Advances in MEMS Based Planar VOA

Chengkuo Lee*,, and RueyShing Huang*****

***Abstract*—MEMS technology is proven to be an enabling technology to realize many components for optical networking applications. Due to its widespread applications, VOA has been one of the most attractive MEMS based key devices in optical communication market. Micromachined shutters and refractive mirrors on top of silicon substrate or on the device layer of SOI (Silicon-on-insulator) substrate are the approaches trapped tremendous research activities, because such approaches enable easier alignment and assembly works. These groups of devices are known as the planar VOAs, or two-dimensional (2-D) VOAs. In this review article, we conduct the comprehensively literature survey with respect to MEMS based planar VOA devices. Apparently MEMS VOA technology is still evolving into a mature technology. MEMS VOA technology is not only the cornerstone to support the future optical communication technology, but the best example for understanding the evolution of optical MEMS technology.**

***Index Terms*—MEMS, Optical MEMS, VOA, Attenuator, Actuator**

I. INTRODUCTION

MEMS (Microelectromechanical Systems) technology has been leveraged to create many crucial components for telecommunication applications, such as, optical switch, variable optical attenuator (VOA), tunable filter, tunable laser, and reconfigurable optical add/drop multiplexer (ROADM), etc. A comprehensive review of MEMS components for optical communication has been reported by Ming. C. Wu et al. [1]. Among these devices, VOA and its array are crucial components for enabling the advanced optical network. The requirements for optical communication components vary with the optical networks in which they are deployed. Optical network topologies typically categorized as three major networks, i.e., long-haul, metropolitan area, and access. Long-haul networks are the conventional long distance point-to-point transport networks that can send signals across one thousand kilometers before the need for regeneration. Metropolitan area networks (MANs) refer to metropolitan area core ring networks. MANs are typically hundreds of kilometers in length and typically do not use amplification. Access networks are the metropolitan area access ring networks, with stretches of few to tens of kilometers (including so-called "last mile"). Since its covered distance is short, the amplification is not necessary. After the widespread deployment of wavelength-division multiplexing (WDM) based long-haul optical networks in late 90's, WDM transmission systems have been evolving from point-to-point transmission to next generation reconfigurable add/drop mesh structure. In terms of signal-to-noise ratio, power equalization is extremely important in such a system. Besides, power equalization should be performed automatically to reduce operational expenditure. On the other hand, such technology trend drives MANs to start evolving into transparent architecture. Regarding multiple service contents in MANs, the capability of handling multiple protocols at varying speeds becomes critical to

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the operation efficiency of MANs. Thus components with features of handling optical signals in a way of protocol transparency, and independence of data rate and wavelength are crucial to the practical implementation about supporting this architecture. Nowadays the single-port VOA is commonly used in application like attenuation control on individual line cards and total signal-level control of the optical input to erbium-doped fiber amplifiers (EDFAs). Typically, MEMS VOA devices offers physical features like transparency (bit rate and protocol independent), tunability, scalability, low electrical operation power consumption, and small form factor.

At nodes of MANs, the optical signals in traffic require easily and cost-effectively to be added into or dropped from a particular optical fiber pipeline, and to be switched from one channel to the other, while the optical signal power of certain channels may need to be attenuated at nodes too. Currently the dynamic gain equalizer (DGE) [2, 3] is provided in conjunction with the wavelength-division multi/demultiplexers (MUX/DEMUXs) to perform the functions of attenuation, reconfigurable and transparent add/drop at nodes. The multi-channeled VOA device can be the channel-power equalizer in WDM cross-connect nodes, and in the transmission networks. Thus the integrated multi-channel VOAs with MUX/DEMUXs will be an alternative to fulfill this market. In view of market requirements, like small footprint and low power consumption, an array structure containing multiple MEMS attenuators in a single silicon chip is preferable for future DWDM applications, while single port VOA is demanded in MAN applications.

II. Early Development Works

The early development works of VOA in late 90's are mainly contributed by two groups at Lucent Technology and the group of Prof. N. F. de Rooij at University of Neuchâtel, Switzerland. In 1994, J. A. Walker et al. has developed a MRAS (Mechanical antireflection switch) device [4]. MARS comprises a suspended membrane with an optical window at the center of membrane. By actuating the membrane with displacement of $\lambda/4$, the light of particular wavelength could be either transmitting or reflecting. The original idea was using MARS as an optical modulator for switching function in FTTH (Fiber-to-the-home) applications. In 1998, J. E. Ford, J. A. Walker and their colleagues further revised MARS structure and applied it to the VOA application. This MARS is a silicon nitride suspended membrane with $\lambda/4$ optical thickness above a silicon substrate with a fixed $3\lambda/4$ spacing. Voltage applied to electrodes on top of the membrane creates an electrostatic force and pulls the membrane closer to the substrate, while membrane tension provides a linear restoring force. When the membrane gap is reduced to $\lambda/2$, the layer becomes an antireflection coating with close to zero reflectivity. It is basically a quarter-wave dielectric antireflection coating suspended above a silicon substrate [5]. The membrane sizes varies from 100~500 μm in diameter. The mechanical resonance frequency of such MARS device is on the order of megahertz. Thus the response time is extremely fast, i.e. 3 μs. The dynamic range of attenuation is 25 dB. However, the insertion loss is 2 dB and wavelength dependent loss is relatively high for attenuation larger than 5 dB. J. E. Ford and J. A. Walker have further applied the concept of MRAS to a MEMS based DGE filter. To form the DGE filter, the optical window of the attenuator was elongated to form a suspended rectangular membrane. An array of strip-electrode pairs along the length of the optical window was arranged. By applying independently controlled voltages to all the electrode pairs, a controllable reflectivity function was developed along the length of the device. The diffraction grating-based, free-space optics system was used to spread the incoming light spectrum spatially along the length of the optical window. An input spectrum with more than 15 dB dynamic range was flattened to less than a 0.25 dB ripple over a 42 nm wide spectrum [2].

In contrast to the suspended dielectric antireflection membrane used in MRAS, D. Bishop, C. R. Giles and B. Barber leaded another team at Lucent Technology in 1998 to develop MEMS VOA using a surface micromachined polysilicon micro-shutter arranged between a transmission fiber and a reception fiber aligned and located on the same axis [6, 7]. In this fiber-to-fiber in-line type VOA the shutter is connected with a movable capacitor plate via the pivoted rigid level arm, and this shutter can move upward and downward in an out-of-plane direction by adjusting the position of capacitor plate due to electrostatic force according to the applied voltage. Thereby it can control relative amount of attenuation by blocking part of light beams. This surface micromachined in-line type

MEMS VOA can achieve dynamic range as high as 50 dB, and insertion loss less than 1 dB, while the reported shutter displacement can reach 15μm under 25 volts dc load. More details of these activities of Lucent Technology can be referred to a review article made by J. A. Walker [8].

In addition to surface micromachined polysilicon based approach, DRIE (Deep reactive ion etching) technology is another major alternative for making MEMS VOA structures from device layer of a SOI (silicon on insulator) wafer. The first demonstration was done by Prof. N. F. de Rooji's group at University of Neuchâtel, Switzerland in 1998 [9]. This SOI based VOA device comprises a movable comb finger electrode connected with micro-shutter via a suspended spring and a stationary comb finger electrode. The attenuation range is determined in terms of the in-plane position of Si micro-shutter, where this in-plane position is controlled via force balance between electrostatic force and spring force. To reduce the return loss of the input light reflected back into the input fiber, the micro-shutter and the fiber end faces are at an 82º angle with respect to the longitudinal direction of fiber channels. This in-line type VOA achieved insertion loss and back-reflection loss less than 1.5dB and –37dB, respectively, while it provided 57dB attenuation at 32 volts bias. Apparently among these early demonstrations, the movable micro-shutter based approaches exhibit promising device features, eg. larger dynamic range. DRIE derived SOI MEMS VOA has silicon trenches to accommodate optical fibers with photolithography process determined alignment accuracy regarding to micro-shutter. This feature makes the tedious assembly and alignment works easier.

III. SURFACE MICROMACHINED MECHANISMS FOR VOA APPLICATION

In 2002, another surface micromachined MEMS in-line type VOA using a pop-up micro-shutter based on electrostatic parallel plate actuation has been reported by Prof. A. Q. Liu's group at NTU, Singapore [10-12]. The pop-up micro-shutter is the same as the design of Lucent Technology, while this pop-up micro-shutter is fixed on a drawbridge plate. The micro-shutter can be moved downward to substrate due to applied dc bias. It demonstrates 45dB attenuation under 8 volts bias and 1.5dB insertion loss. Comparing with references [6, 7], the driving voltage has been reduced a lot by using this unique drawbridge structure.

In 2003, a group at APM, Inc. (Asia Pacific Microsystems, Inc.) developed a new movement translation micromechanism (MTM) to convert and amplify small in-plane displacement into large out-of-plane vertical displacement or large out-of-plane rotational angle. As shown in Fig. 1 and 2, the in-plane displacement was provided by electrically controlled electrothermal actuator (ETA) array. Based on this MTM, only 3 dc volts generated 3.1μm in-plane displacement, then rotational angle of 26.4º and equivalent out-of-plane vertical displacement of 92.7 μm for pop-up micromirror was subsequently derived [13, 14]. Using

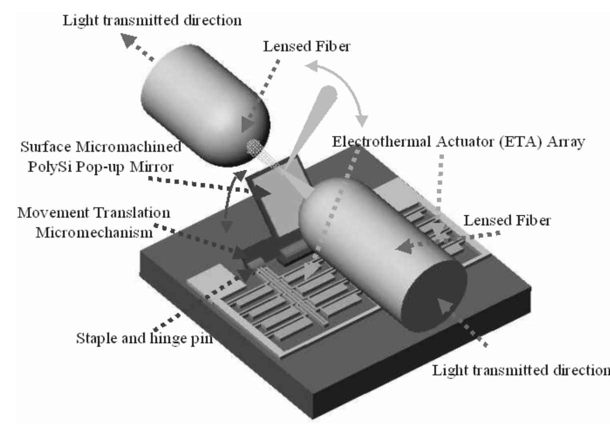


Fig. 1. Schematic drawings of a surface micromachined MEMS VOA comprising a pop-up micromirror, and the input and output fibers. After wet-etching release process, the lense fibers are aligned to achieve the minimum insertion loss first. The attenuated light was reflected toward the out-of-plane direction, when a dc voltage is applied to the ETA array.

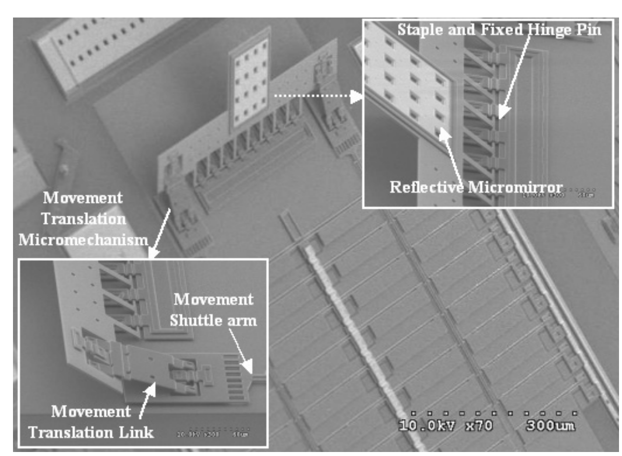


Fig. 2. SEM photo of the MEMS VOA shows that in-plane displacement from the ETA array under dc voltage load is converted into out-of-plane rotation. Upper right inset shows close-up view of pop-up micromirror, staple, and fixed-hinge pin, while bottom left inset shows close-up view of lifted-up MTM structure.

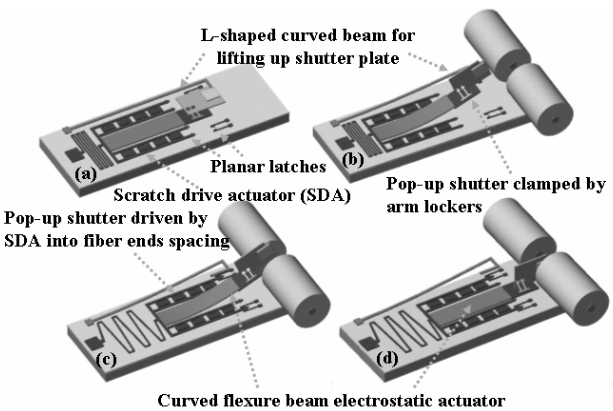


Fig. 3. The schematic drawings of self-assembled VOA with pop-up shutter and stress-induced curved beam electrostatic actuator: (a) device configuration before structure release, (b) device configuration after released and self-assembly, (c) micro-shutter is driven by SDA and moved into the spacing between fiber ends, (d) micro-shutter is moved downward and performed the optical attenuation.

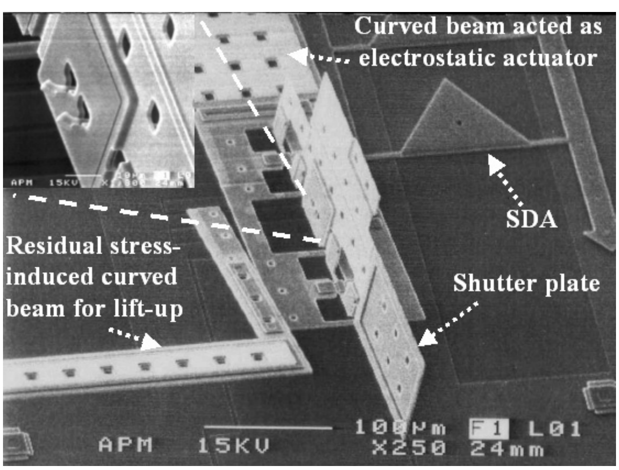


Fig. 4. The SEM photo of MEMS VOA device with the shutter being lifted by L-shape stress-induced curved beam, and clamped by the arrowhead locking element. The inset is the close-up view of the bottom of the shutter plate, which is clamped by the arrowhead locking elements.

this MTM, the in-line type VOA demonstrated 37-dB attenuation range under 3-V dc load, while back-reflection loss, polarization-dependent loss, and wavelength-dependent loss at attenuation of 3 dB are measured as -45dB, 0.05, and 0.28 dB, respectively. It revealed the effort of reducing driving voltage for surface micromachined VOA devices.

In view of that the surface micromachined shutter and structures are vulnerable to be damaged during optic fiber alignment and assembly process, C. Lee et al. proposed a concept and designs for a self-assembled VOA in 2003 [15, 16]. As shown in Fig. 3(a), 3(b) and 4, the self-assembly mechanism allowed reflective shutter to be lifted up and fixed by two individually controlled stress-induced curved polysilicon beams first. Second, this self-assembled reflective shutter was driven by a set of electrostatic scratch drive actuator (SDA) so as to slide into the spacing between input and output fiber ends (Fig. 3(c) and 3(d)). Then the attenuation was determined by the vertical position of self-assembled pop-up polysilicon reflective shutter in which it was controlled by the applied dc bias. This VOA demonstrated continuous attenuation capability, wide attenuation range of 60 dB, and insertion loss less than 1 dB under the 8 and 5 dc volts for bright operation and dark operation, respectively. This self-assembled approach for making VOA reveals the potential solution of getting rid of tedious optical alignment and assembly works, while the damage of fragile surface micromachined polysilicon shutter could be drastically avoided.

IV. Various Attenuation Schemes and Mechanisms Using Electrostatic Comb Actuators

In contrast to the concerns discussed in previous section of surface micromachined VOAs, DRIE derived VOA from SOI substrates with fiber alignment trenches makes the testing, alignment and assembly works easier [9]. The work done at Prof. N. F. de Rooji's group really opens a window for new research activities. Since MEMS VOAs attenuate light signals in free space, the relative wavelength-dependent loss, polarization-dependent loss and insertion loss are lower than other waveguide-based approaches, while return loss and response time can perform as good as the data achieved by the other approaches (eg., any waveguided formats). However, the back reflected light coupling into input fiber was a concern for in-line type MEMS VOAs. In order to have smaller return loss, using fibers with 8°-facet ends is a common solution for in-line type VOA. C.-H. Kim et al. from Seoul National University has reported a new electrostatic comb actuated VOA with off-axis misalignment based light attenuation scheme at the International Conference of Optical MEMS 2002, Lugano, Switzerland, in 2002 [17], while C. Lee revealed similar device configuration done by APM, Inc in an invited talk at the same conference [18]. The devices made by C.-H. Kim exhibited 2.5 dB insertion loss and 50 dB attenuation with respect to 14μm displacement of comb actuator at 5 volts. Meanwhile, APM's relevant results have been published in elsewhere in 2003 [19, 20]. The VOAs In early 2003, the VOAs using off-axis misalignment, i.e., single reflection type, typically achieved 35 dB attenuation and 50 dB attenuation under 10–13 volts and 13-15 volts, respectively. C.-H. Kim et al. of SNU reported their progress in VOA research at the International Conference of Optical MEMS 2003, Hawaii, USA, in 2003 [21]. The reported VOA achieved 35dB attenuation at 10 volts, while the maximum polarization-dependent loss was 0.24dB within 25 dB attenuation range. These data were leading performance at that time. It also reported return loss as of –38 dB and the maximum wavelength dependent loss is 0.7dB at 25dB attenuation. On the other hand, C. Lee et al. at APM have improved the designs of electrostatic comb actuator and done the improvement of single reflection type VOA. Fig. 5 and 6 show the equivalent polarization dependent loss, wavelength dependent loss and similar attenuation versus dc bias characteristics. These data are about the same as data reported by C.-H. Kim. But the return loss is kept smaller than –50dB in 50dB dynamic attenuation range is much better than the data in Ref. [21]. In 2003, A. Bashir et al. at MEMSCAP, Cairo, Egypt, also developed similar single reflection type VOA devices. The relevant results published in 2004. [22]. Their work achieved 30dB attenuation at 32 dc volts. Within the 30dB dynamic range the derived polarization dependant loss was less than 0.1dB in which it was better than the data of the other groups' works.

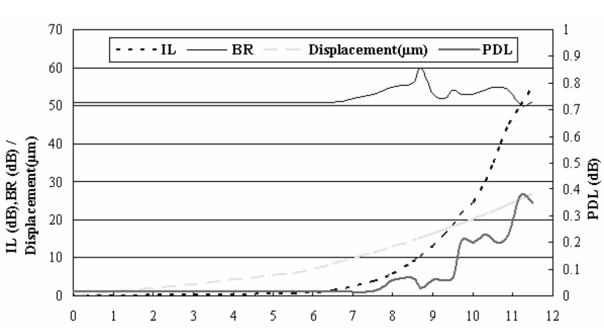


Fig. 5. Measured attenuation characteristic curves of bright operation including insertion loss (IL), back-reflection loss (BR), polarization dependant loss (PDL) and micromirror displacement versus the driving dc voltage.

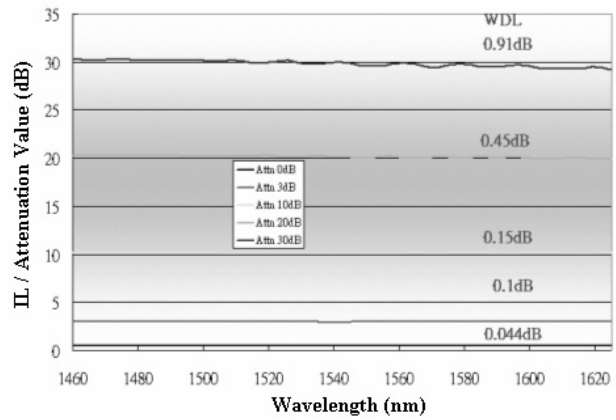


Fig. 6. Curves of wavelength dependent loss for the single reflection type VOA device with respect to various attenuation ranges.

On the other hand, upon the networking equipment configurations, we may need VOAs operated in normally close scheme, i.e., dark type. The dark type VOA means all incoming light is blocked out, i.e., 100% attenuation in the beginning. All the previous reported data and discussion from reference are based on normally open scheme, i.e., bright type. It means the initial attenuation is zero, i.e., initial insertion loss only. In order to clearly illustrate the difference in operation mechanisms for bright and dark types of VOAs with respect to in-line and single reflection types, we explain the relationship between light paths and attenuation mechanisms first.

As illustrated in the upper-left drawing of an in-line type VOA with slanted shutter of 8°-angle (Fig.7a), the insertion loss is maintained initially at its minimum level, and incoming light signals are fully transmitted (i.e., the upper-left drawing of Fig. 7b). This shutter is approaching toward the light in transmission due to an applied electrical bias, then a portion of incoming light being blocked regarding to shutter position as illustrated in the middle-left drawing of Fig.7b. The dark circle denotes the light beam and the dotted circle represents the light receiving area of output port. This drawing illustrates the partially attenuated state of an in-line VOA device. Once the shutter approaches further, then all the light is fully blocked. It is the fully attenuated state as illustrated in the bottom-left drawing of Fig.7b. Besides, the dark type in-line VOA device is kept at its rest state, i.e., zero bias state (the upper-right drawing of Fig. 7b), thus the VOA maintains at their maximum insertion loss at the beginning state. Then a portion of light is allowed to transmit regarding

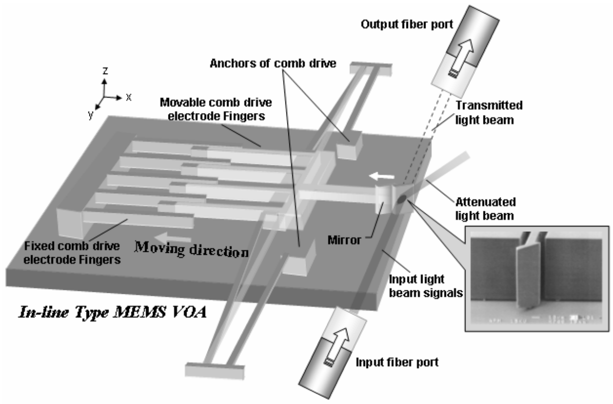


Fig. 7(a). Schematic drawing of the in-line type MEMS VOA; where the SEM photo of a micro-shutter with a mirror plane of a tilted angle is shown in inset.

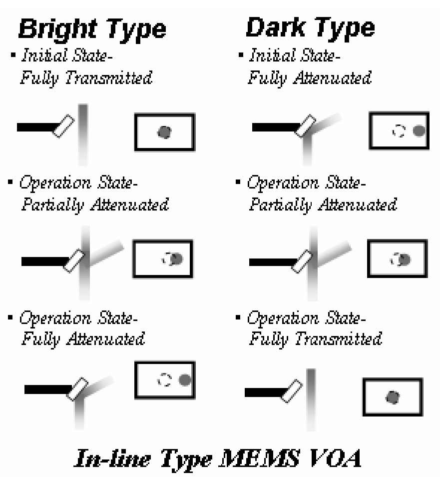


Fig. 7(b). Schematic drawing of light path configuration based on the in-line type attenuation scheme operated in bright and dark types.

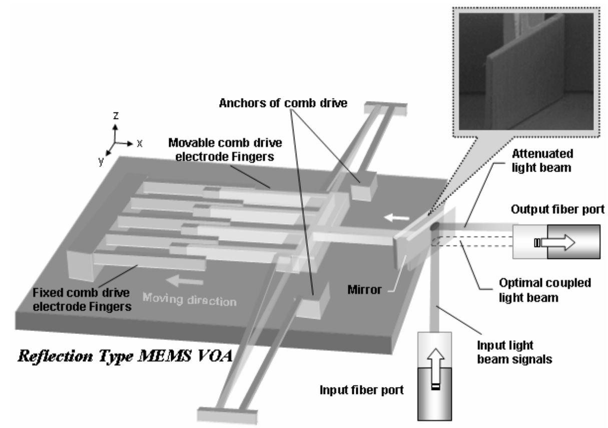


Fig. 7(c). Schematic drawing of the reflection type MEMS VOA; where the SEM photo of a reflective micromirror with a mirror plane of 45° tilted angle is shown in inset.

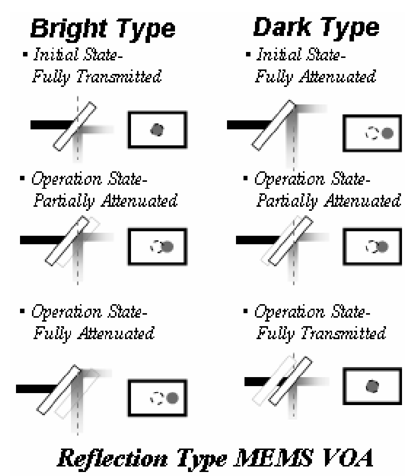


Fig. 7(d). Schematic drawing of light path configuration based on the reflection type attenuation scheme operated in bright and dark types.

to shift of shutter position under a certain level of electrical bias (the middle-right drawing of Fig. 7b). When the applied electrical bias is larger enough to get the shutter away from the light transmission path, all light is fully transmitted and coupled into output port (the bottom-right drawing of Fig.7b).

Fig. 7c illustrates the input fiber port and output fiber port allocated in an orthogonally planar location, where the transmission light incidents a reflective mirror and is reflected toward the output port. It is the so-called reflective type or single reflection VOA. The reflected light path is changed according to different mirror positions which are determined by comb drive actuator according to various applied voltages, therefore the coupled light intensity of reflected light to output port is depending on the path of reflected light. As shown in Fig. 7d, the reflected light is fully coupled into output port and fully attenuated at the beginning for bright type operation and dark type operation, respectively. While the partial attenuated state is considered as the operation state for both bright and dark types, the actuated mirror position versus the initial rest mirror position is opposite to each other, as shown in the middle drawings of Fig. 7d. Once the applied voltage is larger enough, the reflective mirror is pulling back further, and then the reflected light path is shifted far away from the initially optimized light path. Therefore the VOA of bright type operation reaches its full attenuation (the bottom-left drawing of Fig. 7d), while the VOA of dark type operation reaches its full transmission state (the bottom-right drawing of Fig. 7d).

Fig. 8 shows the measured attenuation characteristics for reflective VOA operated in dark operation scheme.

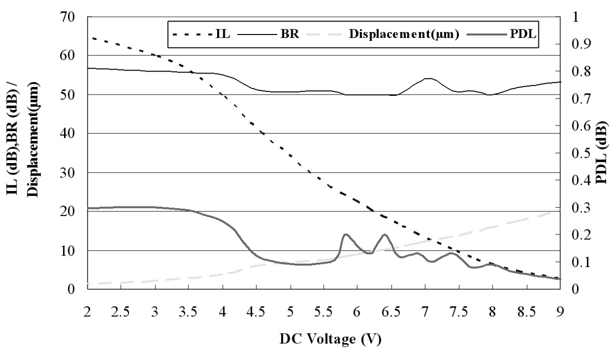
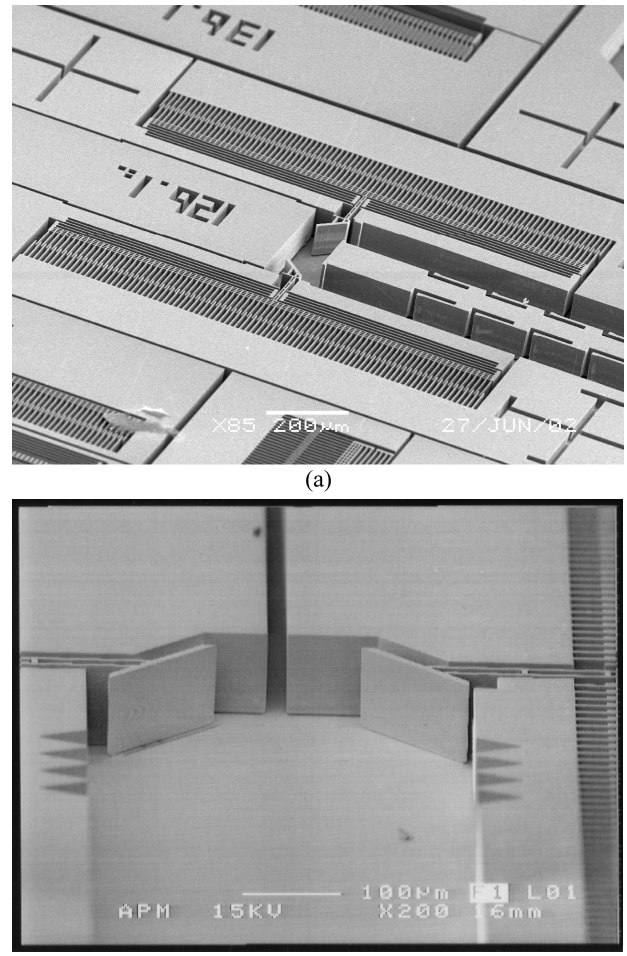


Fig. 8. Measured attenuation characteristic curves of dark operation including insertion loss (IL), back-reflection loss (BR), polarization dependant loss (PDL) and micromirror displacement versus the driving dc voltage.

The dynamic range of 30dB was achieved for dark type operation under driving voltage from 5.25 to 8.25 dc volts. The zero attenuation state, i.e., the full transmission state, was reached by applying 8.25 dc volts for dark type operation. The return loss, i.e., back-reflection loss (BR), was less than –50 dB over the full span for bright type, and -48 dB for dark type, respectively. Besides, the polarization dependent loss was derived as less than 0.15 dB within 10 dB attenuation, less than 0.2 dB for attenuation between 10 dB and 20 dB, and less than 0.3 dB for attenuation between 20 dB and 30 dB, respectively. In summary, the VOAs using single reflection demonstrates extremely well polarization dependent loss and better return loss than shutter based VOAs. With proper design of comb actuators, well optimized DRIE process and appropriate selection of lense fibers, reflective type VOA is superior except to a concern that package of reflective type VOA with 45º between input and output optical fiber ports is not a common layout configuration in application markets.

V. INNOVATIVE ALTERNATIVE APPROACHES

As the layout format concern mentioned in the previous paragraph, C. Lee et al., of APM came up with a new retro-reflective type VOA in 2003, meanwhile VOA of similar concept has been reported by T.-S. Lim et al. of LG Electronics Institute of Technology. T.-S. Lim et al. created a folded-mirror with 45º between two reflective mirrors, where this folded-mirror is connected with a set of comb actuators and is suspended via a silicon beam [23]. This VOA achieved 30 dB attenuation



(b)

Fig. 9 SEM photographs of retro-reflective type MEMS VOA devices; (a) two reflective micromirrors and two coaxially arranged fiber trenches to form a retro-refractive type VOA, (b) close-up view of micromirrors made by using DRIE of SOI substrate.

at 34 dc volts. In contrast to Lim's work, APM's retro-reflective type VOAs comprised two separately controlled reflective micromirrors that are allocated in the front of input and output fibers and then assembled in a planar coaxial layout (Fig. 9). The measured characteristics exhibit insertion loss of less than 0.9 dB, return loss of less than –50 dB, and WDL of less than 0.35 dB and 0.57 dB at 20 dB and 30 dB attenuations, respectively. The measured dynamic range of 50 dB under 7 dc volts and voltage span of 4.7 to 11 dc volts was reported for bright and dark operations, respectively. The relevant results were published in 2004 [24, 25]. Basically this retro-reflective attenuation mechanism resulted in lower operation voltage, since the intensity adjustment depends on the light path shift that is doubled after retro-reflection for the same actuator driving voltage in previous reflective type VOAs. These two micromirrors are potentially capable of being feedback controlled individually; thus, attenuation curve could behave more linear with dedicated control design. Besides, users in optical communication industry are familiar with the planar coaxial layout.

T.-S. Lim et al. further explored the possibility of driving folded-mirror by using rotary comb actuator for VOA application. This VOA comprised a folded-mirror connected with rotary comb via a suspended beam. It reported attenuation of 45dB at a rotation angle of 2.4º under 21 dc volts, and response time of less than 5ms in 2004 [26]. J. Andrew Yeh et al. have reported a novel rotary comb actuator for reflective type VOA applications [27]. It reported 50dB attenuation at a rotation angle of 2.5º under 4.1 dc volts. The response time from 0 to 40 dB attenuation and backward switching time were measured as 3 and 0.5 ms, respectively. The measured insertion loss was 0.95 dB and the polarization dependent loss was 0.3 dB at 20dB attenuation regarding to a wavelength of 1550 nm. The WDL was measured to be 0.19, 0.25, 0.61, and 0.87 dB for attenuation at 0, 3, 10, and 20 dB, respectively.

On the other hand, in 2003, a wedge-shaped silicon optical leaker, i.e., a revised shutter, is proposed as a new refractive type VOA by Y. Y. Kim of Korea Aerospace Research Institute, S. S. Yun, et al., of the Kwang-Ju Institute of Science and Technology, Gwangju, Korea, and Y. G. Lee, et al., of Samsung Electro-Mechanics Company, Suwon, Korea [28]. The fabricated VOA with optical fibers of 8º-facet end achieved wide attenuation range of 43 dB and small return loss of less than -39 dB, while the polarization dependent loss was also measured to be less than 0.08, 0.43, 1.23, and 2.56 dB for the attenuation at 0.6, 10, 20, and 30 dB, respectively. C.-H. Kim and Y.-K. Kim from Seoul National University have integrated two 45º reflective mirrors to form a dual-reflection based in-line type with minute parallel-shifted light propagation axis between input and output ports [29]. It also reported the comprehensive comparison between single reflection VOA using lens fibers and the dual-reflection in-line type VOA using common optical fibers.

Without using 45º reflective mirror, Prof. A. Q. Liu's group at NTU, Singapore proposed a novel elliptical mirror driven by a axial movable comb actuator, where the input and output fibers were arranged and aligned in an orthogonal layout regarding to said elliptical mirror [30]. In this unique design the input and output fibers were allocated at the two focal centers of the reflective elliptical mirror. Since the ellipse can focus the light from one center to the other, the VOA enjoys low insertion loss while using the common single-mode fibers. As the mirror is shifted in the direction of the axial direction of one fiber, the input beam is rapidly defocused, producing wide attenuation range without requiring large mirror displacement. The dynamic range of 44 dB was achieved at 10.7 dc bias, while the response time was measured as 0.22 ms, respectively. The measured insertion loss was 1 dB and the polarization dependent loss was 0.5 dB and 0.8 dB at 20dB and 40 dB attenuations, respectively. The measured WDL was 1.3 dB at 20dB attenuation within 1520-1620nm. Without using expensive optics, eg. lensed fibers, this new design revealed very interesting results with promising application potential.

VI. Reliability Criteria and Concluding Remarks

As we discussed in introduction section, there is a demand of applying MEMS based VOA in format of multiple channels so as to fulfill the requirement of reconfigurable and transparent add/drop function at nodes of optical network. Using silicon deep reactive ion etching (DRIE) to sculpt actuators and micro-mirrors from silicon-on-insulator (SOI) substrates has been the most available micromachining process for VOAs. However, the non-uniformity characteristics of process induced device performance distribution of key parameters are lacking of comprehensive study, while such information is crucial to practical applications in industry. In 2005 C. Lee explored and characterized the performance of arrayed MEMS VOA devices of 8 independently controlled channels, i.e., multi-channeled VOA (MVOA), based on using in-line shutter type, reflective type [31] and retro-reflective type [32]. The channel number is potentially scaled up to 16 channels. In these studies, experimental study of critical parameters such as, insertion loss, polarization dependent loss, return loss and wavelength dependent loss were characterized for several MVOA devices of monolithically integrated multi-channeled configuration based on three kinds of planar light path

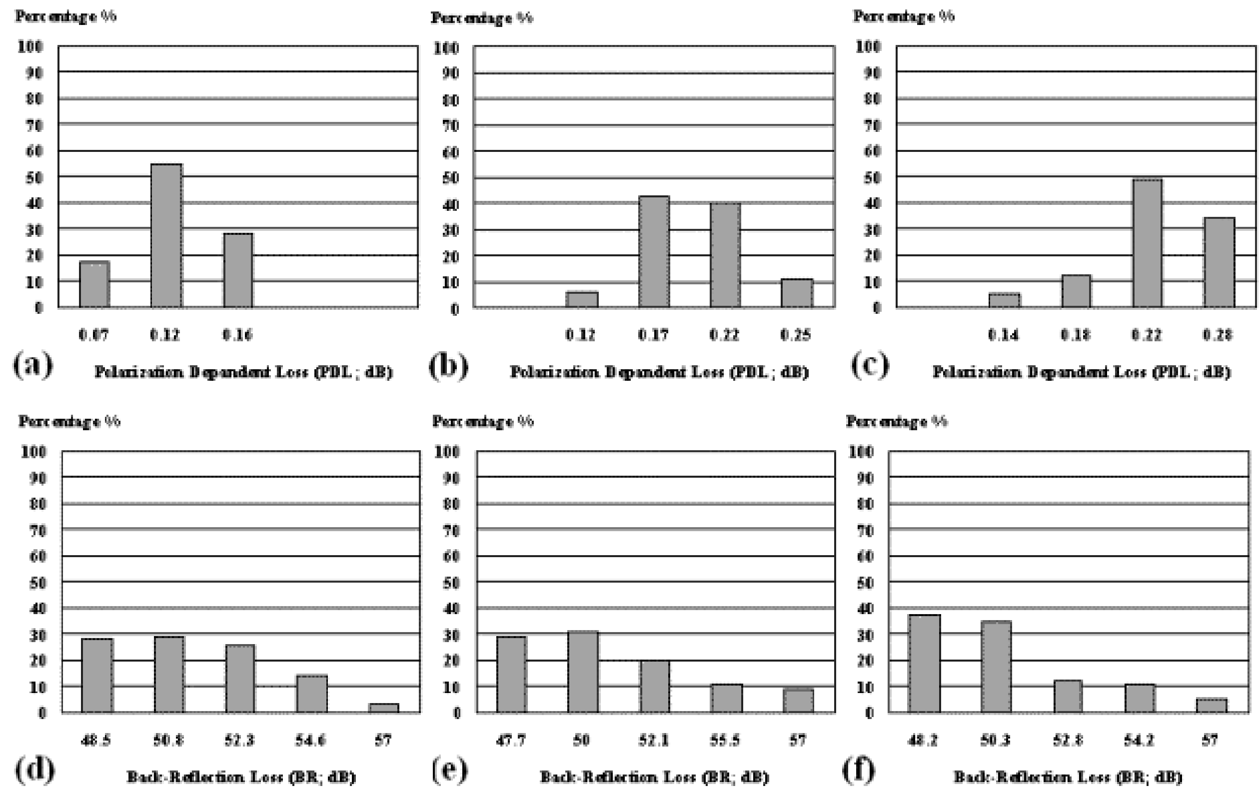


Fig. 10. Histogram of mean value distribution of measured data from each individual channel of multi-channeled VOAs using retro-refractive attenuation scheme regarding to their polarization dependant loss (PDL) and back-reflection loss (BR) characteristics; where (a) and (d) represent the measured at 10-dB attenuation; (b) and (e) regarding to data at 20-dB attenuation; (c) and (f) show the data derived at 30-dB attenuation.

attenuation schemes. Under well-controlled process, the MVOA devices commonly provide excellent optical performance with respect to industrial common specifications. Fig. 10 display the distribution of measured key parameters of several MVOA devices. These data revealed competing optical characteristics, while the monolithic integrated MVOA device is considered as a cost-effective solution in terms of manufacturability, scalability, and ultra-compact footprint.

Moreover, the device characteristics regarding to the Telecordia GR1221 regulation are very interesting for practical applications. According to the Telecordia GR1221 regulation, the measured attenuation dynamic deviation value at 20dB attenuation should be less than ±0.5 dB under a vibration testing condition of 20G periodical shocks with frequency from 20 to 2kHz along with X, Y, and Z axes, where 4 cycles of vibrations are required for each axis. In view of such strict requirement, C. Lee has proposed an H-shaped electrothermal mechanism in conjuction with retro-reflective mirrors for VOA application, as shown in Fig. 11. By drastically reducing the mass and enhancing the stiffness of structure, the mechanical resonant frequency of H-shaped electrothermal VOA becomes much higher than the data of its counterpart, i.e., the electrostatic comb actuator based retro-refractive VOA [33, 34]. Thus the measured dynamic attenuation deviation is less than ±0.03 and ±0.15 dB over the full range of 20 to 2kHz with respect to the axes of in-plane and out-of-plane perpendicular directions to the moving axis, where the moving axis is considered as the central beam with two refractive mirrors of H-shaped structure. As listed in table 1, the measured dynamic attenuation deviation is less than ±0.28, ±0.30, ±0.36 and ±0.10 dB

Table 1. Dynamic Attenuation Characteristics.

Mirror Moving Axis	< ±0.28 dB@100Hz < ±0.36 dB@1KHz	< ±0.30 dB@500Hz < ±0.10 dB@2KHz
In-plane Perpendicular Axis	< ±0.03 dB	Over 20~2K Hz
Out-of-plane Perpendicular Axis	< ±0.15 dB	Over 20~2K Hz

Table 2. Specifications of Commercial MEMS VOAs.

	Lightconnect (FVOA 2000)	Lightconnect (FVOA 5000)	DiCon (MEMS Attenuator)	Santec (MOVA-1)	Sercalo (VXP)	Sercalo (VXA)
Mechanisms	3-D Grating/ Diffractive	3-D Mirror/ Reflection	3-D Mirror/ Reflection	3-D Mirror/ Reflection	2-D Mirror/ Reflection	2-D Mirror/ In-line shutter
Dynamic Range	25dB	40dB	Referred to 20dB for measured data	30dB	30dB	30dB
IL	1.0dB Max. (0.7dB typical)	0.8dB Max. (0.4dB typical)	0.8dB Max.	0.8dB Max.	0.9dB Max. (0.4dB typical)	1.0dB Max. (0.6dB typical)
PDL	0.15dB within 25dB	0.2dB within 40dB (0.14dB typical)	0.15dB within 15dB 0.2dB @ 15 to 20 dB	0.3dB within 20dB	0.15dB within 10dB 0.25dB @ 10 to 20 dB	0.6dB within 10dB 1.2dB @ 10 to 20 dB
BRL	-45dB	-45dB	-50dB Max.	-40dB	-50dB Max. (-55dB typical)	-35dB Max. (-45dB typical)
WDL	0.3dB Max. @ 25dB (0.14dB typical)	0.1dB Max. @ 10dB (0.04dB typical)	0.2dB Max. @ 20dB	0.5dB Max. @ 10dB 1.2dB Max. @ 20dB	0.4dB Max. @ 10dB 1.2dB Max. @ 20dB	0.4dB Max. @ 10dB 1.2dB Max. @ 20dB
Driving Voltage	8 Volts	6.5 Volts	5 Volts	< 20 Volts	5.25 Volts Max. (5V typical)	5.25 Volts Max. (5V typical)
Driving Power	10 mW	0.5 mW	20 µW	<10 mW	30 mW Max. (5 mW typical)	30 mW Max. (5 mW typical)
Response Time	90 µs	20 ms	2 ms Max.	10 ms Max.	2 ms	2 ms

at vibration frequencies of 100, 500, 1k and 2kHz along with mirror moving axis, respectively. Since the nature of symmetric structure of H-shaped VOA device and high aspect ratio of silicon beam along with the out-of-plane perpendicular direction, i.e., the z-direction, provides excellent mechanical stability against to mechanical vibrations.

A well-known MEMS VOA company, Lightconnect, Newark, CA, US, produce a grating based MEMS VOA device using the diffractive type of mechanism, i.e., FVOA3000. This is the first MEMS VOA device complied with Telecordia GR-1209 and GR-1221. Lightconnect's design is a revised design [35, 36] in which it was a modified one from the original design invented by Prof. O. Solgaard [37]. This device shows excellent response time, i.e., 90-µs, regarding to moderate dynamic attenuation range of 25dB. It is worth to mention that Lightconnect announced their 3-D MEMS mirror based VOA, i.e., FVOA5000, passed the Telecordia GR-1209 and GR-1221 in Aug. 2006. In addition to these two well-known MEMS VOA products, we also put the rest well-known commercial MEMS products together in table 2. These products include 3-D MEMS reflection mirror based products from DiCon, Richmond, CA, US [38] and Santec, Komaki, Aichi, Japan [39], planar MEMS reflective mechanism of Sercalo's VXP, and planar MEMS in-line shutter mechaism of Sercalo's VXA [41]. The reflection type of mechanisms generate better average performance than data of in-line shutter and 3-D grating. When we compare the updated data in recent publications [22, 27, 29, 31, 33] with data of Sercalo's single reflection products and in-line shutter products, we will have the impression that general performance of planar MEMS VOA devices in research papers are mush better than Sercalo's products. However, it may not be fair to make such statement. Since research papers typically revealed the best data, while product specification sheet represents the promised performance for all shipped products. It means that products' specification is the minimum performance of products. Thus the products' specification is generally worse than the best data shown in research papers. On the other hand, when we check the data discussed in the multi-channel VOA results in Ref. [32], we may have equivalent PDL performance for retro-reflective MEMS VOA and single reflection VOA of Sercalo's VXP at 10dB and 20dB attenuation. It shows the similar data level when we have a large amount of sampling points. It means these commercial products are not bad at all. One more interesting point is the driving voltage. All these commercial products have the on-chip voltage amplifier except to Santec's one. Therefore they all show driving voltage less than or about 5 volts and response time about 2ms, while Santec's one requires driving voltage less than 20 volts and response time less than 10ms. By leveraging the on-chip voltage amplifier, these devices can deploy stiffer springs so as to gain in fast response time, i.e., 2ms.

The aforementioned data point out the promising application potential of MEMS VOAs. Since the architecture of next generation optical communication evolves step by step into the mesh networks from the present system. New functions and requirements for MEMS VOAs may come to us upon the network evolution. The current market demands of MEMS VOAs already consider as a business of multiple hundred million US dollars.

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