MEMS-based Devices

Chengkuo Lee

[1]Department of Electrical & Computer Engineering, National University of Singapore

Lab website : http://www.ece.nus.edu.sg/stfpage/elelc/publications.html

NUS National University of Singapore

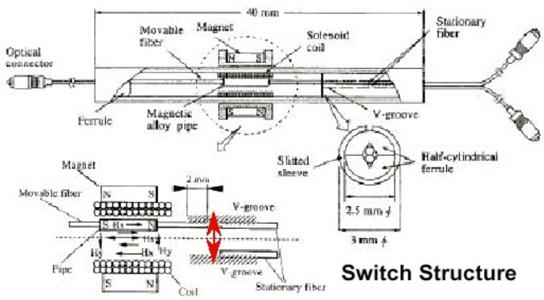
Outline

1. Introduction
2. Actuation Mechanisms
3. Outlooks & Concluding Remarks

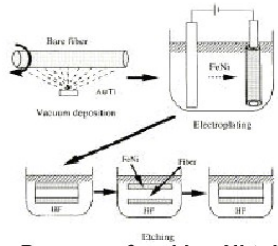
1. Introduction – Early Demonstrations

MEMS Fiber-Optic Switch Using Electromagnet

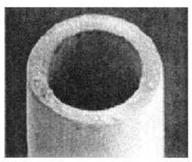
Nagaoka, IEEE J. STQE, Vol5, 1999, NTT



Switch Structure



Process of making Ni tube



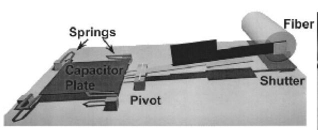
Ni Tube

50 μ m

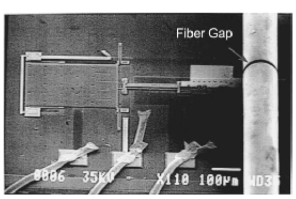
- Insertion loss 0.36 dB
- Return loss 49 dB
- Crosstalk - 70 dB
- Switching 0.2 ms
- Reliability 10^8 cycle (6.5 years)
- Cascaded to 1x8 configuration
- Latched by residual magnetism

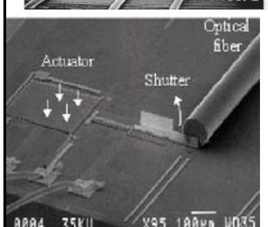
1. Introduction – Early Demonstrations

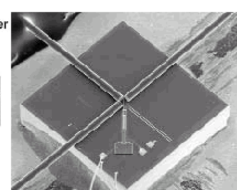
MEMS Moving Mirror - Optic Gate Switch Using Electrostatic Actuator

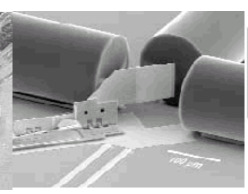


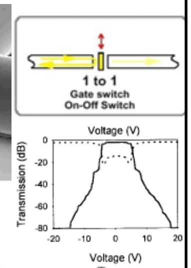
(a)

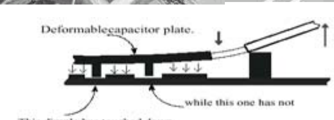












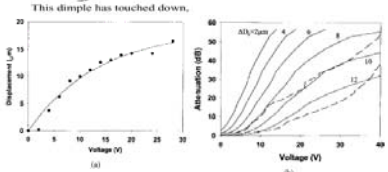
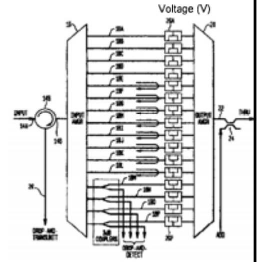


Fig. (a) Measured relative displacement of shutter as a function of applied voltage. Solid line is an exponential curve fit to the data. (b) Attenuation curves calculated from displacement curve and diffracted-beam calculation of fiber-to-fiber coupling with a knife-edge obstruction and for initial displacement of shutter and fiber axis ranging from 2 to 12 μm. Dashed curves are measured attenuation curves for two MEMS VOA's.



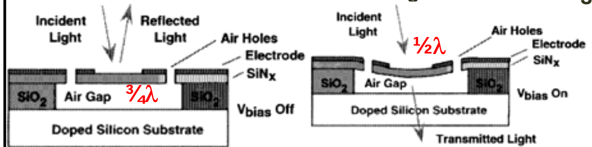
US Patent: 6148124; Lucent Technologie

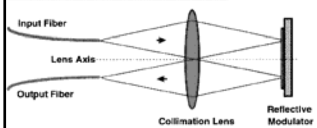
IEEE JSTQE_1999_Vol5_A silicon MEMS optical switch attenuator and its use inlightwave subsystems, C. R. Giles, V. Aksyuk, et al; Lucent Technologies.

1. Introduction – Early Demonstrations

MEMS Based Variable Optical Attenuators (VOAs)

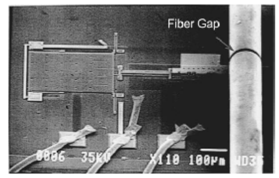
1. Electrostatic Deformable Mirror / Light Valves





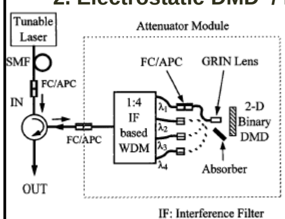
J. E. Ford et al., IEEE J. Lightwave Technol. V. 16, No.9, 1998, pp.1663-69.

3. Electrostatic Parallel Plate / Shutter Surface Micromachining



B. Barber et al., IEEE PHOTONICS TECHNOLOGY LETTERS, V. 10, No.9, 1999, pp.1262-64.

2. Electrostatic DMD / Reflection Mirror



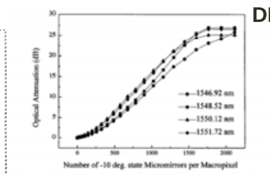
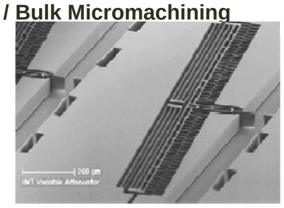


Fig. 4. Optical attenuation data for the four wavelengths versus the number of −10°-state micromirrors in a macropixel that were used in our experimental attenuator.

N. A. Riza et al., Optics Letters, V. 24, No. 5, 1999, pp.282-284.

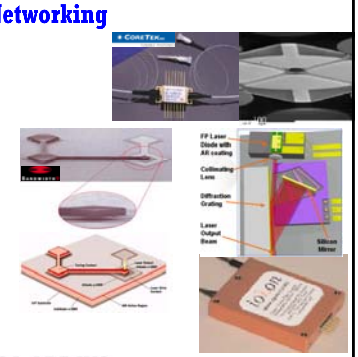
4. Electrostatic Comb Drive Actuator / Shutter DRIE / Bulk Micromachining



C. Marxer, et al.
IEEE PHOTONICS TECH LETTERS, V. 11,1999, pp.233-35.

1. Introduction – Early Demonstrations

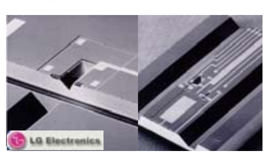
MEMS-Based Devices in Optical Networking

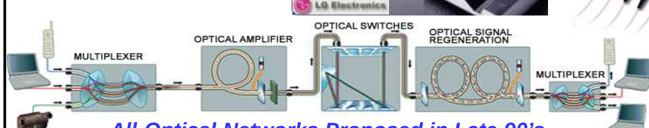


Possible MEMS Applications for Fiber Optic Transmission Network
*Tunable Laser, Filter, Receiver
*External Modular (Data Transmitter)
*Variable Optical Attenuator (VOA) and Dynamic Gain Equalizer
*Chromatic Dispersion Compensator
*Polarization Controller

Possible MEMS Applications for Optical Switching
*Protection Switch
*Switch for OADM
*Switch for OXC

Possible MEMS Applications for Packaging and System Integration
*V-grove and microstructures
*Micro-optics
*Self-alignment
*Optical Interconnection



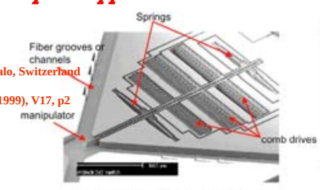


All-Optical Networks Proposed in Late 90's

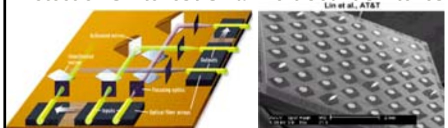
1. Introduction – Design Considerations

Free Space Approach

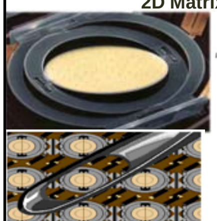
Univ. of Neuchatel, & Sercalo, Switzerland
C. Marxer, N. F. de Rooij,
IEEE J. Lightwave Tech. (1999), V17, p2

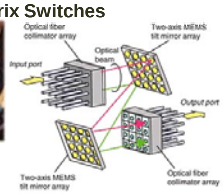


Protection Switches / Small Port Count Switches



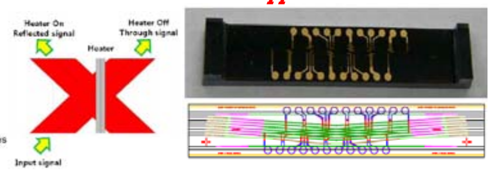
2D Matrix Switches





3D Optical Switches

Guided Wave Approach



4x4 Polymer Optical Matrix Switch
OECC 2012, 4E3-4, J-U Shin et al., ETRI, Korea

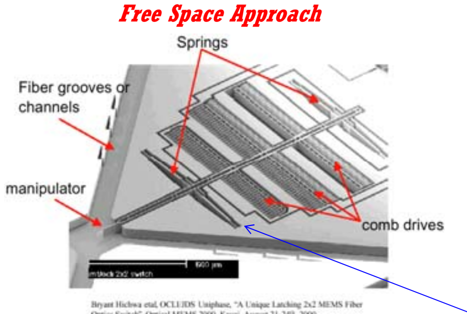
Merits of MEMS-based Devices -

- Small footprint
- Low electrical power consumption
- Low insertion loss
- Wavelength independent
- IP / Protocol Transparent

Lab of Sensors, MEMS & NEMS — OECC 2012, Busan, Korea — 7

1. Introduction – Design Considerations

Free Space Approach



Protection Switches / Small Port Count Switches

Merits of MEMS-based Devices -

- Small footprint
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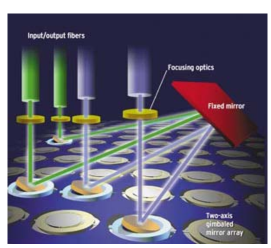
- Low insertion loss
- Wavelength independent
- IP / Protocol Transparent
- Scalability
- Low on-hold power consumption

By using latch mechanisms



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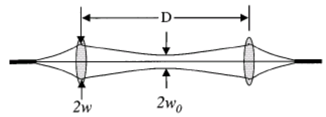
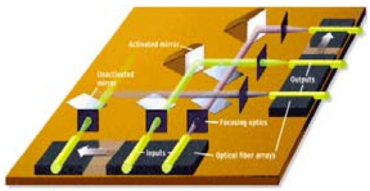
1. Introduction – Design Considerations





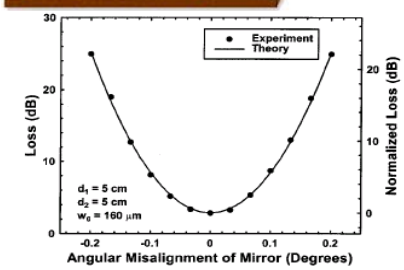


Fig. Comparison between theoretical calculations and experimental results for loss versus angular misalignment.

Merits of MEMS-based Devices -

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- Wavelength independent
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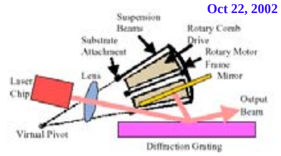
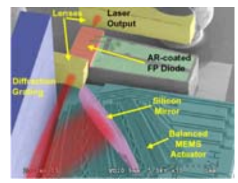
- Scalability
- Low on-hold power consumption

Challenges of MEMS-based Devices -

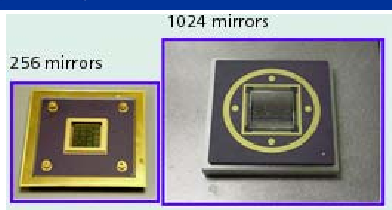
- Alignment accuracy and optical loss occurred in the light path
  e.g. 8x8 matrix switches
  Insertion loss of through-ports –
  Min = 0.4dB; Max = 2.5dB

Iolon Inc., J. H. Jerman and J. D. Grade; Oct 22, 2002

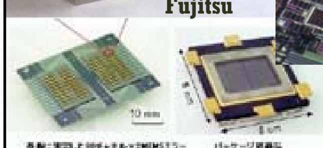




1. Introduction – Design Considerations



Two packaged MEMS mirror arrays for use in optical switch fabrics; By Lucent



Merits of MEMS-based Devices -

- Small footprint
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- Scalability
- Low on-hold power consumption

Challenges of MEMS-based Devices -

- Alignment accuracy and optical loss occurred in the light path
- MEMS Packaging and Electrical I/O

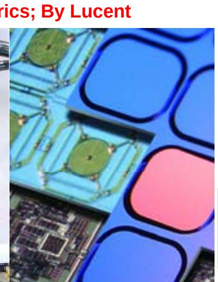
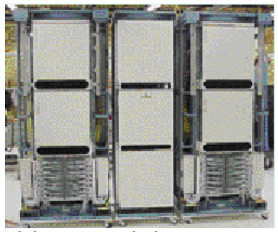


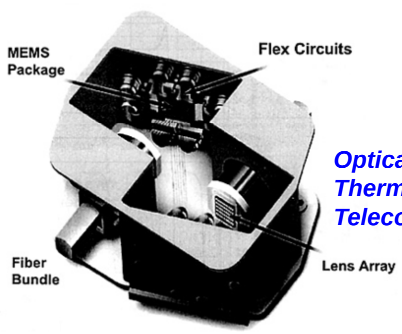
Figure 1. Vertically integrated 1200-mirror MOEMS array. The bottom CMOS wafer includes 4800 digital-to-analog converters with 15-bit resolution and 120-V output. Each mirror is driven by four electrodes fabricated by means of multilayer metalization. Bulk micromachining yields an optically flat mirror surface characterized by a high level of optical performance.

Transparent Networks, Inc

1. Introduction – Design Considerations



Lucent Lambda Router optical cross connect system.



Merits of MEMS-based Devices -

- Small footprint
- Low electrical power consumption
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- Wavelength independent
- IP / Protocol Transparent
- Scalability
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Challenges of MEMS-based Devices -

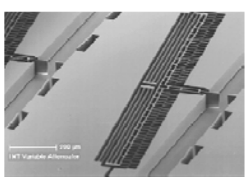
- Alignment accuracy and optical loss occurred in the light path
- MEMS Packaging and Electrical I/O
- Hermetic packaging and housing

Optical alignment accuracy
Thermal management
Telecom reliability

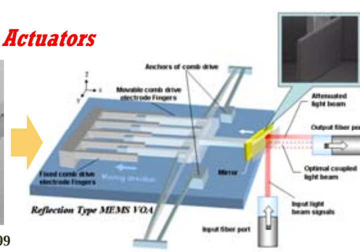
2. Actuation Mechanisms – Case Study of VOAs

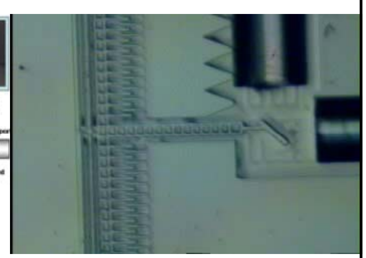
Electrostatic Actuation Mechanisms – Planar VOAs

Comb Actuators



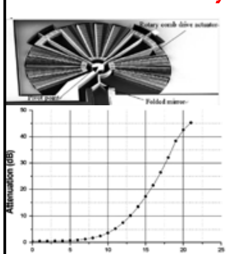
C. Marxer *et al.*, IEEE PTL, 11(2),1999

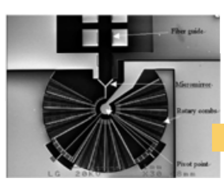




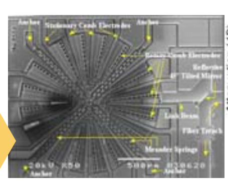
IEEE Comm. Mag., V. 41, p.S16, Aug 2003

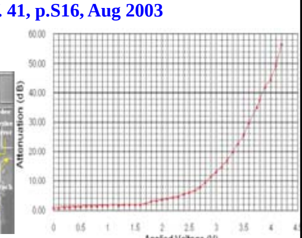
Rotary Comb Actuators





T.-S. Lim, et al.,
IEEE J. Sel. Topics Quantum Electron.,
vol. 10, no. 3, p.558–562, 2004.





IEEE Photonics Tech. Letters. Vol. 18, No. 10, p. 1170-1172, May. 15, 2006.

Development of MEMS VOAs During 2000 ~ 2005

2. Actuation Mechanisms – Case Study of VOAs

Electrostatic Actuation Mechanisms – 3D VOAs

Parallel Plate Actuator – Poly-Si

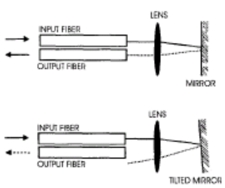


Fig. 1 Schematic of the principle used for the variable optical attenuator.

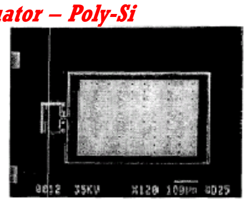
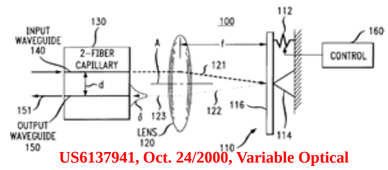


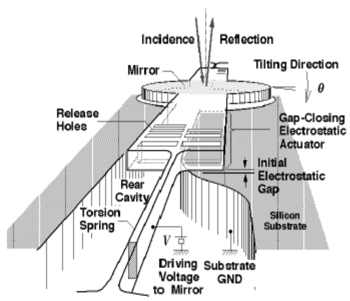
Fig. 2 SEM micrograph showing the silicon chip with the MEMS mirror.

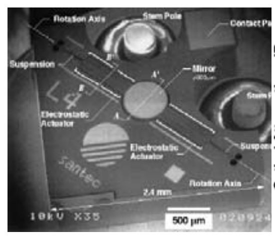


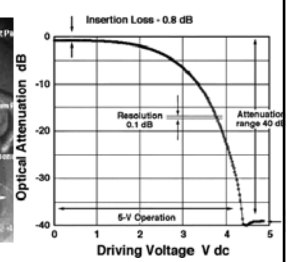
US6137941, Oct. 24/2000, Variable Optical Attenuator, Lucent Technologies

B. M. Andersen, et al., "A MEMS Variable Optical Attenuator for DWDM Optical Amplifiers", *IEEE OFC 2000, 260/WM 17-1. Lucent Technologies*

Parallel Plate Actuator – SOI





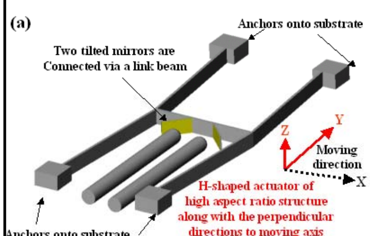


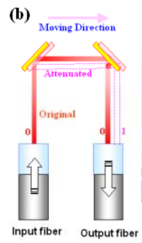
K. Isamoto, et al., *IEEE J. Sel. Topics Quantum Elect.*, vol.10, pp. 570-578, May/June 2004. *Santec Co. and U. Tokyo, Japan*

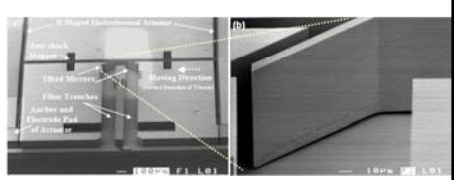
2. Actuation Mechanisms – Case Study of VOAs

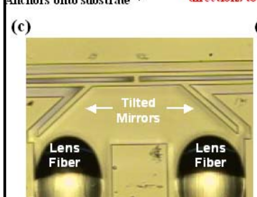
Thermal Actuation Mechanisms – Planar VOAs

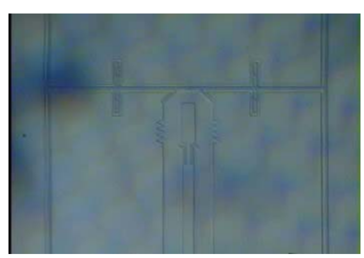
Two Parallel V-Shaped Thermal Actuator (H-Shaped Actuator) – SOI











C. Lee, IEEE Photonics Tech. Lett,, Vol. 18, No. 6, p. 773-775, 2006.
C. Lee, IEEE J. Lightwave Eng. Vol. 25, No.2, p.490-498, 2007.

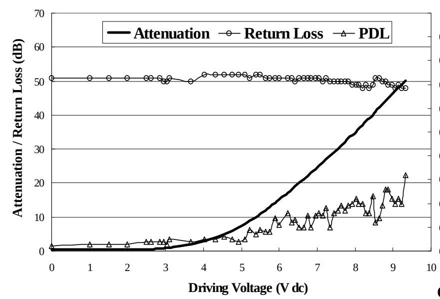
2. Actuation Mechanisms – Case Study of VOAs

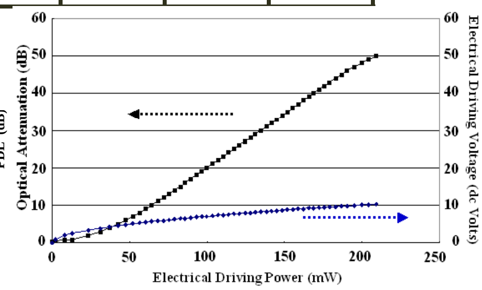
Thermal Actuation Mechanisms – Planar VOAs

Two Parallel V-Shaped Thermal Actuator (H-Shaped Actuator) – SOI

Table 1. Measured PDL, WDL and return loss versus attenuation

Attenuation	0dB	3dB	10dB	20dB	30dB
Measured PDL (dB)	0.05~0.08	0.07~0.10	0.10~0.18	0.20~0.27	0.21~0.39
Measured WDL (dB)	0.04~0.09	0.06~0.15	0.15~0.28	0.30~0.45	0.40~0.65
Measured Return Loss (dB)	51~52	51~52	50~52	50~52	50~52





C. Lee, IEEE Photonics Tech. Lett,, Vol. 18, No. 6, p. 773-775, 2006.
C. Lee, IEEE J. Lightwave Eng. Vol. 25, No.2, p.490-498, 2007.

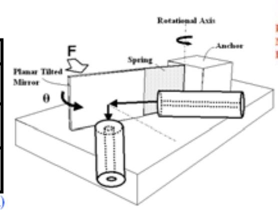
2. Actuation Mechanisms – Case Study of VOAs

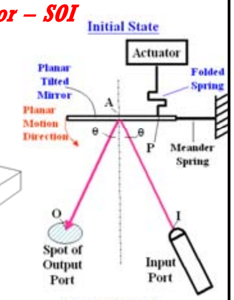
Thermal Actuation Mechanisms – Planar VOAs

Pushing Mechanism Driven by A V-Shaped Thermal Actuator – SOI

TABLE
Measured driving voltage, PDL and BR at different attenuation states

Attenuation	0 dB		10 dB		20 dB		30 dB	
Driving Voltage	0	0	5.5	5.6	6.8	7.1	7.5	8.1
Measured PDL	0.02	0.08	0.02	0.18	0.04	0.20	0.06	0.30
Measured Return Loss	52	51	51	52.5	50	52	49	50

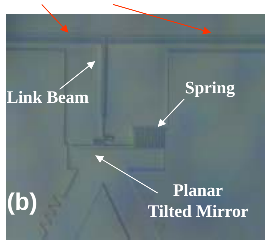


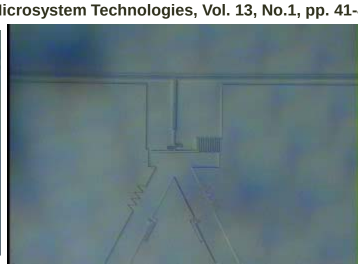


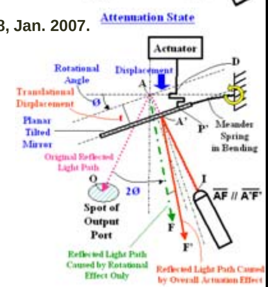
(Tilted Mirror / Retro-Reflection)

Electrothermal Actuators

Microsystem Technologies, Vol. 13, No.1, pp. 41-48, Jan. 2007.

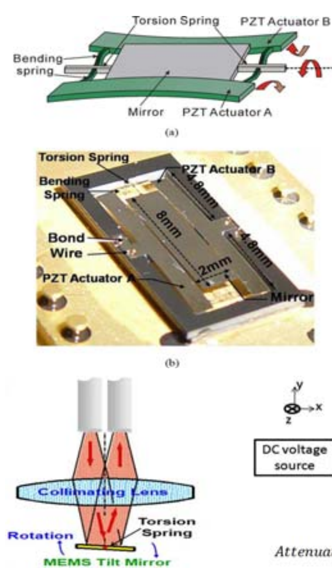


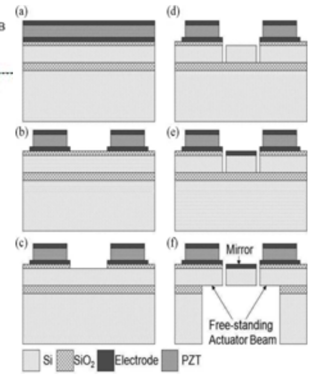


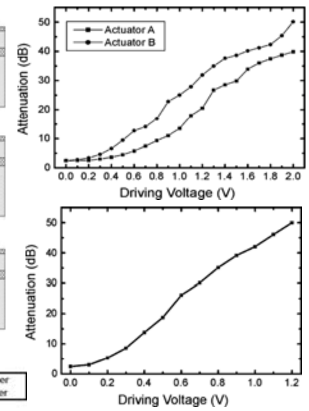


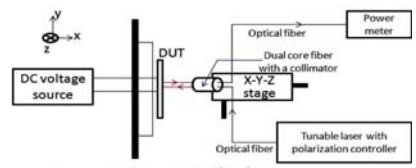
2. Actuation Mechanisms – Case Study of VOAs

Piezoelectric Actuation Mechanisms – 3D VOAs







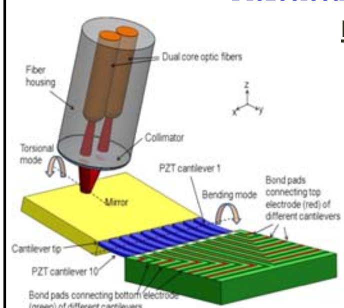


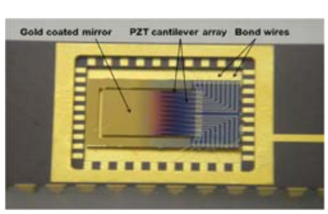
$Attenuation\,(dB) = 10\log\left(\frac{P_{in}}{P_{out}}\right)$, P_{out} of laser source

C. Lee et al., *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 5, pp.1529-1536, Sep/Oct. 2009.

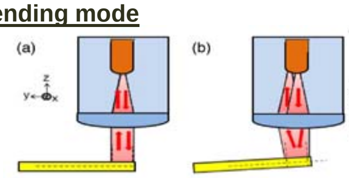
2. Actuation Mechanisms – Case Study of VOAs

Piezoelectric Actuation Mechanisms – 3D VOAs

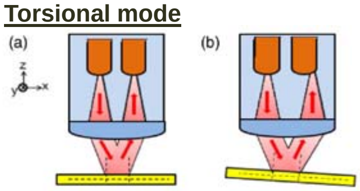


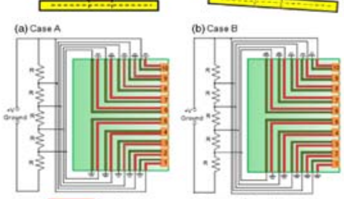


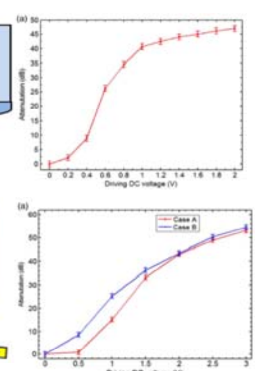
Bending mode



Torsional mode







K. H. Koh et al., *IEEE JMEMS.*, vol. 19, no. 6, pp.1370-1379, Dec 2010.

NUS National University of Singapore

2. Actuation Mechanisms – Case Study of VOAs

Hybrid Actuation Mechanisms – 3D VOAs
~ Thermal + Electromagnetic

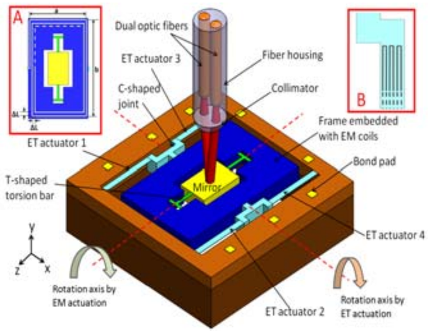


Fig. 1. Schematic drawing of hybrid actuated MEMS VOA with dual fiber arranged in 3-D free space configuration

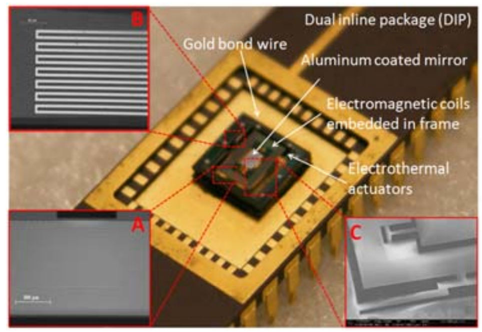


Fig. 2. A magnified photo showing the packaged MEMS VOA device.

- Four electrothermal (ET) actuators responsible for rotation about x-axis.
- Frame embedded with electromagnetic (EM) coil responsible for rotation about z-axis.

K. H. Koh et al., *IEEE JMEMS. Published on-line 2012.*

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2. Actuation Mechanisms – Case Study of VOAs

Hybrid Actuation Mechanisms – 3D VOAs

Electromagnetic

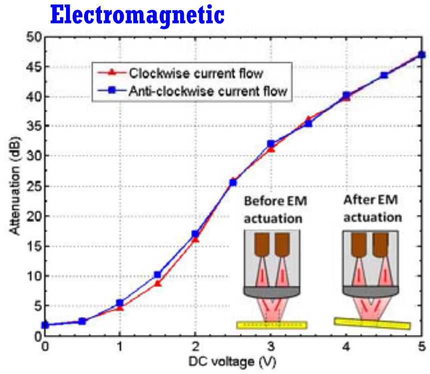


Fig.. Measured attenuation curve versus dc driving voltage for EM attenuation scheme.

- Initial insertion loss of 1.8dB is observed.
- 40 dB attenuation range is obtained at 4 V_{dc}, 26mW.

Thermal

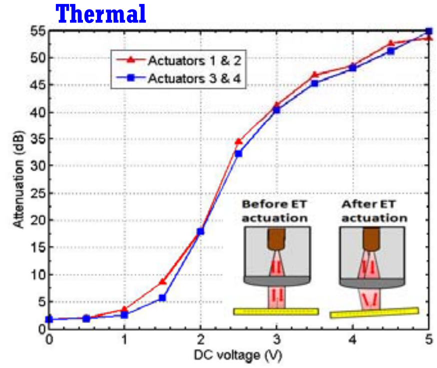


Fig. Measured attenuation curve versus dc driving voltage for ET attenuation scheme.

- Initial insertion loss of 1.8dB is observed.
- 40 dB attenuation range is obtained at 3 V_{dc}, 20mW.
- Result obtained is better than that in EM attenuation scheme.

2. Actuation Mechanisms – Case Study of VOAs

Hybrid Actuation Mechanisms – 3D VOAs
~ Thermal + Electromagnetic

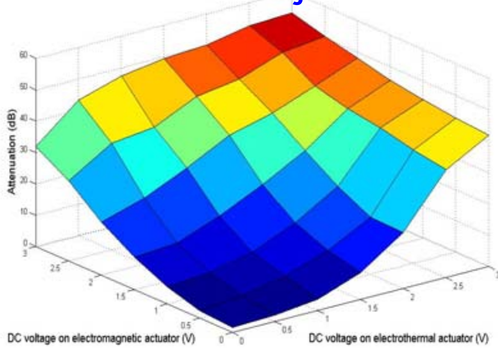
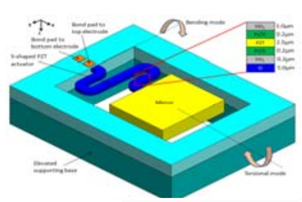


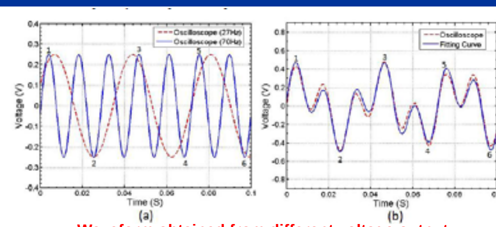
Fig. Bias configuration and attenuation bias curve for mixed mode operation.

- DC biases are applied simultaneously to both EM and ET actuators.
- Various voltage combination can be made to both actuators so as to achieve 40 dB attenuation range.
- Offers an additional degree of freedom in attenuation control.
- Any deviation of attenuation-dc bias characteristic among fabricated VOA devices due to fabrication may be compensated by hybrid attenuation scheme.

2. Actuation Mechanisms – Case Study of μScanner

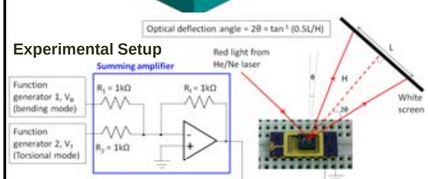
Piezoelectric Actuation Mechanisms –
One actuator w/ two superimposed voltages





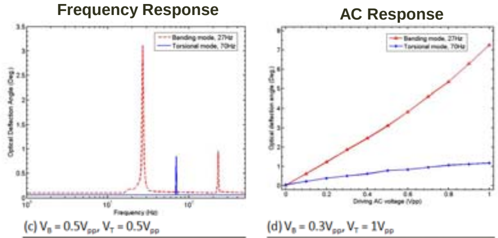
Waveform obtained from different voltage output

Experimental Setup

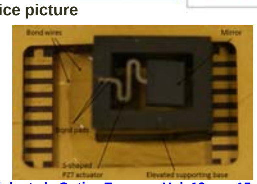


Frequency Response

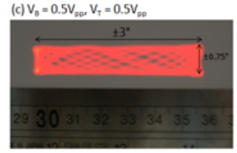
AC Response



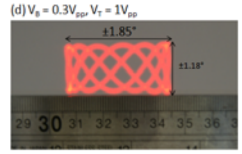
Device picture



(c) $V_B = 0.5V_{pp}$, $V_T = 0.5V_{pp}$

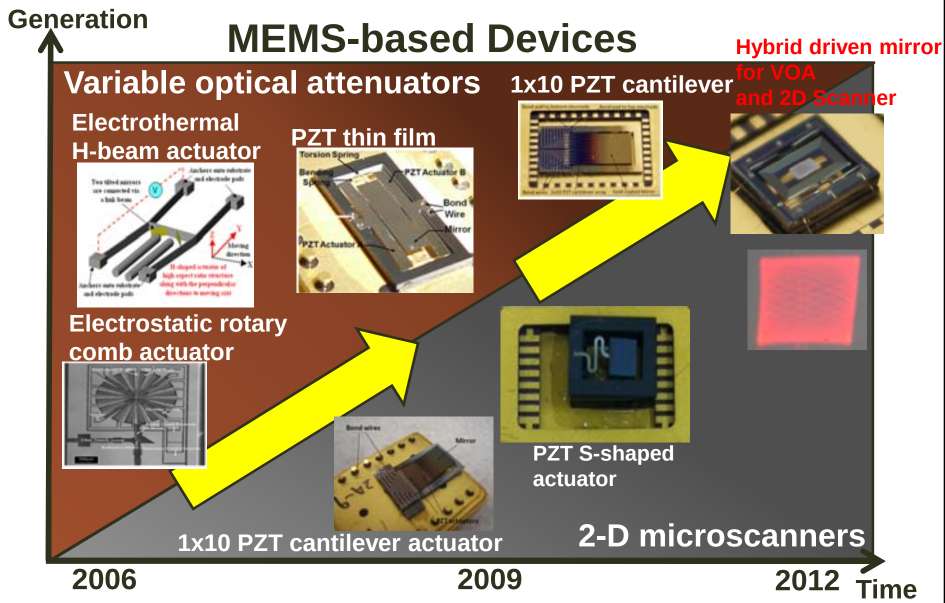


(d) $V_B = 0.3V_{pp}$, $V_T = 1V_{pp}$



K. H. Koh et al., Optics Express, Vol. 19, no. 15, pp. 13812-

3. Outlooks and Concluding Remarks



3. Outlooks and Concluding Remarks

What have been achieved ?

1. Low driving voltage for VOAs @ 40 dB attenuation –

   Piezoelectric – less than 1 V; Thermal – 3 V; Electromagnetic – 4V

   Hybrid – 2V for thermal actuator + 2V for electromagnetic actuator

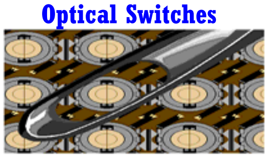
2. Low operation power consumption for hybrid VOA @ 40dB attenuation –

   Hybrid – 20 mW for thermal actuator + 26 mW for electromagnetic actuator

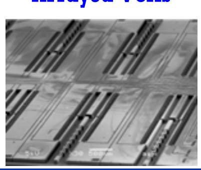
3. CMOS semiconductor process compatibility – Hybrid actuation (Thermal & Electromagnetic)

4. Scalability -

Optical Switches



Arrayed VOAs



3. Outlooks and Concluding Remarks

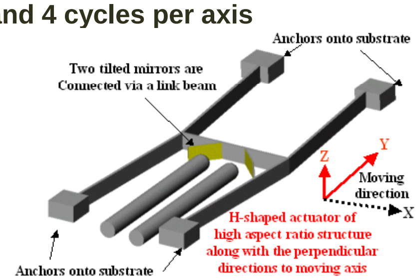
Reliability ?

GR-1221:

Variable Frequency Vibration Test

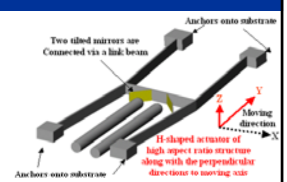
The variable frequency vibration test is based on MIL-STD-883, Method 2007, with the following conditions:

Acceleration : 20G acceleration
Frequency : 20-2000 Hz
Duration: 4 min per cycle and 4 cycles per axis

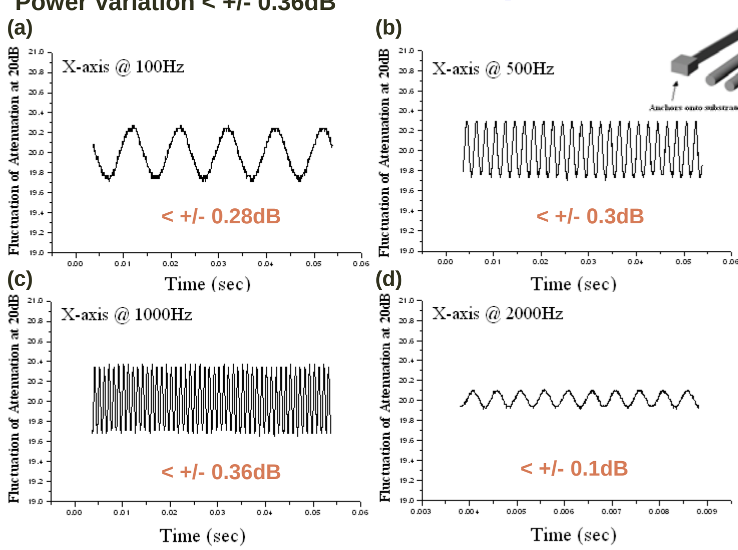


3. Outlooks and Concluding Remarks

Reliability -



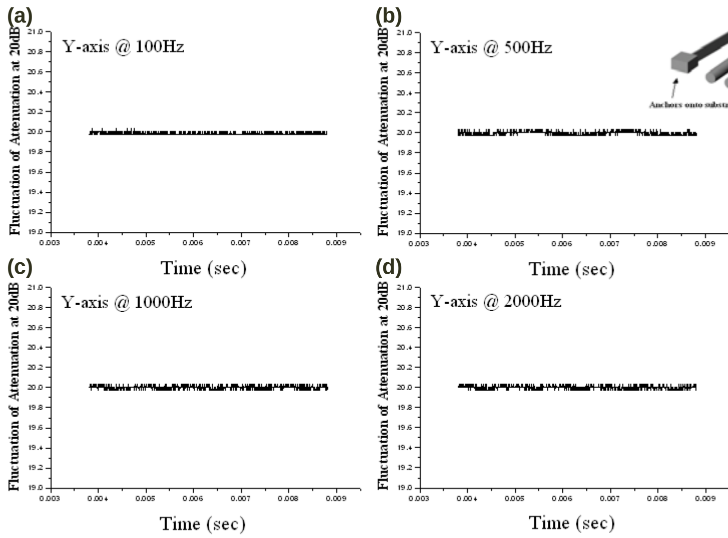
Power Variation < +/- 0.36dB

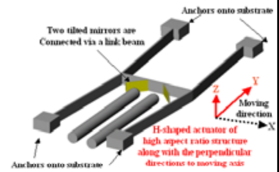


3. Outlooks and Concluding Remarks

Reliability -

Power Variation < +/- 0.03dB

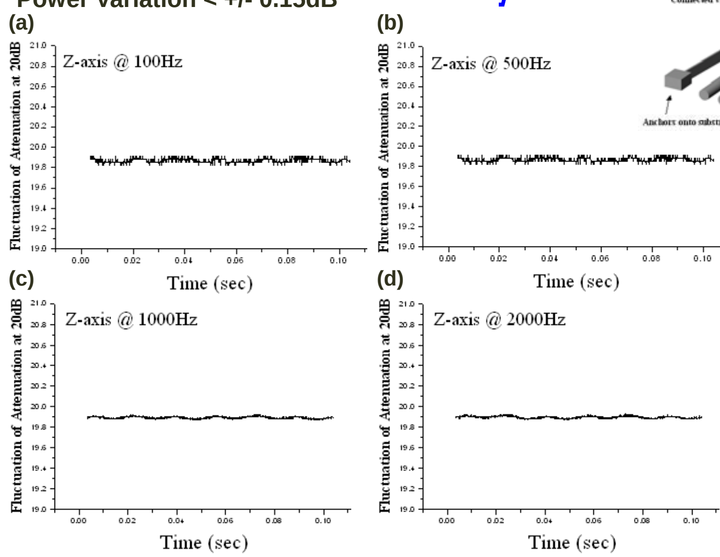


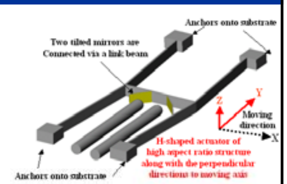


3. Outlooks and Concluding Remarks

Reliability -

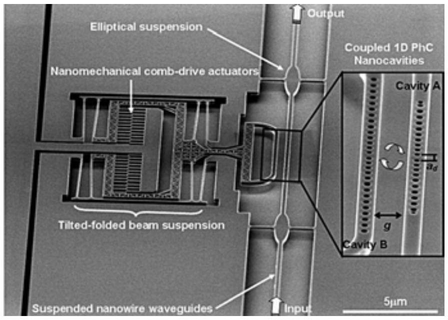
Power Variation < +/- 0.15dB



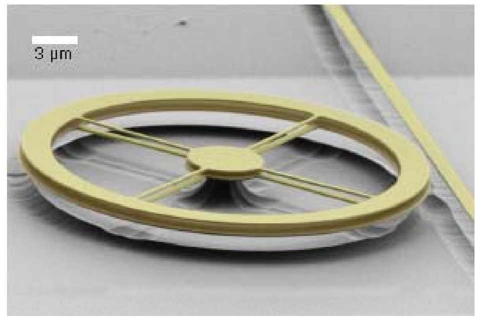


3. Outlooks and Concluding Remarks

What are the next challenges ?



X Chew, et al, "Dynamic tuning of an optical resonator through MEMS-driven coupled photonic crystal nanocavities," *Optics Letters*, Vol. 35, No. 15, p. 2517–2519 (2010).



G. S. Wiederhecker, et al, "Controlling photonic structures ussing optical force," *Nature*, Vol. 463, p. 633-635 (2009).

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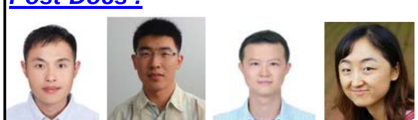
Ministry of Education

NUS/MOE
FRC R-263000692112

Thank You !

Post-Docs :



HUANG Chia-Yi, MA Fusheng, LIN Yu-Sheng, LIU Huicong*

PhD Students :

LOU Liang, KOH Kah How, WANG Nan*, LI Bo, ZHANG Songsong, QIAN You*, ZHOU Huchuan

Prakash Pitchappa, Lokesh DHAKAR, XIANG Zhuolin, WANG Hao, Mehrdad Elyasi, HO Chong Pei, LIU Zhen, WANG Tao

Q & A

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