Optical MEMS in Communication and Sensing

Fabrication, Design, and Scaling of Optical Microsystems

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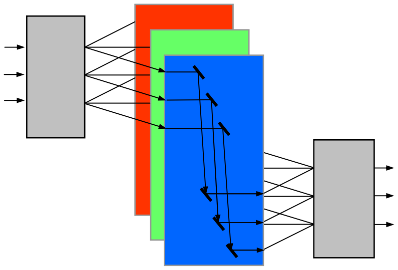
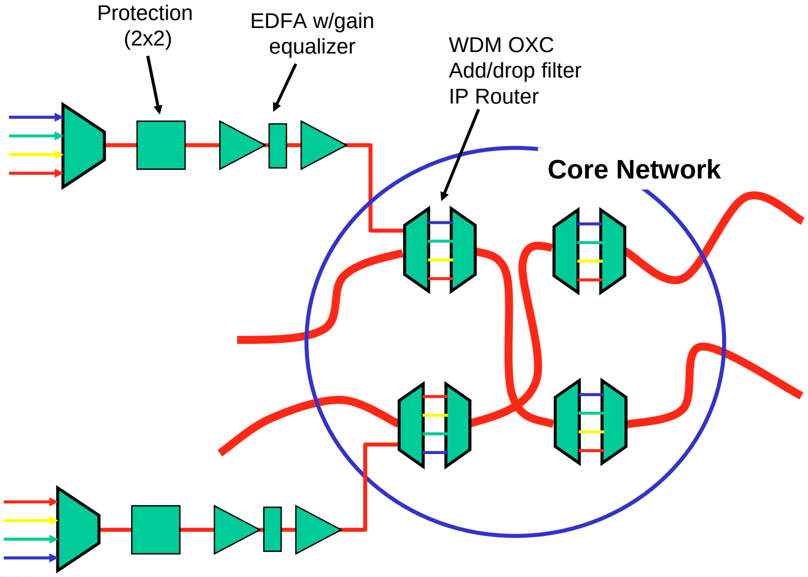
Section 3 Selected Applications

- Optical MEMS for Telco
- Fiber switch concepts and implementations
  - 2x2 switch, Matrix switch, 3-D switch
- In-vivo microscopy
  - Cancer detection, femto-second laser surgery
- Diffractive optical MEMS
  - Displays, sensors, filters, spectrometers



WDM Networks



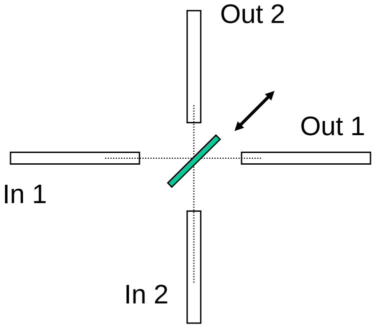
Protection (2x2)

EDFA w/gain equalizer

WDM OXC
Add/drop filter
IP Router

Core Network

2 x 2 fiber-optic switch



- 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.......

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1 x 2 Matrix Switch

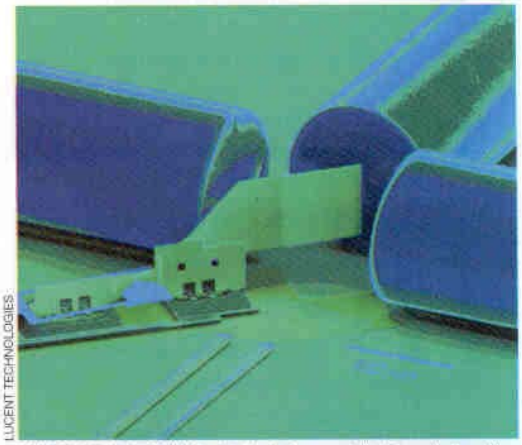
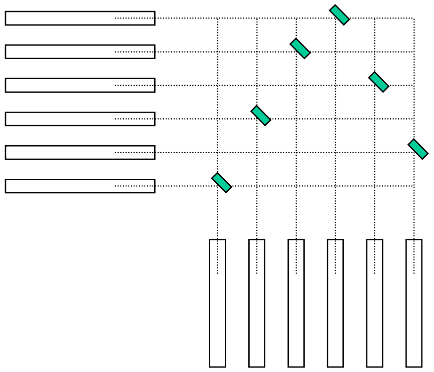

LUCENT TECHNOLOGIES

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

NxN Matrix OXC



- *Advantages:*
  - Alignment
  - Packaging
  - Simple 1 by 2 cross-points
  - Digital mirrors
- *Limitations:*
  - N^2 Scaling
  - Speed
  - Device count => yield
  - Non-standard fabrication processes
  - Large motion
  - Actuator reliability
  - Competition from waveguide based switches

Scaling of NxN Matrix OXC

$$s = N \cdot k\omega_l =$$

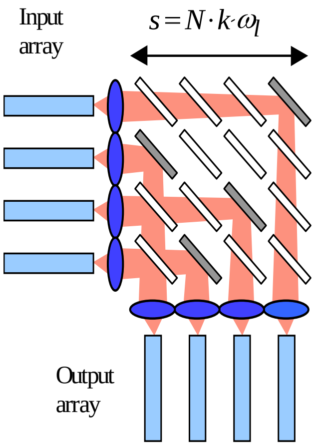
$$N \cdot k\omega_0 \left[1 + \left(\lambda s / \pi\omega_0^2\right)\right]^{1/2}$$

$$\Rightarrow N = \frac{s}{k\omega_0 \left[1 + \left(\lambda s / \pi\omega_0^2\right)\right]^{1/2}}$$

$$\Rightarrow N_{max}(s) = \frac{1}{k}\sqrt{\frac{\pi s}{2\lambda}}$$

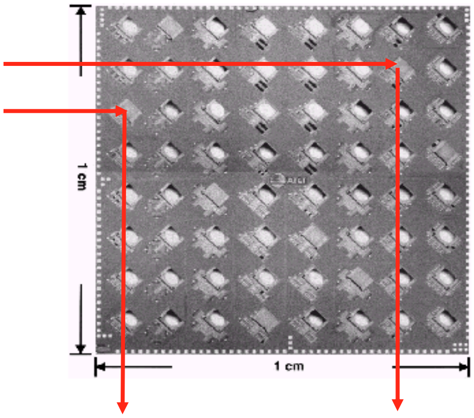
$$\Rightarrow s = \frac{2N^2 \cdot k^2 \lambda}{\pi} =$$

$$\frac{N^2 \cdot 50 \cdot 1.55\mu m}{\pi} \approx N^2 \cdot 25\mu m$$



8x8 Matrix Switch

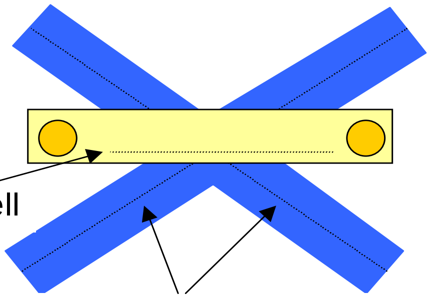
- Pro:
  - Simple packaging
- Con:
  - Scaling
  - Large device count
  - Complex actuator technology



L.Y. Lin, E.L. Goldstein, R.W. Tkach, Journal of selected topics in Quantum Electronics, Vol. 5, No. 1, Jan 1999

Waveguide Cross Connects

Champagne Switch (Agilent)



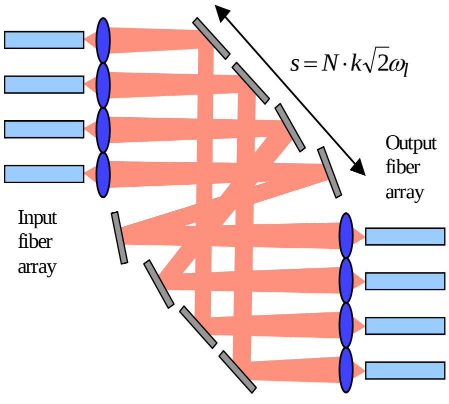
TIR cell

Single mode optical waveguides

Scaling of MEMS matrix cross-bar switch

- Insertion loss
  - Typically the optical signal must travel through N switch points. The insertion loss of each switch point becomes an imporatnt issue
- Yield
  - A NxN cross-bar has N^2 elements
  - Each element must move a large distance
  - => low yield
- Diffraction
  - A free space MEMS cross bar becomes prohibitively large when N>30
- Conclusion: Cross bar switches will in practice be limited to 30x30

Beam Steering MEMS Switch



- *Advantages:*
  - 2N Scaling!
  - Compact design with 2-D mirrors
  - Device count
  - No competition!
- *Limitations:*
  - Speed
  - Mirror quality
  - Alignment, packaging
  - Integration
  - Analog control
  - Fabrication

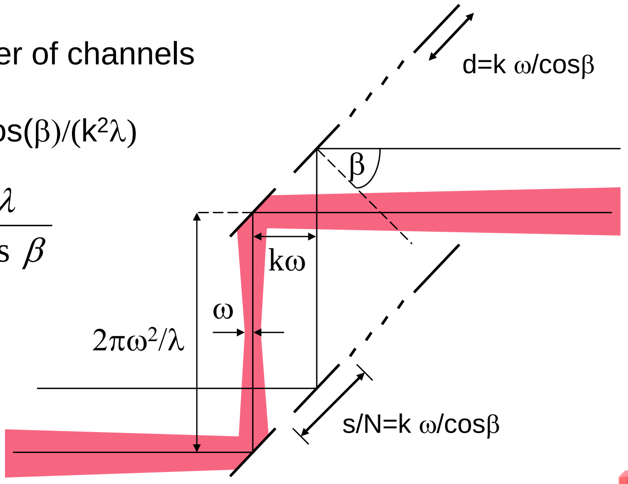
Scaling of Beam Steering Switch

Maximum number of channels (Small angles):

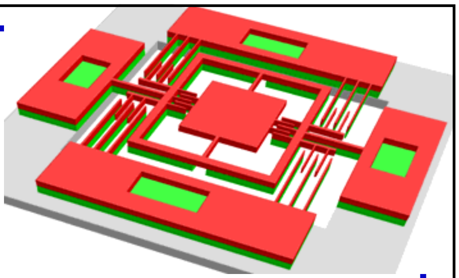
$N_{1\text{-}D}=1+8\pi\cdot d\cdot\theta\cdot\cos(\beta)/(k^2\lambda)$

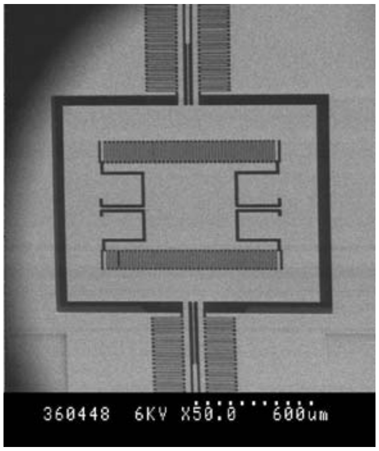
$$s=\frac{N^2\cdot k^2\lambda}{8\pi\cdot\theta\cdot\cos\beta}$$

$$\approx N^2\cdot 10\,\mu m$$

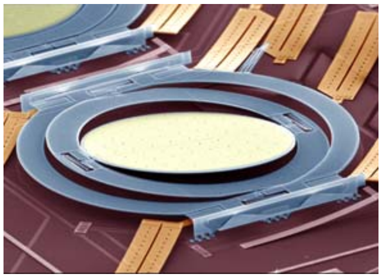


2-Axes uscanners



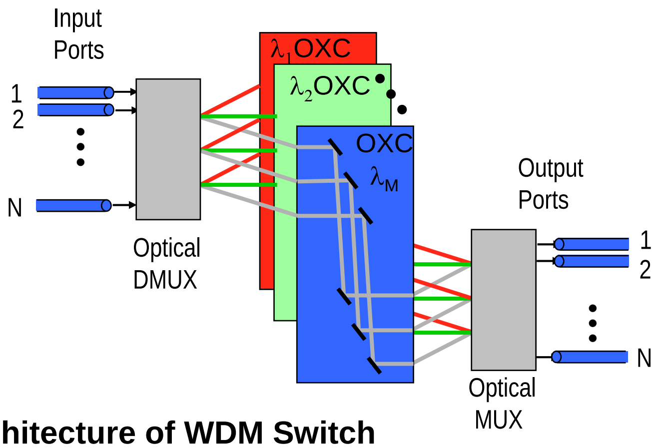


2-axes scanner actuated by self-aligned combdrives



Lucent’s 2D OXC micromirror

Transparent WDM Crossbar Switch



Architecture of WDM Switch

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

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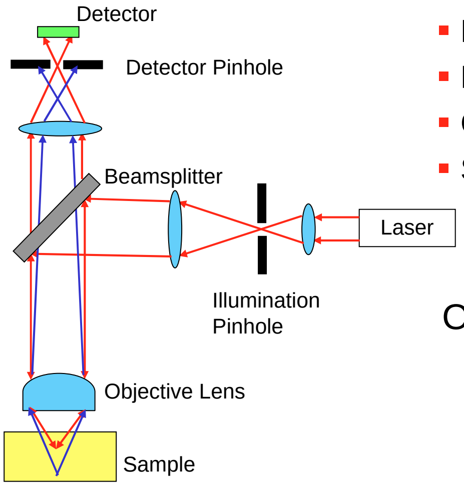
Conclusions – Beam Steering

- **Good News:** The Beam-steering 3-D Switch Architecture allows Scaling to 1,000 by 1,000 fiber ports and beyond!
- **Bad News:** The 2-D mirrors required for The Beam-steering 3-D Switch Architecture are extremely hard to package and operate
- Mirror Design
  - Gimbal for high-resolution 2-D beam steering
  - Mirror motion on the order of 40 micron is required
  - NxN cross-bar switch
- Packaging
  - Fabrication of 2-D fiber arrays
  - Alignment of 2-D fiber arrays
  - Active damping?
  - Complex Control electronics
  - High driving voltage

Confocal Microscopy

- Basic Principle

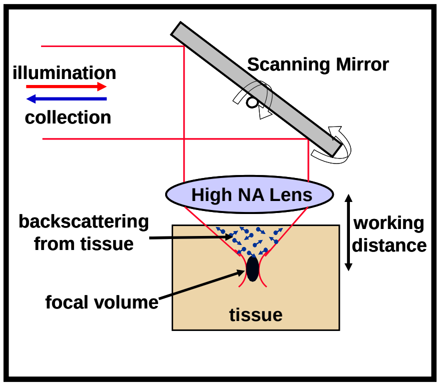


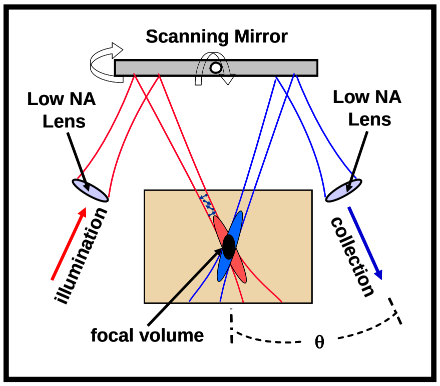
- Point Illumination
- Point Detection
- Confocal Lens System
- Scanned Image

↓

Optical Sectioning

Confocal Architectures



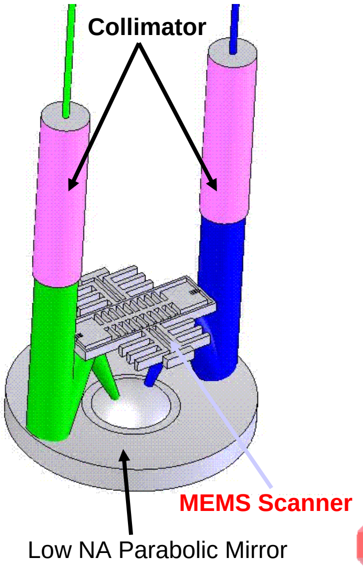


Single-Axis

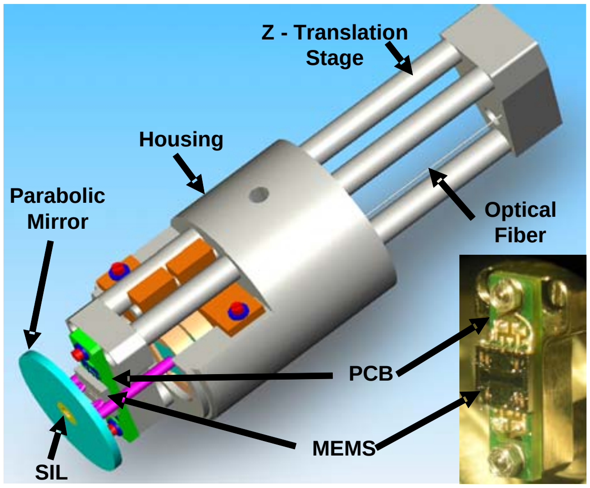
Dual-Axes

Motivation for MEMS

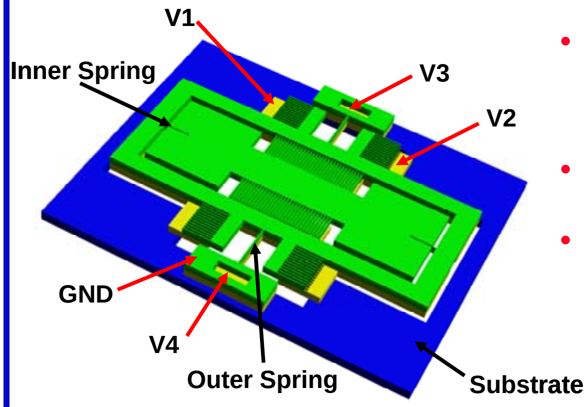
- Enables post-objective scanning
- Scanning in a compact design for *in vivo* imaging
- Higher range of motion for larger field of view
- High quality, flat mirrors for good imaging



Dual-Axes Handheld Probe



MEMS Scanner Design



- Electrostatic actuation
  - Self-aligned vertical comb actuators
- 2-D gimbal structure
- Two SOI layers stacked on the substrate
  - Precise thickness control
  - Electrical isolation

Ra et al., IEEE MEMS 2006

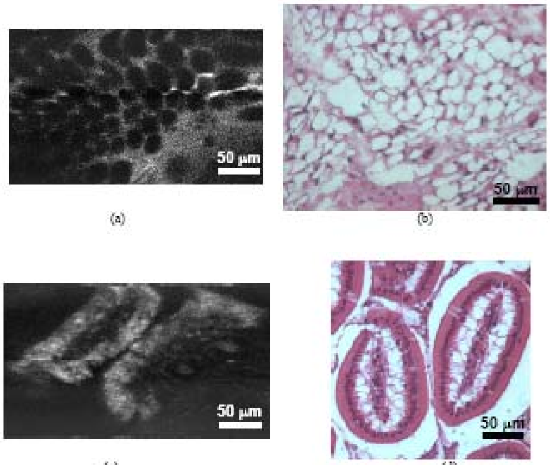
- *Ex vivo* image of freshly excised GFP mouse tissue and corresponding histology slide image

(a) Adipocytes in thigh region

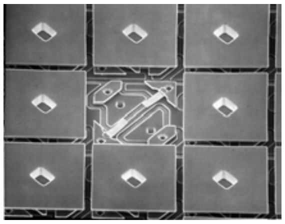
(b) Histology slide of adipocytes

(c) Villi in the small intestine

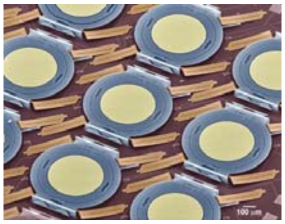
(d) Histology slide of small intestine



Traditional Optical MEMS – Amplitude Modulation

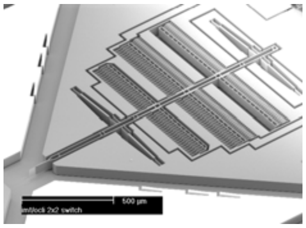


Texas Instrument's DMD



Lucent's Lambda Router

Onix's matrix switch



Bryant Hichwa et al, OCLI/JDS Uniphase, Optical MEMS 2000, Kauai, August 21-24th, 2000.

- Optical MEMS uses IC fabrication technology to create large arrays of precise micro-optical components
- Typical examples are micromirror arrays for projection displays and fiber switches based on amplitude modulation
- Diffractive Optical MEMS utilizes phase modulation to create optical functions

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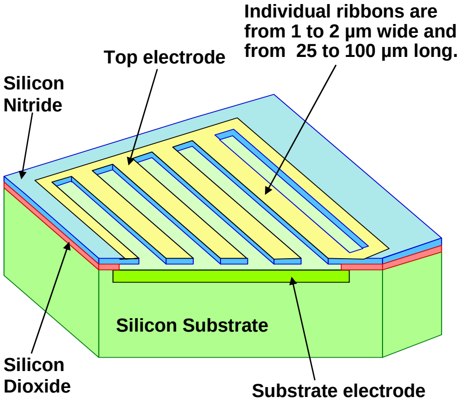
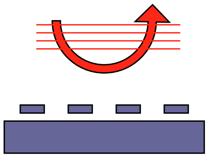
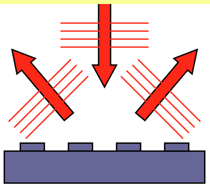
Grating Light Modulator



Beams up, reflection

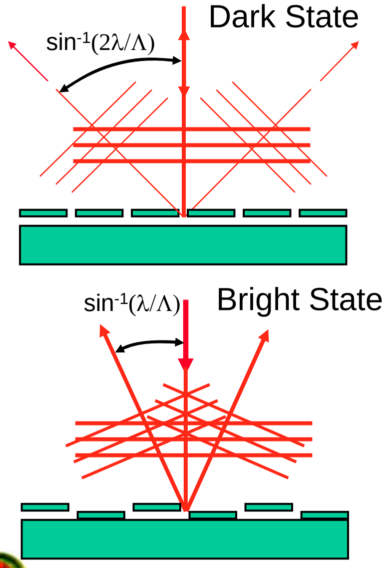


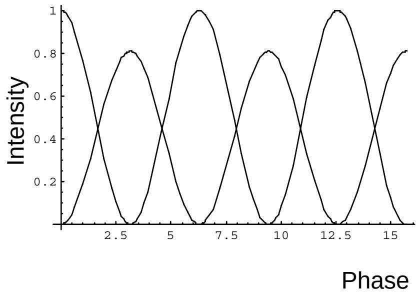
Beams down, diffraction



Cross section

High Contrast GLM



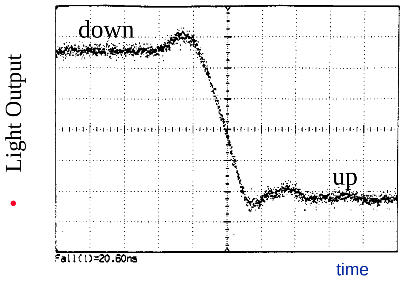


$$I^0 = \frac{I_0}{2}(1+\cos\theta)$$

$$I^{\pm1} = 0.81\cdot\frac{I_0}{2}(1-\cos\theta) \quad \text{(both orders)}$$

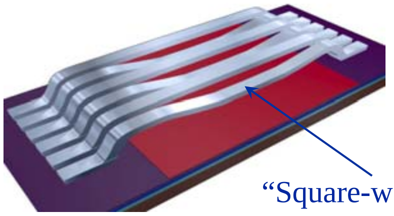
High Speed Switching

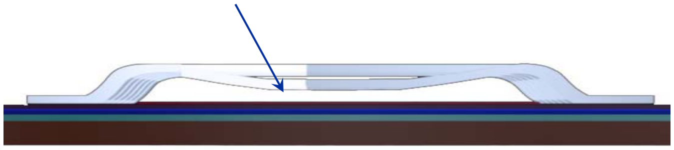
GLV devices switch in as little as 20 nsec (~1,000 times faster than TI DMD)



20 nsec Switching Speed

GLV Pixel Structure





GLV Device Efficiency

Example: 25 µm pixel, 3 ribbon pairs

Aluminum reflectivity: 91%

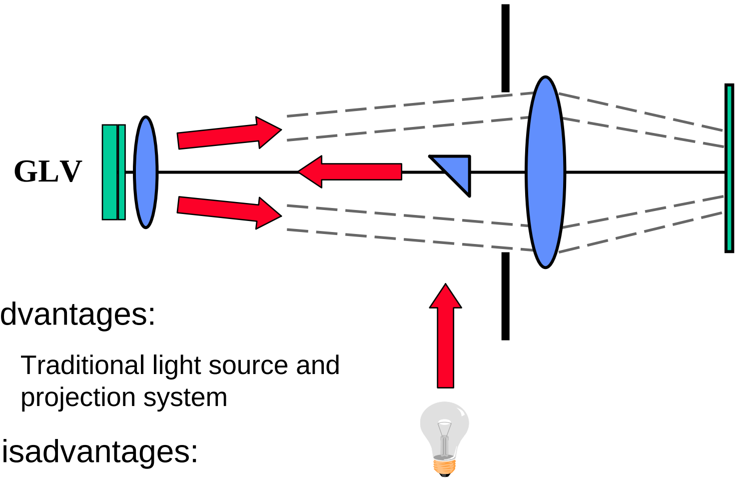
Diffraction efficiency (±1 orders only): 81%

Ribbon / gap fill factor (0.6 µm gaps): 95%

Total device efficiency ~70%

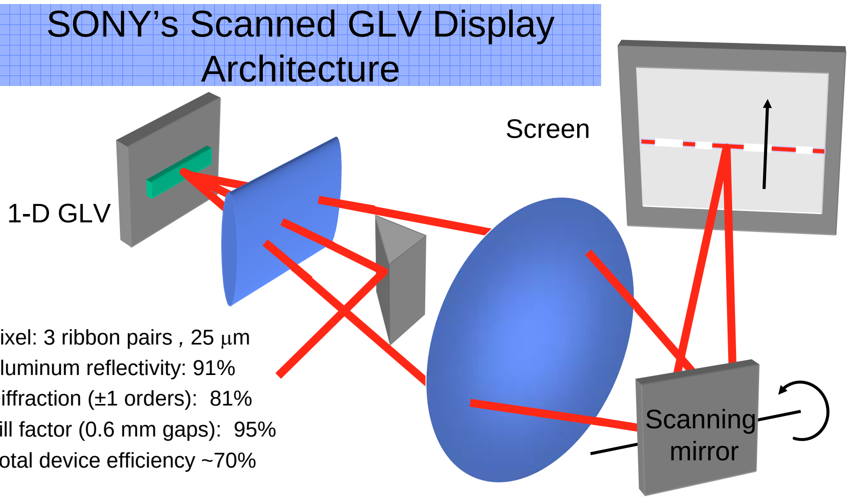
Courtesy of Silicon Light Machines

Basic Projection System



- Advantages:
  - Traditional light source and projection system
- Disadvantages:
  - 2-D Addressing
  - Large Array =>Low yield

SONY's Scanned GLV Display Architecture



Pixel: 3 ribbon pairs , 25 μm
Aluminum reflectivity: 91%
Diffraction (±1 orders): 81%
Fill factor (0.6 mm gaps): 95%
Total device efficiency ~70%

- Advantages: Few elements => high yield, simple integration and multiplexing, analog, no-touch operation
- Requirements: Coherent source, scanning mirror, high speed, good power handling
- S.R. Kubota, "The Grating Light Valve Projector", Optics & Photonics News, vol. 13, no. 9, September 2002, pp. 50-53.

GLM Applications

- Displays – Grating Light Valves (Silicon Light Machines)
- Voltage controlled optical Attenuators & WDM equalizers (Light Connect, Inc.)
- Free-space communication
- Displacement sensors
  - High sensitivity, Simple structure, Easy alignment, Suppression of common mode vibration and laser-pointing noise
  - Near-field probes (arrays)
  - Pressure Sensors
  - Accelerometers
  - IR detectors
  - Bio-sensors

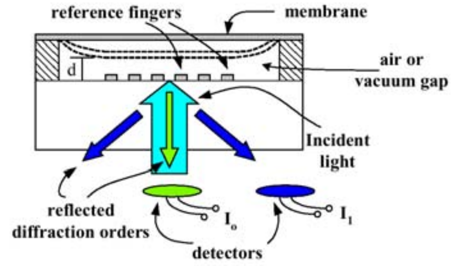


Figure 1. Schematic diagram of the optical microphone with integrated optical diffraction grating.

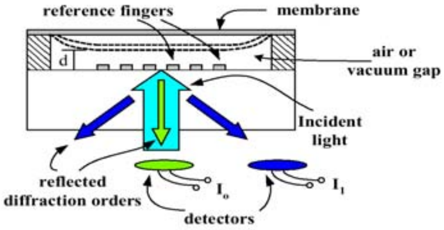
N.A. Hall, F. Levent Degertekin, "Self-Calibrating Micromachined Microphone with Integrated Optical Displacement Detection", Proceedings of Transducer'01, Munich, Germany, June 10-14, 2001.

Voltage Controlled Optical Attenuators and Channel Equalizers

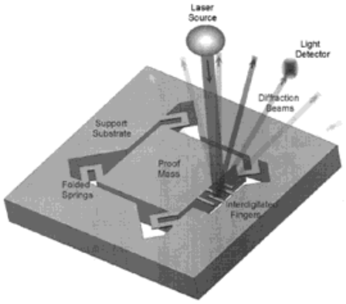
- Requirements for Fiber optic VOAs and Channel Equalizers:
  - Polarization insensitivity
  - Achromaticity
- Polarization Insensitivity is achieved by using a four-fold symmetric grating
- Reduced chromaticity is obtained by building a three-level grating that has equal amounts of chromatic attenuation in both the reflective and diffractive state

A. Godil, "Diffractive MEMS technology Offers a New Platform for Optical Networks", Laser Focus World, May 2002.

Grating Light Modulator Sensors



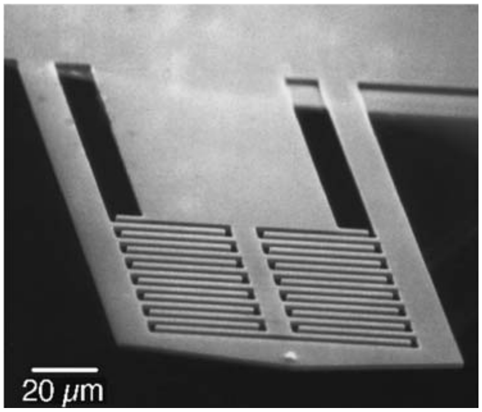
N.A. Hall, F.Levent Degertekin, "Self-Calibrating Micromachined Microphone with Integrated Optical Displacement Detection", Proceedings of Transducer'01, Munich, Germany, June 10-14, 2001.



N.C. Loh, M.A. Schmidt, S.R. Manalis, "Sub-10 cm^3 Interferometric Accelerometer with Nano-g Resolution", Journal of Microelectromechanical Systems, vol. 11, no. 3, June 2002, pp. 181-187.

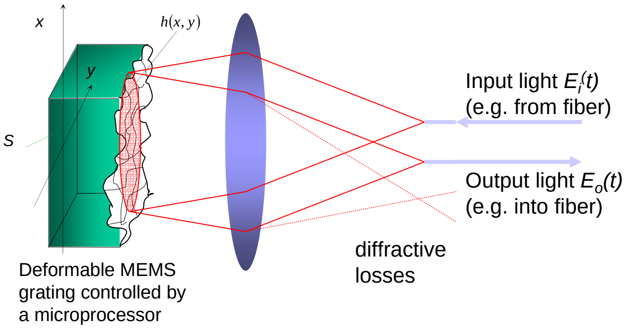
- Simple fabrication and alignment, High sensitivity, suppression of common-mode vibration and laser-pointing noise
- Applications: Near-field probes (arrays), Pressure Sensors, Accelerometers, IR detectors, Bio-sensors

GLM Atomic Force Microscope



G.G. Yaralioglu, A. Atalar, S.R. Manalis, C.F. Quate, “Analysis and Design of an interdigital cantilever as a displacement sensor”, Journal of Applied Physics, vol. 83, no. 12, 15 June 1998, pp. 7405-7415..

Tunable Diffractive Optical Filters



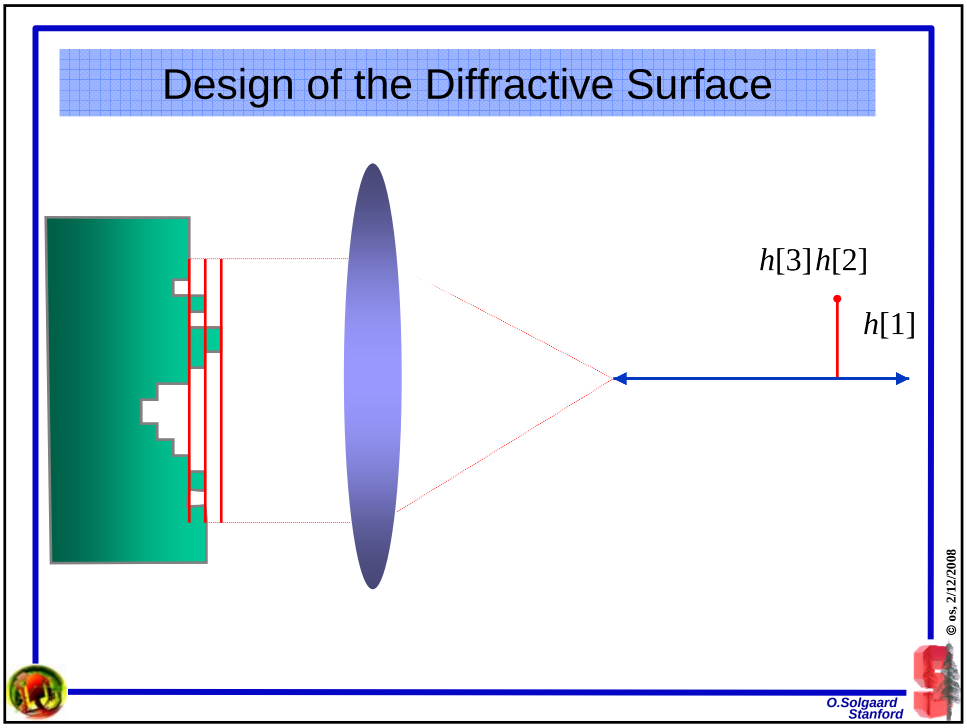
Input light $E_i(t)$
(e.g. from fiber)

Output light $E_o(t)$
(e.g. into fiber)

diffractive
losses

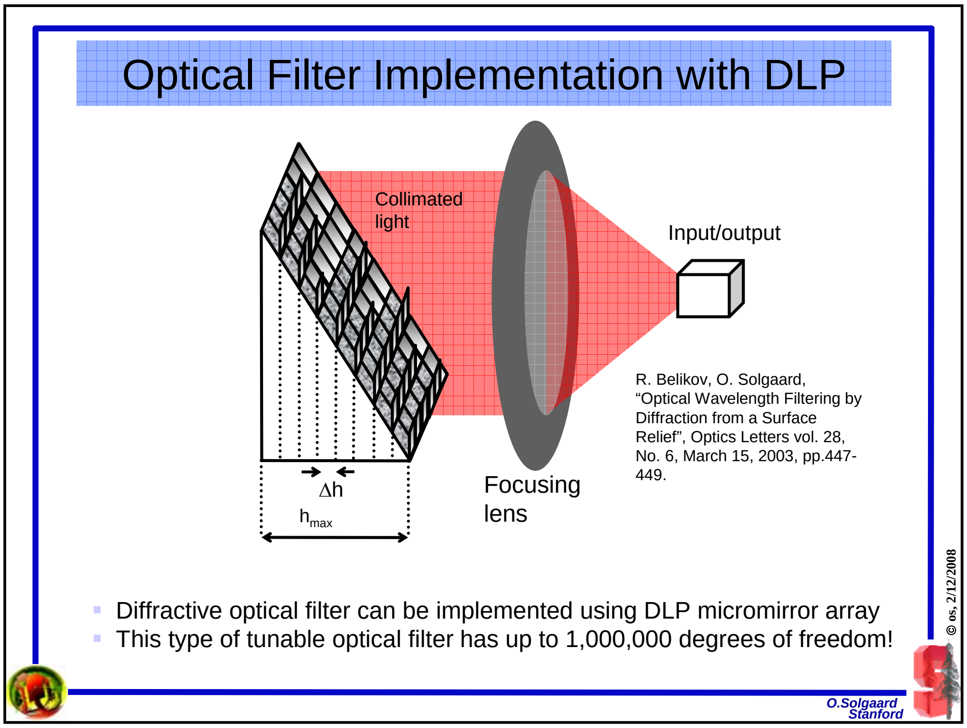
Deformable MEMS
grating controlled by
a microprocessor

- Goal: Programmable optical filters
- Enabling technology: diffractive MEMS micromirror arrays with deformable surfaces



Design of the Diffractive Surface

© os, 2/12/2008



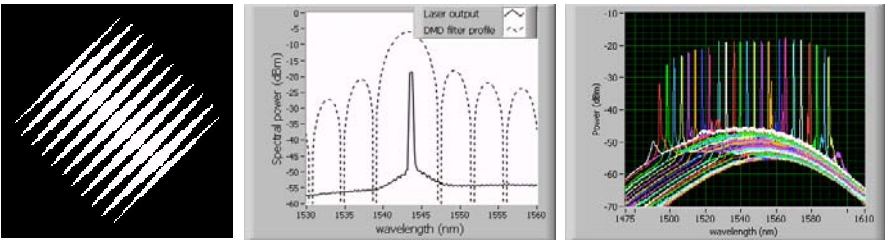
Optical Filter Implementation with DLP

R. Belikov, O. Solgaard, "Optical Wavelength Filtering by Diffraction from a Surface Relief", Optics Letters vol. 28, No. 6, March 15, 2003, pp.447-449.

- Diffractive optical filter can be implemented using DLP micromirror array
- This type of tunable optical filter has up to 1,000,000 degrees of freedom!

© os, 2/12/2008

Measurements: Changing spectral amplitude



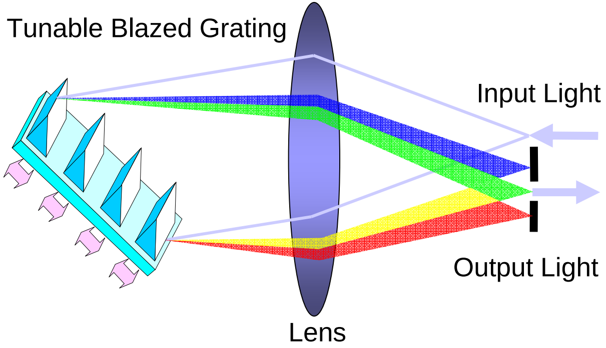
(a) (b) (c)

a) Computed DMD pattern for bandpass filter at 1543nm (white: “on” state, black: “off” state)

b) Measured laser spectrum and simulated DMD filter profile for the pattern in (a)

c) Overlaid spectra showing the tuning of the laser by uploading appropriate DMD patterns.

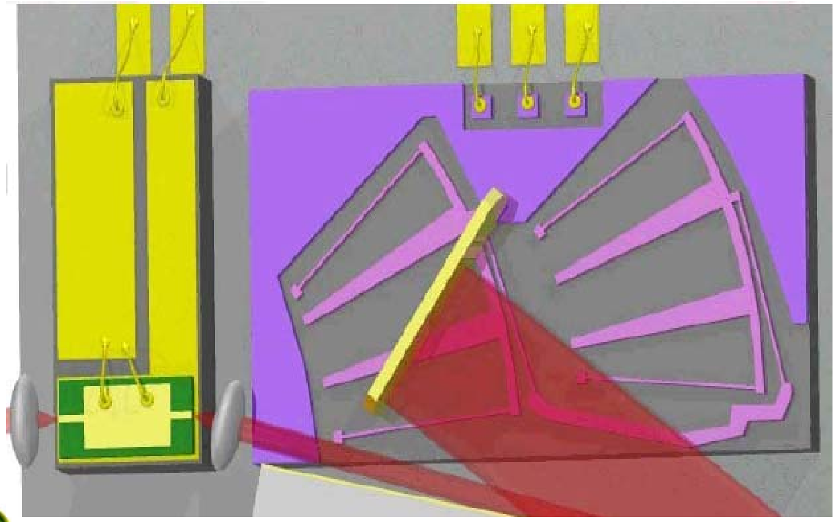
Tunable Blazed Gratings



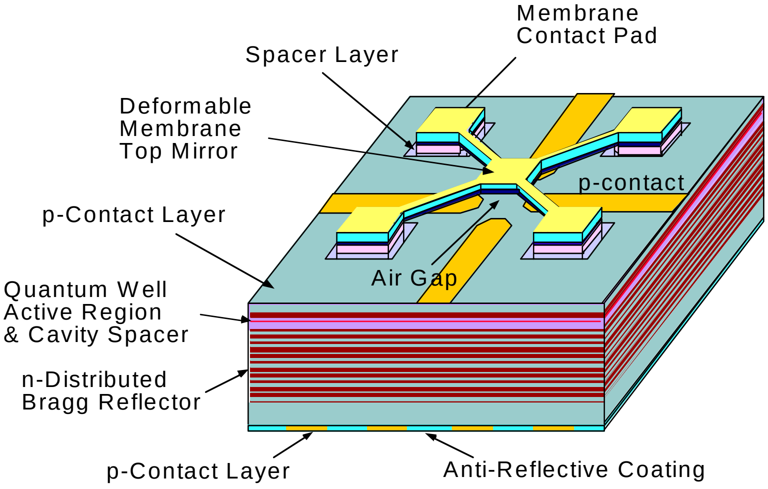
- MEMS Tunable Blazed Gratings combines high diffraction efficiency and high dispersion
- Amplitude modulation is enabled by rotation of grating elements
- Applications: ECL, Tunable Optical Filter, Optical Demultiplexers, Optical Add-Drop Filters, Channel Equalizer….

Tunable Lasers

2002: Iolon introduces tunable external cavity semiconductor lasers



Tunable VCSELs



Membrane
Contact Pad

Spacer Layer

Deformable
Membrane
Top Mirror

p-Contact Layer

p-contact

Air Gap

Quantum Well
Active Region
& Cavity Spacer

n-Distributed
Bragg Reflector

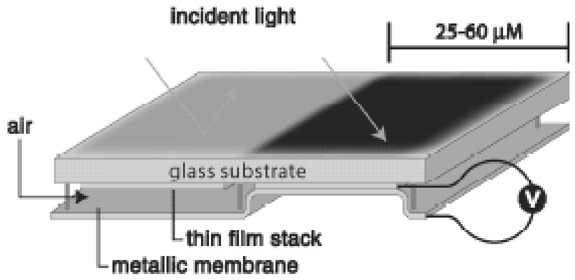
p-Contact Layer

Anti-Reflective Coating

Courtesy J. Harris, Stanford University

Optical MEMS is dead - NOT!

Sept. 2004: QUALCOMM acquires Iridigm Display Corp.



2005	Most Optical MEMS Fiber Switch companies are out of business (there are a few notable exceptions)
2005	Nano-technology is big business!
2006	Nanogratings and Photonic Crystals combined with MEMS enable sensors with improved sensitivity and stability

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Conclusions and future directions

- Micromachined optical switches
  - MEMS is ideally suited for small OXC, very simple 2x2 architecture, straight forward scaling to 32x32
  - Beam steering requires 2N mirrors for NxN matrix and enables scaling to 1,000 by 1,000 or more
- Challenges
  - Optical quality, large switches, reliability, speed, fiber alignment, standardized foundry fabrication process, packaging
- In-vivo imaging with OCT, Confocal microscopy, two-photon microscopy…
- Diffractive SLMs and Coherent Micromirror Arrays (1-D and 2-D) extend the application areas of Optical MEMS
  - Traditional Applications: Projection displays, Fiber switches
  - Emerging applications: Spectroscopy and tunable filters, WDM, CDMA,
  - Advantages: Speed, optical quality, phase corrections
  - Challenges: Complicated fabrication and control
- MEMS leverages parallel-processing and dimensional control of IC manufacturing and enables:
  - Remote sensing, Displacement sensors, Optical scanners, Free-space laser communication, Femto-second laser pulse shaping, Spectroscopy, Fiber switches, Alignment and aberration compensation, Displays, Microscopy, Optical coherence tomography, External cavity lasers, Diffractive lenses, Data storage, Barcode readers, Adaptive optics, Printers, Optical vector scanners, Surveillance, Optical interconnects.....