International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 9, November- 2012

Mems Optical Switches

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Abstract:**The switching speed of electronics cannot keep up with the transmission capacity offered by optics. All optical switch fabrics play a central role in the effort to migrate the switching functional to the optical layer. Optical packet switching provides an almost arbitrary fine granularity but faces significant challenges in the processing and buffering of bits at high speeds. Generalized multiprotocol label switching seeks to eliminate the asynchronous transfer mode and synchronous optical network layers, thus implementing Internet protocol over wavelength division multiplexing. Optical burst switching attempts to minimize the need for processing and buffering by aggregating flows of data packets into bursts. In this paper, we present an extensive overview of the current technologies and techniques concerning optical switching.**

Index TermsMicro-Electro-Mechanical Systems(MEMS), Optical Add/Drop Multiplexer(OADM), Optical Cross Connection(OXC),Polarization Dependent Loss(PDL), Wavelength-Division-Multiplexing(WDM)

I.Introduction:

One of the most promising applications of MEMS technology is in optical communication in general and OXC switches in particular. The OXC switches in today's network rely on electronic cores. As port-count and data rates increase, it becomes increasingly difficult for the electronic switch fabrics to meet future demands. It is widely acknowledged that electronic switch fabrics are the bottleneck in tomorrow's communication networks.This bottleneck has stimulated intensive research in developing new, all optical switching technologies to replace the electronic cores. All optical networks offer many advantages compared to conventional optical-to electronic and electronic-to-optical networks, including cost-effectiveness, immunity from electromagnetic interference, bit-rate/protocol transparency, and ability to implement Wavelength-Division-Multiplexing (WDM) with relative ease. Therefore, it is desirable to manipulate the data-network at the optical level with optical switches. The optic switches are used to reconfigure/restore the network, increase its reliability, and/or acts as the Optical Add/Drop Multiplexer (OADM). There are, indeed, many technologies competing to replace the current electronic switch fabrics. A successful optical switching technology will have to demonstrate superiority in the areas of scalability, insertion loss, Polarization Dependent Loss (PDL), wavelength dependency, small size, low cost, crosstalk, switching speed, manufacturability, serviceability and long term reliability. Conventional mechanical switches, which are based on macroscopic bulk optics, utilize the advantages of free-space optics; however, they suffer from large size, large mass, and slow switching time. On the other hand, guided-wave solid-state switches have yet to show great potential because their high losses and high crosstalk limit their scalability. The recent development of free-space optical MicroElectroMechanical Systems (MEMS) technology has shown superior performance for this application. MEMS optical switches not only retained their conventional counterparts' advantages of free-space optics such as low losses and low crosstalk but also included additional ones such as small size, small mass, and sub millisecond switching time. Furthermore, MEMS fabrication techniques allow integration of micro-optics, micro-actuators, complex micro-mechanical structures and possibly microelectronics on the same substrate to realize integrated Microsystems.

II. MEMSOptical Switching Technologies:

MEMS:MEMS (micro-electro-mechanical systems) refers to miniscule mechanisms made from semiconductor materials such as silicon. They're already in widespread use in other industries and are starting to be used in components for telecom equipment. In the field of optical switches, MEMS are used in a variety of ways. These include arrays of tiny tilting mirrors, which are either 2D or 3D.

In a typical 2D array, the mirrors simply flap up and down in the optical equivalent of a cross-bar switch. When they're down, light beams pass straight over them. When they're up, they deflect the beam to a different output port.

With 3D arrays, the mirrors can be tilted in any direction. The arrays are typically arranged in pairs, facing each other and at an angle of 90 degrees to each other. Incoming light is directed onto a mirror in the first array that deflects it onto a predetermined mirror in the second array. This in turn deflects the light to the predetermined output port. The position of the mirrors has to be controlled very precisely -- to millionths of degrees.

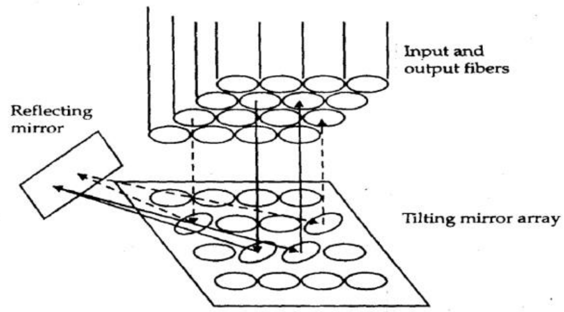

Fig1.Principle of MEMS

MEMS are also used to build small optical switches, ones with only a few ports. The simplest ones operate like sliding doors, blocking off light or allowing it through. In addition, MEMS are used to make actuators, mechanisms for turning a single mirror to bounce light among a small number of fibers.

III. SWITCH ARCHITECTURE OF MEMS OPTICAL SWITCHES:

There are currently two popular approaches to implement MEMS optical switches: (A) 2D MEMS switches; (B) 3D MEMS switches. These two technologies have striking differences in terms of how they are controlled and their ability to redirect light beams. However, both of them have shown promises in finding their niches in telecommunication networks.

a) 2D MEMS switches:

In this architecture, mirrors are arranged in a cross-barconfiguration as shown in Figure 3. Each mirror has only two positions and is placed at the intersections of light paths between the input and output ports. They can eitherbe in the "ON" position to reflect light, or in the "OFF" position to let light pass uninterrupted. The binary nature of the mirror positions greatly simplifies the control scheme. Typically, the control circuitry consists of simple transistor-transistor-logic (TTL) gates and appropriate amplifiers to provide adequate voltage levels to actuate mirrors.For an N×N-port switch, a total of N2 mirrors is required to implement a strictly non-blocking optical switchingfabric. For example a 16×16-port switch will require 256 mirrors. An alternative approach to increasing port-count is to interconnect smaller 2D MEMS switches sub modules to form multistage network architecture suchas the well-known Close network. However, this cascaded architecture typically requires up to thousands of complex interconnects between switch sub modules, thus decrease serviceability of the overall switching system. In addition, the free-space beam propagation distances among portsto- ports switching are not constant; therefore, insertion loss due to Gaussian beam propagation is not uniform for all ports. The minimum and maximum insertion losses of OMM's 2D 16×16 switching subsystem has a difference of greater than 5dB. 2D optical switches find applications in areas of communication networks, which requires smaller ports sizes.

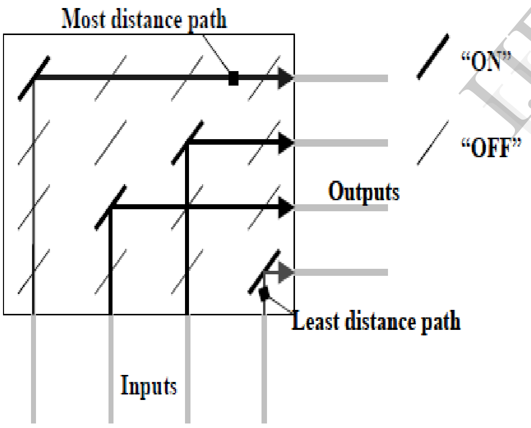

Fig2.A 2D cross-bar switching.

b) 3D MEMS switches:

A 3D or analog MEMS switch has mirrors that can rotate about two axes. Light can be redirected precisely in space to multiple angles – at least as many as the number of inputs. This approach results in only N or 2N mirrors. Currently, majority of the commercial 3D MEMS switch designs use two sets of N mirrors (total of 2N mirrors) to minimize insertion loss. Alternatively, if only N mirrors were used, port-count will be limited by insertion loss that results from finite acceptance angle of fibers/lens. Another advantage is that differences in free-space propagation distances among ports-to-ports switching are much less dependent on the scaling of the port-count. This architecture can be scaled to thousands by thousands of ports with high uniformity in losses. Inevitably, the much more complex switch design and continuous analog control is needed to improve stability and repeatability of the mirror angles. Lucent Technologies announced a 3D OXC using MEMS mirror array called WaveStar Lambda Router. The mirror can rotate on two axes and is controllable continuously to tilt greater than $\underline{+}6^0$. Figure shows the close-up view of Wave Star MEMS mirror.

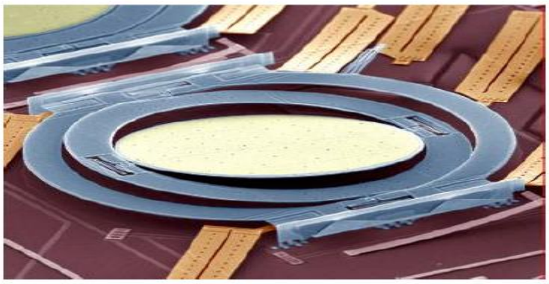

Fig3.Close up view of Wave Star MEMS mirror.

In the first quarter of 2001, Agere Systems, the former Microelectronics Group of Lucent Technologies, announced a fully integrated, 3D 64×64 MEMS optical switch component that will be marketed to makers of optical networking systems. The 5200 series MEMS switch module is based on the scalable 3D switching architecture developed at Lucent Technologies. Amazingly, the switching module has a maximum insertion loss of 6dB and a switching time of less than 10ms. Another notable development in 3D MEMS optical switch is by Nortel Networks (formerly Xros Inc.). Nortel made headlines at the Optical Fiber Conference (OFC) 2000 by showing the first ever all-optical switch called the X-1000 to beat 1000 port barrier. Following the hype created at OFC 2000, Nortel has recently admitted that only a small portion of the X-1000 actually worked. Nortel's 3D switching architecture is illustrated in Figure.

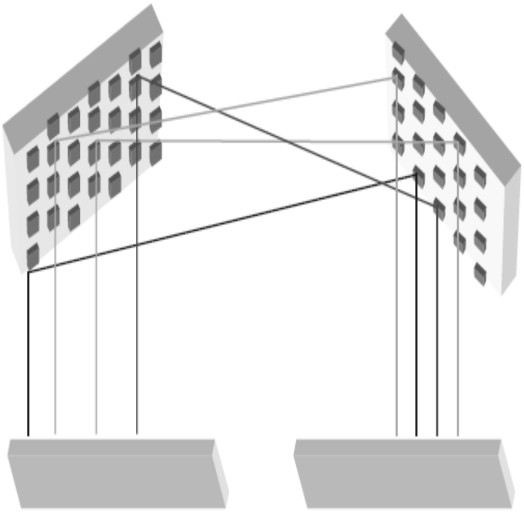

Fig4.A schematic illustration of Nortel's 3D switching.

Nortel's 3D switching architecture utilizes two sets of N mirrors for a total of 2N mirrors. The first plane of N mirrors redirect light from N input fibers to the second plane of N mirrors. All the mirrors on the second plane are addressable by each mirror on the first plane making non-blocking connections. In turn, mirrors on the second plane can each be actively and precisely controlled to redirect light into desired output fibers with minimum insertion loss.

IV. ACTUATING MECHANISMS:

MEMS tilting mirrors alter the free-space propagation oflight beams by moving into their propagation paths, thusachieving their switching functionality. In order forMEMS to be a viable optical switching technology, theactuating mechanisms used to move these mirrors must besmall, easy to fabricate, accurate, predictable, reliable,and consume low power. This section briefly describesthree actuating mechanisms that have been beingresearched extensively in the university laboratories aswell as the industry.

a. Electrostatic: Electrostatic forces involve the attraction forces of twooppositely charged plates. The advantages of electrostaticactuation are that it has a very well researched andunderstood behavior. Furthermore, it has very goodrepeatability, a property that is very important in opticalswitching. The disadvantages include nonlinearity in forceversus voltage relationship, and requirement of highdriving voltages to compensate for the low force potential.The design usually involves mirrors being held in parallelplane ("OFF") to the underlying electrodes. When anelectrode is charged at a different voltage level than thatof its corresponding mirror, the mirror will be tilted downto its "ON" position and thereby reflects light beam todifferent output fiber. Toshiyoshi and Fujita of theUniversity of Tokyo demonstrated a 2×2 switching matrixusing electrostatic actuation. Optical switching matrixwith large isolation of 60dB and small crosstalk of –60Db and insertion loss of 7.66dB are achieved using a bulk micro machined torsion mirror. Figure shows a 2X2switching matrix with collimated light beams from inputcollimated beam fibers (CBFs) being reflected off torsionmirrors, fabricated at 45^0 to light beams, into receivingCBFs.

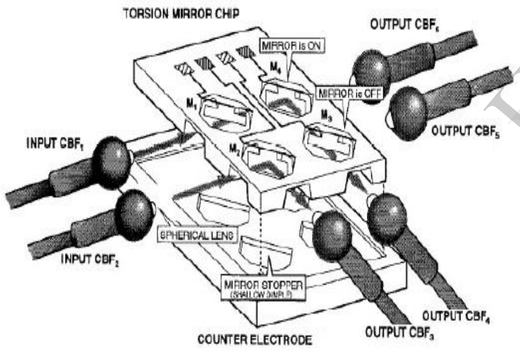

Fig5.Overall 2×2 optical switching matrix design

One of the leading MEMS optical switching companies, OMM, has already started shipping MEMS switching sub-systems, based on electrostatic actuation, in production quantities since the spring of 2000. 2D switching subsystems of sizes 4×4, 8×8, and 16×16 are hermetically sealed and passed Telcordia Technologies' environmental and reliability requirements for carrier class equipment. Passing of the stringent Telcordia tests, which include mechanical reliability and endurance, will help to facilitate widespread acceptance of MEMS-based switching subsystems in telecommunication networks. These switches have been used to route live data traffic in an unmanned central office in Oakland, California, with great success. OMM cites insertion loss of more than 6 dB, crosstalk of –50dB, and switching time of 13ms for a 16×16 subsystem.

b. Electromagnetic: Electromagnetic actuation involves attraction between electromagnets with different polarity. The advantages of electromagnetic actuation are that it requires low driving voltages because it can generate large forces with high linearity. Disadvantages such as shielding from other magnetic devices to prevent crosstalk are difficult, and it has yet to prove reliable. The California Institute of Technology has developed a magnetic 2×2 MEMS fiber optical bypass switch [4]. The operation principle of the magnetic MEMS switch is illustrated in Figure 7. The thin double-sided bulk-micro machined mirror moves up or down in response to changing magnetic field. When the mirror moves up, it blocks the optical path to opposing optical fibers. In this case, light signal is reflected off the mirror into neighboring optical fibers. When the mirror moves down, it moves below the level of the optical fibers, and light signal is transmitted to opposing optical fibers. Electromagnetic actuation can achieve this displacement with less than 100mW.

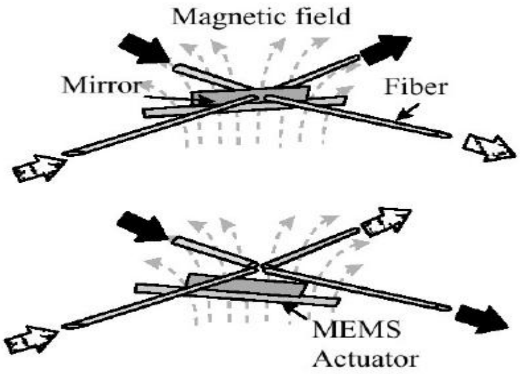

Fig6.Schematic illustration of operation principle of the 2×2 bypass fiber optic switch

Integrated Micro machines Inc. (IMMI) based in Monrovia, California, has developed a 3D MEMS switching subsystem that has much lower loss than itscompetitors. It claims an insertion loss of 3dB regardless of switch size. By using electromagnetic actuation instead of the weaker electrostatic actuation, IMMI claims that the driving voltage does not exceed a maximum of 10V. Low power requirement is a critical criterion especially when IMMI is looking to develop the so-called 1000×1000-port monster switching subsystems. Low insertion loss and low power consumption bring benefits on both the system and economical level. Now, less optically efficient but more manageable fiber arrayconnectors can be used, thereby reducing servicing time. In addition, MEMS/CMOS integration, which eliminates tens of thousands of individual mirror control wires, is possible with lower voltage requirements.

c. Scratch Drive Actuators (SDAs):AT&T research labs have demonstrated an 8×8 Free-Space Micro machined Optical Switches (FS-MOS) for the application of restoration and provisioning in core transportlight wave networks .The mirror and the Scratch Drive Actuators (SDAs) are monolithically integrated on the silicon substrate using surface micromachining techniques. The rotation of the mirror is achieved by connecting the pushrods with the mirror and the translation plate using micro-hinges . The actuators used are an array of SDAs. The translation movementof the translation plate by the SDA's is converted to a rotation movement of the mirror. Figure shows the complete structural design of the FS-MOS. The length of the pushrod is 75μm, and the distance between the hinges at the bottom of the mirror to hinge joint located on the mirror is 70μm. This design allows the mirror to be rotated up to 45^0 when the translation plate is moved 2μm, and 90^0 at a translation distance of 22μm. The number of bias pulses applied to the SDAs determines the plate translation distance, and thus the rotation angle.

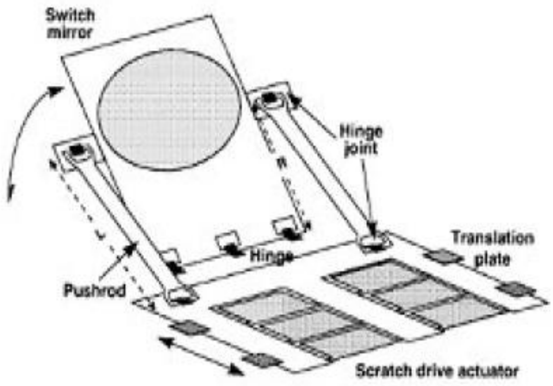

Fig7.Schematic design of free-rotating fiber optic switch

The optical switch has shown to have a switching time of 700µs for rotating the mirror from an “OFF” position to the “ON” position. Losses measured range from a minimum of 3.1dB to a maximum of 3.9dB. In this design, SDAs have shown to have very fast responses and extremely precise translation movement. With the presence of the pushrod and hinge joints, the mirror can be rotated to multiple angles precisely and reliably, two of the most important requirements of 3D MEMS switches. the current 3D MEMS switches require the mirrors to be rotated about two axes. Novel designs incorporating SDAs to provide precise positioning of mirrors about two axes of rotation have the potential to reduce needs for complex feedback control electronics.

V. CHALLENGES:

In the short-term, MEMS appears to be the forerunner which has the potential to dominate applications including OXC, OADM, and servicerestoration/protectionswitches. There remain important issues within MEMStechnology that need to be addressed before thewidespread acceptance in the core-transport network.

• Reliability

Like any other commercially viable products, MEMSswitches should function reliably in changing and oftenadverse environments. Will the behavior of the MEMSswitches that have been held in the “ON” position for afew months before switching to “OFF” during networkrestoration/provision be predictable? Or will stationbetween materials restrict the movements of the switches?Will switch response times and structural integrity of theoptical switches degrade after millions upon millions ofwitching cycles? Concerns regarding reliability ofMEMS-based devices and repeatability in terms ofperformance need to be well studied in the context ofentire optical systems.

• Manufacturability

Characteristics of MEMS-based devices could fluctuate from one batch to the next. Repeatability of material properties and uniformity of processing techniques have to be improved to fully address these concerns. MEMS/CMOS fabrication processes have to be made compatible. The control electronics and wiring schemes can be fabricated in sync with MEMS components thereby eliminates costly hybrid integrations. Researches into novel materials and fabricating processes must be ongoing. MEMS should be driven by technology as well as basic science.

• Serviceability

Matrices of micro-mirrors are fabricated using batch fabrication technique. Will the failure of a single mirror require the replacement of the entire optical switch? Although the inclusion of redundancy in the optical switches will alleviate the problem, it remains to be fully explored.

• Scalability

The ability to incorporate more port-counts when needed is the number one concern of carriers. The increasing amount of data traffic in communication networks, especially for long-distance carriers, will demand even more wavelengths to be deployed. Therefore, optical switches need the capability to scale in order to manipulate the increased number of wavelengths. MEMSbased optical switches must incorporate this key feature to gain widespread acceptance of the carriers.

• Standardization

There is a lack of technological compatibility in the MEMS optical switch market. It is shortsighted to rely on a single vendor for MEMS-based optical switches. However, standardization will come with time. Similarly, there should be compatibility in the front-end MEMS fabricating processes. Ultimately, MEMS industry should mimic what the IC industry has done. Fabrication ofMEMS/Application Specific Integrated Circuit (ASIC) can be contracted to centralized foundries specializing in making MEMS devices. To achieve this, standardized fabrication processes/libraries must be defined.

• Packaging

MEMS-based optical switches have close interaction with the physical world through their mechanical components. How will optical switches be packaged so as to minimize effects of changing temperature, humidity, vibrations, and other environmental elements.Packaging invariably affects the performance of MEMS devices. Therefore, it should be included in the initial design phase.

• Automation

Assembly of MEMS components, and automatic optoelectronic packaging and performance testing of MEMS devices are crucial to reducing product cost andcycle time while maintaining product quality. Issues such as self-testing, self-assembly and automated packaging remains to be fully explored.

• Competing technologies

MEMS-based optical switches are facing major challenges from other all-optical switch technologies, and the constantly evolving electronics switching systems. The current state-of-the-art electronic switching systems offer 512 2.5-Gbit/s ports for a combined capacity of over 1Tbits/s. It seems that the adoptions of optical switching technologies are faced with fierce resistance from electronic switching systems. It should be noted that Lucent’s Lambda Router have yet to be commercially successful and are constantly being outsold by electronic switching systems such as Ciena’s Core Director. Given the current advancement of electronic switching technology, switching technologies such as MEMS will have a lot more to prove before we can enter the era ofpurely optical switching networks.

VI. CONCLUSION

MEMS optical switches have demonstrated to have lower polarization dependent loss (PDL), bit-rate and protocol independent, lower insertion loss, and lower crosstalk than guided-wave solid-state switches. Their superior lowloss performance allows them to be expandable to larger port-counts. When compared to their counterparts, MEMS optical switches are cheaper because of batch fabrication techniques. They are also smaller in size and lighter inmass thus allowing high-density packing on a single silicon substrate. Currently, there are much research interests in integrating micro-optics and electronicscomponents to MEMS devices to realize true integrated optics. Amidst all the hopes and hypes, MEMS-based optical switch has yet to cross major technological hurdles in order to fulfill its potential as the preferred opticalswitching technology in the long term.

ACKNOWLEDGMENT

With warm Thanks to RTTC BSNL Staff, Mysore and My Family members & Friends for supporting me, When I was in a trouble.

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