A BREIF OVERVIEW: OPTICAL SWITCHES AND CROSS-CONNECTS

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ABSTRACT

This paper discusses the current state of optical switches and cross connects in the field of MOEMS. A background in telecommunications is provided for a description of core components (multiplexer, cross-connect) in data networks. The application of optical switches in data-centers is described, including the advantages over existing electrical signal conversion and performance limitations with MEMS based optical switches. Design variations of cross-connects included in the overview are free-space optical micro-mirrors, adiabatic wave couplers, and competing technologies SOA and LCOS. Performance metrics considered for comparison are switching time, scalability, noise, power-consumption and cost. The paper culminates with additional applications and current status of MEMS technologies used for optical switching.

INTRODUCTION

Telecommunications and Fiber Optics

Switches are used extensively in telecommunications to move signals from one location to another within an interconnection network. Familiar uses are with the internet, telephones, cable television, and computer networking. Fiber optics is one variety of signal transmission using the concept of total internal reflection. Data is encoded into light and passed through a medium (silica glass) surrounded with a material with a lower index of refraction to allow for the light to continually move through the cable. The benefits of using fiber-optic over conventional twisted-pair or coaxial cabling is the signal integrity. Information transmitted through fiber can travel long distances without needing to be amplified by active components (opto-electronic repeaters). Information can be passed on one carrier frequency (single mode fiber) or sets of information can be based on multiple carriers (multi-mode fiber). Multimode has a larger bandwidth and can move large amounts of data but cannot travel as far as single mode.

The standards for fiber optic are wavelengths 1310nm and 1550nm. These wavelengths can be transmitted for thousands of kilometers at 10Gb/s, or shorter distances at higher bandwidth. The 1310nm used in single mode fiber has a max attenuation of 1dB/km and 1550nm is 0.4dB/km. Multimode fiber (850nm and 1300nm) has a larger diameter fiber and cannot travel as far due to varied propagation velocities of different frequency signals (modal dispersion). The maximum bandwidth for multimode is 10Gb/s up to 550m [4].

Signals are encoded into light via a transmitter that uses LEDs or currently vertical cavity surface emitting lasers (VCSEL). The opposite end contains a receiver to convert the light to an electrical signal using the photoelectric effect, by devices such as semiconductor-based photodiode.

History of Optical Switches

Prior to the development of fiber optics, long distance communication was achieved with coaxial cabling. Telecommunication switching in that era was done through telephone operators manually patching calls with cord pairs. Digital switching came later from Bell Labs when broadband data and twisted pair cabling became prevalent. Electrical transmission is now replaced by fiber optics when larger bandwidth and greater distance is required. The optical-electrical-optical (OEO) conversion done by switches can become a bottleneck on the macro-scale without parallelization. During the early 2000's Lucent Technologies (a derivative of Bell Laboratories) and many other startups developed MEMS optical switches using micro-mirrors arrays. Since then research has been one to improve the scalability and performance of the switches on the micro scale.

Components of Switches

Switches are an important component to fiber-optic networks. A typical switch is responsible for two main items: cross-connects, and wave-division multiplexing. Multiplexing is the process of adding and subtracting signals that are contained within a fiber. This part is responsible for the information contained within a single fiber. Wave-selective coupling is used to block or allow signals based on their wavelength. In this process, the various source frequencies undergo amplification and attenuation by a variable optical amplifier (VOA) to have comparable power to the rest of the signals contained in the optical fiber. Optical cross-connects are a complementary component for the fiber that directs the contents from an input to an output. This allows for connections in the cross-connect to travel from any input to any output. When both multiplexing and cross-connects are used together, the result is a wavelength selective cross-connect (WSXC). This is visualized in figure 1 and is the underlying system behind switches.

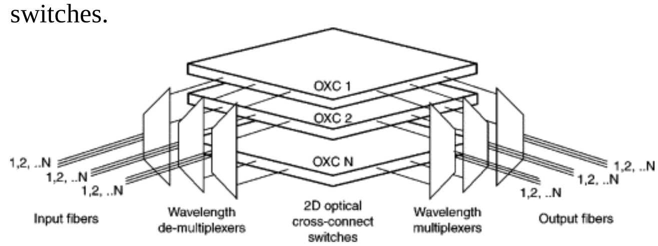

Figure 1: A wave selective optical switch allowing a single input to be directed to any output if they have distinct wavelengths [9].

The capability of a switch can be classified as blocking or non-blocking depending on the orientation of the design. A cross-connect is considered non-blocking if any single input can be directed to any output regardless of where the other input signals are being directed. This is visualized in figure 2 for the 2D cross-bar architecture which is strictly non-blocking.

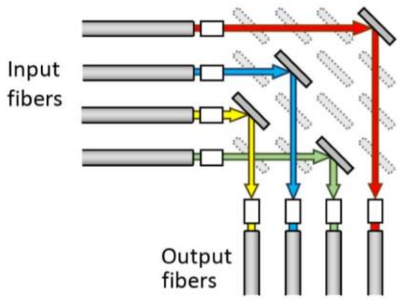

Figure 2: A NxN crossbar architecture for a 2D micro-mirror switching array [8].

COMPETING TECHNOLOGIES

Free-Space MEMS

Free-space MEMS are advantageous because there is no transition from an optical signal to an electrical signal, and back again to an optical signal. This removes the possibility of a bottleneck for the conversion and poses fewer limitations on the bandwidth of the switch such as protocol and data rate.

The main design variations of free-space MEMS involve micro-mirror arrays in 2-D and 3-D orientations. Originally the mirrors would have two states, on and off, which would lower a fixed mirror into the signal path and redirect it to a specific channel. This is the same architecture described in figure 2. Lucent technology has been a large developer of the micro-mirror arrays, specifically in three dimensions. Figure 3 shows a micro mirror on a 2 axis gimble to control the orientation within a switch. This variety of MEMS based free-space switch is actuated by an electro-static force from a large voltage potential used to create an electric field pulling the parallel plates together.

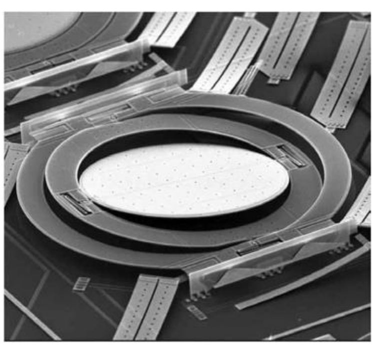

Figure 3: 3D Micro-mirror on 2-axis gimble from Lucent Technologies [9].

There are limitations in free-space MEMS for optical switching due to the propagation of light in free space which increases the insertion loss. The signal at the receiving end does not have as much power as the transmitting end. Another limitation with the technology is the fact that the actuation is dictated by the mechanical motion of the 2-axis gimble meaning that the switching speed has a limit based on the movement. However, an advantage of the micro-mirror switching arrays is the scalability. Lucent Labs has created a 1296x1296 [8] switch based on the 3D MEMS design. This can be competitive in applications where switching speed is not of the highest importance, but rather the number of ports.

Coupling Transmission

Another competing method for MEMS based switching to vary the coupling coefficients to allow different modes to be transmitted. The vertical adiabatic directional wave-coupler uses waveguides to have a through state where the vertical gap is significant and coupling is limited, and a drop state where the tapered waveguides are coupled to the input signal and redirect the fiber. Changing the displacement between the two waveguides is the most common way of tuning the coupling rate.

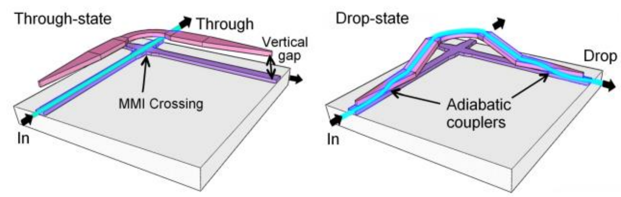

Figure 4: Vertical adiabatic directional wave-coupler in through and drop states [8].

The adiabatic vertical directional wave-coupler is a more efficient design of the moveable waveguide switches and has been integrated successfully for a 64x64 switch. Other designs include a laterally moving directional coupler and a micro-ring resonator. However, the limitation with the directional coupler is the low optical bandwidth. Micro-ring resonators serve a specific purpose for tuning signals depending on the resonant wavelength of the silicon ring used in wavelength division multiplexing.

Coupling technologies suffer from power consumption throughout switching, and limited scalability due to the complex nature of implementing an adiabatic vertical directional wave-coupler. The advantages of this technology come with the switching speed, the fastest for electro-mechanical switches (0.91 micro-seconds). The vertical adiabatic directional wave coupler is normally operated using electro-static actuation, but there is research into increasing efficiency by utilizing a buckling instability. In this case, the bi-stable states of the waveguide are formed by compressive stresses in the polysilicon thin film layer of the device [7]. The advantages of using the buckling instability of the beam allows the switch to go between two latched stable states, meaning power is only consumed during switching. It also allows for greater deformation during buckling. It is difficult to achieve hundreds of nano-meters displacement using electro-static actuation. Using the bi-stable adiabatic switch, the performance characteristics of the typical vertical adiabatic directional wave-coupler are retained while operating at theoretically 28 V [7]. The design is shown in detail in figure 5.

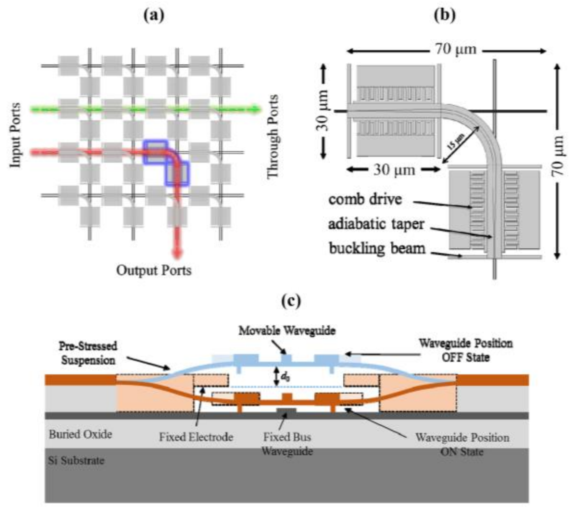

Figure 5: Bi-stable adiabatic wave-coupler driven by buckling instability and comb-drive actuators [7].

A design variation of switching using coupling is a nano-scale horizontal and vertical directional coupler. The design is based off the vertical switching coupling design but have the advantage of lower switching voltage (<5V) and thereby waveguide travel (<55nm) due to the electro-static actuation of the cantilevers. The mode of operation takes advantage of asymmetric coupling instead of pure vertical separation, the system of two horizontal couplings is varied by changing the symmetry and introducing a phase mismatch in the two channels. This can be seen is figure 6 with the two sets of waveguides forming independent effective refractive indexes (ERI) that allow the signal to be passed through the bus or cross state. Although the speed is slower than electro-optical switches, it is competitive under tight power consumption and voltage requirements [6].

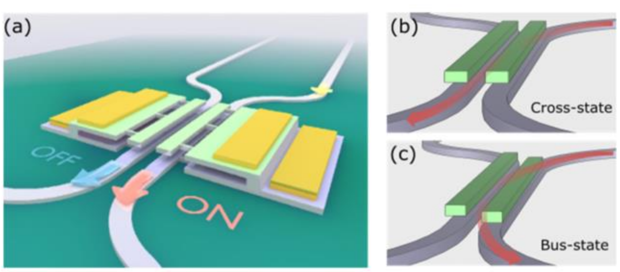

Figure 6: Nano switch based off 4 modes of horizontal and vertical coupling to provide bus and cross states with low cantilever beam deflection [6].

Liquid Crystal on Silicon (LCOS)

Liquid Crystals can be used in an optical switch to allow for phase manipulation. A LCOS optical switch is composed of a glass substrate, tin oxide electrode, alignment layers, liquid crystal material, aluminum pixel mirror array and CMOS backplane [3]. Applying a voltage across the crystal can change the refractive index of the material and tune the phase of the incident light. The incoming fiber disperses the light and switches based off the pixels on the LCOS which act as a phase-only diffraction grating [3]. By doing this an output phase angle is created to direct the various wavelength light. An example setup is shown in figure 7, using a diffraction grating as an on-board wavelength division multiplexer.

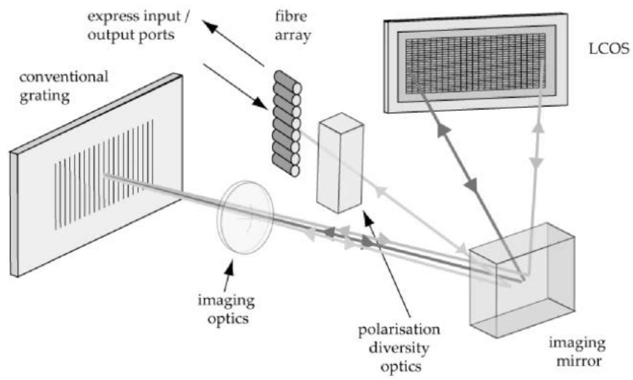

Figure 7: Example setup diagram for switching using a liquid crystal optical switch [2]

LCOS can operate on a broadcast and select architecture [5] which is strictly non-blocking. This requires 2*N couplers and N^2 ON/OFF selectors to connect N inputs to N outputs. This is complex in scaling the number of ports. However, this mechanism is not mechanical and does not require any moving parts to switch signals.

Semiconductor Optical Amplifier (SOA)

SOA based optical switches act as ON/OFF gates to ensure the correct switching of the input signal. It operates on the same broadcast and select architecture as LCOS. SOA have the advantage of being high-gain amplifiers which suppresses crosstalk and has lossless operation [1]. This variety of switch has performance on the order of sub nano-seconds, making them the fastest switch in operation. The benefits of the switch are at the cost of power consumption. Power is being used to amplify the input signals and allow for fast switching with great signal integrity. Scalability also becomes an issue with heat dissipation and circuit complexity. It is expected the maximum dimension to be observed with SOA based switches is 64x64 by cascading SOA elements [8].

PERFORMANCE COMPARISON

Scalability and Actuation Speed

MEMS based optical switches favorable for scalability are with the 3D micro-mirror arrays, as mentioned Lucent technologies has been developing larger scale switches using the 2-axis gimble method of controlling the direction of the output. The current maximum number of ports is 1296x1296 in 2001, however the insertion loss is significant (5.1dB) and the switching time is slow (5ms), with a narrow operating range for wavelength (1530nm-1560nm) [8]. The limitation on scalability is driven by the precision of manufacturing, since mirror size scales with number of ports.

Improvements are made to adiabatic vertical directional wave-guide MEMS based switches, however the max dimension is currently 64x64 (2016). For that configuration, it does possess one of the fastest switching speed of opto-mechanical switches at 0.91 micro-seconds.

Scalability with LCOS is difficult due to complexity associated with each additional port. There are many components involved in order to perform the switching. Due to the lack of moving components and low voltage control, LCOS can achieve micro-second actuation [8] but may range from 10ms to 100ms depending on architecture [3].

Opto-electrical switching by SOA offers the fastest available switching at less than 10ns. The scalability of this technology is low due to the available number of transistors that can be placed in a given unit area.

Table 1: General dimension and switching time of competing optical switch technology [8].

Technology	Dimension	Switch Time
Waveguide	64x64	0.91 us
Free-space	1296x1296	5ms
SOA	8x8	2.5ns
LCOS	1x20	100ms

Insertion Loss and Crosstalk

The insertion loss of the nano-scale four waveguide directional coupler is less than 0.3dB (theoretical) in both bus and cross states. The crosstalk for the bus state is less than -20dB in the range of operation. Compared to the existing adiabatic couplers. Insertion loss for LCOS mainly come from the polarization of the input signal, and crosstalk from the quantization of the pixel spatial and phase information. At maximum, insertion loss can be 7.6dB and cross talk of -19.4dB [3]. SOA based optical switches consume power to increase extinction ratio to suppress crosstalk, their operation is lossless due to the gain of the amplifier [8].

Overall Viability

The viability of MEMS based optical switches is looking to be in a hybrid architecture based on slow and fast optical cross-connects for multiple optical communication avenues within a network [8]. LCOS are beneficial and relatively fast due to their lack of moving components, however the complexity associated with creating many ports (maximum dimension 2x2 at a 1550nm wavelength) limits their applications. SOA still outperforms MEMS electro-mechanical methods but are limited due to the complexity associated with many ports capable of the large bandwidth needed in the future of data transfer.

CONCLUSION

The current infrastructure for optical-switching is limited with the aspect of optical buffering. As of now, there is no pure optical buffering over a network and as a result network traffic contention drops packets. As a result, the replacement of existing network switches with a pure optical solution is unlikely. Optical switches will likely be complementary to the conventional electronic switches [3]. The bandwidth of existing analog switches is limited to approximately 10Gb/s on a single wire, this has led to mass parallelization of the switches and an increase in footprint to accommodate the increased data transfer required by a modern datacenter. Fiber-optics is an appropriate solution due to the high current bandwidth of 100Gb/s and target of 20Tb/s [3]. MEMs based optical switches are available in several designs ranging from the micro-mirror arrays to directional couplers and have the benefits of low power consumption and small footprint. In comparison, the micro-mirrors require mechanical motion to operate and are limited by their actuation method. The electro-static actuation is also a relatively large voltage, difficult to produce on the microscale. The advantage of the micro-mirror array is the scalability with Lucent Technologies creating a 1296x1296 switch.

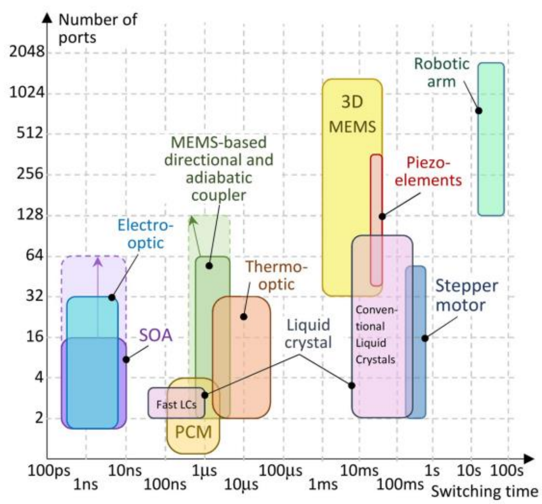

Figure 8: Comparison of MEMS with other switching technologies [8].

On the other hand, the vertical adiabatic coupler can perform switching quickly (0.91 micro-seconds), on par with some electro-optic solutions. However due to the footprint of the solution, the ability to cascade is limited and scalability becomes an issue. Variations of the coupler design have addressed the issues of power-consumption and large displacement of the vertical waveguides. The bi-stable solution makes use of buckling instabilities to allow for two latched states requiring no power when stationary and a moderate theoretical actuation voltage of 28V. A 3-D nano-scale version of the coupling design uses asymmetric waveguide distributions to move create the bus and cross states. More research is to be done to determine the viability of the designs to create a fast MEMS switch with low actuation voltages and minimal footprints.

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