Lecture for EE 233

Optical MEMS for Telecommunication Systems

Ming C. Wu
University of California, Berkeley
Department of EECS & Berkeley Sensor and Actuator Center (BSAC)
wu@eecs.berkeley.edu

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  - PhC switch: M.C. “Mark” Lee
  - MEMS Microdisk: M.C. “Mark” Lee, Jin Yao, David Leuenberger
  - Si Photonics: Sagi Mathai, Joanna Lai, Xin Sun (Prof. Tsu-Jae King)
OUTLINE

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

Why Optical MEMS ?

• Optical MEMS offers
  – Low optical insertion loss
  – Low crosstalk
  – Transparency (wavelength, polarization, bit rate, data format)
  – Low power consumption

• Why ?
  – The effect of moving optical elements is stronger than electro-optic, thermal-optic effects
  – Very efficient beam steering devices

• What
  – Switches
  – Tunable devices (delay, dispersion, wavelength, bandwidth, dynamic gain equalization, etc)
Optical MEMS

Fusion of Three Technologies

Laser 1960
Semiconductor Laser Waveguide

Integrated Circuit 1958
Transistor

Resonant Gate Transistor
Nathanson, 1967

Petersen, "Silicon as a mechanical material," IEEE Trans. 70, 1982

Micro Optics

Opto-
Mechanics

Opto-
Electronic

Optical MEMS

Micro Mechanics

Electronic-
Mechanics or MEMS

Micro Electronics

25 Years of Optical MEMS

Scanning Mirror (Petersen, IBM)
Micomotoers (Berkeley)
Free-Space Optical Bench (UCLA/Berkeley)
3D MEMS Switches

1980 1990 2000

Digital Micromirror Device (DMD, TI)
Grating Light Valve (GLV, Stanford)
2D MEMS Switches (Tokyo U)

Silicon Light Machine
Digital Micromirror Devices (DMD)

~ 1 million DMD's on a chip

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

Digital Micromirror Device (DMD)

Texas Instruments

L. Hornbeck, Electronic Imaging, 1997
Detailed Layer Structure of DMD

L. Hornbeck, Electronic Imaging, 1997

TI's Digital Micromirror Devices (DMD)

(Texas Instruments, Digital Micromirror Device™)
Transfer Characteristics of Torsion Mirrors

![Graph showing transfer characteristics of torsion mirrors with pull-in voltage or stiffness voltage formula: $V_s = \sqrt{\frac{2 \cdot z_0^3}{\varepsilon WL'C}}$]

Principle of Projection System Using DMD

![Diagram of a projection system using DMD with pixel mirrors and light source]

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Projection Display Using Digital Micromirror Display (DMD)

• DLP Board
• Processor
• Memory
• Projection Lens
• DMD
• Shaping Lens
• Optics
• Color Filter
• Condensing Lens
• Light Source

Bulk Micromachining

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

- <111>
- <100>
- <110>
- Vertical Sidewall

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

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

- Combine with silicon-on-insulator (SOI) or III-V epi wafer
- Suspended structure in one-step etching + releasing
- Multi-layer structure by additional wafer bonding
Surface-Micromachining: 2 “Standard” Foundry Process

MUMPs

SUMMiT

- MEMSCAP

- Sandia National Lab
- Fairchild (SUMMiT-4)

MEMS Technologies and Optical Element Size

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<td>Surface-Micromachining (Poly-Si, Al)</td>
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<td>Projection display</td>
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<td>2D MEMS Switch</td>
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</table>
Optical Designs

Direct Coupling Without Lenses

- Short propagation distance
- May be used for small switches or VOAs
Example: 2x2 Switch


Free-Space Optics: Gaussian Beam

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

\[ b = \frac{\pi w_0^2}{\lambda} \]  

(Confocal Parameter)

- Larger beam waist ➔ Long collimation length
- System size ~ 2b
- Mirror diameter ~ 2aw₀, \( a \sim 1.5 \) to 2
Space Division Switches:

(1) 2D MEMS Optical Switches

(2) 3D MEMS Optical Switches

Scaling of 2D MEMS Optical Switches

\[ N : \text{Port Count} \]
\[ P : \text{Fiber Pitch} \]
\[ L = NP \approx 2b = \frac{2\pi w_0^2}{\lambda} : \text{Chip Length} \]
\[ \eta = \frac{2R}{P} : \text{Fill Factor of Micromirror} \]
\[ R = a w_0 : \text{Mirror Radius,} \]
\[ a \sim 1.5 \text{ to } 2 \]

\[ \Rightarrow N \approx \frac{\pi \eta}{a \lambda} w_0 \]
\[ L = \left( \frac{2a^2 \lambda}{\pi \eta^2} \right) \cdot N^2 \]
Port Count of 2D MEMS Switches

Port Count vs Beam Size

Loss Due to Mirror Tilt

Fill Factor = 70%, 50%, 30%

Mirror Tilt = 0.2°, 0.1°, 0.05°

Port Count: \( N \approx \frac{\pi \eta w_k}{a \lambda} \)

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

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

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

16x16 Switch

Absolute angular uniformity ~ ± 0.05°

L. Fan, et al., OFC 2002
Scaling of 3D MEMS OXC

- Input Collimators
- 2D Array of 2-Axis Micromirrors
- Output Collimators

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

Optical Path Length: \( L = 2b = \frac{2 \pi w^2}{\lambda} \)

\( \Delta \theta \): Mechanical Scan Angle
\( R = aw_0 \): Mirror Radius
\( a \sim 1.5 \) to 2
\( w_0 \): Beam Waist

Lucent’s Lambda Router

(Lucent Lambda Router)
2D Scanners with Staggered Vertical Combdrives

Fujitsu, 2002

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Fujitsu Micromirror for 3-D MEMS Optical Switch

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Fujitsu’s 3-D MEMS Switch

(a)

Distortions by Thermal expansion & irregular mechanical shock (longitudinal direction)

In
MEMS Chip
Out
MEMS Chip

(b)

Roof-type mirror
Beam collimators

In
MEMS mirrors
Out

MEMS Si SiO2(O, D)

Mitsuhiro Yano, Fumio Yamagishi, and Toshitaka Tsuda, IEEE J. SELECTED TOPICS QUANTUM ELECTRONICS, VOL. 11, p. 383, MARCH/APRIL 2005
Fujitsu’s 3-D MEMS Switch

87x77x53 (mm³)

Wavelength-Selective Switches (WSS)
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Optical Network Architecture

- OADM (Ring)
  - Add-Drop with fixed \( \lambda \)’s
- ROADM (Ring)
  - Add-Drop with programmable \( \lambda \)’s
- 1xN Wavelength-Selective Switch (Mesh)
  - Multi-degree ROADM
- NxN Wavelength-Selective Cross Connect (Mesh)
Fourier Transform Pulse Shaper

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


Dynamic WDM Functions

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

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1x4 Wavelength-Selective Switch (WSS)

• D. Marom et al. (Lucent), OFC 2002
  – 1x4 WSS
  – Channel spacing: 50 or 100 GHz
  – MEMS performance: 12° (> 55 V )

• T. Ducellier et al. (JDS-U), ECOC 2002
  – 1x4 WSS
  – Channel spacing: 100 GHz
  – MEMS performance: ±2°
WSS provides:
- Port switching
- Wide passbands
- 10 dB DSE
- Blocking
- Low insert loss
- Low PDL, DGD

Analog Micromirror Array (UCLA)

- Fixed fingers
- Movable fingers
- Hidden springs
- Anchor

**Scan Angles**

<table>
<thead>
<tr>
<th>Applied Voltage (V)</th>
<th>Rotation Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5μm</td>
<td>0</td>
</tr>
<tr>
<td>1μm</td>
<td>1</td>
</tr>
<tr>
<td>2μm</td>
<td>2</td>
</tr>
<tr>
<td>3μm</td>
<td>3</td>
</tr>
<tr>
<td>DMD-Like</td>
<td>0.00085°</td>
</tr>
</tbody>
</table>

**Specifications**

- **Voltage**: 6 V
- **Fill Factor**: 98%
- **Res. Freq.**: 3.4 kHz
- **Stability (3hr)**: ±0.00085°
- **System (3hr)**: ± 0.0035dB

- J.C. Tsai, et al (UCLA) IEEE PTL 2004, p. 1041
Scaling of WSS

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

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

\[ N_{\text{spatial}} \cdot N_\lambda = \frac{\pi \cdot BW}{22 \lambda \cdot f^\#} \left( \frac{\partial \theta}{\partial \lambda} \right)_{\text{Grating}} \]

- System size ~ 2f
- Total capacity \((N_{\text{spatial}} \cdot N_\lambda)\) is constant
  - Proportional to \(f\)

Approach for Increasing Port Count (1)

- Use anamorphic prism pair to compress lateral beam size on MEMS micromirrors
- Elliptical beams on MEMS mirrors \(\rightarrow\) Rectangular micromirror
Approach for Increasing Port Count (2)

- 1xN² WSS:
  - 2D collimator array
  - 1D array of 2-axis micromirror array

- Port count is increased from N to N²
  - N is the diffraction-limited linear port count

- High port count WSS
  - 1x32 WSS has been demonstrated

High-Fill Factor 2-Axis Micromirror Array

- Gimbal-less
  - High Fill factor (> 98%)

- Large scan angle
  - 3x angle amplification by leverage

- Low voltage
  - Powerful vertical combdrive actuators

J.-C. Tsai, L. Fan, D. Hah, and M.C. Wu, IEEE LEOS International Conference on Optical MEMS 2004
SEM of Gimbal-less 2-Axis Analog Micromirror Array

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

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

Planar Lightwave Circuit (PLC) MEMS
Reconfigurable Optical Add/Drop Multiplexer (ROADM)

(a) Configuration of 16ch-100GHz OADM  (b) Photograph of OADM

(VG courtesy of K. Okamoto)

PLC 1x9 WSS

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

C.R. Doerr, et al. (Lucent), OFC 2002 Postdeadline Paper, FA3
2x2 MEMS Waveguide WSXC

- 3 diffraction orders by AWG
- Optical phases of (+1, 0, -1) orders modulated by MEMS piston mirrors
- Chip ~ 5 x 9 mm²


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

Hybrid PLC and Free-Space Implementation

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

Switch to Port 1
Switch to Port 2
Compact Spectral Pulse Shaper (D. Marom)

**Hybrid PLC and Free-Space Implementation**

- Fiber optic region
- Guided wave region
- Free space region

- Short pulse laser
- MEMS piston motion micromirror array
  - >2π phase modulation
  - Polarization insensitive

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

**2D arrangement of ports for scalable 1x9 WSS**

**Array** of Waveguide Dispersive Elements
- Collimating/Focusing lenses
- MEMS mirror linear array
Interleaved spectrum switched to all output ports

Free-Space and Hybrid Integrated 1xN WSS

Free-Space 1xN WSS
- Grating
- Optical Fibers
- Resolution Lens
- Large space
- Complicated alignment

Hybrid 1xN WSS
- Silica PLC has low insertion loss
- Hybrid integration requires external collimator and lens

D. Marom, et al. (Lucent), OFC 2002.
S. Huang, et al. (UCLA), O-MEMS 2002.

T. Ducellier et al. (Metconnex), ECOC, 2004
D.M. Marom et al. (Lucent), OMEMS 2004
D.M. Marom et al. (Lucent), ECOC 2005
Silicon-Based Monolithic 1x4 Wavelength-Selective Switch

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

C.H. Chi et al., CLEO 2005

Integrated Optical Components

- Parabolic Collimator
- Parabolic Focusing Reflector
- Blazed Micro-grating
- Electrostatic Micromirror

C.H. Chi et al., OFC 2006
**4x4 Wavelength-Selective Cross Connect**

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

**Monolithic 4x4 WSXC – Planar Integration**

- Support Broadcast and Multicast Functions
- 1x4 MMI splitter
- Waveguide Bending
- Waveguide Crossing

**Free-Space WSXC**

- D. M. Marom et al. (Lucent), ECOC 2003
- C. H. Chi et al., OFC 2006
Simulation

- **MMI (3D BPM)**
  - Splitting Loss = 6.1 dB
  - Nonuniformity = 0.004 dB

- **Waveguide Bend (2D FDTD)**
  - R = 100 μm
  - Loss = 1 dB
  - 1 μm Offset

- **Waveguide Crossing (2D FDTD)**
  - Loss 0.05 dB
  - Crosstalk -66 dB

Fabricated Device

- 1x4 WSS
- Solid Immersion Mirror
- Micromirror
- Collimator
- Micro-grating
- 4x4 WSXC
Spectral Response of 4x4 WSXC

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

Transfer Curve of 4x4 WSX

- Signals are selected from each input port and transported to the designated output port
- Extinction ratio from In1 is lower due to imperfect AR coating
Diffractive Optical MEMS

Grating Light Valve

- Applications
  - Projection display
  - Variable optical attenuators (VOA)
  - Gain equalizers
  - Wavelength blockers

- Companies
  - Silicon light machine (Cypress), Lightconnect, Polychromix, Kodak

Telecommunications Applications

Dynamic Spectral Equalizer (DSE)

MEMS Switchable WDM Deinterleaver Based on Gires-Tournois Interferometer

Olav Solgaard, Stanford University

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

Whispering Gallery Mode (WGM)

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

St Paul’s Cathedral, London
WGM in Silica Microsphere

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

Optical Microresonators

- Filter proposed by Marcatili (Bell Labs), 1969
- Channel dropping filter
- Needs high Q $> 10^5$
- Surface roughness $< 1$ nm
Microring Resonator-Based PIC

Thermally Tuned with Vernier Architecture

Variable Quality Factor

De-coupled | Under-coupled | Critically Coupled | Over-coupled
---|---|---|---
Frequency | Frequency | Frequency | Frequency

Scaling of Optical Wires

- In sensitive to surface roughness
- Multi-mode
- Lower density

Single Mode
\[ w \times t \leq 0.18 \, \mu m^2 \]

Surface Roughness
\[ \delta_{rms} \leq 1 \, nm \]

< 0.25-nm Surface Roughness by H\textsubscript{2} Annealing

Before Annealing

After Annealing

Surface Roughness < 0.25 nm
Microdisk Resonator with MEMS Tunable Coupler (First Generation Device)

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

Second-Generation MEMS Microdisk Resonator

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

Under Coupling ($\kappa < \alpha$)

Over Coupling ($\kappa > \alpha$)

Critical Coupling ($\kappa = \alpha$)

Microdisk

Slightly-bent

Largely-bent

Resonant Wavelength = 1549.37 nm

Parallel Configuration

Cross Configuration

Reconfigurable Optical Add-Drop Multiplexer (ROADM)

Input Through Add Drop

Transmission At Resonance

Transmission Through

Waveguide-Disk Spacing
Dynamic Wavelength Add-Drop

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

Spoiling Q by MEMS Metal Membrane

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

SUMMARY

• Tremendous progresses have been made in
  – MEMS devices and manufacturing
  – Micro-optics
  – Packaging
  – Control

• New trends in Optical MEMS – Integration
  – Higher level of integration, less free-space alignment
  – MEMS-PLC integration
  – MEMS-nanophotonics integration
  – Electronics integration
  – Single-chip optical MEMS system