



MEMS-based Devices

Chengkuo Lee

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

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

Outline

- 1 Introduction**
- 2 Actuation Mechanisms**
- 3 Outlooks & Concluding Remarks**

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1. Introduction – Early Demonstrations

MEMS Fiber-Optic Switch Using Electromagnet
Nagaoka, IEEE J. STQE, Vol5, 1999, NTT

Switch Structure

Process of making Ni tube

- 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

Ni Tube $50 \mu\text{m}$

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1. Introduction – Early Demonstrations

MEMS Moving Mirror - Optic Gate Switch Using Electrostatic Actuator

(a)

(b)

(c)

(d)

(e)

(f)

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 VOAs.

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

US Patent: 6148124; Lucent Technologies

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1. Introduction – Early Demonstrations

MEMS Based Variable Optical Attenuators (VOAs)

1. Electrostatic Deformable Mirror / Light Valves

Incident Light
Reflected Light
Air Holes
Electrode
SiNx
Vbias Off
Doped Silicon Substrate
Vbias On
Air Holes
Electrode
SiNx
Doped Silicon Substrate
Transmitted Light

Input Fiber
Lens Axis
Output Fiber
Collimation Lens
Reflective Modulator

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

2. Electrostatic DMD / Reflection Mirror

Tunable Laser
SMF
IN
OUT
FC/APC
FC/APC
Attenuator Module
IF: Interference Filter
L:4
IF based WDM
A₁
A₂
A₃
A₄
Binary DMD
Absorber
GRIN Lens

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

3. Electrostatic Parallel Plate / Shutter Surface Micromachining

Fiber Cap
3.86 3.51 1.18 100μm 1031

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

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

IMT Variable Attenuator
1.00 μm

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

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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-groove and microstructures
- * Micro-optics
- * Self-alignment
- * Optical Interconnection

MULTIPLEXER
OPTICAL AMPLIFIER
OPTICAL SWITCHES
OPTICAL SIGNAL REGENERATION
MULTIPLEXER

All-Optical Networks Proposed in Late 90's

LG Electronics
JDS Uniphase
iQ Optics

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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

Guided Wave Approach

Heater On Reflected signal
Heater Off Through signal
Heater

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

Protection Switches / Small Port Count Switches

Lin et al., AT&T

2D Matrix Switches

Input port
Optical beam
Two-axis MEMS tilt mirror array
Output port

3D Optical Switches

Two-axis MEMS tilt mirror array
Optical fiber collimator array
Input port
Output port

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1. Introduction – Design Considerations

Free Space Approach

Bryant Hichwa et al., OCLLIDS Uniphase, "A Unique Latching 2x2 MEMS Fiber Optics Switch," Optical MEMS 2000, Kauai, August 21-24th, 2000

Protection Switches / Small Port Count Switches

Merits of MEMS-based Devices -

- Small footprint
- Low electrical power consumption
- Low insertion loss
- Wavelength independent
- IP / Protocol Transparent
- **Scalability** ——————
By using latch mechanisms
- **Low on-hold power consumption**

Input/output fibers
Focusing optics
Fixed mirror
Two-axis micromirror array

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1. Introduction – Design Considerations

The diagram illustrates a MEMS-based optical switch. It shows a top view of a micro-mirror array with dimensions D, 2w, and 2w₀. Below it is a cross-sectional view of the device structure with labels for 'Activated mirror', 'Unactuated mirror', 'Focusing optics', 'Optical fiber array', and 'Inputs'. A graph below the cross-section plots 'Loss (dB)' and 'Normalized Loss (dB)' against 'Angular Misalignment of Mirror (Degrees)'. The graph shows a theoretical curve (solid line) and experimental data points (black dots). Parameters listed are d₁ = 5 cm, d₂ = 5 cm, w₀ = 160 μm.

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

Merits of MEMS-based Devices -

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

A photograph of a MEMS-based optical switch assembly. Labels point to various components: Laser Output, AR-coated FP Diode, Diffraction Grating, Silicon Mirror, Relaxed MEMS Actuator, Frame, Mirror, Rotary Motor, Frame, Substrate Attachment, Suspension Beam, and Virtual Pivot. A lens and a laser chip are also shown.

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1. Introduction – Design Considerations

Two photographs of MEMS mirror arrays. The left one is labeled '256 mirrors' and the right one is labeled '1024 mirrors'. Below them is a red text box stating: 'Two packaged MEMS mirror arrays for use in optical switch fabrics; By Lucent'.

Merits of MEMS-based Devices -

- Small footprint
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- Wavelength independent
- IP / Protocol Transparent
- 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

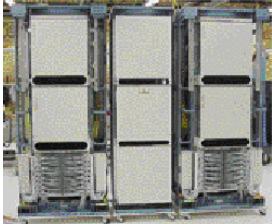
Figure 1. Vertically integrated 1200-mirror MOEMS array. The bottom CMOS wafer includes 4800 digital-to-analog converters with 15-bit resolution and 120-V output. Each mirror is driven by four electrodes fabricated by means of multilayer metalization. Bulk micromachining yields an optically flat mirror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

Fujitsu Transparent Networks, Inc

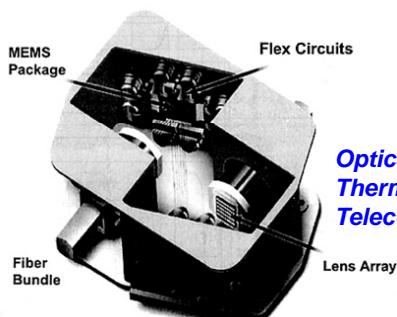
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1. Introduction – Design Considerations



Lucent Lambda Router optical cross connect system.



MEMS Package
Flex Circuits
Fiber Bundle
Lens Array

*Optical alignment accuracy
Thermal management
Telecom reliability*

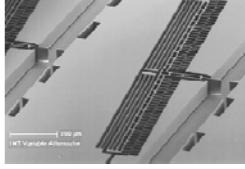
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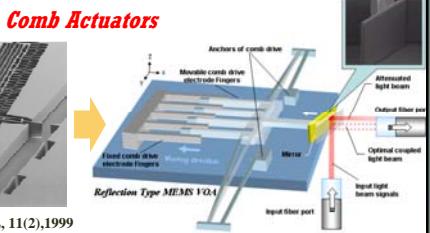
2. Actuation Mechanisms – Case Study of VOAs

Electrostatic Actuation Mechanisms – Planar VOAs

Comb Actuators



4.200 μ m LHT Variable Attenuator

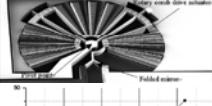


Anchors of comb driver
Mountable comb driver electrode Fingers
Flexible comb drive electrode Fingers
Working distance
Reflection Type MEMS VOA
Input fiber port
Output fiber port
Control fiber port
Mirrored
Attenuated light beam
Optical coupled light beam
Input light beam signals

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

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

Rotary Comb Actuators

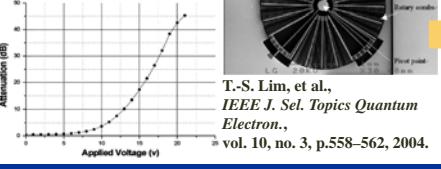


20.00 μ m
Rotary comb drive actuator
Folded extens.



Fiber field
Rotary comb
Pivot point
Germometer
Piezo

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



Attenuation (dB)
Applied Voltage (V)

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

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Merits of MEMS-based Devices -

- Small footprint
- Low electrical power consumption
- Low insertion loss
- Wavelength independent
- IP / Protocol Transparent
- 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
- Hermetic packaging and housing

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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.

Parallel Plate Actuator – SOI

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

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

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2. Actuation Mechanisms – Case Study of VOAs

Thermal Actuation Mechanisms – Planar VOAs

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

(a) Schematic diagram of the Two Parallel V-Shaped Thermal Actuator (H-Shaped Actuator) – SOI mechanism. It shows two tilted mirrors connected via a link beam, anchored onto a substrate. The actuator has a high aspect ratio structure along with the perpendicular directions to the moving axis. The moving direction is indicated by a red arrow.

(b) Diagram illustrating the optical path: Input fiber → Original light path → Attenuated light path → Output fiber. The moving direction of the mirrors is shown as a red arrow.

(c) Micrograph showing the tilted mirrors and lens fibers.

(d) Photograph of the device assembly.

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.

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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

The graph plots Attenuation (solid line), Return Loss (open circles), and PDL (triangles) against Driving Voltage (V dc) from 0 to 10. Attenuation increases from ~50 dB at 0V to ~55 dB at 10V. Return Loss remains constant at ~0.5 dB. PDL increases from ~0.1 dB at 0V to ~0.25 dB at 10V.

The graph plots Optical Attenuation (dB) against Electrical Driving Power (mW) from 0 to 250. Attenuation increases linearly from 0 dB at 0 mW to approximately 55 dB at 200 mW.

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.

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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
Measured PDL	0.02	0.08	0.02	0.18
Measured Return Loss	52	51	51	52.5

(Tilted Mirror / Retro-Reflection)

The schematic shows the initial state where a folded spring is attached to an actuator, which is connected to a planar tilted mirror. The mirror is mounted on a rotational axis. An input port (I) enters from the right, and a spot of output port (O) exits to the left. The actuator is shown in its initial position. In the attenuation state, the actuator is displaced, causing the mirror to rotate. This rotation is transmitted through a meander spring to the mirror. The mirror's position is labeled with a new angle θ' and a rotational axis F'. The input port (I) and output port (O) remain fixed. The meander spring is labeled as bending under displacement D.

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

Two SEM images show the electrothermal actuators. The left image (b) shows the actuators with labels: Link Beam, Spring, and Planar Tilted Mirror. The right image shows the actuators in a different state, likely after actuation.

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2. Actuation Mechanisms – Case Study of VOAs

Piezoelectric Actuation Mechanisms – 3D VOAs

The diagram illustrates a 3D VOA structure with two PZT actuators (A and B) and a mirror. It shows cross-sectional views (a-d) and a top-down view (b) of the device. A legend indicates layers: Si, SiO₂, Electrode, and PZT. Two graphs show Attenuation (dB) vs Driving Voltage (V) for Actuator A (red circles) and Actuator B (blue circles). The left graph covers 0.0 to 2.0 V, and the right graph covers 0.0 to 1.2 V.

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.

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2. Actuation Mechanisms – Case Study of VOAs

Piezoelectric Actuation Mechanisms – 3D VOAs

Bending mode

This section shows a bending mode actuation mechanism. It includes a schematic of the fiber housing and a detailed view of the cantilever array. Two graphs show Attenuation (dB) vs Driving DC Voltage (V) for Case A (red circles) and Case B (blue circles).

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

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

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2. Actuation Mechanisms – Case Study of VOAs

Hybrid Actuation Mechanisms – 3D VOAs ~ Thermal + Electromagnetic

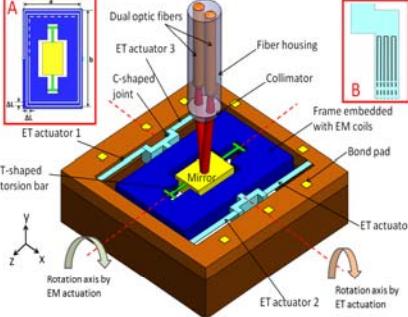


Fig. 1. Schematic drawing of hybrid actuated MEMS VOA with dual fiber arranged in 3-D free space configuration

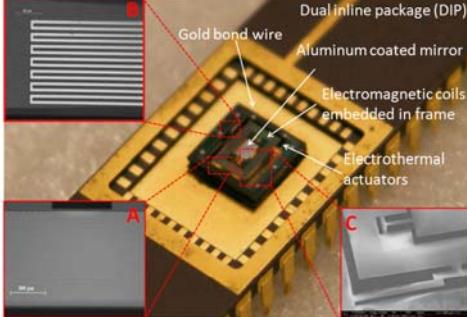


Fig. 2. A magnified photo showing the packaged MEMS VOA device.

- ❖ 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

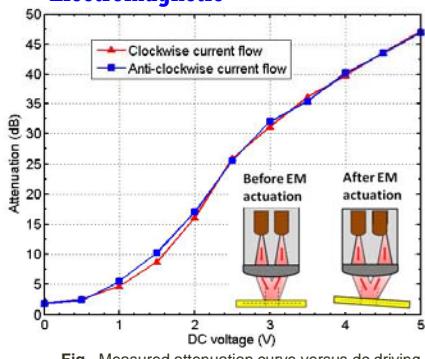


Fig.. Measured attenuation curve versus dc driving voltage for EM attenuation scheme.

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

Thermal

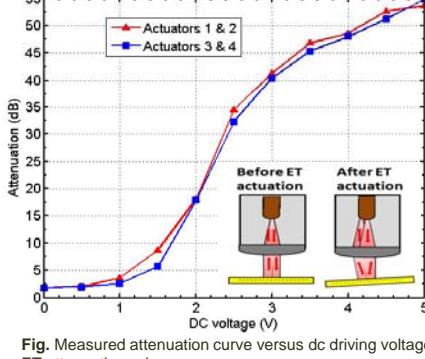


Fig. Measured attenuation curve versus dc driving voltage for ET attenuation scheme.

- ❖ 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.

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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.

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2. Actuation Mechanisms – Case Study of μ Scanner

Piezoelectric Actuation Mechanisms – One actuator w/ two superimposed voltages

Experimental Setup

Summing amplifier circuit diagram:

- Function generator 1, V_B (Bending mode)
- Function generator 2, V_T (Torsional mode)
- Resistors: $R_1 = 3k\Omega$, $R_2 = 3k\Omega$, $R_3 = 3k\Omega$
- Op-amp
- Red light from He/Ne laser
- Optical deflection angle = $2\theta = \tan^{-1}(0.5L/H)$
- White screen

Device picture

Frequency Response

(a) Waveform obtained from different voltage output

(b) AC Response

AC Response

(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-

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3. Outlooks and Concluding Remarks

Generation

MEMS-based Devices

Variable optical attenuators

Electrothermal H-beam actuator

PZT thin film

Electrostatic rotary comb actuator

1x10 PZT cantilever

PZT S-shaped actuator

2-D microscanners

Hybrid driven mirror for VOA and 2D Scanner

2006

2009

2012

Time

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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



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3. Outlooks and Concluding Remarks

Reliability ?

GR-1221:

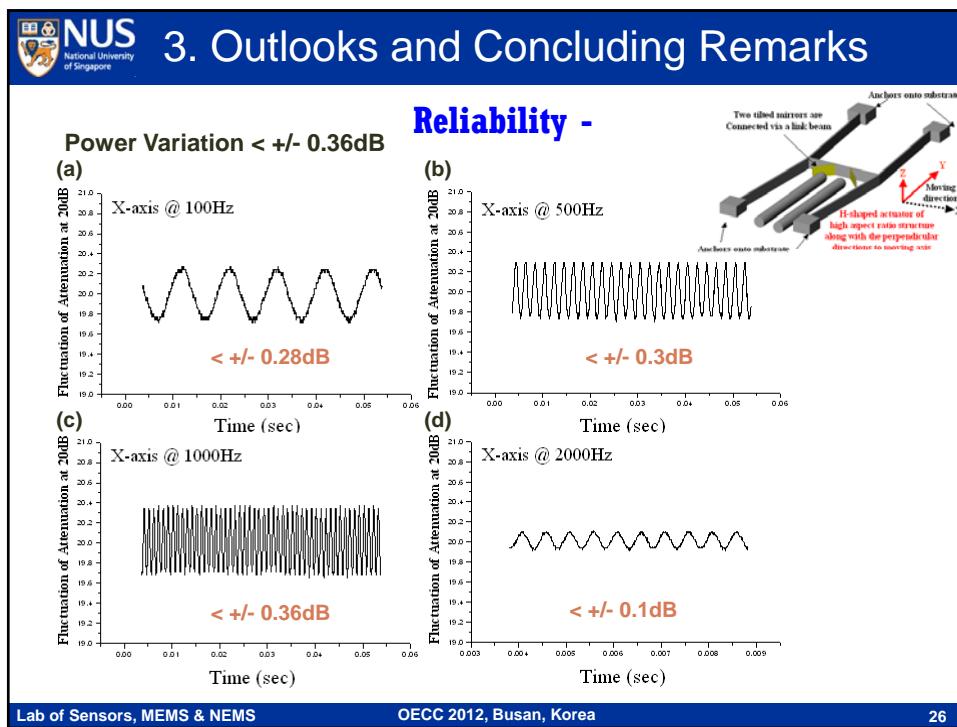
Variable Frequency Vibration Test

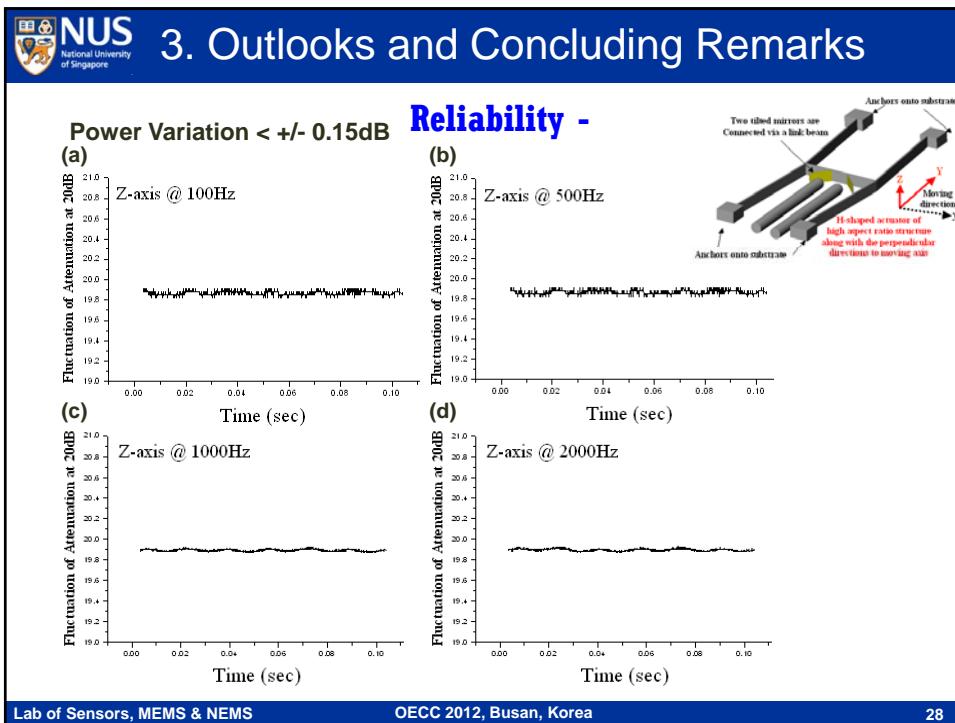
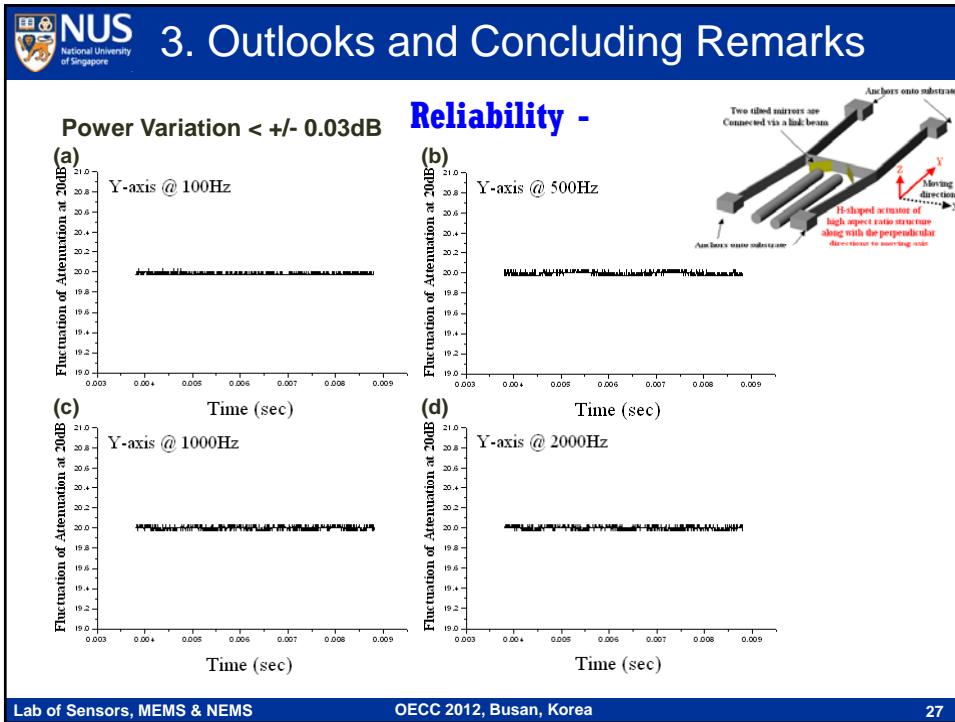
The variable frequency vibration test is based on MIL-STD-883, Method 2007, with the following conditions:

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

Two tilted mirrors are Connected via a link beam
 Anchors onto substrate
 H-shaped actuator of high aspect ratio structure along with the perpendicular directions to moving axis
 Moving direction X
 Y
 Z

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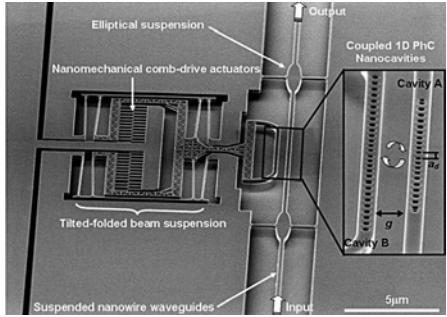
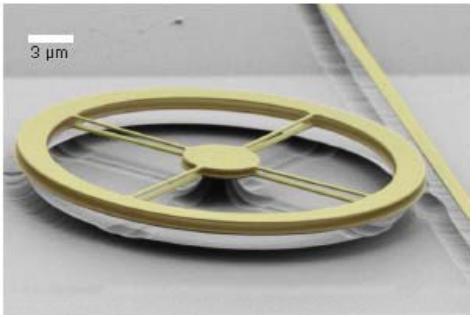




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3. Outlooks and Concluding Remarks

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).

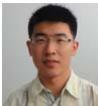
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Post-Docs :

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

Thank You !

Q & A 

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