Optical MEMS for Lightwave Communication

Ming C. Wu, *Fellow, IEEE*, Olav Solgaard, *Member, IEEE*, and Joseph E. Ford

Invited Paper

***Abstract*—The intensive investment in optical microelectromechanical systems (MEMS) in the last decade has led to many successful components that satisfy the requirements of lightwave communication networks. In this paper, we review the current state of the art of MEMS devices and subsystems for lightwave communication applications. Depending on the design, these components can either be broadband (wavelength independent) or wavelength selective. Broadband devices include optical switches, crossconnects, optical attenuators, and data modulators, while wavelength-selective components encompass wavelength add/drop multiplexers, wavelength-selective switches and crossconnects, spectral equalizers, dispersion compensators, spectrometers, and tunable lasers. Integration of MEMS and planar lightwave circuits, microresonators, and photonic crystals could lead to further reduction in size and cost.**

***Index Terms*—Microelectromechanical devices, optical fiber communication, optical signal processing, optical switches.**

I. Introduction

NEARLY three decades ago, Petersen published a paper on the micromechanical spatial light modulator (SLM) array [1] and another on the silicon torsion mirror [2]. Thirty years later, this has become a thriving field known as optical microelectromechanical systems (MEMS), sometimes also called microoptoelectromechanical systems, with several conferences dedicated to the field. It is a key enabling technology for the "dynamic" processing of optical signals. The first market driver of optical MEMS was display [3], [4]. The digital micromirror devices developed by Texas Instruments Incorporated are one of the most successful MEMS products. They are now widely used in portable projectors, large-screen TVs, and digital cinemas [3]. The applications of optical MEMS in telecommunications started in the 1990s [5], [6]. Early efforts have focused on the development of optical MEMS devices and fabrication technologies [7]–[10]. The telecom boom in the late 1990s and early 2000s has accelerated maturation of the technology. A wide range of optical MEMS components were taken from laboratories to reliable products that meet Telcordia qualifications. Although not all commercialization endeavors were successful due to the market downturn, the technology developed is available for new applications in communications and other areas [11].

In this paper, we will review the recent developments in optical MEMS for communication applications. With the rapid expansion of the field and proliferation of literature, it is not possible to cover all developments in the last decade. Instead, we will focus on a selected set of applications and discuss the design tradeoffs in MEMS devices and systems. Topics selected in this paper include optical switches, filters, dispersion compensators, spectral equalizers, spectrometers, tunable lasers, and other dense-wavelength-division-multiplexing (DWDM) devices such as wavelength add/drop multiplexers (WADMs), wavelength-selective switches (WSSs), and wavelength-selective crossconnects (WSXC). Most of the practical components reported were based on free-space optics. There are increasing interests in extending the benefits of optical MEMS to guided-wave optics or even nanoscopic photonic structures. This new trend will be discussed at the end of this paper.

Various types of optical switches are needed in telecommunication networks. Small $1 \times N$ and $N \times N$ switches are useful for protection, while optical crossconnect (OXC) offers fast provisioning and network management at the wavelength level. Nodes in ring networks employ WADMs. As the networks evolve toward mesh configuration, WSSs and WSXC become important. Dispersion compensators and spectral equalizers are essential for improving the link performance as the data rates approach 40 Gb/s. Spectral filters and tunable lasers increase the flexibility of DWDM nodes.

This paper is organized as follows: Section II discusses broadband (wavelength-independent) devices, including data modulators, variable optical attenuators (VOAs), and two-dimensional (2-D) and three-dimensional (3-D) MEMS optical switches. Section III describes wavelength-selective MEMS, including spectral equalizers, WADMs, WSSs, WSXCs, filters, dispersion compensators, transform spectrometers, and tunable lasers. Section IV focuses on the integration of MEMS and planar lightwave circuits (PLC). Section V introduces new device concepts based on MEMS-actuated microresonators and photonic crystals, and Section VI concludes this paper.

Manuscript received July 7, 2006; revised October 2, 2006. This work was supported in part by the U.S. Defense Advanced Research Project Agency (DARPA)/Army Research Office under Grant W911NF-05-1-0359 and DARPA under Grant MDA972-02-1-0020.

M. C. Wu is with the Berkeley Sensor and Actuator Center (BSAC) and Electrical Engineering and Computer Sciences Department, University of California, Berkeley, CA 94720 USA (e-mail: wu@eecs.berkeley.edu).

O. Solgaard is with the E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 USA (e-mail: solgaard@stanford.edu).

J. E. Ford is with the Department of Electrical and Computer Engineering, University of California, San Diego, CA 92093-0407 USA (e-mail: jeford@ucsd.edu).

Color versions of Figs. 3, 5, 10–12, 14, 15, 17, 18, 20, 22, and 25–28 are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2006.886405

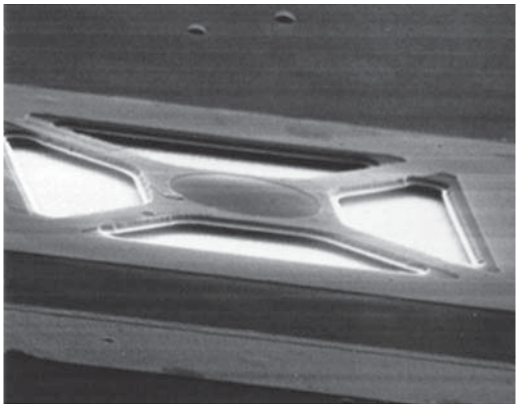

Fig. 1. MEMS etalon modulator used for digital data modulation at over 1 Mb/s. The circular optical aperture is 22 μm in diameter.

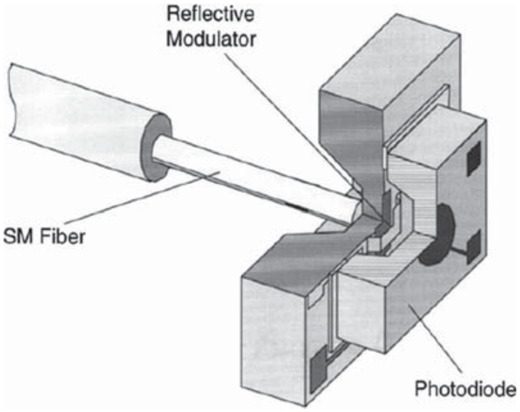

Fig. 2. Package configuration for a MEMS data transceiver.

II. Wavelength-Independent MEMS

A. Data Modulators

The first practical application of MEMS devices in fiber communications was as an optical data modulator, originally intended for a low-cost fiber-to-the-home network. A modulator is essentially a 1×1 switch, operated in either transmission (two fibers) or reflection (single fiber). The optical power is provided by a constant-intensity remote source, and the modulator imprints a data signal by opening and closing in response to an applied voltage. Signaling in DWDM fiber networks usually requires an expensive wavelength-controlled laser at each remote terminal. Passive data modulators offered a potentially inexpensive solution, but waveguide modulators were too expensive and too narrow in optical spectral bandwidth to be practical. MEMS offered a new and practical solution.

The mechanical antireflection switch (MARS) modulator is a variable air-gap etalon operated in reflection. The basic structure is a quarter-wave dielectric antireflection (AR) coating suspended above a silicon substrate [5]. The quarter-wave layer is made of silicon nitride with $1/4\lambda$ optical path (index times thickness), which is roughly 0.2 μm for the 1550-nm telecom wavelength. The mechanically active silicon nitride layer is suspended over an air gap created by a $3/4\lambda$-thick phosphosilicate glass sacrificial layer (0.6 μm). Without deformation, the device acts as a dielectric mirror with about 70% (-1.5-dB) reflectivity. 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 AR coating with close to zero reflectivity. A switching contrast ratio of 10 dB or more was readily achieved over a wide (30-nm) spectral bandwidth.

The initial MARS device shown in Fig. 1 consisted of a 22-μm optical window supported by X-shaped arms and had a resonant frequency of 1.1 MHz. Later devices used a higher-yield structure with a symmetric "drum head" geometry [12], [13]. These devices were capable of relatively high-speed operation: by optimizing the size and spacing of the etch, access holes provide critical mechanical damping, and digital the-home, related modulators are useful for low-power dissipation telemetry from remote sensors using free-space optical communications.

These early devices provided a proving ground for the reliability and packaging of optical MEMS telecom components. Initial skepticism from conservative telecom engineers was combated by the parallel testing of device array operated for months to provide trillions of operating cycles. The packaging of optical MEMS devices provided new challenges for MEMS engineers, but the simple end-coupled configuration was relatively straightforward to implement. Fig. 2 shows the configuration for a duplex modulator incorporating a MEMS etalon, where data can be received by a photodiode and transmitted by modulating the etalon reflectivity [15].

B. Variable Attenuators

Data modulators are operated with digital signals, but the fundamental response of an etalon modulator is analog. Electrically controlled VOAs at that time were constructed with bulk optical components with electromechanical actuation, with 10–100-ms response. Erbium fiber amplifiers can use VOA to suppress transient power surges, but the time scale required was 10 μs, much slower than the data modulation rate. MEMS provided an attractive replacement for optomechanical VOAs, and this turned out to be the first volume application for MEMS devices in telecom networks.

The first MEMS VOA was fabricated by scaling the optical aperture of a MARS modulator from 25 to 300 μm so that it could be illuminated with a collimated beam. The reflected signal was focused into a separate output fiber, avoiding the need for external splitters or circulators to separate the output signal [16]. The first such VOA device is shown in Fig. 3. The wavelength dependence of a simple etalon was reduced using a more complex three-layer dielectric stack as the mechanically active structure, where the original $1/4\lambda$ silicon nitride layer is sandwiched between conductive polysilicon top ($1/2\lambda$ thickness) and bottom ($1/4\lambda$ thickness) layers. This attenuator provided fast (3 μs) response with 30-dB controllable attenuation over the 40-nm operating bandwidth, with 0.06-dB polarization-dependent loss, and also supported the 100-mW

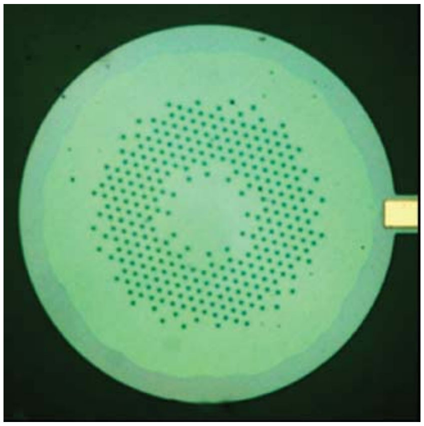

Fig. 3. MEMS etalon variable attenuator using a 0.5-mm diameter drumhead geometry. The lighter area covers an air gap between the silicon substrate. The hexagonally distributed spots are etch access holes.

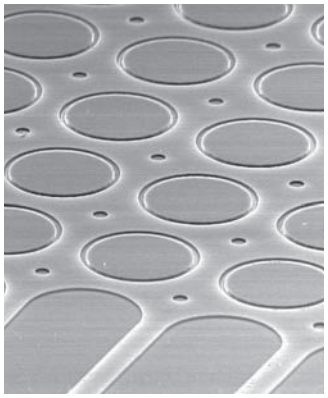

Fig. 4. Lightconnect's diffractive MEMS VOA.

The most direct possible approach to attenuation is to use a MEMS actuator to insert an optical block between the input and output fiber. This was implemented with a surface micromachining (MUMPS process) [17] and with a comb-driven silicon-on-insulator (SOI) device [18]. Such VOAs offered excellent dynamic range (measurement limited at 90 dB), but the polarization-dependent loss could be large ($\gg 1$ dB) at high attenuations.

Further improvement was needed and was made. Combining the collimated beam geometry with a first-surface torsion mirror reflector provided a low-insertion-loss structure with excellent spectral and polarization performance. For example, the device demonstrated by Isamoto *et al.* [19] achieved 40-dB attenuation with a 600-μm mirror driven with 5 V to tilt up to 0.3°. Similar configurations were commercialized, although the specific designs have not been published.

Another commercial MEMS VOA is based on a diffractive MEMS device [4] also used with a collimated beam. This device provides excellent optical performance as well as high speed: stable operation with 30-dB contrast and less than 40-μs response time using an 8-V drive. A novel structure with circularly symmetric features, shown in Fig. 4, was used to suppress the polarization-dependent loss to under 0.2 dB [20].

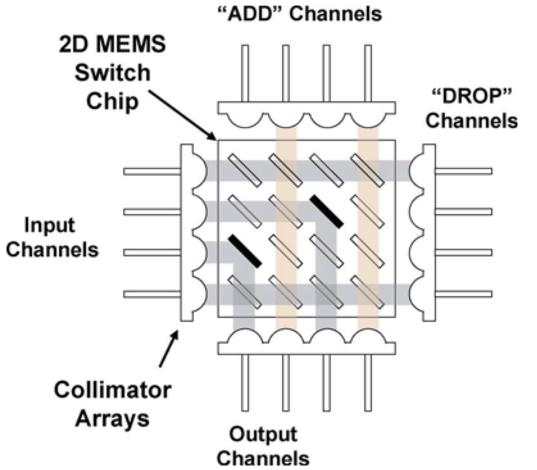

Fig. 5. Schematic of 2-D MEMS optical switches.

C. Two-Dimensional MEMS Switches

Protection switches are made of $1 \times N$ or small $N \times N$ switches. This can be realized by a 2-D array of vertical micromirrors commonly known as a 2-D MEMS switch. Fig. 5 shows the generic schematic of such a switch. The optical beams are collimated to reduce diffraction loss. The micromirrors are "digital": They either direct the optical beams to the orthogonal output ports or pass them to the drop ports. Generally, only one micromirror in a column or row is in the reflection position during operation.

The first MEMS 2-D switch (2 × 2) was reported in [22] and quickly followed by related work [23], [24]. For 2 × 2 switches, low insertion loss (0.6 dB) can be achieved without using collimators, especially when the micromirror is immersed in index-matching fluid [25]. Latchable 2 × 2 switches incorporating MEMS bistable structures were later commercialized [26], [27]. Larger switches require optical collimators to reduce diffraction loss. Switches with 8 × 8 and 16 × 16 ports were demonstrated [28], [29]. There are two basic approaches for the actuation of the micromirror. The first is based on the rotation of the micromirror [22], [28], [30], [31]. The mirror is initially parallel to the substrate (OFF position). When actuated, it is rotated to the vertical position (ON). The second approach moves the vertical micromirrors in and out of the optical paths without changing the mirror angle [23]–[25], [29], [32], [33]. The 2-D switches have been realized by both bulk-micromachining [22]–[25] and surface-micromachining [28]–[30], [32] technologies. Electrostatic actuation is most commonly used [22]–[29], [32]. Magnetic actuation has also been demonstrated [23], with some in conjunction with electrostatic clamping [30].

The port count of 2-D switches is determined by several factors, including mirror angle, size, fill factor (mirror width divided by unit cell width), and curvature. The expandability of the 2-D switch has been studied in [34] and [35]. To minimize optical diffraction loss, a confocal geometry is used with the average optical path length equal to the Rayleigh range, which is proportional to the square of the optical beam waist. Larger mirrors are therefore required to

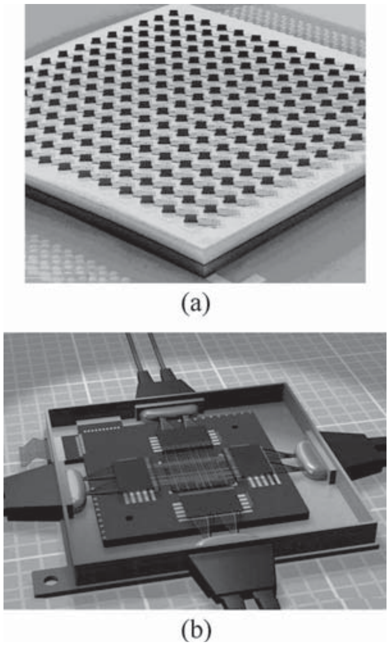

Fig. 6. (a) SEM of OMM's 16 × 16 switch (reprinted from [29] with permission). (b) Photograph of the packaged switch (reprinted from [36] with permission).

the linear dimension of the chip scales as N^2 [35]. Large chips are more susceptible to imperfections in mirror angles, which cause walkoff of optical beams at the receiving fibers. Ultimately, the chip size will be limited by the fabrication precision of the micromirrors. 16 × 16 switches have been realized, and 32 × 32 switches are within the capability of today's technology.

Fig. 6(a) shows a scanning electron micrograph (SEM) of OMM's 2-D switch [29]. A vertical mirror is attached at the tip of a cantilever. The tilted cantilever can be pulled down electrostatically. The mirror angle is maintained at 90° during switching. The switch is fabricated using a standard three-polysilicon-layer surface-micromachining process. The mirrors are assembled into vertical position with angular distribution of $(90 \pm 0.1)^\circ$. The hermetic switch package is shown in Fig. 6(b) [36]. Maximum insertion losses of 1.7 and 3.1 dB have been obtained for 8 × 8 and 16 × 16 switches, respectively, and the crosstalk is less than −50 dB. The switching time is less than 7 ms. Packaging is critical to attain long-term reliability and satisfy Telcordia qualification for telecommunication applications [36].

There were also significant efforts in nonmirror-based MEMS 2-D switches [37], [38]. Both Agilent's Champaign switch [37] and NTT's OLIVE switch [38] used microfluidic actuation to switch light between intersecting waveguides. The Champaign switch used thermally generated bubbles to displace index-matching fluids at waveguide intersections, causing the light to bend by total internal reflection (TIR). The OLIVE switch used thermal-capillary force to move trapped bubbles. One drawback of these approaches is the cumulative losses and crosstalks through multiple waveguide intersections. The

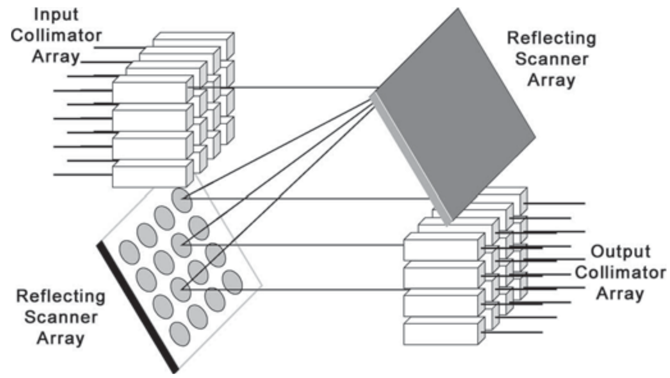

Fig. 7. Schematic of a 3-D MEMS switch.

D. Three-Dimensional MEMS Switches

A transparent optical crossconnect (OXC) with large port count can be realized by 3-D MEMS switches illustrated in Fig. 7. The input and output fibers are arranged in 2-D arrays. The optical beams are steered in three dimensions by two stages of dual-axis micromirrors, directing it toward the desired output port. The 3-D MEMS switch has a favorable scaling law with respect to port count: Assuming the maximum scan angle of the mirror is fixed, the optical path length is proportional to N in an $N \times N$ switch. To maintain confocal configuration for minimum loss, the beam waist, and therefore the mirror size, needs to scale as $\sqrt{N}$. As a result, the linear dimension of the mirror chip scales as $\sqrt{N} \cdot \sqrt{N} = N$ [39]–[41]. In addition, it has low and uniform insertion loss. The 3-D MEMS OXC is a subject of intense interest during the telecom boom around the turn of the century [42]–[46]. Early efforts (before 2002) focused on OXCs with port count $\sim 1000 \times 1000$ [47], [48], driven by the explosion of Internet data transport. Recently, interest has shifted to applications in metropolitan area networks, including metro access and metro core networks, which requires OXC with medium port count $(\sim 100 \times 100)$, with emphasis on low cost, low-power consumption, and small footprint [44], [49]. Our discussion here will focus on this trend.

Detailed design tradeoffs and system implementations of the 3-D MEMS OXC have been reported recently [42]–[46]. Two schemes have been proposed to reduce the size of the switch and tilt angle of the micromirror. Lucent inserted a Fourier lens between the two micromirror chips with the focal length equal to the Rayleigh range of the optical beam (Fig. 8) [50]. This reduces the required scan angle of the mirror. In addition, the mirrors can be placed at the beam waist, resulting in $\sqrt{2}$ times smaller optical beams. This permits the use of smaller mirrors and/or reduction of the crosstalk. Fujitsu used a "rooftop" mirror to connect two adjacent micromirror chips (photograph show in Fig. 9) [44]. The rooftop mirror shifts the optical beams laterally, reducing the tilt angle requirement. Folding of the optical beam also shrinks the footprint of the switch.

In the compact switch category, Lucent's 64 × 64 switch has a size of $100 \times 120 \times 20$ mm^3, which can be mounted on a standard circuit board [49]. The insertion loss is 1.9 dB. Fujitsu's 80 × 80 switch has a packaged size of $77 \times 87 \times$

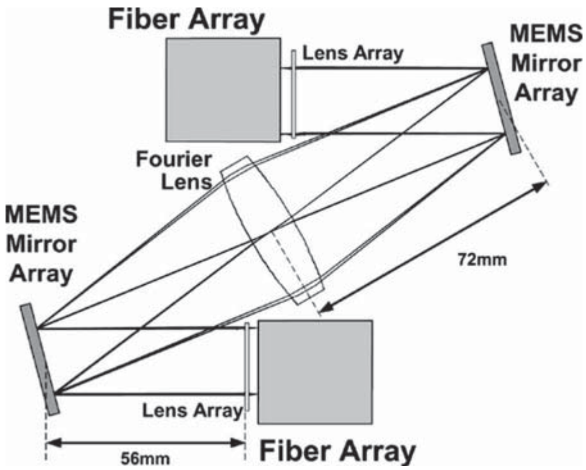

Fig. 8. Lucent's optical system layout for OXC (reprinted from [50] with permission). A Fourier lens is inserted between the two MEMS chips to reduce the required tilt of the mirror and beam size.

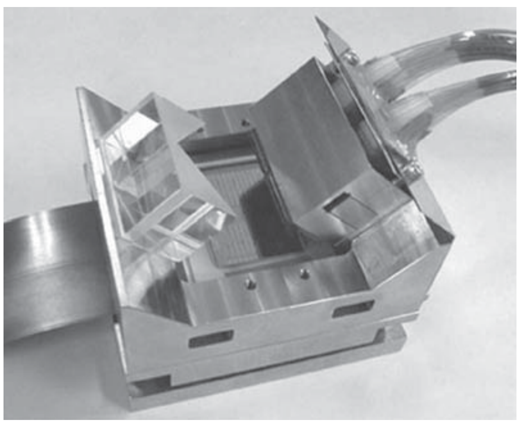

Fig. 9. Photograph of Fujitsu's 80 × 80 OXC with a rooftop reflector connecting the two MEMS chips (reprinted from [44] with permission). The packaged size is $77 \times 87 \times 53$ mm^3.

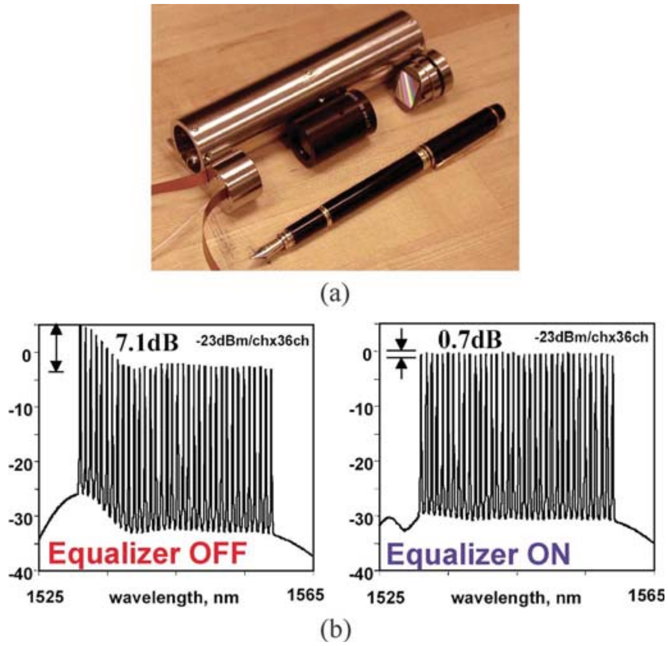

Fig. 10. (a) Dynamic spectral equalizer package and (b) transmission spectra showing the improvement in channel uniformity for a 36-channel DWDM transmission.

without any signal degradation. The total power consumption of Fujitsu's switch is only 8.5 W, thanks to the low operating voltage of the mirrors. NTT's 100 × 100 switch has a size of $80 \times 60 \times 35$ mm^3 with an insertion loss of 4 dB [43].

The two-axis micromirror array is the key enabling device of the 3-D switch. Important parameters include size, tilt angle, flatness, fill factor, and resonant frequency of the mirror. Additionally, the stability of the mirror plays a critical role in the complexity of the control schemes. Early development focused on surface-micromachined two-axis scanners [51], [52]. The residue stress limits the mirror size to approximately 1 mm, and the different thermal expansion coefficients between the mirror and the metal coating also cause the mirror curvature to change with temperature. Bulk-micromachined single-crystalline silicon micromirrors are often used in high-port-count OXCs that require larger mirror size [46], [53]–[56].

Electrostatic actuation is most commonly used because of its low-power consumption and ease of control. Early devices use parallel-plate actuators, which have high actuation voltage increases the complexity of electronics [58]. Micromirrors with vertical comb drive actuators, first reported in [59], offer many advantages. They have a much larger torque, which one can use to reduce the operating voltage as well as increase the resonant frequency. In addition, they are free from the pull-in effect, further increasing the stable tilt angles. It should be mentioned that lateral pull-in between comb fingers is a potential issue but could be mitigated by MEMS design (such as V-shaped torsion beam [60] or off-centered combs [61]). Several variations of vertical comb drive mirrors have been reported, including self-aligned vertical combs [62], [63], angular vertical combs [64], [65], electrostatically assembled vertical combs [66], and thick vertical combs (100 μm) attached to mirror edges on double-sided SOI wafers [44], [60].

III. Wavelength-Selective MEMS

A. *Spectral Equalizers*

The natural extension of a single variable attenuator is to provide a VOA for each channel of a DWDM transmission system. The surface-normal geometries of the etalon mirror- and grating-based attenuators discussed in Section II-B were all compatible with a free-space imaging spectrometer. An input fiber is imaged through a diffraction grating so that each spectral channel is laterally shifted to illuminate one modulator in a linear array. The reflected signal, attenuated to the desired value, is collected into a single output fiber by a second pass through the imaging spectrometer. The first such MEMS spectral equalizer used a continuous etalon membrane [67]. This approach was later implemented in the compact package shown in Fig. 10, which located the MEMS device array next to a

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase® Smarter legal research.