Transparent Optical Networks with Large MEMS-Based Optical Switches
(invited paper)

Roger Helkey
Calient Networks
25 Castilian Dr, Goleta CA 93117
tel: 805-455-1286, fax: 805-562-1919

Abstract

MEMS-based optical switches provide low-loss, high bandwidth switching for large numbers of optical paths, and are an enabling technology for a number of important applications. These applications include network management, reconfigurable WDM mesh networks and ring networks, automated fiber management, remote test and monitoring, and lab automation.

Switch Technology

Arrays of Micro-Electro-Mechanical mirrors that rotate in two axes can be used to build large, low loss optical switches with hundreds or thousands of optical ports [1,2]. As shown in Figure 1, an array of input lenses produces an array of free space optical beams from an array of fiber inputs. Each free-space input beam is incident on an input mirror that can rotate in two axes to direct the input beam to one of an array of output mirrors. The array of output mirrors directs each beam to an array of lenses that couple each beam into an output fiber. By adjusting the angle of the mirrors, the signal from any input fiber can be connected to any output fiber. A compact, cost effective implementation for large optical switches uses two collimator arrays each containing an array of precisely positioned fibers together with a monolithic lens array, and two monolithic MEMS mirror arrays.

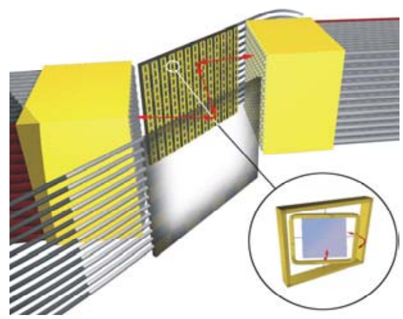

Figure 1. Optical switch configuration based on MEMS mirrors that rotate in two axes.

(i) Optical Performance

The diffraction component of this type of MEMS-based optical switch loss can be kept <1 dB, even for very large switches. Other major loss contributions are the lens array focal length non-uniformity and optical connector loss. As shown in Figure 2, a total median loss under 1.5 dB is achievable for these large optical switches [3,4]. Numerous optical tests have shown that large optical switches can be built with negligible optical distortion besides a small amount of optical loss, polarization dependant loss <0.2 dB, and the dispersion equivalent to a short piece of optical fiber.

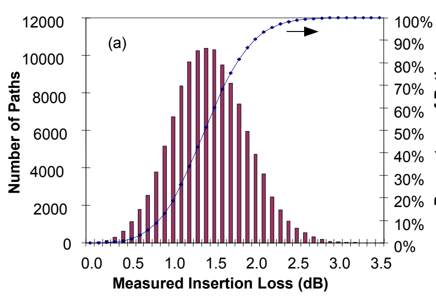

Figure 2. Measured optical loss for 330x330 connections.

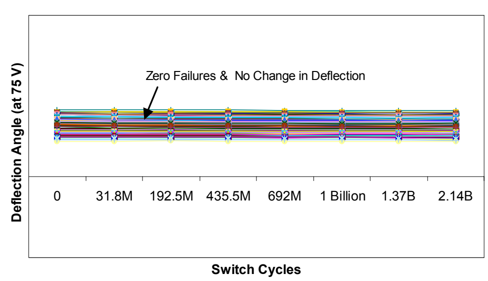

Figure 3. MEMS deflection test for 176 mirrors, at 60ºC demonstrating over $2x10^9$ cycles on each mirror, for a total $>3x10^{11}$ mirror cycles without failures.

(ii) Reliability

Reliability is a very important aspect of optical networking components. Electrical switches have many components in the active path, and so control of the failure mechanisms becomes critical to effective deployment. In contrast to electrical switches, large optical switches have only passive mirrors and other optical elements directly in the signal path. Although the core switch is a passive element, mirrors do have mechanical and electrical breakdown mechanisms that must be minimized. MEMS mirrors have been demonstrated to switch reliably far beyond 10^9 switching cycles as shown in Fig. 3, as long as the mirrors are designed to be non-contacting. The electrical breakdown mechanisms can be reduced below a calculated 10 FIT rate by proper isolation design and an appropriate burn-in process.

(iii) Switch Size Scaling

The diffraction-based scaling of the optical switch as a function of the maximum number of input ports or output ports N is shown in Table 1, assuming that the mirror deflection angle and mirror array fill factor are constant. There is no theoretical limit to the size of optical switches that can be fabricated, as the maximum port count of an optical switch is proportional to the diameter of the MEMS mirrors, and the mirrors can be made quite large [2,3]. However, the free-space volume in which the optical switching occurs is proportional to the cube of the maximum number of switch ports, and so with existing technology the practical size of a single switch is limited by diffraction to around 1,000 ports [2] to 4,000 ports.

Non-blocking optical switches can be built that are effectively much larger than this practical switch size limit by using a Clos architecture, where a large optical switch is constructed of a number of smaller optical switches configured in three stages as shown in Figure 5. For example, a number of 256-port optical switches could be combined in a Clos architecture to form a non-blocking 32,000 port optical switch. The complexity of the Clos configuration is higher than that of a single unprotected large switch, but is comparable to the complexity of a pair of large optical switches used for 1:1 protection, as the first and third stage Clos optical switches can perform the protection switching function equivalent to the input and output 1x2 optical switches used in a 1:1 protected switch configuration.

parameter	symbol	scaling
Beam radius at waist	w_0	$\sqrt{N}$
Beam radius at MEMS mirror	w_m	$\sqrt{N}$
Mirror diameter	D	$\sqrt{N}$
Mirror array area	A	N^2
Optical path length	L	N
Active switching volume	V	N^3

Table 1: Scaling of optical switch parameters as a function of the maximum switch port count N.

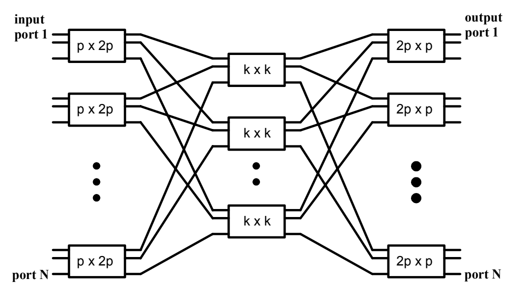

Figure 4. CLOS switch configuration scaling to beyond 32,000 input and output ports.

Switch Applications

(i) Network Management

Optical fiber bandwidth is a valuable commodity that needs to be efficiently utilized, yet it is difficult to accurately manually identify all fibers in a large optical network, and it is expensive to manually provision these fibers. The ideal network management solution is to use optical switches to manage and provision the network under software control. Generalized Multiprotocol Label Switching (GMPLS) is a set of protocols that is becoming widely used for network management [5-7]. In addition to managing the network configuration using optical switches, GMPLS can provision and monitor other optical networking equipment such as DWDM equipment using the Link Management Protocol (LMP) [8]. The use of GMPLS software control enables 'lights out' networking operation, where an entire facility can be fully automated to allow remotely monitoring and diagnosing equipment and traffic, or even reconfiguring a central office without the presence of any staff.

(ii) WDM Mesh and Ring Networks

Mesh networks more effectively use network resources than do ring networks, and so mesh networks offer significant cost savings compared to ring networks [9]. Recent mesh networks using optical switches include Japan's SuperSINET [10].

Wavelength provisioning and management in mesh networks can be implemented effectively using large optical switches as shown in Figure 5, where OEO switches provide grooming at the perimeter of the network. A large mesh network node shown in Figure 6 might require 260 optical switch ports. For example, an order-4 node with 40 wavelengths would have 160 input and output wavelengths to switch, and might have 100 add-ports and 100 drop-ports. Some applications require nearly 100% add-drop capability, increasing this estimated switch size closer to 320 ports. Even larger optical switch requirements are anticipated in future networks.

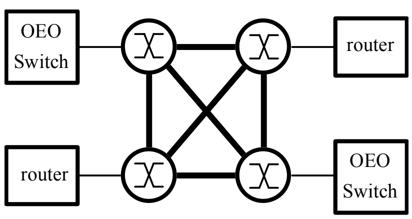

Figure 5. Mesh network with wavelength division multiplexing.

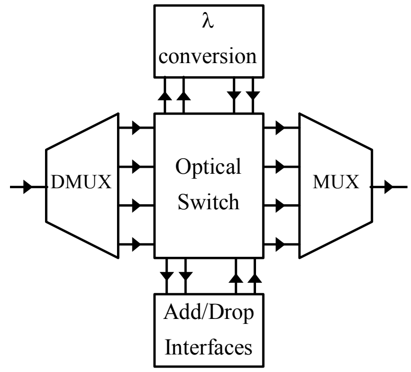

Figure 6. Optical node in the mesh network using a large optical switch to manage wavelength routing and add/drop channels.

(iii) Remote Test and Measurement

Traffic monitoring in optical networks presents substantial challenges, as large amounts of data are flowing through the network. Distributing enough monitoring equipment throughout the network to capture all desired traffic data is too expensive to be practical, and electrically switching traffic to centralized monitoring locations is also very expensive.

The application of a large optical switch to remote test and measurement is shown in Figure 9, where tap couplers are used to sample light from each through-port between the Line Termination Unit (LTU) and the Network Protection Equipment (NPE), and an optical switch directs the sampled traffic to one of a few monitor devices. These monitor devices can be located near the measurement site, or can be located remotely. Typically the optical switch in the RTM application has a highly asymmetric number of ports, for example 300 input ports and 5 output ports.

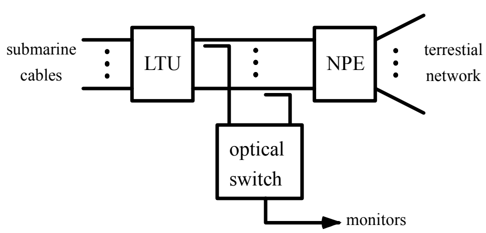

Figure 7. Remote test and monitoring example at a submarine cable landing site.

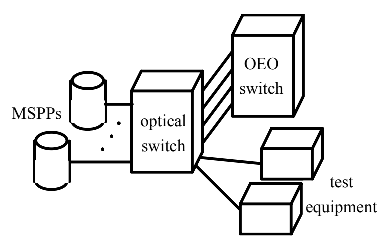

Figure 8. Test lab sharing to allow optical reconfiguration of a test network.

(iv) Automated Fiber Management and Lab Automation

Telecom central offices contain a vast number of fiber interconnects which need to be provisioned to add or expand new services. Error-free management of this fiber is a significant contributor to carrier operational expenditures. Large low-loss optical switches are ideal for automation of fiber management, leading to more efficient management and utilization of network resources.

Test laboratories commonly share a few pieces of very expensive equipment. This equipment may need to be shared among many users performing tests, or may need to be reconfigured frequently to test many different network configurations for regression testing. MEMS based optical switches are ideal for automation of optical test laboratories, in order to more efficiently share expensive optical test equipment as shown in Figure 8. For example, the cost of a router port is much higher than the cost of an optical switch port [11], and the cost of a 10 Gbit/s router can be close to two orders of magnitude higher than the cost of a broadband optical switch port. In addition, the optical switch also will enable future 40 Gbit/s operation. Sharing this expensive router using an optical switch leads to large increase in test capability and large reductions in capital equipment expenditure.

The required optical switching needs to be performed with low loss and negligible optical distortion in order to perform effective testing with the optical switch in the test path. In addition, transmission at 10 Gbit/s has been demonstrated with 40 passes through a Calient large optical switch with less than 1 dB power penalty [12], providing convincing evidence that optical switches can be used transparently for lab automation.

Summary

Large optical switches are inherently optically transparent to bit rate and data format and can be low loss, making them ideal for a number of applications such as network management, reconfigurable WDM mesh and ring networks, automated fiber management, remote test and monitoring, and lab automation. Properly designed MEMS switches can be highly reliability, scaling up to thousands of ports in a single switch or tens of thousands of ports or more in a Clos configuration.

The author would like to thank Shifu Yuan, Xuezhe Zheng, Volkan Kaman, Olivier Jerphagnon, Chandra Pusarla, John Bowers, Ayan Banerjee, and John Drake for their support.

References

1. R. Helkey et al., “Design of Large MEMS-Based Photonic Switches”, Optics and Photonics News, p. 42-45, 2002.
2. J. Kim, “1100x1100 port MEMS-based optical crossconnect with 4-dB maximum loss”, IEEE Photonics Technology Letters, p.1537-1539, Nov. 2003.
3. X. Zheng et al., "Three-dimensional MEMS photonic cross-connect switch design and performance," IEEE J. Select. Topics Quantum Electron., p. 571-578, 2003.
4. V. Aksyuk et al., “238x238 micromechanical optical crossconnect,” IEEE Photonics Technology Letters, p. 587-589, Apr. 2003.
5. E. Mannie et al., “Generalized multi-protocol label switching (GMPLS) architecture,” Work in Progress, draft-ietf-ccamp-gmpls-architecture-04.txt, 2003.
6. A. Banerjee et al., “Generalized multiprotocol label switching: an overview of routing and management enhancements”, IEEE Commun. Mag., p. 144-51, 2001.
7. T. Otani et al., “Field trial of GMPLS controlled PXCs and IP/MPLS routers using existing network facilities”, European Conference on Optical Communication, Tu3.4.3, 2003.
8. T. Otani et al., “Interworking DWDM equipment and PXC operations using GMPLS for a reliable optical network”, Optical Fiber Communications Conference, PDP3, 2004.
9. S. Wilkinson et al., “SONET Mesh Network architecture”, Proceedings of NFOEC, p. 293-302, 2003.
10. S. Asano, “SuperSINET”, noc.transpac.org/meeting/sinet.ppt.
11. K. Coffman, “The role of optical layer cross-connects in emerging network architecture,” in Proc. IEEE Military Communication Conf. (MILCOM), p. 1199-1203, 2000.
12. V. Kaman et al., “Cascadability of Large Scale 3-D MEMS based Low-Loss Photonic Cross-Connects”, submitted for publication.