Transparent Optical Switches: Technology Issues and Challenges

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1. Introduction

Increased traffic volume due to the introduction of new broadband services is driving carriers to the deployment of an optical transport layer based on Wavelength Division Multiplexing (WDM) [1]. The network infrastructure of existing core networks is currently undergoing a transformation from rings using SONET Add/Drop Multiplexers (ADMs) to mesh topologies using Optical Cross-connects (OXCs). A core optical network architecture can be opaque or transparent. An opaque architecture means that the optical signal carrying traffic undergoes an Optical to Electronic to Optical (OEO) conversion at different places in the network. A transparent architecture means that the optical signal carrying traffic stays in the optical domain from the time it is generated at the edge of the network until it leaves the network.

Even though the applications driving the large scale deployment of transparent optical switches are not currently in place (niche applications in today's networks only use a very small number of transparent switches), and the traffic demand does not currently justify the use of transparent switches that are cost effective at very high bit rates, it is possible that at some point in the future transparent switches may be deployed in the network. Based on this assumption, this paper explores the technology issues and challenges that are associated with 3D MEMS-based switch fabrics. These fabrics offer the most viable approach to make single-stage switch fabrics with large port counts that can be used for the deployment of transparent switches in the network.

Figure 1 illustrates the four different node architectures that can comprise a core optical network. The first architecture shows a fixed patch panel. Fixed patch panels located between WDM systems with transponders are currently being replaced by opaque (OEO) switching nodes (with electrical switch fabrics) as shown in architecture of Figure 1(b). This is an opaque network architecture, as the optical signal undergoes OEO conversions [2]. The third architecture shows a transparent (OOO) switch between WDM systems with transponders that is complemented by an OEO switch for drop traffic. This is once again an opaque network architecture, as the optical signal undergoes OEO conversions at the WDM transponders. The fourth architecture shows a completely transparent network topology, consisting of transparent optical switches and WDM systems that contain no transponders. In such an architecture, the signal stays in the optical domain until it exits the network.

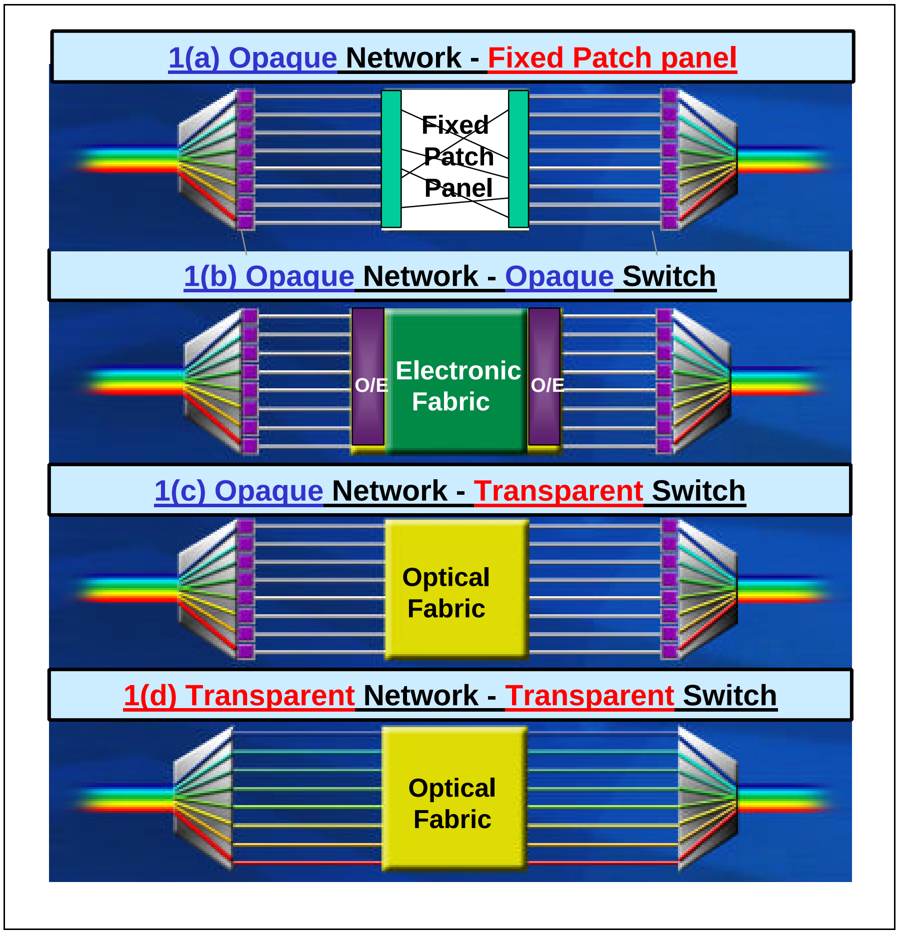

Figure 1: Node Architectures for a Core Optical Network

2. Transparent Network Architecture

The transparent network shown in Figure 1(d) and elaborated on in Figure 2 is a seemingly attractive vision. A signal (wavelength) passing through an office does not undergo opto-electronic conversion. Similarly, a client Network Element (NE), such as a router, interfaces with the switch using long-haul optics to interface with the WDM equipment without any O/E conversion. Since a signal from a client NE connected via a specific wavelength must remain on the same wavelength when there is no wavelength conversion, only a small size switch fabric is needed to interconnect the WDMs and NEs in a node. This architecture also implies end-to-end bit rate and data format transparency. Note that another architecture of a transparent switch in a transparent network may include a single large fabric instead of multiple switch matrices of small port counts. If one is to provide flexibility, such an architecture design would require the use of tunable lasers at the clients and wavelength conversion.

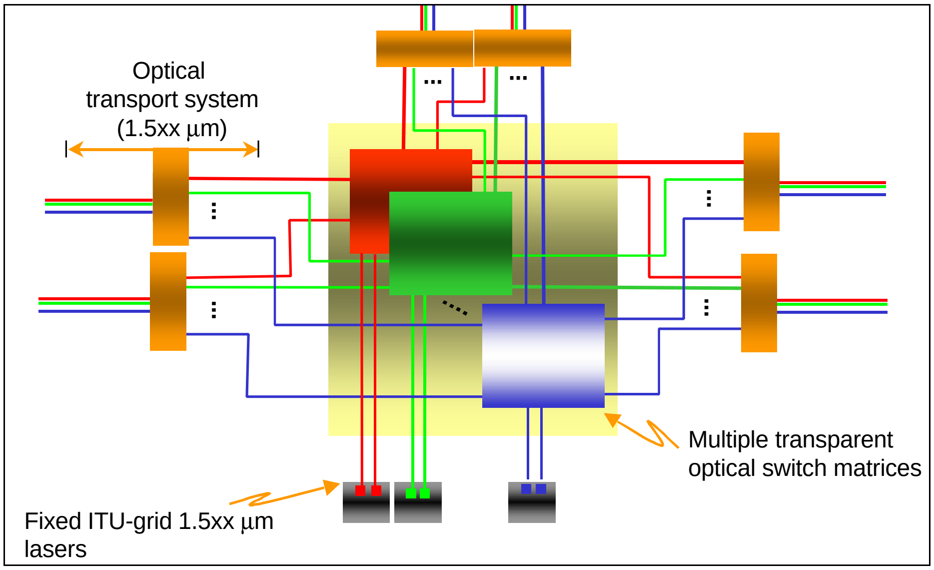

Figure 2: Transparent switch architecture in a transparent network

This network may provide significant footprint and power savings and on the surface suggests cost savings. However, while the transparent network architecture may be a viable option for small-scale networks with pre-determined routes and limited numbers of nodes, it is not a practical solution for a core network for the following reasons:

1. Based on the current state and history of research in the wavelength conversion arena, it is highly unlikely that there will be field-deployable wavelength conversion technology in the optical domain available in the next several years. In addition, for this technology to be effective and in order to build a flexible network for unrestricted routing and restoration capacity sharing, an all-optical 3R[1] function must be available. Even though a number of laboratory experiments have demonstrated all-optical 3R, a commercial product that harnesses such a technology does not currently exist [3]. Such a network that does not allow for wavelength conversion is essentially a network of n (n being the number of WDM channels) disjoint layers. Inflexible usage

of wavelengths in this network would lead to increased bandwidth and network operational cost, thus negating the savings that may result from eliminating opto-electronic conversion.

2. Physical impairments such as chromatic dispersion, polarization mode dispersion (PMD), fiber non-linearities, polarization dependent degradations, WDM filter pass-band narrowing, component crosstalk, amplifier noise, etc, accumulate over the physical path of the signal due to the absence of opto-electronic conversion. The accumulation of these impairments requires engineering of end-to-end systems in fixed configurations [4-7]. It is thus not possible to build a large network with an acceptable degree of flexibility.
3. The design of high-capacity DWDM systems is based on intricate proprietary techniques, eluding any hope of interoperability among multiple vendors in the foreseeable future. Since the interface optics at the client NE launches a signal through the all-optical switch directly into the WDM system without O/E conversion, and it is not possible to develop a standard for the interface for a high capacity WDM, the operators will not have the flexibility to select the client NE vendor and the WDM vendor independently. Consequently, transparent networks by necessity are single vendor (including the client network elements) solutions.
4. In the absence of wavelength conversion, only client-based 1+1 dedicated protection can be easily provided [8,9]. The wavelength continuity constraint on backup paths makes resource sharing almost impossible in transparent networks and consequently no shared mesh restoration can be easily offered. This in turn means that the capacity requirement for protected services is significantly higher (80-100%) for transparent compared to opaque networks [10].
5. As mentioned above, the absence of wavelength conversion leads to inflexible usage of wavelengths in the network and to dedicated protection of the lightpaths. This in turn leads to higher overall network cost due to the increased network capacity required and the increased network operational cost.

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[1] 3R function implies retiming, reshaping and regeneration of the signal.

6. Finally, in addition to all the limitations discussed above, the challenge of performance-engineering continental-scale transparent reconfigurable wavelength-routed networks remains severe and, in networks that push limits, remains unsolved despite some attempts at formalizing the routing problem [11].

It is thus evident that the following key carrier requirements would not be met if a transparent network architecture were implemented:

- Flexibility of configuration,
- Wavelength conversion,
- Multi-vendor interoperability of transport equipment (WDM),
- Low network-level cost.

Therefore, an opaque network solution will remain for now the only practical and cost-effective way of building a dynamic, scalable, and manageable core backbone network.

3. Opaque Network Architecture

Even though the opaque network solution may be more expensive in terms of equipment costs when the core network capacity increases significantly, the opaque network offers the following key ingredients for a large-scale manageable network:

1. No cascading of physical impairments. This eliminates the need to engineer end-to-end systems (only span engineering is required) and allows full flexibility in signal routing.
2. Multi-vendor interoperability using standard intra-office interfaces.
3. Wavelength conversion enabled. Network capacity can be utilized for service without any restrictions and additional significant cost savings can be offered by sharing restoration capacity in a mesh architecture (see Figure 3).
4. Use of an all-optical switch enabled without any compromise of the control and management functions. Overhead visibility (available through the OEO function that complements the OOO switch) provides support for the management and control functions that are taken for granted in today's networks.
5. The network size and the length of the lightpaths can be large, since regeneration and re-timing is present along the physical path of the signal.

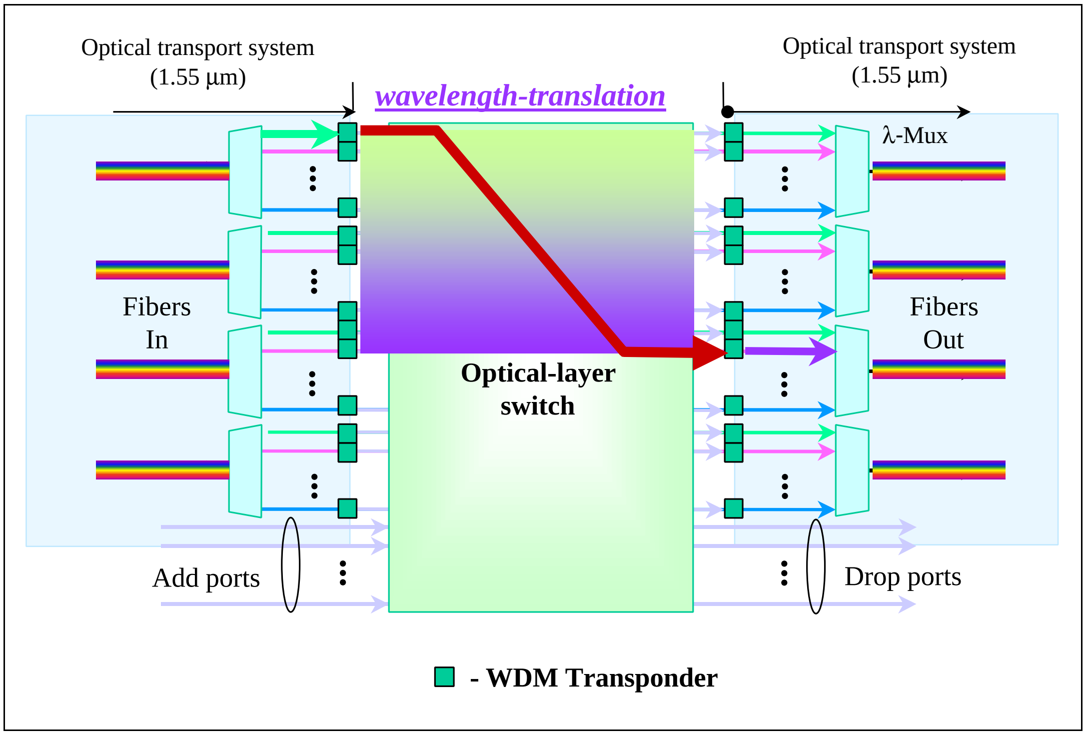

Figure 3: Wavelength translation as a by-product of an opaque network architecture

We now turn our attention to opaque network architectures in which WDM systems contain transponders. Today's architecture contains opaque switches (with an electronic switch fabric) in an opaque network (with transponders present in the WDM system). This architecture is shown in Figure 4. The interfaces to the fabric are opaque interfaces, which means that transceivers are present at all interfaces to the switch, and these transceivers provide an OE (input) and EO (output) conversion of the signal. The presence of the transceivers at the edges of the switch fabric enables the switch to access the SONET/SDH overhead bytes for control and signaling functions. The opaque transceivers provide support for fault detection and isolation, performance monitoring, connection verification, neighbor/topology discovery and signaling, as well as support for implementing the network routing and restoration protocols.

This approach however, is faced with a number of challenges: It will eventually reach scaling limitations in signal bit rate, switch matrix port count, and NE cost. This is one of the key motivations in developing transparent switch systems. For high-port count fabrics, analog gimbal-mirror (3D switches) MEMS-based switches offer the most viable approach [12,13]. It is important to point out that the opaque switches will still remain in the network architecture in order to provide some key network functions, such as grooming and multiplexing, Service Level Agreements (SLA) verification, and control and management. If grooming and multiplexing functions are not required, it is possible to provide SLA verification, and control and management functions via a transparent switch with O/E interfaces for the drop ports.

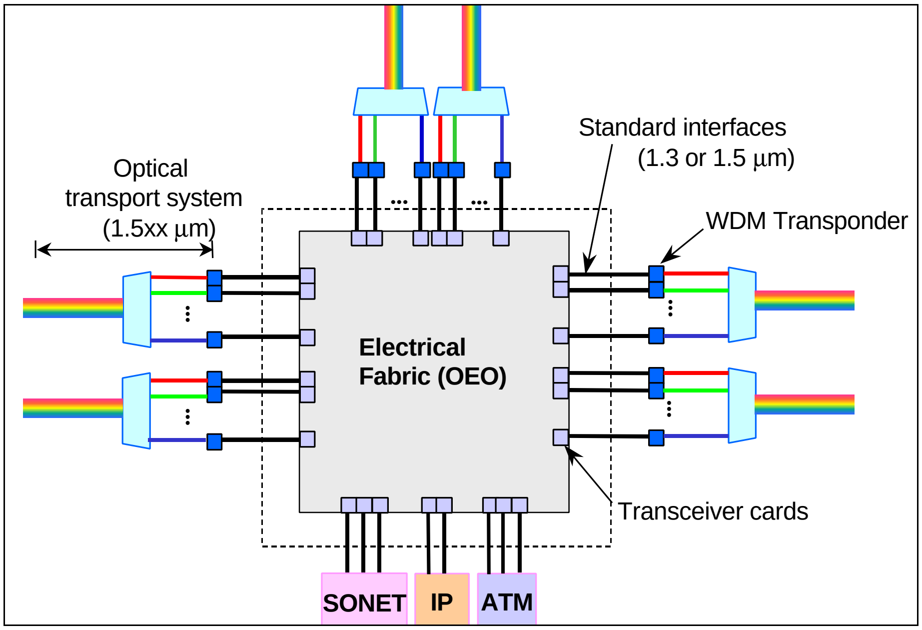

Figure 4: Opaque switch architecture

The value of optical switching is that, unlike integrated electronic switches, an optical switch fabric's complexity is a flat function, independent of the bit rate of the signals it handles (Figure 5). Moreover, for the foreseeable future we can safely assume that few components will be as small, cheap, and low in power-consumption as a silicon micro-mirror. Therefore, as bit rates rise, optical switch fabrics are expected to prevail. This will likely happen on time scales that are gated by the ability of vendors to meet carrier reliability and operational requirements with lightwave micromachine (for MEMS-based switch fabric) technology. Even though in early stages of OC-48 and OC-192 development the crossover point shown in Figure 5 appeared to be at the OC-48 and then the OC-192 rates, our analysis indicates that the crossover point is now expected to be at the OC-768 rate. This is true because the continuing decrease of the cost of electronic components.

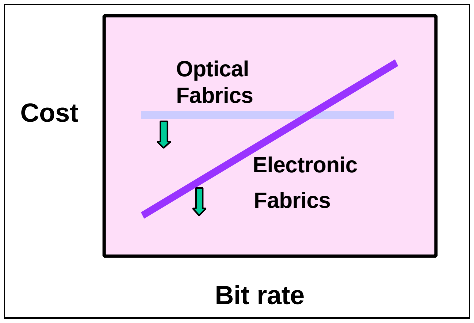

Figure 5: Advantages of Optical Fabrics

Transparent switches are expected to be cheaper in terms of the switching fabric and interface card cost compared to opaque switches. However, this will not happen until a certain level of mass production of the switch fabric is achieved. This will then result in significant cost reduction to network operators because a large amount of the traffic that passes through an office will be able to bypass the OEO switch (typically approximately 75% through-to-total ratio). Since the switch fabric is bit-rate and data format independent, the switch matrix can scale more easily than electrical switch fabrics. However, the main challenge to such architectures is providing the control and management functionalities that are readily available when we have access to the electrical signal and consequently to the SONET/SDH overhead bytes. This challenge, however, can be met by relying on the opaque interfaces (provided by an opaque switching node or by O/E drop ports integrated at the transparent switch) that complement the OOO switching fabric.

Figure 6 shows a transparent switch architecture that has transparent interface cards but no opaque transceiver (TR) cards on its sides. The optical switch fabric is bit-rate independent and it accommodates any data rates available (e.g., OC-48, OC-192, OC-768). The drop-side ports are connected to an OEO switch that provides SONET/SDH line termination through its opaque ports. Note that integrating the opaque interfaces at the drop-side interfaces of the transparent switch can also provide the opaque function. O/E drop interfaces in an OOO switch can be a cost-effective solution but cannot do grooming or multiplexing. Thus, network level cost reduction may be achieved with two switches (an OOO and an OEO switch) even though the cost of two switches may be higher than the cost of an OOO switch with opaque drop-side interfaces. The decision to deploy two switches or one switch with opaque drop side interfaces will be based on the network needs. If the two-switch approach is adopted, a communication interface between the OOO and OEO switches (e.g., an Ethernet external communication channel) is required to perform control and management functions between the two switches.

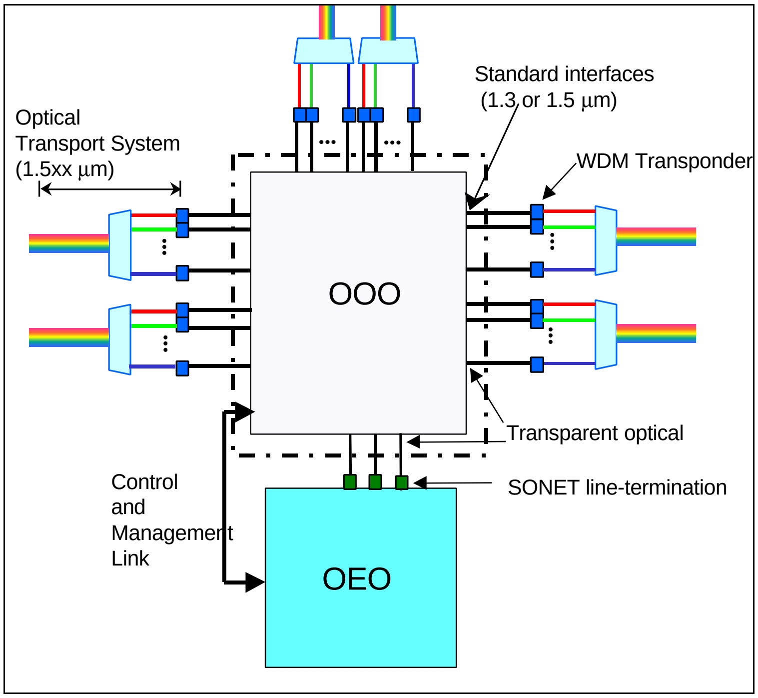

Figure 6: Transparent switch architecture

Transparent switches essentially help relieve the demand for OEO switch ports and reduce the cost of transporting lightpaths. This is accomplished by having all lightpaths pass-through (glass-through) the OOO switches, thus bypassing the OEO switches. Note that this can be a significant portion of the network traffic.

One of the issues associated with a transparent switch is power budget management. Because of the relatively high insertion loss contributed by the optical switch fabrics and the optical path through the central office, SR optics cannot be supported with a transparent switch. Therefore, such architectures can only support IR optical interfaces and its low-cost version, High Power VSR currently being developed in the OIF [14]. Thus, any client that has IR or High Power VSR interfaces will be connected directly to the transparent switch. Any client that has SR interfaces will be connected to the switch through the OEO node. Furthermore, the lack of access to the electrical signal and consequently to the overhead bytes at the transparent switch interfaces pose a number of challenges in creating a seamless interoperable and manageable network. Network control and management features such as fault monitoring and localization, neighbor and topology discovery, SONET keep-alive generation, sophisticated signaling, performance monitoring and connection verification are collectively very difficult to achieve in a transparent switch without forfeiting the economies that the switch was designed to extract.

4. Switch Fabric for Transparent Switches

Let us now consider the technology that will provide switch fabrics for all-optical switches. Micro-electromechanical systems (MEMS) offer the most promising means of building the high-port-count switch fabrics that are needed for the core-network cross-connects [12,13]. MEMS flip-up mirror arrays (2D switches) offer the potential for small (<32) port count OXCs [15,16,17]. Analog gimbal-mirror (3D switches) MEMS-based switches offer the most viable approach to make a single-stage switch with port counts numbering from the hundreds to thousands.

Figure 7 shows how a beam of light is switched from an input to an output port using such a fabric. In these fabrics, two matrices of gimbal-mounted MEMS mirrors with 2-axis control are used to provide beam switching in a 3D volume between two 2D arrays of collimated fibers. The first demonstration of a MEMS device and system prototype for this type of OXC was the Texas Instruments/Astarte Fiber Networks’ Beehive switch [18], though the device technology achieved in this program was rapidly improved upon by many others during the last few years. The ability of this architecture to achieve large port counts, while retaining reasonable optical performance, is the primary driver for these systems. However, this potential does not come without some fundamental challenges. The challenges and present reality associated with each 3D-MEMS switch subsystem, are discussed here in turn.

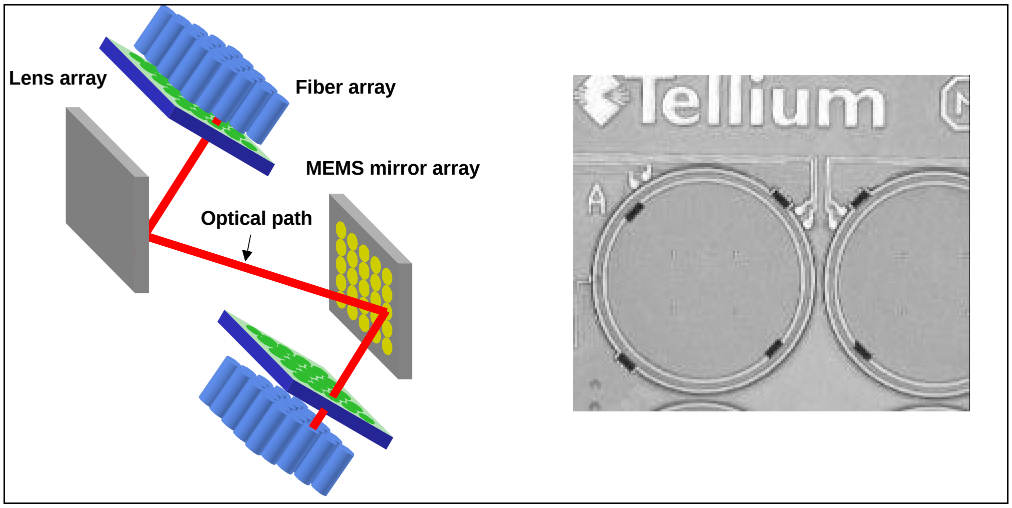

Figure 7: a) Schematic of a 3D MEMS OXC architecture. b) Photograph of a gimbal-mounted 2-axis MEMS mirror.

Although the public perception of MEMS switches is that they are real and ready for shipping, the reality is actually very different. Reliability qualification of MEMS switches is still ongoing, though some levels of NEBS and other forms of certification are being achieved. At present, no service-grade field-deployable large port-count (250+) fabrics have been shipped by any company, though serious efforts are still underway at the 256-port level. Fabrics with 1000 ports or more are still research programs, though efforts in this area have slowed due to diminished demand, and it does not appear that any fully populated fabrics of this size have yet been completed.

In what can be considered the typical MEMS-based OXC configuration, there are five main subsystems: MEMS chips, optical fiber arrays, lenslet arrays, mirror position-control systems, and packaging subsystems. The specifics and complexity of each of these components depends dramatically upon the size and configuration of the cross-connect itself, and presents significant challenges to the successful large-scale deployment of these network elements.

(a) Optical Fiber Bundles

The optical signals to be switched by the optical cross-connect enter and exit the fabric via two-dimensional arrays of optical fibers. The position of each fiber within each array must be accurate in five dimensions, x, y, z, and both axes of tilt (see Figure 8). The required translational accuracy of all fibers is measured in microns, with variant optical design choices permitting no substantial relaxation of these requirements. Milliradian accuracy in fiber tilt is required. Tolerances of this order place extremely high demands on fiber bundle manufacturers. Thus far, capability has been demonstrated for low-volume supplies of fiber bundles with fiber counts of a few hundred elements. The challenges faced in extending this capability to 1,000+ fibers become more extreme as fiber handling and management issues become more complex and the difficulty of achieving high yield arrays increases. The fiber bundles are in general constructed using epoxy packing. These systems are currently struggling to achieve the required positional accuracies with reasonable yield on day one; aging properties over tens of years have not yet been seriously explored.

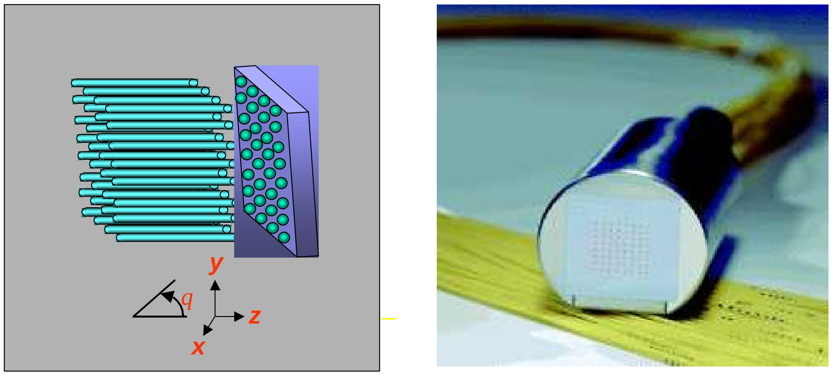

Figure 8: Fiber Bundles

(b) Lenslet Arrays

In order to achieve low loss through the switch fabric, collimation of the optical signals is required. This is typically achieved through the use of 2D arrays of lenslets on the same pitch as the optical fibers (see Figure 9). Various lenslet materials ranging from epoxies to glass, silicon, and polymers are being explored. One of the chief technical hurdles is that of achieving sufficiently tight variations in focal length. As with fiber arrays, the capability of producing low volumes of arrays with hundreds of elements with sufficient yield has been demonstrated; arrays of 1,000 or more lenslets are now at the frontier. At 1,000+ element sizes, the present state of the component supply chain for both fiber arrays and lenslet arrays can best be described as active research. It is expected, however, that volume availability will be achieved in the next couple of years.

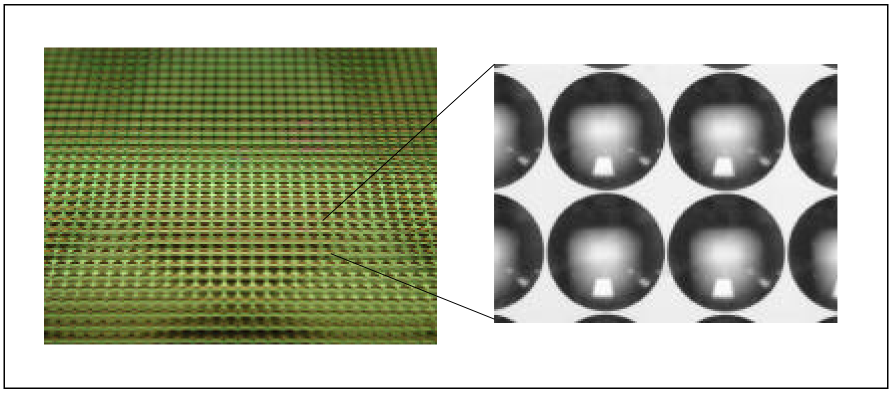

Figure 9: Lenslet Arrays

(c) MEMS Mirror Chips

The most common approach to providing beam steering functionality is to use 2D arrays of gimbal-mounted 2-axis controllable mirrors. MEMS mirror chips have been developed using either polysilicon or single-crystal silicon (SCS) for the mirror structural material. Although polysilicon is the technology with widespread use in MEMS systems for over ten years, it is not well suited to optical MEMS applications due to inherent stress and stress gradient through the material thickness. This stress and stress gradient typically cause curling of released plates in polysilicon even in the absence of metalization that only becomes exacerbated after deposition of mirror metals that have their own stress characteristics. Finally, since polysilicon and metal films have different thermal expansion coefficients, the amount of curling is thermally sensitive and very difficult to control over time and operating conditions (see Figure 10). The curling contributes significant loss to the optical system employing polysilicon mirrors. In recognition of the fact that polysilicon mirrors are highly challenged to provide the extreme flatness required, on the order of 1 m radius of curvature, the majority of switch fabric producers have moved toward single-crystal silicon as the material of choice. Single-crystal silicon offers significant advantages over polysilicon for optical MEMS technology due primarily to its very low inherent stress characteristics and total lack of a stress gradient through the thickness of the material. Although it is a relatively new material system to MEMS technologists, it is readily accessible through the use of well-known silicon-on-insulator (SOI) technology and new deep reactive ion etching techniques.

As evidence of the trend toward single-crystal silicon MEMS, acquisitions of several SOI foundries have recently taken place, such as Analog Devices' purchase of BCO Technologies.

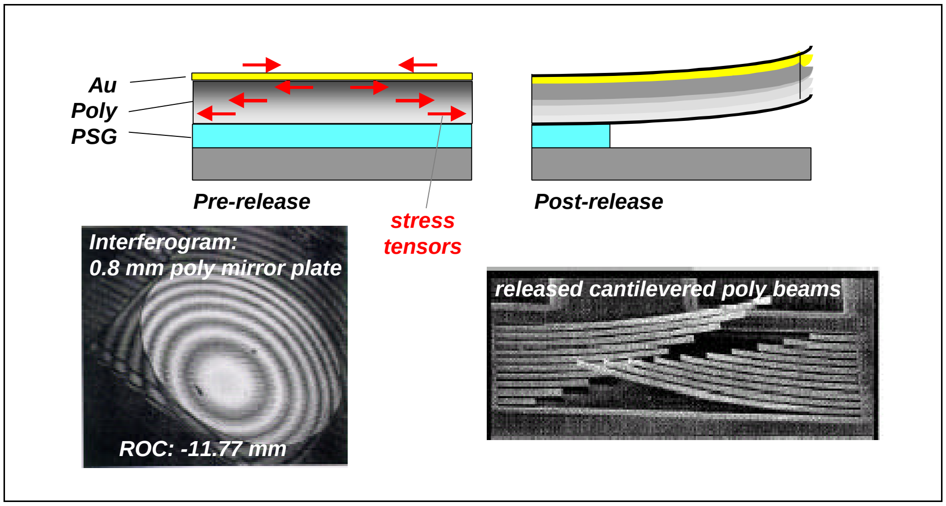

Figure 10: Surface-micromachined polysilicon

While making fiber bundles and lenslet arrays beyond a few hundred elements is difficult, growth of MEMS mirror arrays beyond this size poses even greater fundamental challenges. Each MEMS mirror requires about four electrode leads in order to achieve 2-axis control. Therefore, a 256-mirror chip would require roughly 1,000 electrical I/O pads. This is approximately the limit posed by state-of-the-art chip-packaging technology. As one scales the system up to include 1,000-mirror arrays, the I/O count clearly reaches about 4,000 (see Figure 11). Though such pinout counts have been reported in the largest research die, they are well in excess of limits imposed by the state of the art in manufacturable packaging. However, these I/O counts can potentially be reduced to a manageable level by innovative MEMS chip and electronics design.

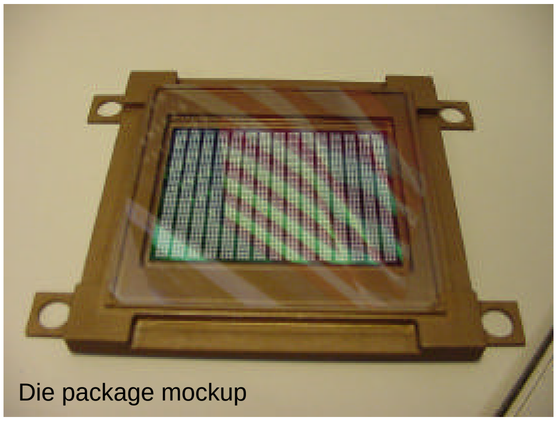

Figure 11: The electronic I/O bottleneck – Die package mockup

(d) MEMS Reliability

The entire MEMS field is relatively immature and therefore reliability concerns have only recently begun to be addressed by the community at large. Reliability of MEMS devices has been found to be exceptionally design-dependent with only some general cross-material system characteristics. It is understood that reliability can be designed into a component by avoiding operating characteristics such as surface contact, friction, and wear. MEMS designs based on flexure elements have been shown to be orders of magnitude more reliable than designs exhibiting these characteristics.

Since the predominant material system investigated to date has been polysilicon, much of the reliability study has concentrated on polysilicon structures such as the Analog Devices' ADXL50 accelerometer or Sandia National Lab's gear/linkage systems. Unfortunately, while polysilicon and single-crystal silicon have much in common, their reliability characteristics are quite different. This fact has particular significance in the area of compliance testing, because the time required for testing is commonly on the order of one year. The replacement of a polysilicon element with a single-crystal silicon element will therefore require new and equivalent testing and may delay deployment in commercial systems.

(e) Mirror Control

Because 3D MEMS switches couple single-mode fibers through free-space propagation regions on the order of tens of cm, the demands that they place on control systems are quite severe. The requirement for control is simple: upon execution of a switch command, place two micromirrors, each with two angular degrees of freedom, in sub-milliradian alignment within a few msec and hold this alignment through stochastic vibration, electronic component variations, and temperature variations over twenty years with reliability suitable for core-networking applications.

Four facts make this requirement particularly demanding. First, electrostatic MEMS actuators are strongly nonlinear; thus, the control systems required are nonlinear. Second, because making a connection requires the control of four angular variables, these nonlinear systems must search and hold connection in a coupled four-dimensional space. Third, the micro-electro-mechanics of MEMS structures result in large regions of electromechanical instability in the operating space, while the need to restrain operating voltages generates strong incentives to operate systems within these regions of instability. Finally, even after one has devised a control system that overcomes the above challenges, such a system needs to know in real time, with sub-milliradian accuracy, the angular position of each mirror in each of its two orthogonal axes. This mirror position-sense system is in fact one of the more challenging parts of a MEMS switch control system. To address this issue, substantial innovation in the development of fundamentally new components and subsystems is required. Figure 12 shows the "control constaletion" that clearly demonstrates how a set of tightly-coupled problems has to be resolved in order to address the control requirement.

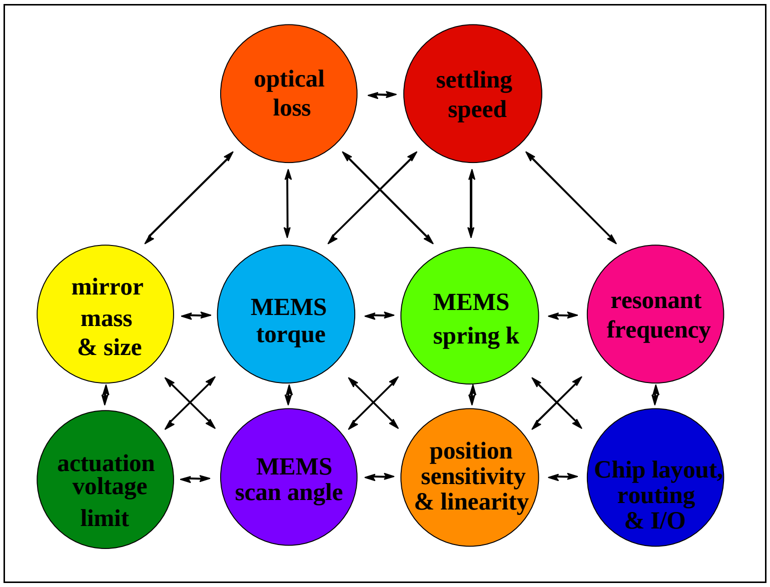

Figure 12: The Control Constaletion

Due to the four challenges enumerated above, the control systems for 3D MEMS switches are in fact one of the larger risks in a MEMS switching program and commonly represent the development items with the longest lead times. Due to the difficulty of developing these control systems in accordance with advertised time scales, the claim has repeatedly been made that real-time servo control is not needed in 3D MEMS switches—a claim that, in view of the above constraints, is clearly unsustainable. However, with the development of a suitable servo-control scheme and system monitoring [19], low-loss connectivity can be attained and maintained throughout the 20-year lifetime of the OXC.

(f) Packaging

Packaging of 3D MEMS fabrics requires precise positioning of micron and sub-milliradian tolerances. One of the more critical positional-stability requirements occurs at the combination of the fiber bundle and lenslet array. As described earlier, each fiber and lens element must be accurately placed over its lifetime with allowable errors measured in microns. Once each array is formed to this specification, the fibers and lens arrays must be aligned to one another with the same precision in four dimensions and held there through the lifetime of the switch. This provides a great challenge to the packaging of the system, since error in this alignment is one of the largest contributors to insertion loss. Other opto-mechanical packaging requirements include the placement of the now-collimated fiber bundles with respect to the MEMS chips and holding these positions stable during ambient temperature changes of tens of degrees Celsius. Finally, routing and management of thousands of electrical cables and optical fibers into the switch bay in a compact and organized manner is required [20].

5. Conclusion

The current state of affairs in terms of network deployment, applications and traffic demand does not justify the large scale use of transparent switches in today's networks. Some niche applications do exist, but can mostly be addressed using a number of small transparent switches. Provided that the traffic grows and the bit rates increase substantially there may emerge a potential need for an additional network layer utilizing transparent optical switches. Even from the technology standpoint, the present state of 3D MEMS-based switches is at best "advanced development" for 256 port fabrics and "advanced research" for 1,000 port fabrics. In the meantime, the deployment of transparent network elements is expected to remain limited to wavelength selective cross-connect (WSXC) architectures and Reconfigurable Optical Add Drop Multiplexers (ROADMs) on high capacity routes.

Furthermore, we anticipate that opaque switches will always remain for the embedded service base even after the transparent switches are eventually introduced in the network. These opaque switches will provide the grooming and multiplexing functions, as well as some of the necessary control and management functions, and will scale and decrease in cost with rapid progress in electronics.

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