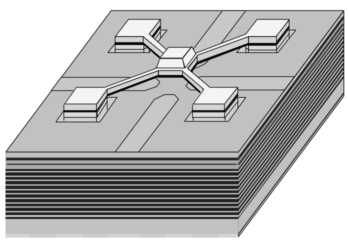


- Pattern photoresist for membrane release



- Wet Etch membrane release
- Plasma removal of photoresist

SEM Images of Tunable Structure

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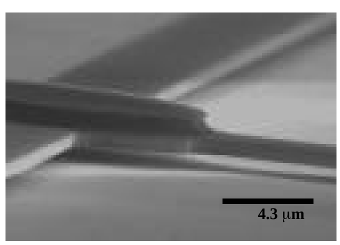
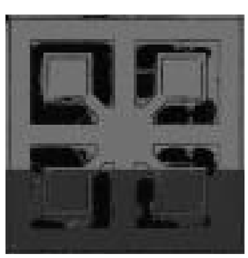
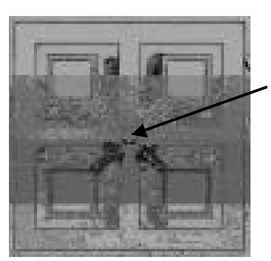


- 20-40 μm diameter membrane central reflector
- Shadow indicates the full releasing of the membrane.
- 85 X 5 μm membrane legs





Oxidized current aperture

Semiconductor Coupled Cavity: 1.5 Pair Dielectric DBR

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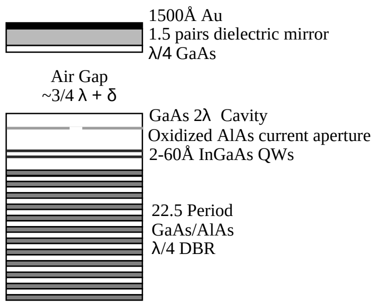
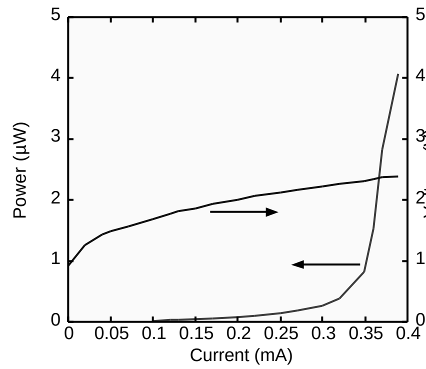
Structure





- **$SiO_2/Si_3N_4/SiO_2$ stress-matched 1.5 pair dielectric DBR**
- **99.91% calculated top mirror reflectivity**
- **Typical device I_{th} ~ 0.35-0.7mA, Quantum efficiency ~ 6.5%**

Semiconductor Coupled Cavity: 1.5 Pair Dielectric DBR

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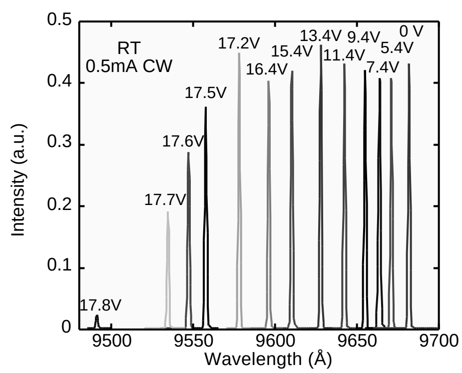

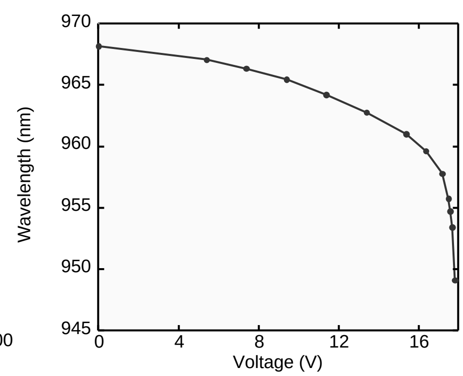

- **19.1 nm continuous tuning for 17.8 V membrane bias**
- **24 dB mode suppression ratio**

VCSEL Wavelength Tuning Transient Response

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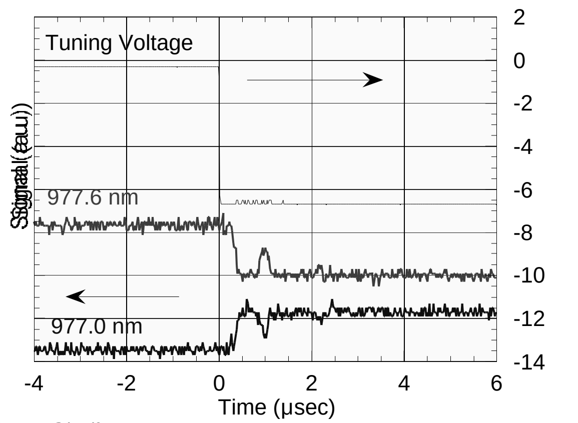
- **Wavelength switching from 977.6 nm to 977.0 nm**
- **< 1 μsec rise time, ~ 2 μsec settling time**



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Resonant Cavity Photodetection

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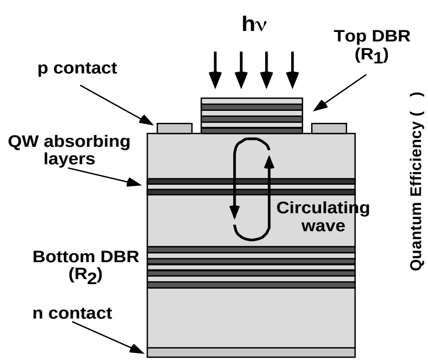

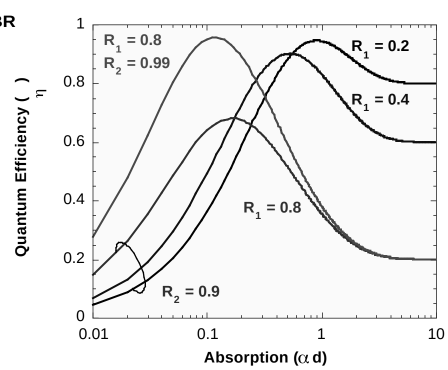

- **Quantum Efficiency**

$$\eta_{max} = \left\{ \frac{(1+R_2 e^{-\alpha d})}{(1-\sqrt{R_1 R_2} e^{-\alpha d})^2} \right\} (1-R_1)(1-e^{-\alpha d})$$

(Kishino, 1991)

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Tunable PIN Photodiode

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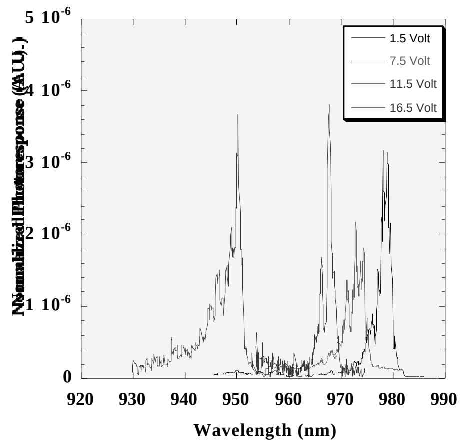
- Reverse Bias The Tunable Laser (PIN diode)
- Narrow Linewidth (below 4nm)
- Tuning Range: 28.5 nm



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Mirror Curvature

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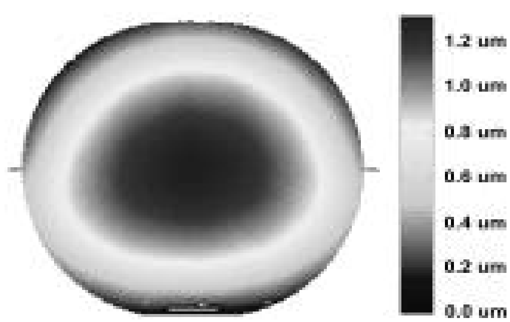
- 2-D Interferometry
- Optical far-field measurements

MUMPS Poly2



Static deformation 1.2 µm

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New AlO_x/GaAs Top Membrane Structure

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- AlO_x/GaAs: higher index contrast ratio, fewer DBR mirror pairs
- Independent leg thickness enables stress and deflection optimization.

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One-Dimensional Model of Movable Membrane

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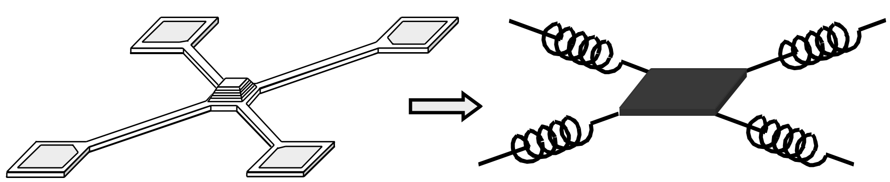

- One-Dimensional Model: Four springs with Hook’s constant k_{eff} attached to central reflector
- The balance of forces: Electrostatic force contributed from central plate and four legs is equal to the effective spring force
- Describe the system accurately without loss of physical meaning

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Optical Properties of the cavity

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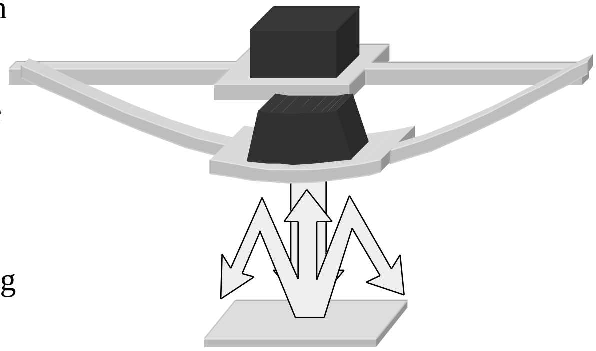
- Modeling of O-MEMS devices is virtually non-existant: serious design limitation
- Surface deformation scatters light out of the cavity
- Cavity loss increases linewidth
- Two top membrane designs compared using Fox & Li method



Optical Field Distribution

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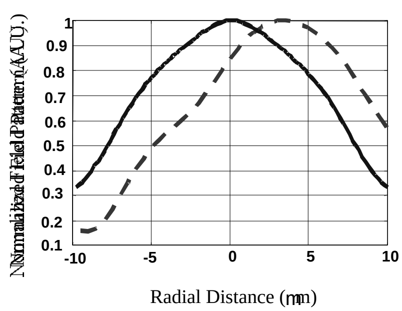
- Fox & Li method used to simulate a plane wave bouncing between two mirrors.
- Examples
  - Tilted but flat surface
  - Symmetrically bent surface
- Result:
  - Tilted: the mode shifts
  - Symmetrical: the mode intensity decreases in center, but increases at edges--leads to multi-mode lasing



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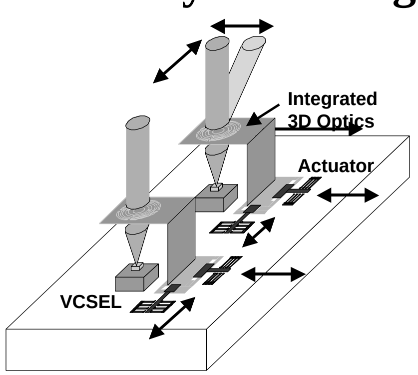
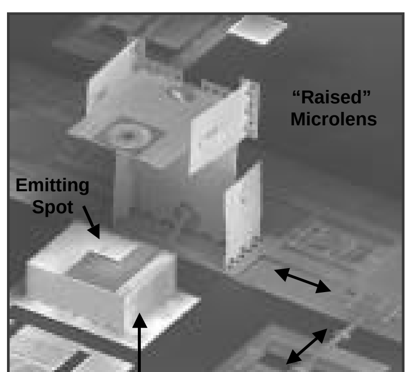
2D Scanning Microlens with Integrated Microactuators and Hybrid-Integrated VCSEL



Si Free-Space
Micro-Optical Bench

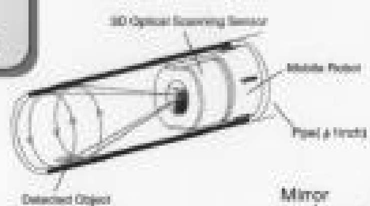


Hybrid-Integrated
Vertical Cavity
Surface-Emitting Laser

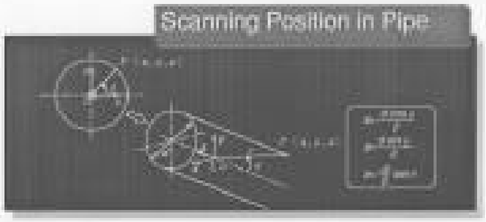
Sensor Structure for Pipe Inspection

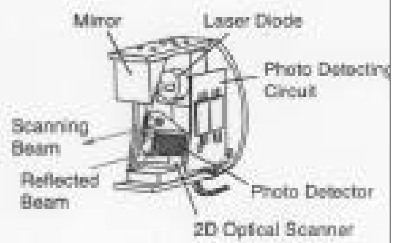
Circular Scanning

Reflected Beam Intensity Detecting



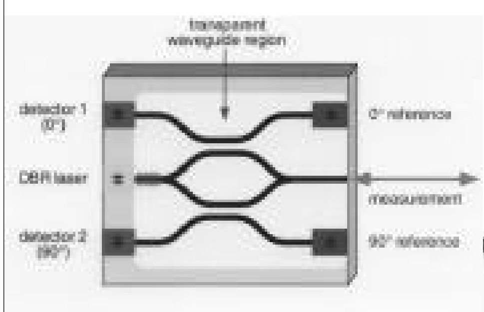
Scanning Position in Pipe





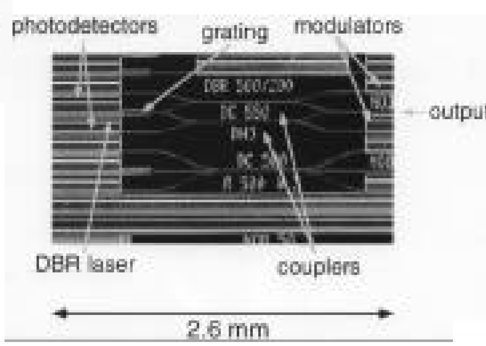
OMRON

Integrated Michelson Interferometer



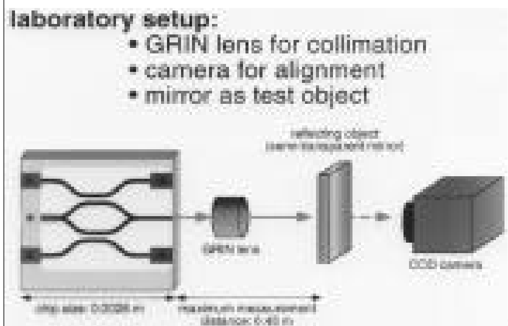
Measure displacement and Movement direction of external Object with high resolution

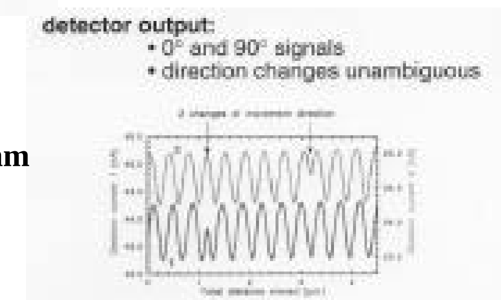
Integrated Interferometer



PSI PAUL SCHERRER INSTITUT
Zurich, Switzerland

Displacement Sensor Performance





System resolution < 20nm

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Zurich, Switzerland

Micro Bio-Assay System

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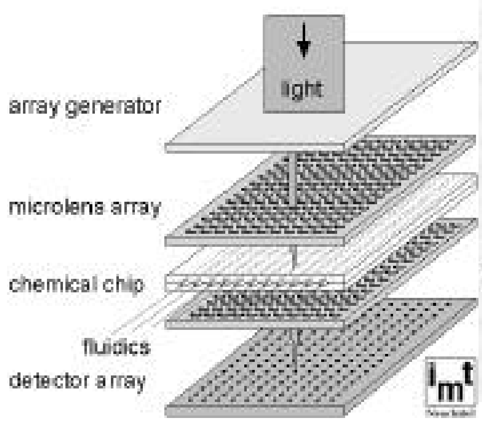

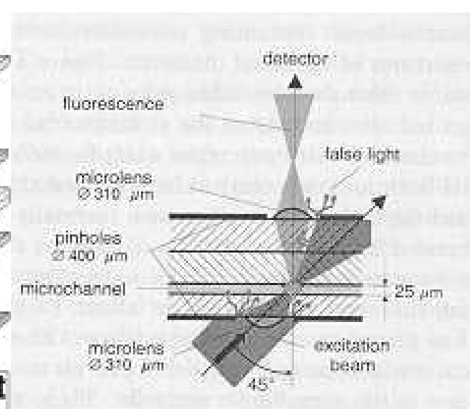

Micro Bio-Assay System

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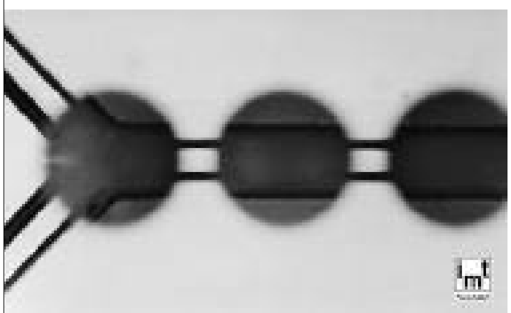
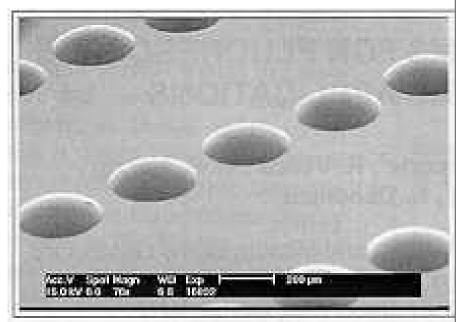
Micro Fluidic Chamber | **Micro Lens Array**





Cavity Ring Down Spectroscopy

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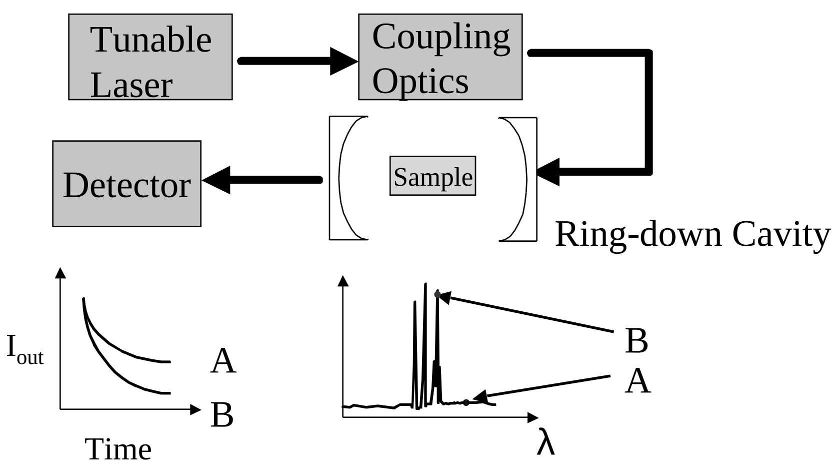
Absorption spectroscopy for detection of low levels of species



O-MEMS is an Enabling Technology for the New Millennium

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- Communications: Fiber Switches. Femtosecond Lasers, Pulse Shaping, Modulators, Tunable Optical Devices
- Optical Interconnects
- Optical Data Storage
- Displays: Projection, Head Mounted - Virtual Reality
- Repro-graphics: Printing, Scanners
- Adaptive Optics
- Optical Transducers and Sensors
- Optical Spectroscopy and Instrumentation

Where To Find Information?

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O-MEMS WWW Web Sites

- http://snowmass.stanford.edu/
  Tunable Filters, Photodetectors and Lasers:
- http://www.htc.honeywell.com/cap/sensors/sensors.html
  fiber-optic and sensors
- http://www.sandia.gov/LabNews/LN09-15-95/microengine.html
  Microengines
- http://www.janet.ucla.edu/dmsr.index.html
  Micromachined optical bench
- http://eto.sysplan.com/ETO/MEMS/Prog_Summaries/steering.html
  DARPA ETO Electromagnetic/Optical Beam Steering program
- http://www.ti.com/dlp/docs/papers/mems/0memsab.htm
  TI's Digital Mirror Devices
- http://www1.psi.ch/www_f3b_hn/home.html
  Interferometer
- http://dmtwww.epfl.ch/ims/www.html
  MEMS WWW sites around the world