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Enabling Devices using MicroElectroMechanical System (MEMS) Technology for Optical Networking

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Abstract: Abstract: Optical communication systems are the premier conduit for providing broadband data across continents, nations, cities, neighborhoods, and are now starting to penetrate into private homes. This spectacular achievement is the culmination of years of research and development efforts in diverse fields. Recently we are witnessing the evolution of these communication systems towards optical networking. The advent of optical networking has been enabled by a suite of complementary optical subsystems that are pivotal to the operation and management of these networks. These optical microsystems directly interact with the optical signal and-through functionality afforded by design-are able to filter, switch, attenuate, and adapt the optical communication channels carried by the network. In this talk I will review a sampling of these enabling devices and focus on the MEMS technology required for its implementation.

Introduction

Optical communications has been researched and developed for many decades, and has brought the transport technology to a very mature level. Its fundamental goals are to increase the transmission capacity, the transmission range, and/or the transmission capacity-range product. Optical networking is the next phase beyond optical communications, the effective utilization of the transport layer to deliver the connectivity, accessibility, reliability, and survivability at the network level. It is about protocols for access, routing, protection, and restoration, as well as the electronic, optical, and optoelectronic (or photonic) hardware required for implementing it. Optical networks are customized and optimized for a specific operating environment; a continental-scale backbone network for connecting cities is very different from a neighborhood access network for individual households or from an optical data network within a supercomputing center. Backbone networks as well as smaller scale metropolitan networks are most receptive to deployment of components offering adaptability and reconfigurability.

For efficiently utilizing backbone and metropolitan optical networks, light paths carried on specific wavelengths are required to be managed. Light paths need to be extracted and reintroduced at different nodes of the network at the command of a centralized control center. This functionality is known as Reconfigurable Optical Add-Drop Multiplexing (ROADM). More recently, the ROADM equipment has acquired the additional task of light path link switching at network nodes. The optical network topography is nonuniform, having links of different lengths due to the locations of cities and possible mix of optical fiber types. Moreover, with lightpath link switching the accummulated signal distorsions cannot be optimized for a-priori. Adaptive components can be used to optimize the overall channel performance, with tunable dispersion compensators as an example. The price premium for the introduction of tunable and adaptable components more than pays for itself in performance and operational savings.

The components supporting optical networks can be realized by combining clever optical microsystems with micro-electro-mechanical-system (MEMS) actuators. Optical beams can be accurately steered for realizing fiber switches, from basic 1×2 switches to large switch fabrics. Spectrally selective components can be introduced and adjusted to create tunable filters. The spectrum containing the collection of wavelength channels can be spatially dispersed and switched to different fiber in the case of wavelength-selective switches. In the high-resolution limit, the spectral content of the optical signal can be adjusted to eliminate distorsions that the signal has accummulated. Each of these examples requires a dedicated optical microsystem and customized MEMS components.

MEMS Optical Fiber Switches

While smaller 1×2 and 2×2 optical fiber switches can be constructed using many competitive technologies, larger switches are implemented exclusively using MEMS technology. We shall distinguish between 1×*N* sharing switches [1], small fiber count *N*×*N* switches [2], and large fiber count *N*×*N* switches [3].

Sharing switches, which switch light from an input port to one of *N* output ports, have an optical system that accommodates *N*+1 optical fibers. Typical values for the number of fibers *N* is 4 or 8. Such switches are typically used in reverse, as *N*×1 switches, for sharing a common resource among the *N* fibers. Beam displacement with one tilting micromirror in the beam path is an effective switching technique for 1×*N* switches. Each of the *N* fibers can be addressed by a unique mirror angle. A typical optical arrangement and its corresponding MEMS micromirror is illustrated in Fig. 1-a.

Small optical fiber switches use a crossbar design that is planar in structure, with the input linear fiber array arranged at one facet of the switch and the output linear fiber array arranged at a second facet of the switch, at 90° to the first facet. The fiber arrays are mated to matching collimating lens arrays, such that the beams from the input and output fibers generate a regular grid. Each beam from an input fiber intersects every beam of the output fiber. For an input/output array of *N* fibers, there are thus N^2 such beam intersections. Switching from any input fiber to any output fiber in the crossbar design is accomplished by placing a mirror at the respective beam intersection position. Each of these mirrors is bi-stable; in one state it is not in the beam path whereas in the second state it is at 45° and completes the connection. A typical optical arrangement and its corresponding MEMS micromirror is illustrated in Fig. 1-b.

Large optical fiber switches utilize a beam scanning design within the free-space volume of the switch, with an input two-dimensional fiber array at one facet of the switch and an output two-dimensional fiber array at the opposing facet. The fiber arrays are mated to matching collimating lens arrays, forming light beams from the input fibers onto the output fibers. To establish a connection from any input fiber to any output fiber, the beam from the input is directed to the desired output and then realigned to efficiently couple into the output fiber. Thus, every connection is required to have two beam scanning elements. Since there are *N* input and output fibers in an *N*×*N* switch, the number of actuators in the switch is 2*N*, in comparison to N^2 of the crossbar switch. However, each actuator has to assume one of *N* possible positions for each switching state.

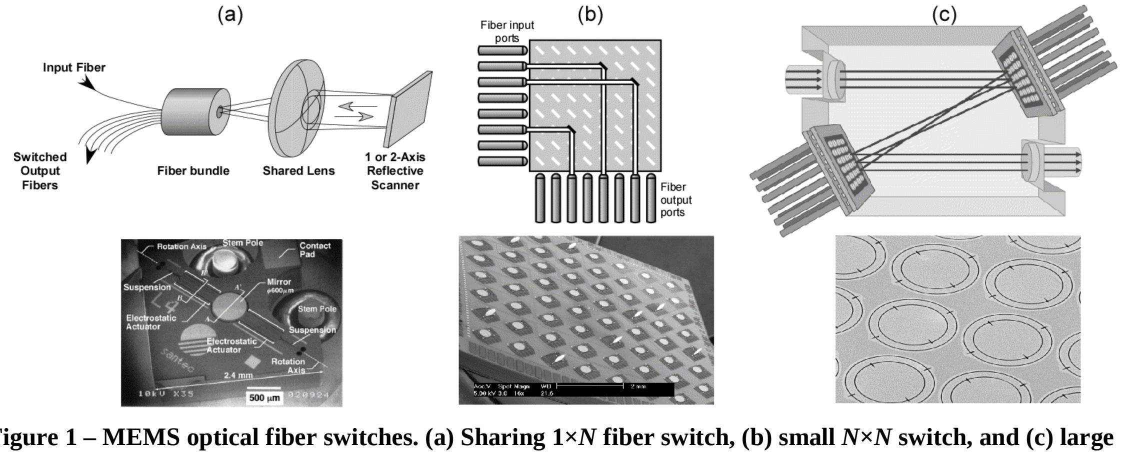

Figure 1 – MEMS optical fiber switches. (a) Sharing 1×*N* fiber switch, (b) small *N*×*N* switch, and (c) large *N*×*N* switch. In each case a different mirror function is required.

Mirrors can be introduced to fold the propagation length between the input and output fiber arrays, resulting in a more compact switch form factor. When MEMS micromirrors perform the beam scanning, they can be part of the folding mechanism. A typical optical arrangement and its corresponding MEMS micromirror is illustrated in Fig. 1-c.

MEMS Wavelength-Selective Switches

Wavelength-selective switches (WSS) are transparent optical switching subsystems, which can route and attenuate wavelength channels in meeting with ROADM requirements. A WSS contains some means of separating or demultiplexing the wavelength channels at the ingress ports, followed by an optical switch fabric and means of recombining or multiplexing back the wavelengths into one or more egress ports, following the switching function. There is no wavelength conversion or OEO inside a WSS; the switch is optically transparent for the photons carrying the data. The simplest WSS is a channel blocker, with a single input and output fiber, having the capability to power equalize or completely attenuate the WDM channels. The more capable 1×*K* WSS has a single input and *K* output fibers, adding the capability to independently route the individual WDM channels among the *K* fibers. Finally, the *K*×*K* Wavelength-Selective Crossconnect (WSXC) handles *K* input and *K* output fibers with the ability to switch any wavelength from any input fiber to any output fiber, provided there is no wavelength contention. The drawback of the WSXC is its sensitivity to failures; if the switch malfunctions or needs to be replaced, then all the WDM traffic flowing on the *K* fibers is halted. The 1×*K* WSS module, which can be used to construct an equivalent *K*×*K* WSXC, is more robust solution as the traffic is partitioned according to originating fiber port, and only a subset of the traffic will be affected by a single failure. We shall focus on the 1×*K* WSS module herein.

A WSS design based on a free-space configuration has two major subassemblies (see Fig. 2-left) [4]; the first used to spatially overlap the beams from the individual input and output fibers, to allow for switching between multiple ports, and the second to spectrally resolve the channels and introduce the wavelength selectivity. The role of the first subassembly is to image the input and *K* output optical fibers end faces onto an angular multiplexed common magnified spot. This subassembly converts the distinct spatial locations of the fibers to unique angular propagation directions. The second subassembly introduces the desired wavelength-selectivity property with the use of a diffraction grating. It spatially disperses the input magnified common spot, consisting of the *N* DWDM channels, onto the MEMS micromirror array, such that each channel is imaged upon

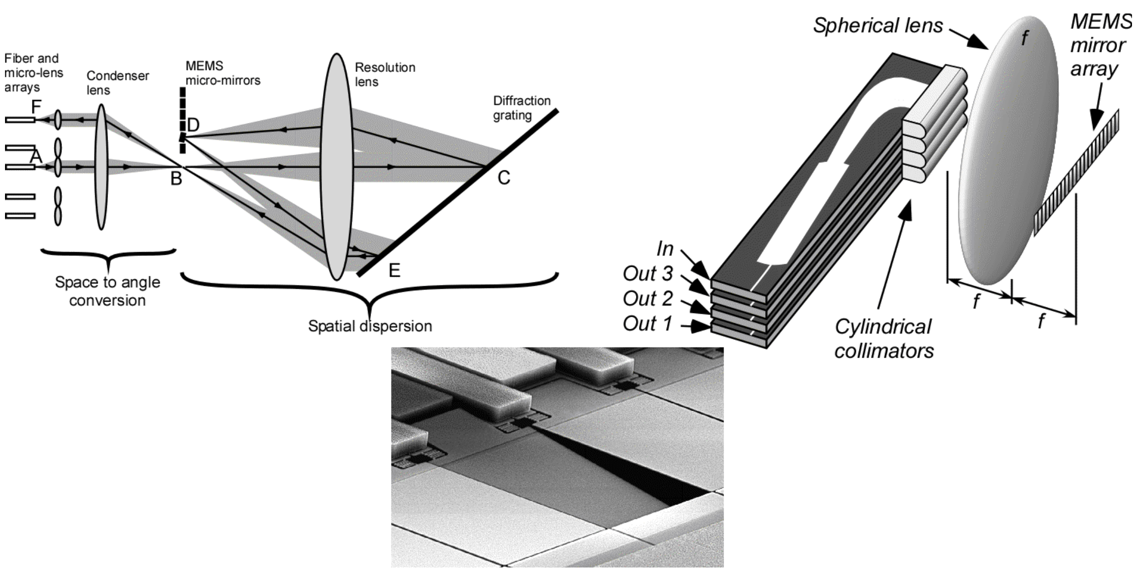

Figure 2 – Architectures for wavelength-selective switches. Free-space implementation (left) and hybrid guided-wave and free-space implementation (right) achieve same overlap of fiber spectra onto MEMS device. Switching is performed by a high fill-factor array of tilting mirrors.

a separate mirror in the array for independent addressing. Each micromirror in the array can be tilted to a desired angle, which subsequently determines the output fiber to which the reflected light will couple upon imaging back to the fiber array, on a DWDM channel basis. The first subassembly determines the optical beam magnification ratio, the fiber array layout, and the required mirror tilts to reach each output fiber. The second subassembly determines the amount of spatial dispersion for separating the DWDM channels and obtaining the necessary pass band characteristic.

Greater compactness can be achieve if we choose to utilize a hybrid guided-wave and free-space optics approach for constructing a wavelength-selective switch (see Fig. 2-right) [5]. The guiding elements are planar lightwave circuits (PLC) arranged in a stack, each attached to an I/O fiber. Each PLC distributes the optical signal across an arrayed waveguide grating (AWG) of incremental length differences that terminates at the output PLC facet. The AWG output signal implements a phased array, due to the propagation length differences in the grating arms. We employ an external bulk lens to spatially Fourier transform the phased array signal, yielding a spatially-dispersed optical signal at the lens’s back focal plane. The bulk lens aperture subtends the phased array output of all the PLCs in the stack, which superimposes the spectrally-dispersed signals of the PLCs at the lens’s back focal plane. A MEMS micromirror array placed at the back focal plane switches the spectral components of each DWDM channel separately. The PLCs are distinguished by a unique vertical propagation direction, facilitating wavelength switching between the PLCs with a MEMS micromirror array that tilts in the vertical plane. The mirror tilt angle determines which PLC a particular channel will couple to from the input port. To minimize the vertical mode height of the MEMS micromirrors, the light radiating out of the PLC is collimated in the vertical (stacked) direction by a cylindrical lens that is affixed to each PLC.

MEMS Adaptive Filters

The concept of the WSS can be extended with higher resolving power optical arrangements, such that the signal's inherent optical bandwidth is directly accessible. With access to the signal's spectrum, impairements such as chromatic dispersion can be directly corrected for achieving a tunable dispersion comensator (TDC). A hybrid guided-wave and free-space optical arrangement is used again due to the advantages afforded by the customization of the PLC (see Fig. 3) [6]. Light enters the PLC containing an extremely high resolution AWG through the single waveguide that is attached to an optical circulator, used to separate the input and output signal. The light passes through a first free-space region in the PLC, is coupled into the AWG, followed by a second free-space region. At this second free-space region the PLC is cut and the light is then spectrally spread out across a variable curvature reflecting membrane. There is a plano-cylindrical glass lens attached to the PLC that collimates the light in the plane of the PLC. To achieve linear chromatic dispersion, one must apply a phase distribution that varies quadratically with wavelength. The quadratic phase function is achieved by employing a reflective membrane whose curvature can be

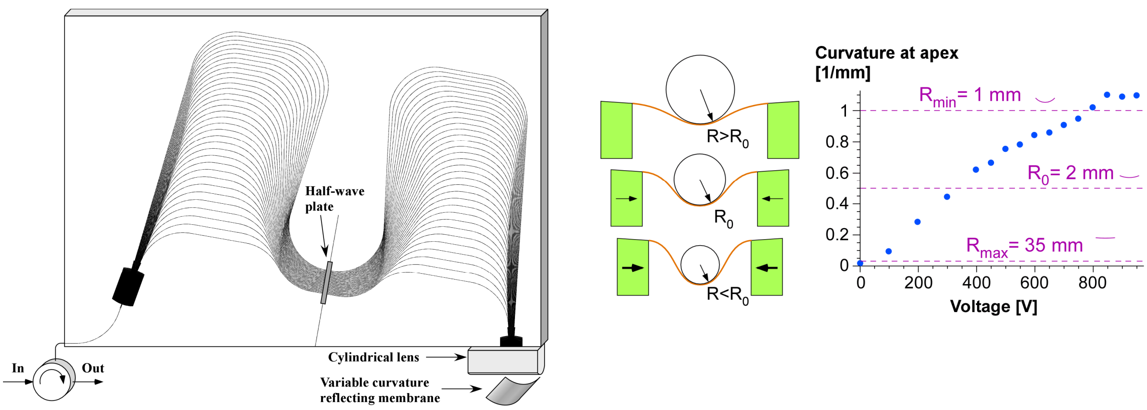

Figure 3 – MEMS tunable dispersion compensator. An arrayed waveguide grating disperses the signal, whereas a reflective membrane whose curvature is adjusted sets the amount of dispersion.

adjusted. We use the buckling mode of the membrane for changing its curvature. The reflecting membrane is stretched across two inward-propagating actuators at a large initial radius of curvature. As the two actuators are activated, the membrane ends are brought closer to each other and the radius of curvature decreases. A dispersion tuning range of 1000 ps/nm has been achieved for all channels simultaneously.

Conclusions

Optical microsystems with MEMS actuators can offer the functionality, flexibility, low power consumption, low insertion loss and compactness required for optical communication networks. Reported optical microsystems have demonstrated most of the passive and slow active enabling elements for optical networking, such as reconfigurable optical add-drop multiplexing, fiber cross-connect switching, channel selection filters for monitoring, tunable dispersion compensating elements, etc. The maturation of MEMS technology fortuitously coincided with, or even helped enabled, the transition to optical networking, by demonstrating the feasibility of performing the required tasks for reconfigurable networks. Innovation in this field will continue to flourish, with the key objectives being greater integration of functionality at smaller size and volume scales (as demonstrated in the hybrid guided-wave and free-space optics arrangements), robust and reliable MEMS design operating at lower voltages, and lower-cost processes.

References

1. J. E. Ford and D. J. DiGiovanni, "1×N fiber bundle scanning switch," IEEE Photon. Technol. Lett. 10, 967-969, 1998.
2. L. Y. Lin, E. L. Goldstein, and R. W. Tkach, "Free-space micromachined optical switches for optical networking," IEEE J. Select. Topics Quantum Electron. 5, 4–9, 1999.
3. D. T. Neilson, et al., "256×256 Port Optical Cross-Connect Subsystem," IEEE J. Lightwave Technol. 22, 1499-1509, 2004.
4. D. M. Marom, et al., "Wavelength-Selective 1×K Switches using Free-Space Optics and MEMS Micromirrors: Theory, Design, and Implementation," IEEE J. Lightwave Technol. 23, 1620-30, 2005.
5. D. M. Marom, C. R. Doerr, N. R. Basavanhally, M. Cappuzzo, L. Gomez, E. Chen, A. Wong-Foy, and E. Laskowski, "Wavelength-selective 1×2 switch utilizing a planar lightwave circuit stack and a MEMS micromirror array," *Optical MEMS 2004*, Takamatsu, Japan, Aug. 2004.
6. C. R. Doerr, D. M. Marom, M. A. Cappuzzo, E. Y. Chen, A. Wong-Foy, L. T. Gomez, and S. Chandrasekhar, "40-Gb/s colorless tunable dispersion compensator with 1000-ps/nm tuning range employing a planar lightwave circuit and a deformable mirror," *Optical Fiber Conference (OFC 2005)*, Anaheim, CA, post-deadline paper PDP-5, March 2005.