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MEMS Technology in Optical Layer Networks

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Abstract

The rate at which bandwidth demand in communications networks has grown has caused service providers to move rapidly to dense wavelength-division-multiplexed networks. This has in turn spawned a number of new application areas in which there is no clear technological winner, leaving room for new technologies such as MEMS to create inroads. In this paper, these applications are discussed and examples of several MEMS devices being developed for use in wavelength-division-multiplexed networks optical transport systems are presented.

Introduction

The unprecedented growth of the Internet has left service providers desperately searching for ways to increase available bandwidth. Presently, efforts are underway to jam more and more wavelengths down a fiber at ever increasing density and over an ever-broadening spectral range. Just a few years ago, WDM systems may have carried eight wavelengths at data rates of 2.5 Gb/s. In the coming year, it is expected that we will see commercial deployment of systems carrying 240 wavelengths at 10 Gb/s, as well as initial deployment of 40 Gb/s systems. As an added means of providing more available bandwidth through optimization of the network, fast reprovisioning, and rapid restoration, dynamic network elements such as wavelength add-drop and optical cross-point switches are desired.

An unfortunate consequence of this progression is that network management is becoming increasingly challenging as total power levels rise, bit period shrinks, and wavelength spacing becomes ever denser. Accumulating signal impairments such as polarization dependant loss (PDL), polarization mode dispersion (PMD), signal non-uniformity, and spectral dispersion require precise network management. In addition, dynamic network elements such as wavelength add-drop and optical cross-connects create changes to network conditions that further exacerbate these issues. The use of dynamic network switching elements therefore creates the need for dynamic transmission elements to detect and mitigate transmission impairments, such as dynamic power equalizers, dispersion compensators, and PMD compensators.

In reality, there are precious few technology solutions available to address the myriad of applications arising today. The solution space includes such possibilities as liquid crystals, surface waveguides, piezoelectrics, acousto-optics, and electro-magnetics. Examples of power equalizers, wavelength add-drops, cross-point switches, and other components have been reported over the past several years [1,2,3], but issues such as power consumption, polarization, controllability, and physical size still plague most of these approaches.

MEMS in Photonics

The field of MEMS as it is known today is relatively young. Applied research in the area has been conducted on a broad scale for little over a decade. A number of examples of commercial successes exist however, most notably the Analog Devices' ADXL line of air-bag accelerometers and Texas Instruments' DMD display technology. Due to the difficulty of providing high mechanical output power from MEMS systems, early promises of such things as plaque eating robots and other "science fiction-like" systems have failed to materialize. What has emerged however is the realization of the synergy between photonics and MEMS wherein low-torque actuators can be used to manipulate light through either beam-steering or thin-film effects. The fortuitous timing of this realization with the explosion in optical communications has led to a variety of exciting applications of MEMS technology to optical networks. In particular, solutions to many of the DWDM challenges discussed earlier would appear to be within reach.

Further positive attributes of MEMS in optical networks include very low power dissipation (due to electro-static actuation), extremely small size, and fast switching speeds due to that small size and low mass.

A challenge facing MEMS designers however, is inherent to the scale of the devices. Although MEMS elements by virtue of their small size and low mass can actuate very rapidly, tens of nanosecond operation has been reported [4], controlling that motion and avoiding unwanted resonances can prove challenging [5]. Additionally, obtaining motions larger than a few tens of microns or a few degrees of tilt angle can be challenging. Finally, it should not be surprising, given the relative immaturity of the field, that MEMS reliability is still an open question. Due to the high stakes however, there is a large effort underway generally in the field as well as by each individual company developing MEMS technology to prove high reliability for these systems.

Switching Applications

As mentioned above, it is desirable to add switching functionality to the optical network, primarily at the individual wavelength level, in order to provide rapid provisioning and restoration to the network. Provisioning arises from the desire of service providers to respond to service requests in a matter of minutes as opposed to the weeks and months presently required. Restoration arises from the need to recover from network failure (due to a errant backhoe for example) by rerouting of traffic within a matter of 100 ms. The widely anticipated vehicle for providing provisioning and restoration is the optical cross-connect (OXC) operating at the wavelength level. With the number of wavelengths per fiber now numbering in the hundreds, the port count of the OXCs will need to be in the thousands. In addition, the OXC must operate in a fully non-blocking manner; i.e. every input must be able to be switched to every output without restriction. Scalability therefore becomes of paramount concern in the decision of which technology to use. Other important considerations include insertion loss, physical size, polarization effects, and switching time. Table 1 shows the spectrum of switching technology that potentially can be applied to OXCs. Only MEMS promises to satisfy all requirements for large port count OXCs.

	Free-space		Guided Wave	
	MEMS	Liquid Crystal	Thermo-Optic Bubble	Thermo-Optic/ Electro-optic Waveguide
scalability	√	X	X	X
loss	√	?	X	?
switching time	√	?	?	√
cross-talk	√	?	?	?
polarization effects	√	? √	? √	X
wavelength independence	√	√	√	X
bit-rate independence	√	√	√	√
power consumption	√	√	X	X
	√ good		? unsure	X bad

Table 1: Large *port-count switching technology candidates.*

The expectation that MEMS is the technology of choice for large port count OXCs is born out by the rate of genesis of companies in this space. There is seemingly a new entry per week in the OXC game either at the MEMS chip component level, OXC fabric level, or full OXC system level. The one feature all these companies have in common is the plan to use a field of MEMS mirrors to effect free-space switching between arrays of optical fibers.

Due to the general level of confusion surrounding exactly what is meant by OXC, an attempt will be made here to explain what is meant by OXC fabric and OXC system. An OXC fabric consists of the optical package containing a number of subcomponents, a MEMS mirror chip(s), arrays of collimated optical fibers, or optical fibers with precise relative spacing and arrays of collimators on spacings to match that of the fiber arrays, and the control electronics used to position the MEMS mirrors. An OXC system contains the OXC fabric as a sub-system, but includes the software system required to manage the interface to the optical transport system and provide signaling, routing, and restoration functions. The OXC system may also include transponders at the interfaces depending upon the intended transparency of the switch.

In practice, OXC fabrics fall into two broad categories based on the manner in which the free-space optical switching is performed. In one embodiment, all the light signals emanate from a linear array of fibers and the switching occurs in a single plane where each optical signal is switched to any of a second linear array of fibers. This approach requires N^2 MEMS mirror elements for a cross-connect with N ports. This approach was first demonstrated at AT&T Labs using and is shown in Figure 1 [6]. Due to practical optics considerations, these "2D" fabrics are limited in port count to 32x32 and below. It has been proposed to use a three-stage "CLOS" architecture to scale these small fabrics into as large as 1000x1000 fabrics, but when one considers the optical loss through three stages of switch, the complexity of the interconnect scheme required, and the shear number of fiber terminations involved, this approach is deemed problematic.

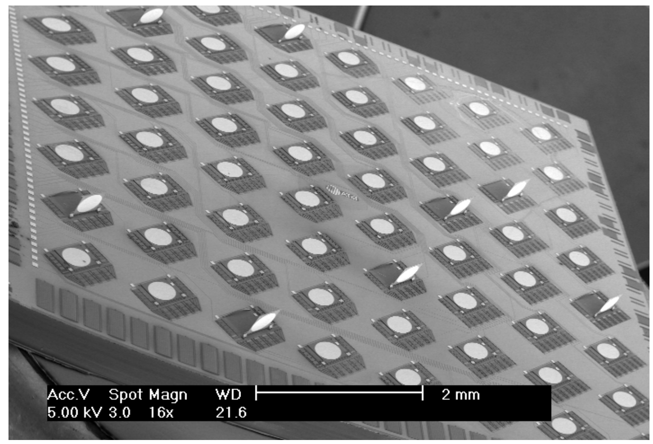

Figure 1: *A 2D MEMS OXC chip [6].*

The second category of OXC fabrics uses two matrices of gimbal-mounted MEMS mirrors with 2-axis control to provide beam switching in a 3D volume between two 2D arrays of collimated fibers. The first demonstration of a MEMS device for this type of OXC was the Texas Instruments/Astarte Fiber Networks' Beehive switch (Tellium, Inc. has recently announced plans to acquire Astarte). In the past several years, a number of prominent players in the telecom world have announced 256 port OXC fabrics based on this "3D" architecture, most notably Lucent's LamdaRouter and Nortel's Optera PX (through their acquisition of XROS). Using the 3D approach, it is expected that OXC fabrics can scale in a single stage to 1000x1000 ports and above, although at present the largest demonstrated fabric is 256x256 ports. A number of companies have announced plans for high port OXC systems including Lucent, Calient, Nortel, and Tellium. A schematic showing the switching functionality of a 3D fabric is shown in Figure 2.

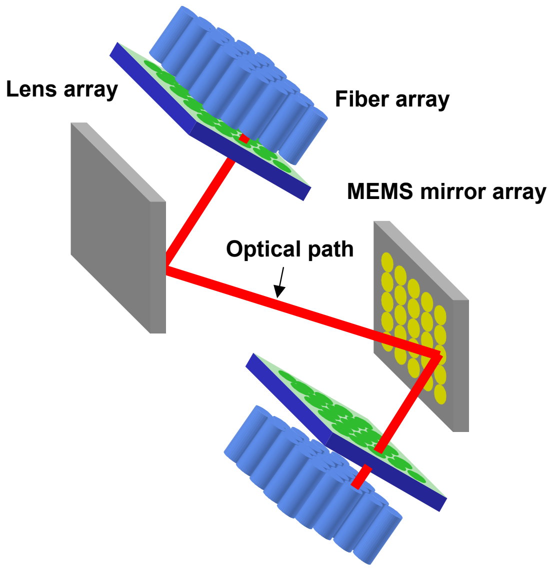

Figure 2: *Schematic of a 3D OXC fabric.*

In this traditional "point and shoot" design, each input and output fiber and associated collimating lens has a dedicated MEMS mirror assigned to it in order to ensure the signal is within the acceptance angle of the fiber. The switching function occurs in the space between the two mirror arrays. Milliradian control is required to ensure the connection between an input and an output fiber is achieved with low loss. Due to the non-linear nature of electrostatic actuation (the most widely used MEMS method) and the required position precision, the demands placed on the mirror control algorithm are quite severe, although for at least up to 256 port fabrics sufficient controllability has been demonstrated. A photograph of a gimbal-mounted mirror intended for use in a 3D architecture is shown in Figure 3 [7].

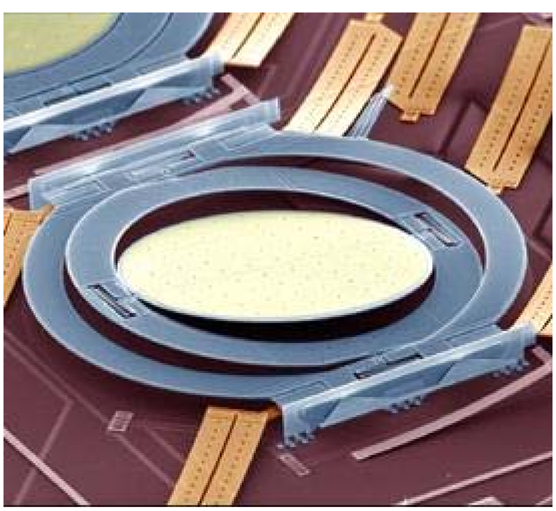

Figure 3: *LambdaRouter mirror [7].*

Switching applications exist that require very small port counts, for example 1x2 or 2x2. One such application arises from the need to provide 1+1 switch protection in an OXC. Typically, in order to eliminate single point of failure in the network, two fabrics carry identical traffic within an OXC, with the output from the OXC being selected by an optical 1x2 switch. Low optical loss and reliability are the primary considerations for these switches along with switching speed. Although there are no commercial products in this space using MEMS technology, a good deal of work is being done and an example of a MEMS based 2x2 optical switch is shown in Figure 4. In this switch, tapered optical fibers are aligned in an x-pattern in-plane using deep reactive ion etched (RIE) features in a silicon substrate. A knife blade reflector is moved in and out of the space between the fibers using a lateral comb-drive mechanism [8]. In this manner, the optical signals either propagate straight across the gap between the fibers in a crossing pattern, or are reflected into the adjacent fiber in a bar pattern, yielding a standard 2x2 cross-bar switch.

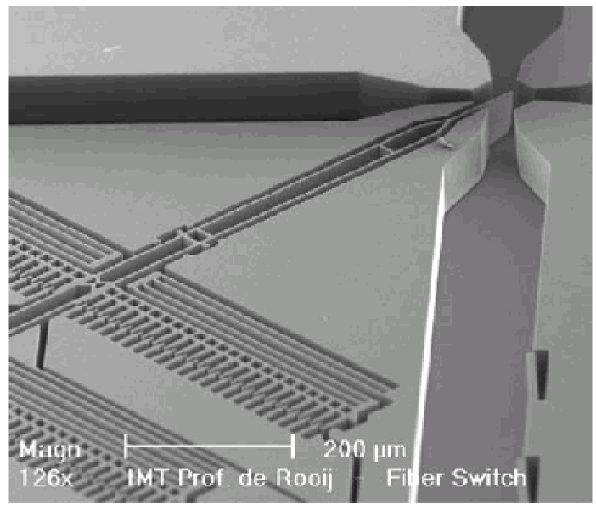

Figure 4: *2x2 cross-bar switch [8].*

Programmable Wavelength Add/Drop

Wavelength add/drop is another highly desirable network function, particularly in the Metro and Metro access markets. Typically, there are 32 or fewer wavelengths in a metro ring architecture. A programmable wavelength add/drop allows any number of the wavelengths in a ring to be sent out to a drop node while being able to add a signal back in from the node, resulting in greater network flexibility through dynamic bandwidth allocation, as well as fault recovery capability. Since the every signal in the ring must pass through a number of add/drops, optical loss and pass-band narrowing are significant considerations.

An example of a MEMS-based programmable wavelength add/drop is shown in Figure 5 [9]. In this system, WDM signals enter a free-space switching area via a first circulator where they are spatially dispersed (by a diffraction grating) along a 1D array of two position tilting micromirrors that either reflect the light back to the first circulator where they pass on to the rest of the system, or redirect it to a second output circulator, the drop port. Added signals are brought to the free-space switching space via the second circulator where they are combined with the passed wavelengths and are then sent to the rest of the system. In this way a full four-port add/drop is developed. The switching chip consists of a surface-micromachined array of torsional polysilicon mirrors (fabricated in Cronos Integrated Microsystems' MUMPS process) and is shown in Figure 6. The mirror area is 30x50 microns and can be tilted through an angle of roughly 6 degrees. The structural material is polysilicon with a deposited coating of chrome and gold. Due to differential stress and thermal expansion characteristics, significant curling of the mirrors was evident contributing to insertion losses of 5 to 8 dB for the system. 622 Mb/s data was transmitted through the switch however, with no apparent cross-talk and full add/drop functionality was demonstrated and is shown in Figure 7.

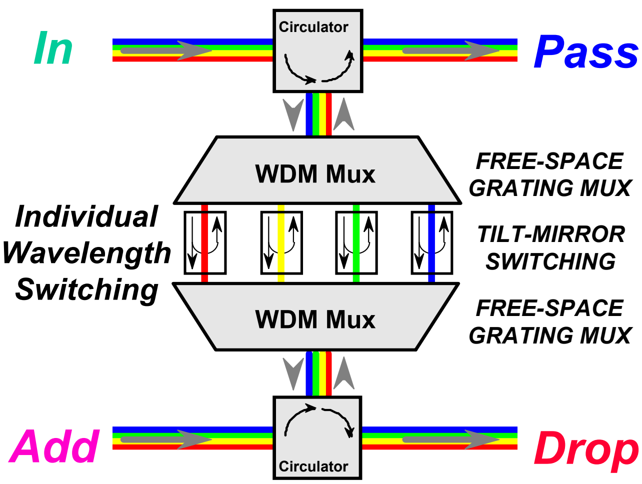

Figure 5: *Schematic representation of a MEMS-based programmable wavelength add/drop system.*

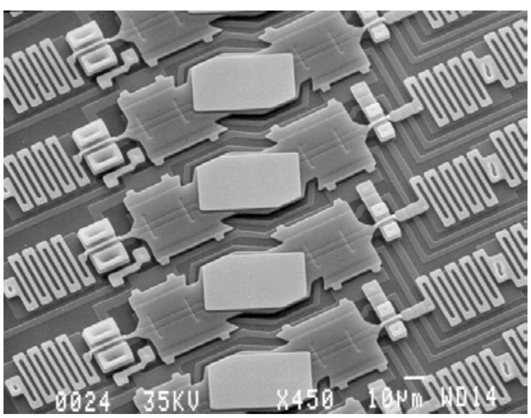

Figure 6: *Array of MEMS tilting mirrors.*

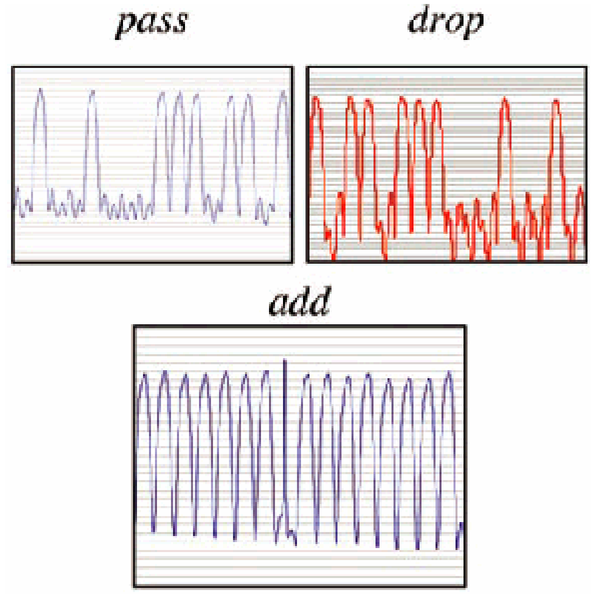

Figure 7: *Wavelength signals at the pass and drop ports and at the pass port with an added narrow-line laser signal.*

Transmission Applications

As bit-rates move toward 40 Gb/s and wavelength spacing becomes ever narrower, system effects from accumulated impairments such as power non-uniformity, chromatic dispersion, and polarization effects become more severe. A number of network elements have been proposed to address these issues, and commercial availability of several of these is expected soon.

Power Compensation

Variable optical attenuators are used to control optical power in various places in the fiber network. One such application is in optical amplifiers (OAs) where they are used in conjunction with fixed gain-flattening filters to control the gain profile of the Er-doped fiber stage in order to achieve the widest range of spectral power uniformity in the OA output. A MEMS device based on MARS technology [10] has been developed for such an application. In the MARS technology, a multi-layer dielectric mirror is formed from a silicon substrate, an air gap, and a suspended stack of thin films. The surface normal reflectivity of the device can be varied over a 30-dB range by application of a simple drive voltage [11]. The optical window of the device is sufficiently large as to accommodate the use of a multiple fiber ferrule/GRIN lens arrangement in a simple package with low loss. This arrangement has the benefit of providing transmissive-like operation with a reflective device resulting in a low-cost, relatively low-loss (2-dB) device. Due to the characteristics of the MARS technology, full range attenuation can be accomplished on the order of one microsecond. The MARS structure and the simple two-fiber package are shown in Figure 8.

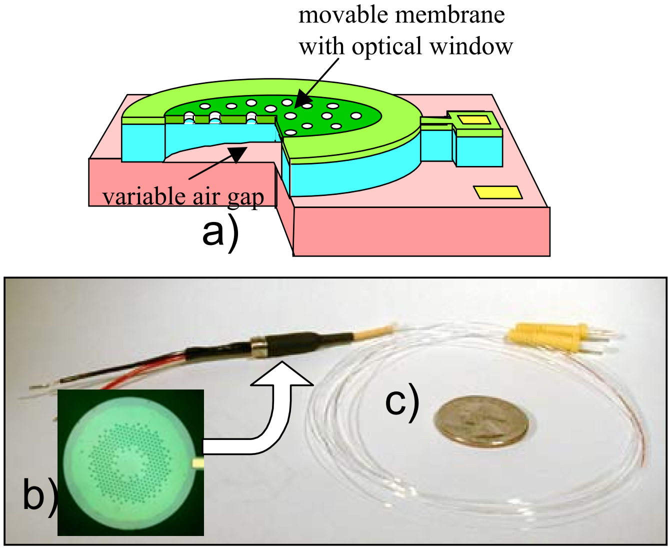

Figure 8: a) *Simple schematic of a MARS device, b) photograph of a 500 μm-diameter attenuator, c) package.*

Again, as networks become more dynamic, more wavelengths are carried in a single fiber, and data rate increases, more direct means of providing power equalization becomes necessary. Acousto-optic and liquid crystal approaches have shown some success toward providing spectral power control. A MEMS approach based on the afore-mentioned MARS technology has also shown promise [12]. In this approach, MEMS technology is combined with free-space optics utilizing diffractive elements (similar to the wavelength add/drop described above) to create a powerful approach to wavelength control. Here, the simple MARS structure was physically enlarged to form a 0.3-mm x 1.5-mm mechanically-active region and individually addressable electrode pairs were disposed along its length. By using a diffraction grating to spatially spread the optical spectrum along the length of the optical window located between the pairs of electrodes, each pair of electrodes can be used to provide local attenuation and therefore selectively attenuate wavelength regions. A tube-based optics system is shown in Figure 9, wherein an input signal passes through a multi-element lens to a diffraction grating, is directed onto the optical window of the MARS equalizer which applies a reflectivity function on the spectrum. The spectral signal is then reflected back through the lens to the diffractive grating and then again through the lens where it is focussed back into the optical fiber. A circulator is used to separate the input and output signals, thus achieving transmissive-like behavior from the system.

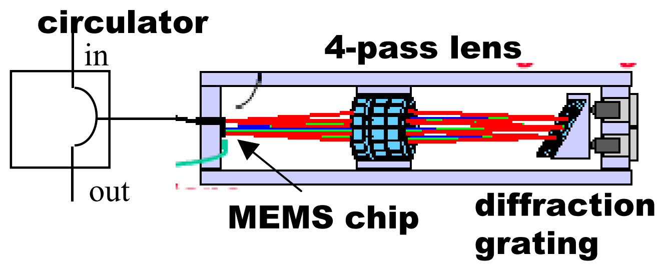

Figure 9: *Free-space optics system for providing spectrally diverse signals to MEMS devices.*

A simple schematic and photograph of the MARS equalizer chip are shown in Figures 10 and 11, and a plot of input and equalized output spectrum is shown in Figure 12. Operating characteristics of > 30dB dynamic range, continuous 42 nm-wide spectral range (>100 nm is achievable), 6 dB excess loss, and very low polarization dependant loss (PDL) of <0.05 dB have been demonstrated.

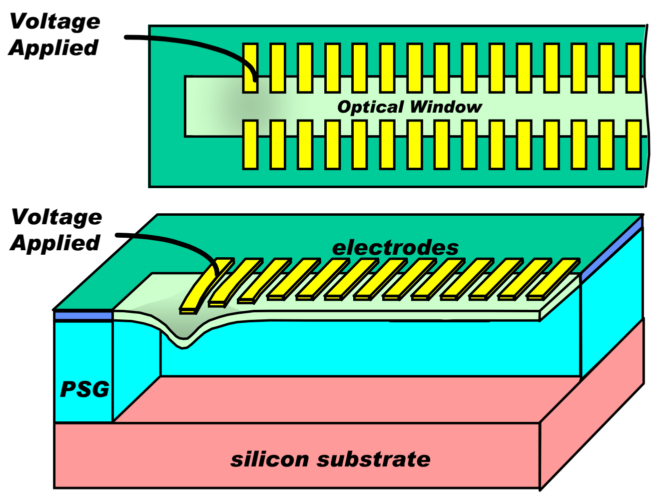

Figure 10: *Schematic representation of a MARS equalizer.*

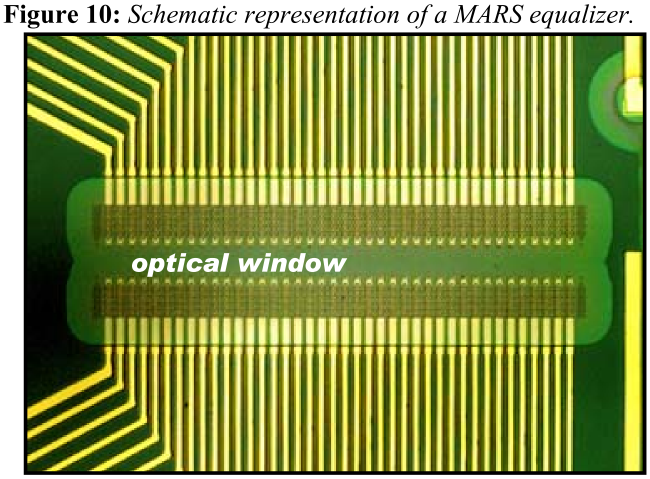

Figure 11: *Photograph of an equalizer chip with a 0.3 mm x 1.5 mm mechanically-active region and a 70 μm x 1.5 mm optical window.*

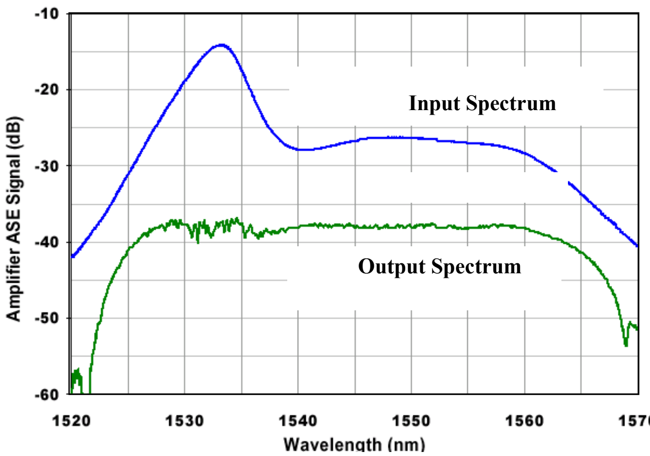

Figure 12: *Gain equalization using a MARS equalizer. Input ASE signal with >14 dB dynamic range was flattened to < 1dB ripple over a 32 nm-wide spectral range.*

Dispersion Compensation

Chromatic dispersion occurs due to non-uniform wavelength propagation speeds in optical fibers. As the bit-period shrinks with increasing data rate, this dispersion can create a significant bit-error-rate penalty. Fixed dispersion compensation engineering cannot sufficiently solve this problem, particularly as the networks become dynamic.

Dynamic dispersion and dispersion slope compensation has been proposed using Gires-Tournois interferometers, planar waveguides, and recently MEMS technology. A MARS attenuator with a highly reflective back surface is used to form a tunable partial reflector and Fabry-Perot cavity wherein the periodic frequency-dependant group phase delay can be varied. Using a two-stage system, a tuning range of 150 ps/nm with a passband width of 47.5 GHz with a group delay ripple of + 3ps was demonstrated [12]. Thermo-electric coolers can be used to tune the substrate thicknesses and thus the cavity optical thicknesses in order to control the free-spectral range and relative phase of each stage.

Polarization mode dispersion, arising from non-uniform radial symmetry in the cores of optical fibers, will require dynamic compensation. This asymmetry leads to different group velocities for the two orthogonal polarization modes, resulting in distortion. The differential delay between the polarizations needs to be held to less than $1/10^{th}$ of the bit-period, and becomes a significant factor at 40 Gb/s data rates.

Thus far, no practical implementation of a PMD compensator has been demonstrated, but a polarization rotator based on MEMS has been reported [13]. By combining this polarization rotator with a pair of polarization beam-splitters and a tunable delay line, dynamic compensation of the fast and slow axis components of an optical wave has been demonstrated. A schematic of the optical system is shown in Figure 13, and a photograph of the MEMS free-space polarization rotator is shown in Figure 14.

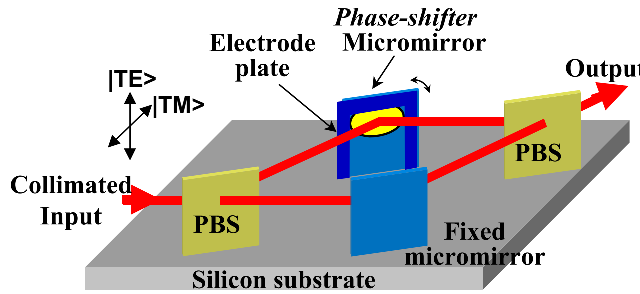

Figure 13: *Schematic of a MEMS polarization rotator.*

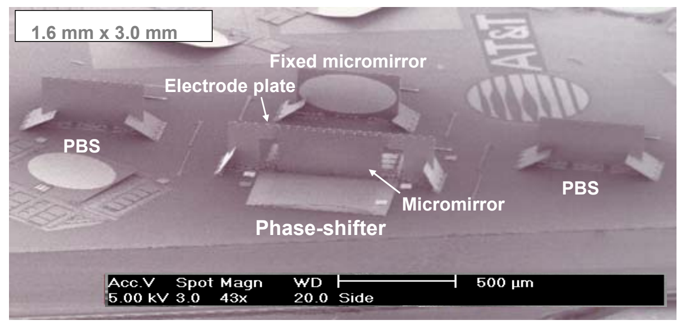

Figure 14: *SEM photo of the implemented system shown in Figure 12.*

Conclusions

The MEMS field is rapidly reaching a maturity level that will enable it to take advantage of the synergy with optics and the desperate need for new components and sub-systems to solve the thorny issues arising from the race to faster, denser WDM communications networks. A number of MEMS-based systems are in either field trials or being readied for general availability, even as the reliability of these systems is being investigated. Even with an uncertain reliability story however, it is clear that MEMS technology holds great promise for tremendous impact on the future of optical communications.

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