Electro-Thermal Actuated MEMS Mirrors for 100G Fiberoptic Switching and Attenuation Components

Luzhong Yin and Guanghai Jin

Agiltron, Inc.
15 Presidential Way
Woburn, MA 01801
www.agiltron.com

1 Introduction

In the telecommunication and data communication industries, fiber optic switches and variable optical attenuators (VOA) are crucial fundamental functional blocks of optical fiber networks. Currently many service providers are using the 100G technology roll out as an opportunity to upgrade their optical network infrastructure. This is leading to a large demand for advanced optical switches and VOAs.

The operation of optical switches and VOAs is based on various mechanisms including mechanical movement and steering, change of coupling ratio, and polarization rotation. Micro-electro mechanical systems (MEMS) technology is of significant interest because such devices are small in size, operate with low power consumption, and can be volume manufactured at low cost.

MEMS technology has been extensively developed and widely commercialized. The integration of MEMS components into optical devices is increasingly successful and optical MEMS components are becoming proven and established in telecom and datacom applications. The ability of MEMS actuators to obtain a large range of in-plane translational or rotational motion is necessary to address a broad range of component specifications for fiber optic communications applications. Some applications require continuous analog motion while others require bi-stable positioning. It is advantageous for a MEMS component technology to be able to provide both these types of motion.

Of critical importance and a major differentiator in optical MEMS technology is the method for actuating mechanical motion. The use of electro-static force is the most widely used approach for actuation of optical MEMS devices. While presenting advantages of small device size and low power consumption, this method of MEMS actuation requires a very high electric field across a very small gap between electrodes in order to generate sufficient force for mechanical motion. This, in turn, requires costly hermetic packaging to avoid electric field breakdown under certain operating conditions. Another significant limitation of electro-static MEMS for optical switching application is the complexity, and therefore impracticality, of implementing devices with the key functional capability of latching performance. It is noteworthy that some MEMS device designs based on electro-magnetic actuation also have eliminated the need for the expensive hermetic packaging, but they require external magnets for their operation.

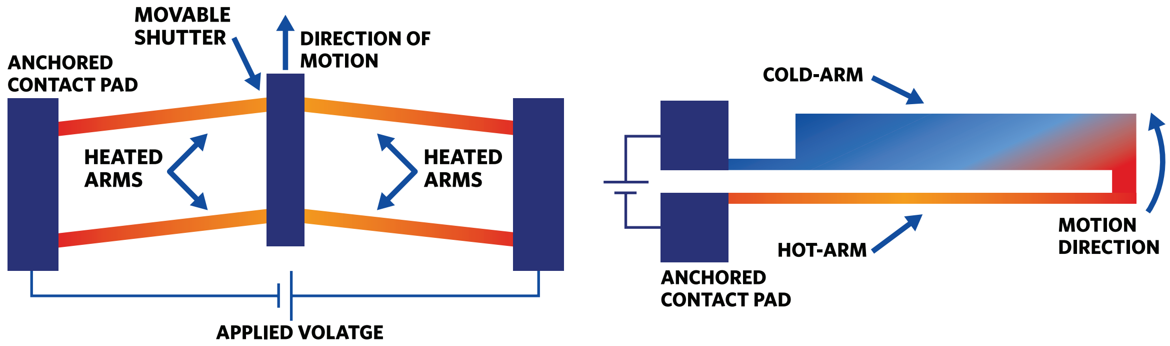
1 Introduction

Compared to other MEMS technologies, electro-thermal driven mechanical actuators based on the Joule heating principle provide unique advantages for fiber optic components including:

- Large actuation force
- Low driving voltage
- Large range of analog motion
- Compatible with latching (bi-stable) feature
- High reliability (billions of operating cycles demonstrated)
- Simple design for manufacturing
- No requirement for expensive hermetic packaging
- Intrinsic tolerance to electrostatic discharge

Electro-thermal actuated MEMS devices operate by thermally induced mechanical expansion of mechanical supports through applied voltage induced current flow and Joule heating of the designed electrical resistance support structures. Two designs of electro-thermal actuators have been successfully demonstrated to reliably provide in-plane mechanical movement of an optical mirror or shutter[1-5]. These are referred to as the pseudobimorph or "U" beam actuator and the bent-beam or "V" beam actuator, with both shown schematically in Figure 1[1-4].

Figure 1: Schematic diagrams of V (left) and U (right) shape electro-thermal actuators



First consider the electro-thermal actuation operation of the V-shape arm device for in-plane translational motion. When an electric voltage is applied across the contact pad electrodes, electrical current will flow through the resistive V-shape supporting arms and rapidly raise the temperature of the arms by Joule heating. Consequently, the arms will mechanically expand, pushing the central structure (movable shutter) upward. Similarly due to Joule heating primarily in one dominant electrically resistive arm of the U-shape device, mechanical expansion of the high temperature arm relative to the cold arm provides in-plane rotational motion of the optical shutter arm.

To further benefit, both designs effectively amplify[1-4] the relatively small displacement of the actual mechanical expansion and thereby achieve the range of motion necessary for MEMS application to low loss fiber optic components[5].

2 Electro-Thermal MEMS Actuated Mirror/Shutter

In response to increasing 100G market demand, a series of MEMS electro-thermal actuated mirror/shutter based components have been developed. These components leverage the unique attributes of MEMS electro-thermal actuated mirror/shutter configurations, including those noted in the Table 1. While the MEMS optical element may function as either a mirror or a shutter depending on specific device architecture, the term mirror will be used generically from this point forward for simplicity.

Table 1: Unique attributes of MEMS electro-thermal actuated mirror/shutter

Attribute	Note
Large in-plane displacement	> 550 μm in a small chip size of 3.4mm x2.3mm
Designed with no wear-out and fatigue	Single-crystal silicon architecture
Direct precision control	No need for active compensation such as closed-loop or look-up table control
High repeatability and durability	Lifetime of over 10^9 cycles has been verified through Telcordia (GR-1073-CORE Section 5.5.4) compliant testing
Low driving voltage	Driving voltage < 5V is compatible with the low voltage board design
Intrinsic tolerance to EDS	Verified by human body model
Latching functionality	Both bi-stable latching and continuous analog motion mirror/shutter implementation available
No need for hermetic package	Negligible electric field at MEMS device

In order to satisfy the variety functionalities of fiber optic components, the novel MEMS electro-thermal actuation mirror devices are implemented in both analog motion and bistable configurations. The former one can be used not only in optical switches but also in optical attenuators. The latching type is mainly used in optical switches or protection shutters as the MEMS mirror maintains its last bistable state after the driving voltage is removed.

2.1 Advanced Electro-Thermal Actuation

The optical MEMS electro-thermal actuators are based on the combination of V- and U-shape structures shown in Figure 1 and leveraging their significant advantages of large actuation force and motion amplification. The designs optimize the range of motion, driving voltage requirements, stable mechanical properties, and chip size for fiber optic component application. The MEMS-chip is fabricated from a silicon-on-insulator (SOI) wafer whose single-crystal-silicon mechanical properties

2 Electro-Thermal MEMS Actuated Mirror/Shutter

provide for extraordinarily high device reliability. Over one billion operating cycles have been demonstrated.

Figure 2 shows the measured in-plane displacement versus driving voltage for a representative electro-thermal actuation MEMS mirror, where the chip size is only 3.4mm x 2.3mm x 0.9mm. The displacement of 570µm enables a 550µm diameter MEMS mirror to align with fiber optic collimators for realizing fiber optic switches and VOAs.

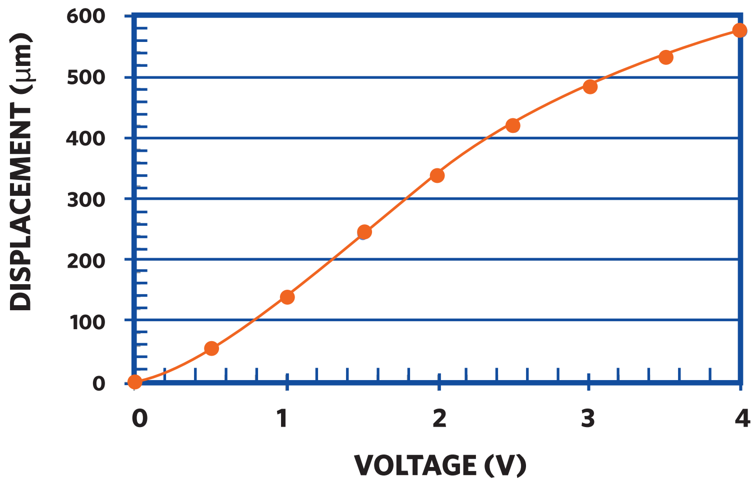


Figure 2: In-plane displacement vs. voltage for a representative MEMS electro-thermal actuated optical mirror.

This MEMS electro-thermal actuated mirror is used as a fundamental building block in fiber optic switching to deflect a collimated input beam between two different outputs. In this switch configuration, it is critical that the MEMS mirror remain in precise optical alignment throughout its repetitive operating lifetime. This key attribute is inherent in the MEMS design due to the constrained in-plane motion and the near elimination of motion-induced wear-out attributable to the mechanical properties of the silicon construction. Further, the precise angular alignment of the mirror with the optical beams is maintained over the operating temperature range without the need for extrinsic compensation, greatly simplify the driving electronics.

When implementing this MEMs architecture in a VOA configuration, the electro-thermal actuated mirror is used as a shutter, utilizing the range of continuous analog motion to variably block the optical beam to attenuate the output. In this configuration, the position of MEMS mirror must be precisely controlled through its range of motion over the specified operating temperature range. The intrinsic attributes of the electro-thermal actuation allow for passive in-package temperature compensation instead of more complex and costly closed-loop or look-up table control in the driving electronics. A series of 20, 50, 230, 320, 400, 500 and 700 µm size MEMS mirror switch and attenuator products are currently in production.

2.2 Bistable MEMS Architecture and Operation

The capability of a MEMS actuator to operate with bi-stability of the optical mirror element is crucial for implementation of latching switches, which is a very desirable switch attribute due to reliability, energy savings, and other considerations. To our knowledge, this technology is the first practical implementation of a MEMS switch providing a large area mirror in a small chip size. The design of the latching MEMS electro-thermal actuators and micro-mirror is schematically shown in Figure 3 and comprising two analog motion V-shape electro-thermal actuators, one micro-mirror, and supporting arms on each side of the mirror. The micro-mirror is held by the pair of curved and bendable arms. This architecture provides two positions of mechanical equilibrium due to the intrinsic push/pull condition of the curved arms, thereby locking the micro-mirror in either of the two stable positions as desired.

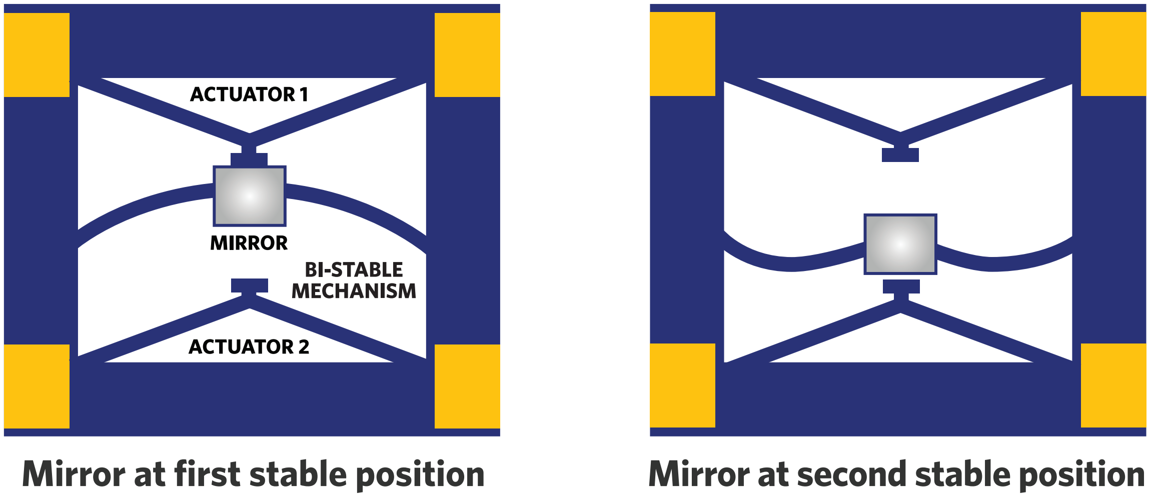


Figure 3: Schematic design diagram of bistable micro-mirror

Figure 4 schematically presents the numerical model for mirror displacement versus the applied force for such a bistable mechanical structure. Under mechanical equilibrium of the curved holding arms, the MEMS mirror will hold at either the "a" or "b" stable position. Consider the mirror to be held at the initial position indicated as "a", also noted as a stable position in Figure 3. When the driving voltage is applied across the V-shape actuator "1", a small and brief current flow through the actuator structure results in Joule heating and thermal-mechanical expansion of the V-shape arms. Referring again to Figure 4, this generates a negative mechanical force which displaces the mirror toward the opposing stable position "b." The key latching action is achieved when the continuously increasing mechanical force exceeds the threshold point, noted as "-F" in Figure 4, at which time the micro-mirror rapidly moves to the second bi-stable state physically opposite the first state position. Movement of the micro-mirror to the second bi-stable position does not require any more pushing force by the V-shape arm #1 beyond the force "-F". After this transition, a new mechanical force equilibrium in the curved arms is established, retaining the mirror at the stable "b" position.

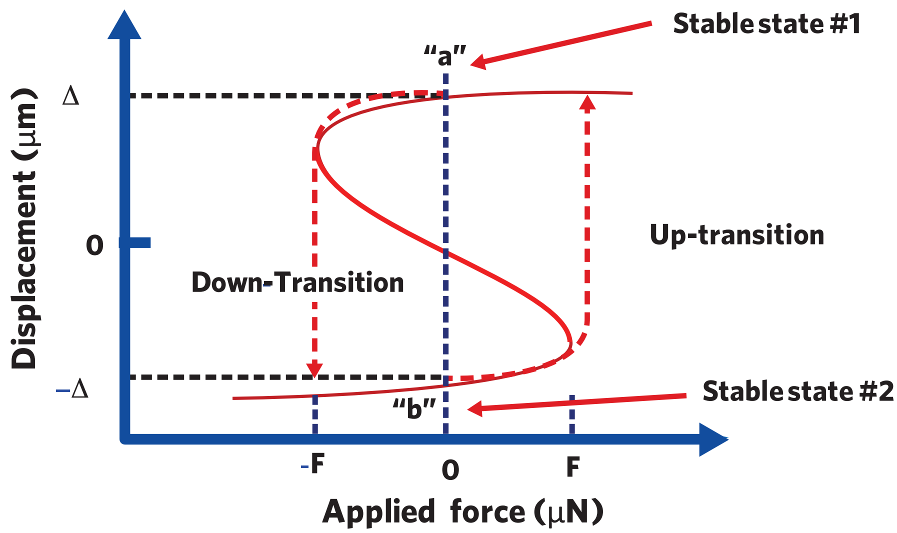


Figure 4: Schematic of displacement vs. applied force in bistable structure

Similarly, the MEMS mirror can be pushed back to position "a" by applying the voltage across V-shape actuator #2. Summarizing, the MEMS mirror is switched between its two stable positions by applying the driving voltage on the appropriate V-shape actuators electrodes. Since a pushing force is not required subsequent to the mechanical transition, the driving voltage can be a simple pulse. No driving power is required to maintain the mirror in either of the two stable positions.

The latching MEMS architecture has been optimized as to mirror in-plane displacement, mechanical force transition threshold, driving voltage, chip size, and mechanical stiffness, and gaps and interaction surface between actuators and micro mirror and reliability. The design and fabrication engineering of V-shape arms and mirror minimize mechanical wear or fatigue such that the switching cycle life exceeds 10^9 cycles for mirror displacements of up to 500 μm.

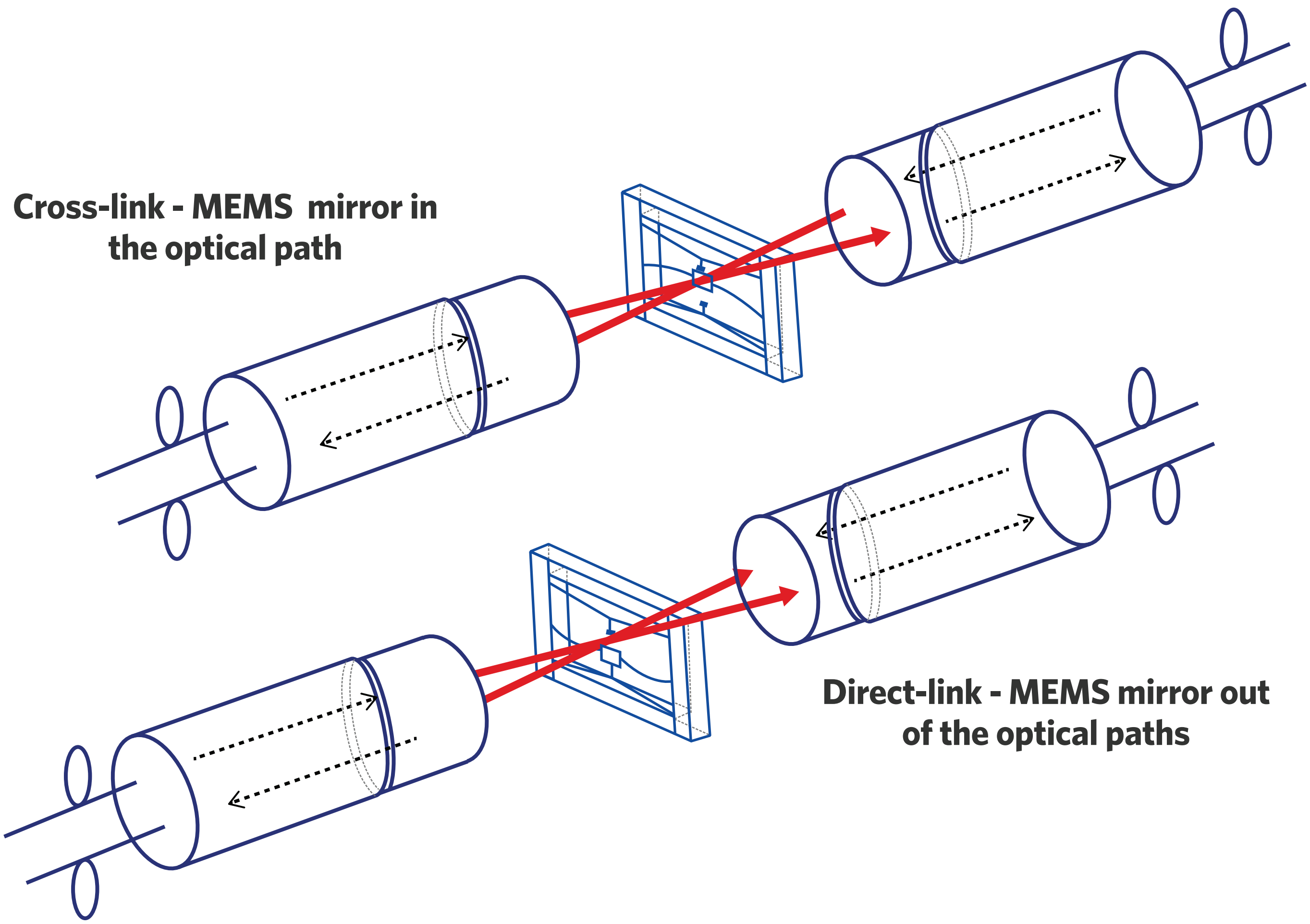
3 Electro-thermal MEMS Based Fiber Optic Components

The wide range of configurations of analog-motion and bi-stable MEMS mirror structures enabled by electro-thermal MEMS actuation provide for great flexibility in designs to reflect or block a collimated optical beam for switching and attenuation components. When used in a VOA, analog motion of the MEMs mirror is used to continuously variably block the optical path by applying an electrical control signal to the electrodes. For optical switching, the MEMS mirror is used to reflect the light beam between two optical paths.

3.1 Fiber optic switches

The use of MEMS mirrors in optical switches offers significant optical performance advantages. These are explained by considering the specific 2x2 switch configuration shown schematically in Figure 5, for which a MEMS mirror is simply moved between two discrete positions, one in and one out of the optical path, between two dual-fiber collimating lenses

Figure 5: Schematic diagram of 2x2 switch with a MEMS mirror.



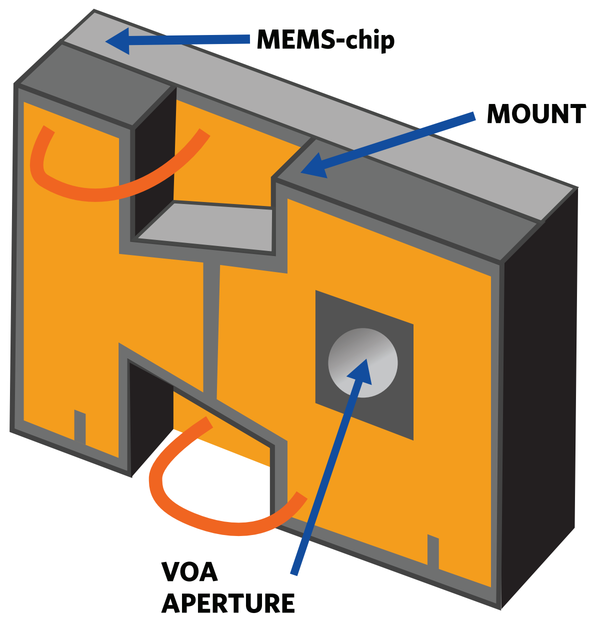
When positioned in the optical path, the MEMS mirror will reflect both of the two collimated beams, input from the opposing directions, to outputs at the same collimating lenses, making a crossing-link connection. However, when the MEMS mirror is positioned out of the optical path, the collimated input beams will be coupled straight through to the opposing collimating lens, forming direct-links. The extremely high optical quality resulting from the MEMS mirror fabrication process results in low insertion loss, specified at less than 0.3dB for the optical switch in its cross-link mode. The MEMS mirror movement is strictly in-plane, so the optical alignment of MEMs mirror to optical path is precisely maintained over its specified operating temperature range without the need for closed-loop controlled compensation, allowing for simple driving electronics.

The ready manufacturability of a variety of configurations of the MEMS electro-thermal actuators and mirrors enables a multiplicity of latching and non-latching switch products. Currently available products include latching and non-latching single-mode and multi-mode optical fiber switches with multiple wavelength capability, including 1x1, 1x2, 2x2, dual 1x1, dual 2x2 bypass, dual-full 2x2, 1x3, 1x4, 3x3, 4x4, 1x8 and 1x16 configurations.

3.2 Free space variable optical attenuator

A key attribute of electro-thermal actuation MEMS technology for variable optical attenuator (VOA) applications is the large in-plane motion of the MEMs mirror. Current production versions of the free space VOA (FS-VOA) are available with aperture sizes of 230, 320, 400, 500 and 700µm. These aperture sizes and the miniature package size are ideal for free space VOA integration with lasers and photo-detectors for compact transceiver production. Normally bright (open) and normally dark versions are available.

Figure 6 shows the schematic diagram of the packaged free-space VOA and a photograph of the production device. This small FS-VOA has package dimensions of 3.4mm x 2.5mm x 0.9mm. Electrical connections can be made by a variety of options including L pins, mounting short, or flying wire.



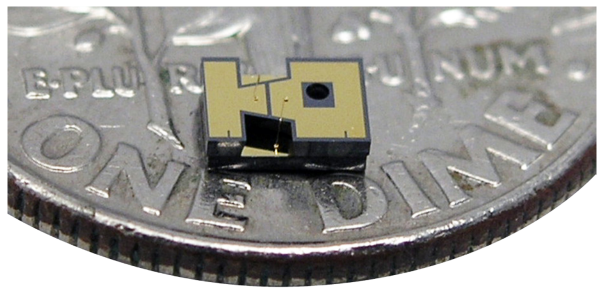


Figure 6: Schematic diagram of FS-VOA (above) and photograph of production device.

The gold-coated FS-VOA mirror is directly driven by an analog DC voltage. The response time over the full attenuation range is 5ms for the 500mm diameter aperture FS-VOA.

3.3 Fiberoptic variable optical attenuator

Complementary to the configuration for the FS-VOA application, relatively miniaturized MEMS electro-thermal actuation shutter devices are manufactured for integration with a dual fiber collimator to produce miniature optical fiber pigtailed VOA. Figure 7 shows the schematic of a compact VOA utilizing this reflective MEMS core. The product package is only 3.5mm diameter and 14.5mm long.

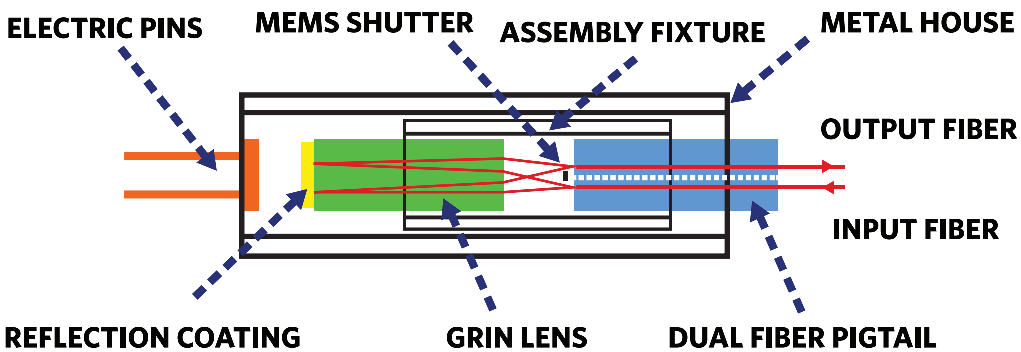
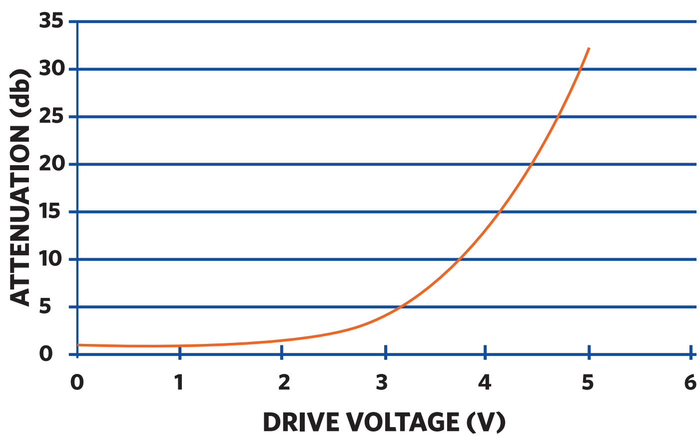


Figure 7: Schematic diagram of reflective fiber-optic VOA based on MEMS shutter

In operation, the analog-motion MEMS shutter is driven by DC voltage to block the output beam path, thereby variably attenuating the optical intensity of the output fiber. Due to its placement in close proximity to the input fiber pigtail where the beam size is small, the MEMS shutter and its required motion is as small as 15µm for single mode fiber without sacrificing the attenuation range. Again, the unique attributes inherent to electro-thermal actuation allow on-chip passive compensation of temperature related drift and fluctuation over a 75C operating temperature range. There is no need for active compensation by circuitry for temperature sensing or look-up table. Figure 8 shows the measured attenuation with driving voltage.

Figure 8: Attenuation vs. driving voltage

Several variations of simple and low cost electro-thermal MEMS based VOAs are in volume production and VOA array products are in development.



4 Summary

Analog and latching types of electro-thermal actuated optical MEMS provide the cores for unique optical switch and variable attenuator products for light path control in communication networks. The performance of these active MEMS mirror/shutter devices make them particularly well suited for application in telecom and datacom optical light path switching and attenuation.

4.1 References

[1] J.H. Comtois and V. M Bright, "Applications for surface-micromachined polysilicon thermal actuators and arrays," Sensors and Actuators A, Vol. 58, pp. 19-25, 1997.

[2] L.Que, J.-S. Park and Y.B. Gianchandani, "Bent-Beam Electro-Thermal Actuators for High Force Applications," IEEE Conf. on Micro Electro Mechanical Systems, Orlando, Florida. pp. 31-36, Jan., 1999.

[3] Michael S. Baker, Richard A. Plass, Thomas J. Headley, Jeremy A. Walraven, Final Report: Compliant Thermo-Mechanical MEMS Actuators LDRD #52553, SANDIA REPORT SAND2004-6635, December 2004

[4] Leslie M. Phinney, Michael S. Baker and Justin R. Serrano (2012). Thermal Microactuators, Microelectromechanical Systems and Devices, Dr Nazmul Islam (Ed.), ISBN: 978-953-51-0306-6, InTech

[5] D J Bell, T J Lu, N A Fleck and S M Spearing, MEMS actuators and sensors: observations on their performance and selection for purpose, J. Micromech. Microeng. 15 (2005) S153–S164.