

1 Introduction to all optical switching technologies

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1.1 Introduction

As the Internet and modern communications becomes increasingly prevalent across the globe, fiber optics - as the defacto infrastructure that supports the information revolution - is racing to keep up. The demand for Internet services is driving the growth of data traffic worldwide. Software developers and users are constantly adopting applications that devour more and more bandwidth in order to speed delivery of information. As multiple forms of traffic place increasingly heavy burdens on fiber networks, carriers are looking for innovative ways to push more data through existing fiber.

Generally, the current telecom infrastructure is a mix, with fiber optic cables in the 'core' long-haul backbone networks, some fiber and copper wire in metro or regional networks, and primarily copper wire for access networks and 'last mile' connections to customers (though other technologies -- such as cable, satellite, and fixed wireless -- are also used). The Holy Grail in telecommunications and networking today is the 'all-optical network', where every communication would remain an optical transmission from start to finish. The speed and capacity of such a network - with hundreds, if not thousands, of channels per fiber strand - would be practically limitless.

To this end, several key developments have emerged that are exploiting and extending the capability of current fiber optic systems in significant ways; we will **briefly** discuss two of these: **Dense Wave Division Multiplexing (DWDM)** and **Optical Switching**.

2 DWDM

One of the most critical technologies enabling the capacity expansion of fiber optic systems is Dense Wavelength Division Multiplexing (DWDM), which can exponentially increase the bandwidth of a fiber optic strand.

Telecom transmissions, whether voice or data, have always been multiplexed in some way. Multiplexing simply involves combining multiple communications into a single compact transmission. Initially, digital systems used Time Division Multiplexing (TDM), which broke different voice or data signals into pieces and sent them in alternating slots in one stream. According to the Economist, TDM has historically enabled a single fiber strand to carry up to 32,000 voice calls simultaneously (or roughly 2.4 gigabits per second (Gbps))

Wave Division Multiplexing (WDM), which was introduced in 1995, splits light waves into different frequencies of infrared light, with each frequency capable of transmitting data at high speeds. Many systems in use today have reached 40 different wavelengths (hence the term 'dense'), per fiber, which effectively multiplies the capacity of the network by 40 fold. It has been reported that the newest equipment splits light waves into as many as 160 channels, and prototypes in labs have apparently reached as high as 15,000 channels.

3 Optical switching

Most networking equipment today is still based on electronic-signals, meaning that the optical signals have to be converted to electrical ones, to be amplified, regenerated or switched, and then reconverted to optical signals. This is generally referred to as an '**optical-to-electronic-to-optical**' (**OEO**) conversion and is a significant bottleneck in transmission.

Huge amounts of information traveling around an optical network needs to be switched through various points known as **nodes**. Information arriving at a node will be forwarded on towards its final destination via the best possible path, which may be determined by such factors as distance, cost, and the reliability of specific routes. The conventional way to switch the information is to detect the light from the input optical fibers, convert it to an electrical signal, and then convert that back to a laser light signal, which is then sent down the fiber you want the information to go back out on. For example, in a long-haul network, an OEO conversion may occur as often as every 600 kilometers just for amplification purposes.

The basic premise of **Optical Switching** is that by replacing existing electronic network switches with optical ones, the need for OEO conversions is removed. Clearly, the advantages of being able to avoid the OEO conversion stage are significant. First, optical switching should be cheaper, as there is no need for lots of expensive high-speed electronics. Removing this complexity should also make for physically smaller switches.

Unfortunately, optical switching technology is still very much in its infancy. There have been numerous proposals as to how to implement light switching between optical fibers, such as semiconductor amplifiers, liquid crystals, holographic crystals, and tiny mirrors. One of the most common techniques being developed is that of the tiny moveable mirrors known as **micro-electro-mechanical systems (MEMS)**.

MEMS consist of mirrors no larger in diameter than a human hair that are arranged on special pivots so that they can be moved in three dimensions. Several hundred such mirrors can be placed together on mirror arrays no larger than a few centimeters square. Light from an input fiber is aimed at a mirror, which is directed to move the light to another mirror on a facing array. This mirror then reflects the light down towards the desired output optical fiber.^[1]

4 Introduction to MEMS

Micro-electro-mechanical systems (MEMS) are in widespread use in some other industries, but their use for telecom applications is relatively recent.

In telecom, MEMS has become synonymous with the arrays of tiny tilting mirrors used for optical switching fabric, although the same technology is being used to make a wide range of other components as well.

Since MEMS creates so many mirrors on a single chip, the cost per switching element is relatively low. However, since it involves moving parts, MEMS is fairly slow to switch – requiring milliseconds to do so. This is fine for lambda provisioning or restoration but is too slow for optical burst switching or optical packet switching applications.

Conventional MEMS works by reflecting the beam of light from the surface of a tiny mirror. MEMS systems have moving parts, and the speed at which the mirror moves is limited. By applying more current, the mirror can move faster, but there's a limit to how much current can be sent into the array of mirrors. If this weren't bad enough, it seems that the speed and angular displacement terms in the calculation of the required current have integer powers of around 4 or 5, and so the bottom line is that we have to put a lot of current into the array for a small improvement in speed. By changing the mirror design so that the angle through which light is bent is smaller, it's possible to achieve faster switching speeds. This technique is known as "fast MEMS."

MEMS arrays can be built on a single-chip, single-plane approach. In other words they are 2 dimensional (2D MEMS). In a simplistic approach it's also possible to stack a number of 2D MEMS arrays on top of each other to create a 3D MEMS array. In fact, real 3D MEMS systems are somewhat more complex than this, but the general principle holds.

A huge drawback of 3D MEMS is the fact that the thousands of mirrors require complex software to coordinate their operations. In particular, one vendor has suggested that there are over a million lines of code in their implementation (although the reference may be to the overall switch software, and not just the MEMS subsystem). While it's possible to test software extensively, the opportunity for bugs increases geometrically with the size of the code base.

On the upside, MEMS is a very rapidly changing technology. Since it seems to have a monopoly on the high port-count optical switch market for the moment, a huge amount of investment is going into the implementations and into solving the basic problems.

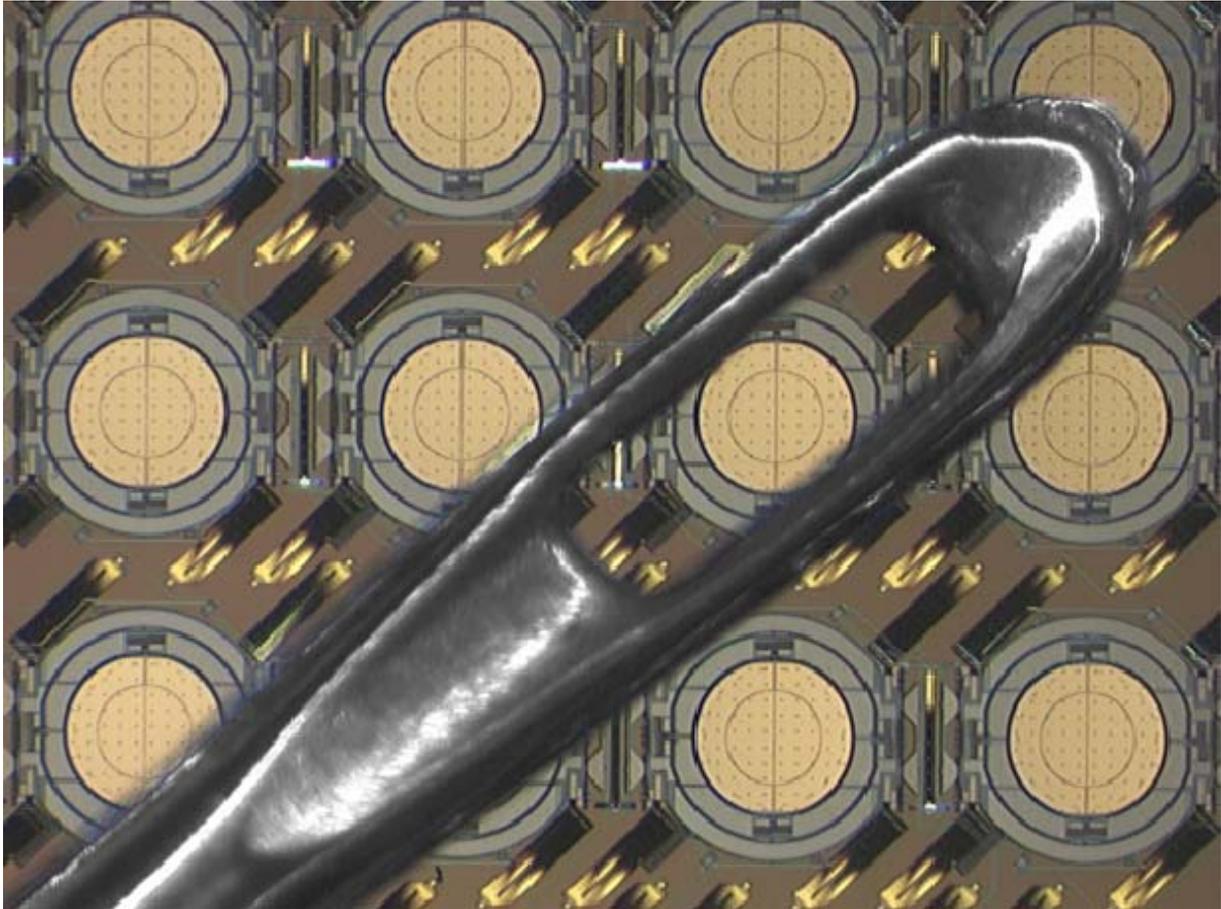


Figure 4-1: MEMS^[2]

4.1 Micro-Electro-Mechanical-Systems Switches

Micro Electro Mechanical Systems (MEMS) are semiconductor-made micro-mechanisms, which are generally used as movable micro-mirrors that can deflect optical signals from input to output fibers ^{[3][4]}. As far as medium- and large-size switching fabrics are concerned, micro-mirrors can be arranged into two-dimensional or three-dimensional arrays ^[5]. In these switches, mirrors are steered in order to deflect light beams properly. Small-size switches can be also made, as shown in the following figure :

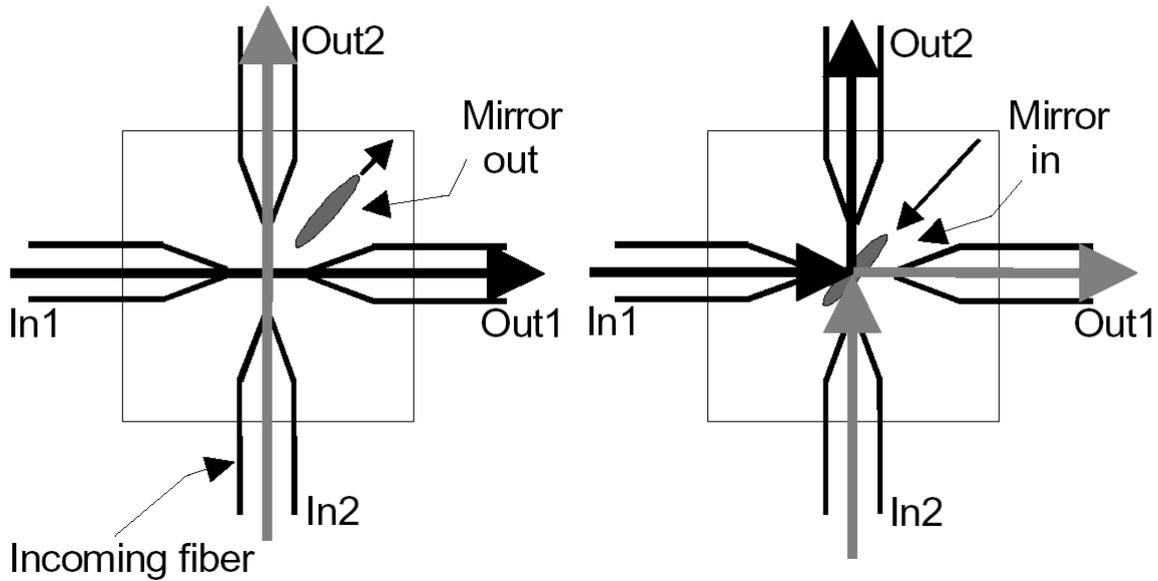


Figure 4-2: MEMs Switch

In this case, the mirror slides along the 45° direction, yielding the BAR or CROSS states. MEMS switches feature good scalability. Two-dimensional arrays with size 32x32 are already available and can be used as basic building blocks, in single-stage architecture, to scale up to 256 ports.

4.2 Liquid-Crystal switches

Liquid-crystal state is a phase that is exhibited by a large number of organic materials over certain temperature ranges. In the liquid-crystal phase, molecules can take up a certain mean relative orientation, due to their permanent electrical dipole moment. It is thus possible, by applying a suitable voltage across a cell filled with a liquid-crystal material, to act on the orientation of the molecules. Hence, optical properties of the material are varied.

A 1X2 Liquid-Crystal (LC) optical switch structure is shown in the following figure. A polarizing beam splitter divides incoming signals into two polarization components, which are then directed to two active cells filled in with liquid crystals. Depending on whether a driving voltage is applied or not, the active cells either change the polarization states of the incident beams or leave them unaltered. The beam combiner, then, directs the beam to the desired output port.

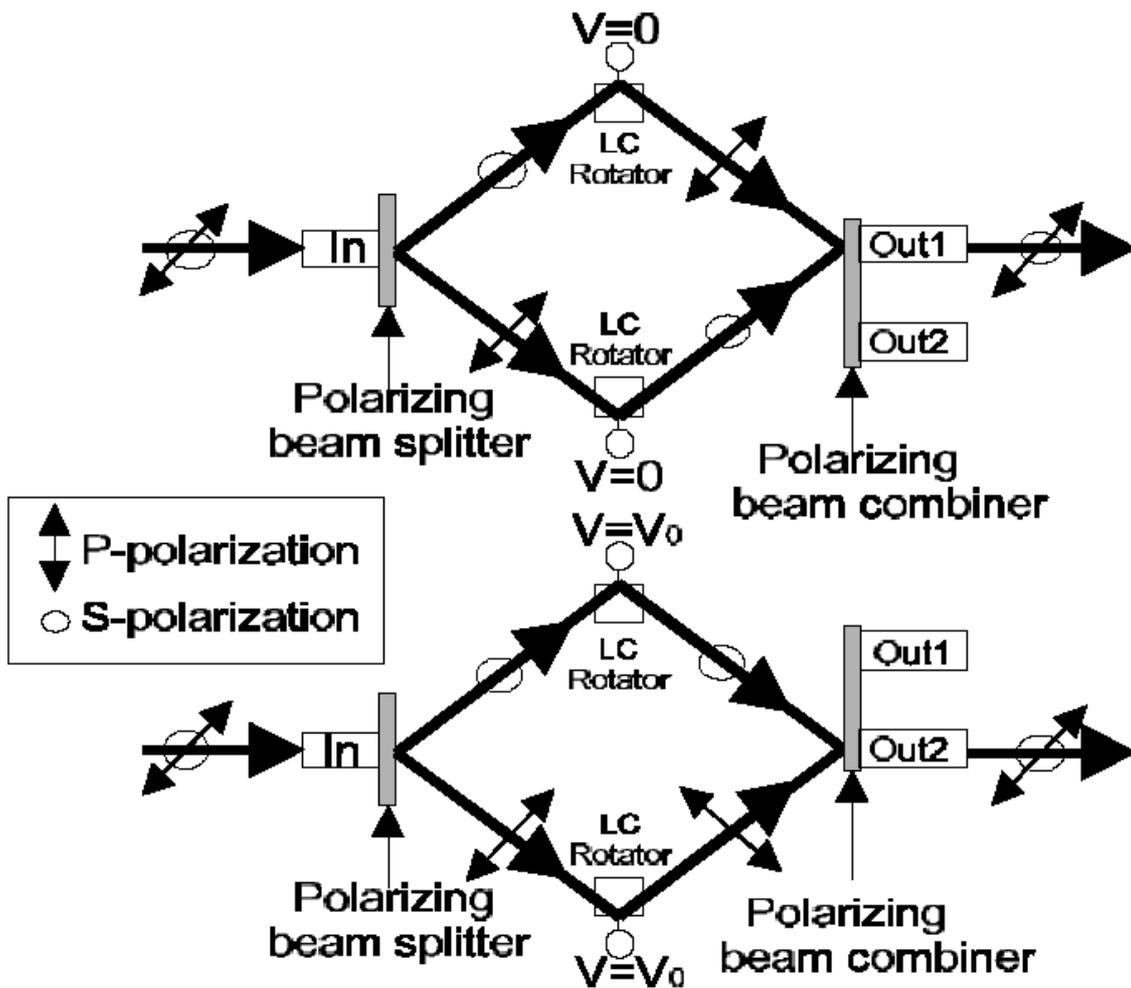


Figure 4-3: Liquid Crystal Optical Switch

These switches are wavelength selective, i.e. they can switch signals depending on their wavelength. This is a very attractive feature, as it allows adding and dropping single wavelengths from a multi-wavelength beam, without the need of electronically process the whole signal.

4.3 Bubble switches

This technology has been proposed by Agilent Tech. Inc. ^[6] and is based on the same principle as for ink-jet printers. The switch is made up of two layers: a silica bottom layer, through which optical signals travel, and a silicon top layer, containing the ink-jet technology. In the bottom layer, two series of waveguides intersect each other at an angle of around 120° . At each cross-point between two guides, a tiny hollow is filled in with a liquid that exhibits the same refractive index of silica, in order to allow propagation of signals in normal conditions. Thus, a light beam travels straight through the guide, unless the guide is interrupted by a bubble placed in one of the hollows at the cross-points. In this case, light is deflected into a new guide crossing the path of the previous one. Bubbles are generated by means of tiny electrodes placed in the top silicon layer, which heat the liquid until it gasifies. This technology offers a good scalability: Agilent is developing 32X32 and 16X32 subsystems, which can be connected in a multistage architecture to scale the number of ports up to 512.

4.4 Thermo-Optic switches

The operation of these devices is based on the thermo-optic effect. It consists in the variation of the refractive index of a dielectric material, due to temperature variation of the material itself. There are two categories of thermo-optic switches: interferometric and digital optical switches. While the former need a particular value of the driving voltage to achieve the switching of signals, the latter are characterized by a threshold value of the driving voltage and a step-like response (hence, the adjective digital).

Interferometric switches are usually based on Mach-Zender interferometers. These devices, consist of a first 3-dB coupler that splits the signal into two beams, which then travel through two distinct arms of same length, and of a second 3-dB coupler which merges and finally splits the signal again ^[7]. Heating one arm of the interferometer causes its refractive index to change. Consequently, a variation of the optical path of that arm is experienced. It is thus possible to vary the phase difference between the light beams, by heating one arm of the interferometer. Hence, as interference is constructive or destructive, the power on alternate outputs is minimized or maximized. The output port is thus selected.

Digital optical switches are integrated optical devices generally made of silica on silicon ^{[8][9]}. The switch is composed of two interacting waveguide arms (Fig. 4-4) through which light propagates. The phase error between the beams at the two arms determines the output port. Heating one of the arms changes its refractive index, and the light is transmitted down one path rather than the other. An electrode through control electronics provides the heating. The scalability of this technology is limited by the relatively high power consumption due to the need of heating waveguides, to achieve the switching of signals.

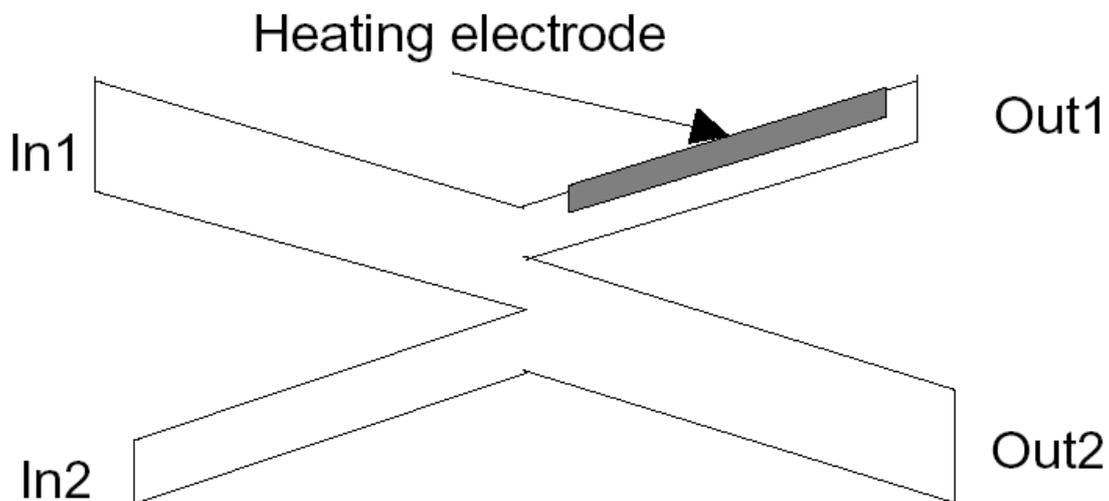


Figure 4-4: 2 x 2 digital optical switch

4.5 Liquid-Crystals-in-Polymer switches

This solution, proposed by Digilens Inc. ^[10], is used to make small size switches. A 1x2 switch is built filling in an active cell with a mixture of liquid crystals and a particular monomer. This mixture, then, undergoes a process of polymerization that produces a stable structure, characterized by the alternation of polymer layers and liquid-crystal micro-droplets layers. The refractive index of the polymeric layers normally differs from that of the liquid-crystal layers. By applying a suitable driving voltage, the orientation of the optical axis of the liquid-crystal micro-droplets changes. This variation can be made such to match the refractive index of the polymeric layers with the one of the liquid-crystal micro-droplets layers. In this case, the cell is transparent to the light beam and the *In*→*Out1* state is thus achieved (Fig. 4-5). On the contrary, if there is no driving voltage applied, the difference of the refractive indexes makes the active cell to work as a Bragg grating, deflecting the signal to achieve the *In*→*Out2* state (following figure).

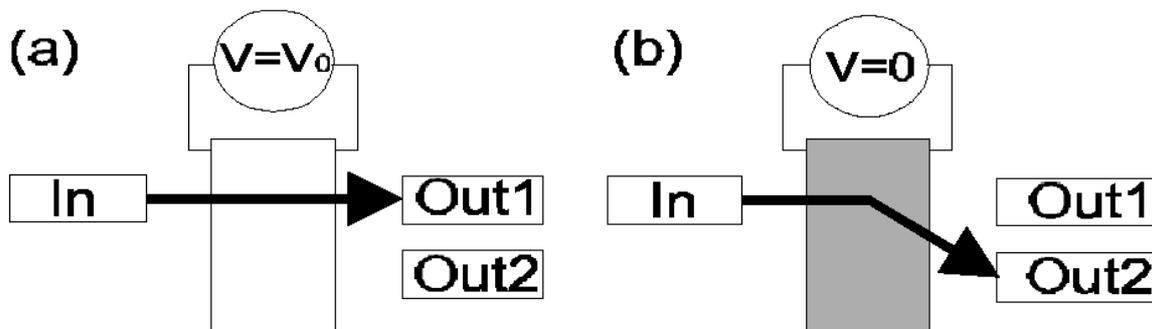


Figure 4-5: 1x2 liquid-crystal-in-polymers switch

4.6 Electro-Holographic switches

Electro-holography is a beam-deflection method based on controlling the reconstruction process of volume holograms by means of an electric field. Holograms are stored as spatial distribution of charge in crystals ^[11]. The application of a driving voltage is used to activate prestored holograms in order to deflect properly light beams. In both states of the switch, the output beams are diffracted beams. As shown in Fig. 4-6, if there is no voltage applied the crystal is transparent to optical signals that pass straight, while, if a suitable driving voltage is applied, the optical signals crossing the crystal are deflected. As it is possible to store several holograms in the same crystal, these devices can be used to drop even single wavelengths, or groups of wavelengths, from a WDM signal. This technology offers a good scalability.

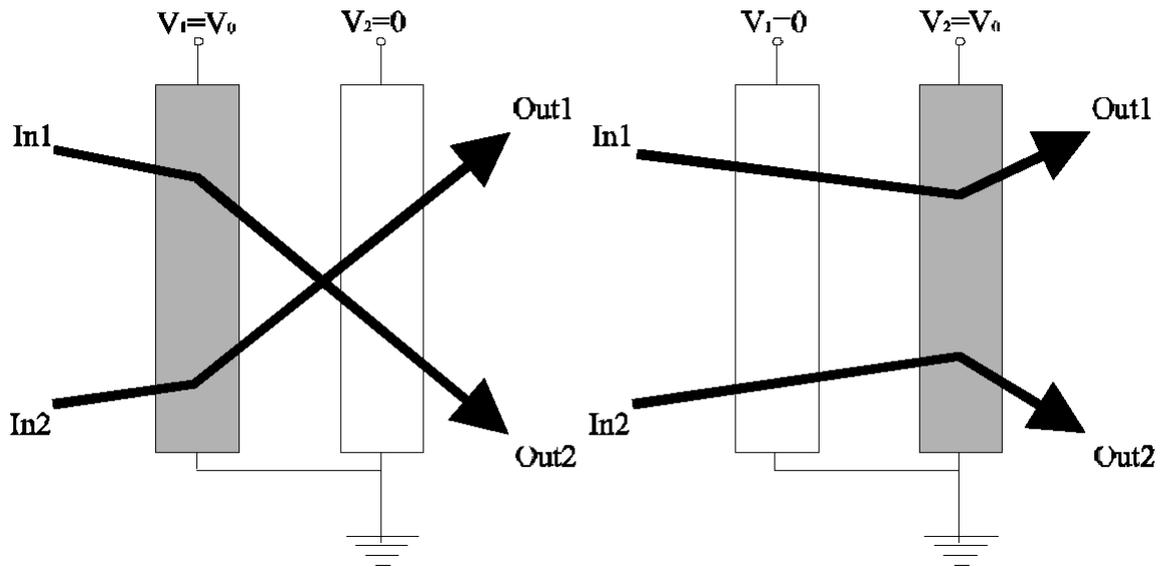


Figure 4-6: Scheme of 2x2 electro-holographic switch

5 Characteristic and performance Data

Table 5-1 reports some performance data of optical switches, from references cited previously: the wavelength range (λ), insertion loss (IL), cross-talk attenuation (α_{xtalk}), polarization-dependent loss (P_{pol}), power dissipation (P_{diss}) and switching time (τ_s) are reported. Moreover, 1x2 LC-inpolymers, 32x32-bubbles and 16x16-interferometric switches feature $P_{\text{diss}}=50$ mW, $P_{\text{diss}}=25$ W and $P_{\text{diss}}=20$ W, respectively.

	λ	IL	α_{xtalk}	P_{pol}	τ_s
2x2 MEMS	1290÷ 1625 nm	1 dB	>50 dB		<1 ms
1x2 liquid crystal	1525÷ 1575 nm	<1 dB	>40 dB	0.2 dB	4 ms
1x2 liquid crystal in polymers	III window				100 μ s
2x2 electro- holographic	1310÷ 1550 nm		>30 dB		<30 ns
2x2 SOA	1525÷ 1575 nm		25 dB ⁽¹⁾	<3 dB	<1 ns
32x32 MEMS 2D array	1290÷ 1625 nm	5 dB	>50 dB	<0.2 dB	5 ms
32x32 bubbles	1270÷ 1650 nm	<7.5 dB	>50 dB	<0.3 dB	<10 ms
16x16 interf. thermo-optic	1530÷ 1570 nm	<3 dB	>38 dB ⁽¹⁾	<0.5 dB	<3 ms

Table 5-1: Characteristics and performance data table

6 Examples of applications

As pointed out in the previous section, optical switches can be used in a wide range of applications.

Optical switching. Optical switches can be used as basic building blocks for network nodes to provide optical circuit or packet switching. Switching times in the ms range are sufficient for circuit switching. Nevertheless, to the purpose of optical packet switching, switching times in the ns range are required.

Optical add-drop multiplexing. Optical add-drop multiplexers are used to add and drop specific wavelengths from multi-wavelength signals, to avoid electronic processing. For this application, wavelength selective switches are required. Switching times in the ms range are adequate.

Fiber restoration and protection switching. Small-size switches are used to restore optical paths in the event of link failure. For this application, 2x2 switches, with switching times in the ms range, are commonly used.

Signal monitoring. For ease of network management, optical switches can be used for signal monitoring. To this purpose, wavelength-selective switches are commonly used.

6.1 Optical Cross Connects

Channel cross connecting is a key function in most communications systems. In electronic systems, digital cross-connect (DXC) is constructed with massively integrated circuitry and is capable of interconnecting thousands of inputs with thousands of outputs. Electricity, however, can easily be made to follow paths through electronic components, a fact of nature that makes electrical cross connecting easy. Cross-connection in optical domain is much more difficult task than in electrical world. It may be accomplished converting optical data streams into electronic data, using electronic cross-connection technology, and then converting electronic data streams into optical. This is known as the hybrid, or opaque OXC. Another way is to cross-connect optical channels directly in the photonic domain with all-optical (transparent) OXC.

6.2 Hybrid OXC

The hybrid approach is currently more popular because there exists expertise in designing high-bandwidth multichannel ($N \times N$) nonblocking electronic cross connect fabrics. In this case, N may be in the order of thousands. The basic idea of hybrid OXC is shown in the following figure.

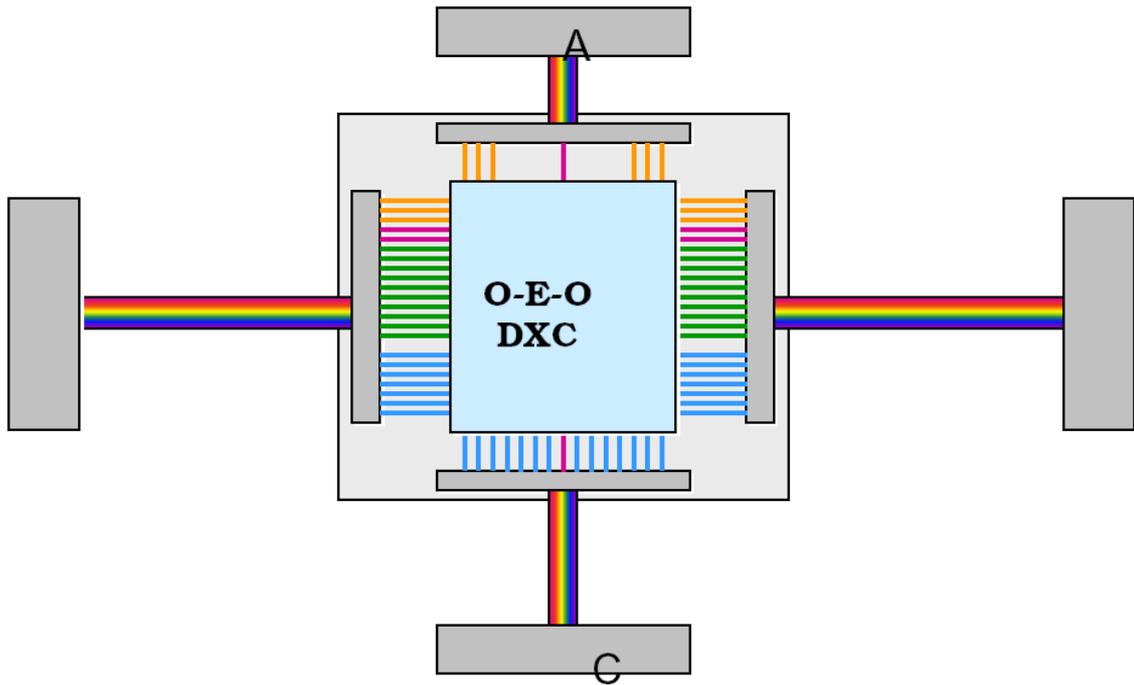


Figure 6-1: Hybrid OCX

6.3 All optical OXC

The whole idea behind fiber optics, in general, is to make the light stay in the fiber. How can light waves be induced to change fiber without changing the light into electricity? This is what the all-optical cross-connect does. All optical, or photonic OXCs, as the name indicates, don't need expensive Optical – Electrical – Optical (OEO) conversion, but the signal stays in photonic domain through the switching. This is the first requirement for transparent operation. Photonic OXCs can be divided to free space optical switching devices, optical solid-state devices and electromechanical mirror-based devices. Among the most promising switches with many input ports to many output ports is the generalized Mach-Zehnder WGR. In this device, a given wavelength at any input port appears at a specified output port (Figure 6-2). This type of free space optical switching is also known as wavelength routing.

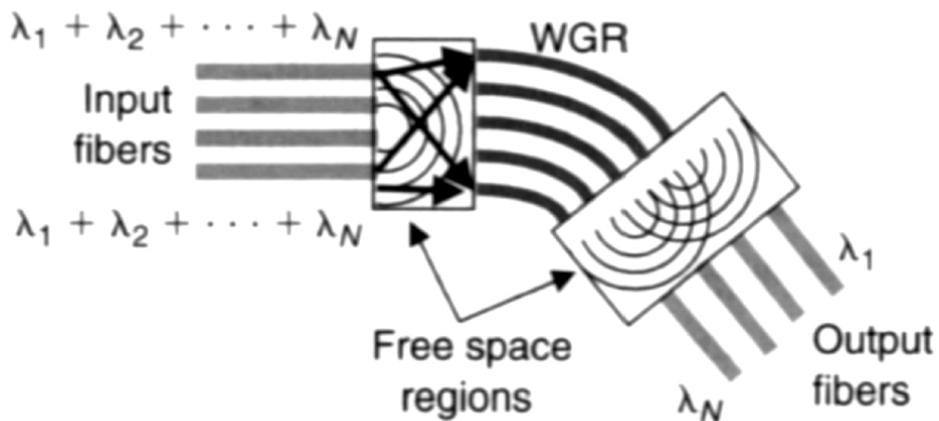


Figure 6-2: Mach-Zehnder WGR

In another type of free space optical switching, a laser beam is mechanically steered to one of many fibers. In a matrix of beams facing a matrix of fibers, for example, one of the source beams and a receiving fiber would be steered so that they faced each other to achieve connectivity in space. This requires extreme accuracy and switching speed to be successful. Solid-state optical cross-connect devices are semiconductor directional couplers. These devices can change one of their optical properties on a path upon the application of a control signal. The optical property may be polarization, propagation constant, absorption, or index of refraction. Depending on the type of material, the optical property may change upon application of heat, light, mechanical pressure, electric current or voltage.

One of the basic properties of light is reflection. Reflecting the light with a shiny surface can change the direction of light. One of the techniques used in all optical OXCs is based on this. This technology, also known as microelectromechanical systems (MEMS), uses the semiconductor processing, which is a proven technology. This technology is expected to become popular creating different nanomachines that may be used in communications and in other fields as well.

The simplest way to guide the light is described in figures below. An optical switch whereby the mirror may let an optical beam pass through or reflects it in a different direction. The mirror may move to accomplish this by one of many methods, depending on the fabrication technology. It may be connected, for example, so that by rotating the mirror between two positions a beam is directed to one of two directions. It may be pulled down or up depending on voltage.

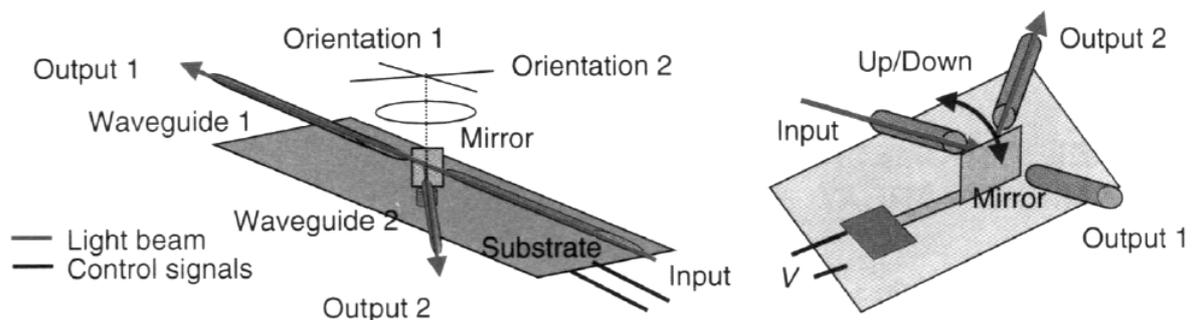


Figure 6-3: Micromachined mirrors can be rotating (a) or moving up and down (b)

By using the reflection of light and MEMS technology different kind on mirror arrays can be implemented. Based on this technology, each mirror, connected with a micromachined electrical actuator, may be independently tilted so that an incident light beam is reflected in a desired direction. Thus, an array of N mirrors can direct N optical input signals impinging on them to N positions in space, where output waveguides are positioned. The idea of four-mirror switching array is shown in the next figure. Clearly, this technique may be extended to construct an $N \times N$ mirror matrixes, 3D MEMS, where N can be potentially 1000.

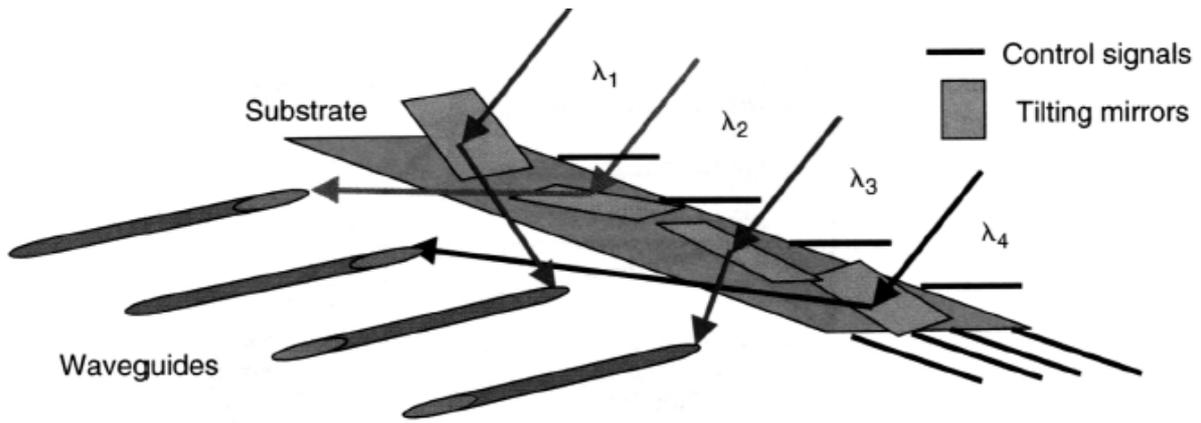


Figure 6-4: Four mirror switching array

MEMS technology promises low-loss connectivity, compact design, and large interconnecting matrixes. However, the precision of tilting the mirrors is very critical and as they are tilted, their orientation must always and consistently rest at exactly the right angle. Minor deviations in angle position may increase both optical signal loss and cross talk. Moreover, as a mirror changes position, the reflected light beam traverses the optical field of other output fibers, and thus caution should be taken to prevent the reflected beam from becoming coupled to these traversed output fibers.

All-optical switching is used in high-bandwidth, few-channel cross-connecting equipment. N in this case is up to perhaps 32, but photonic cross-connects with N in the range of up to 1000 is in the experimental and planning phases.

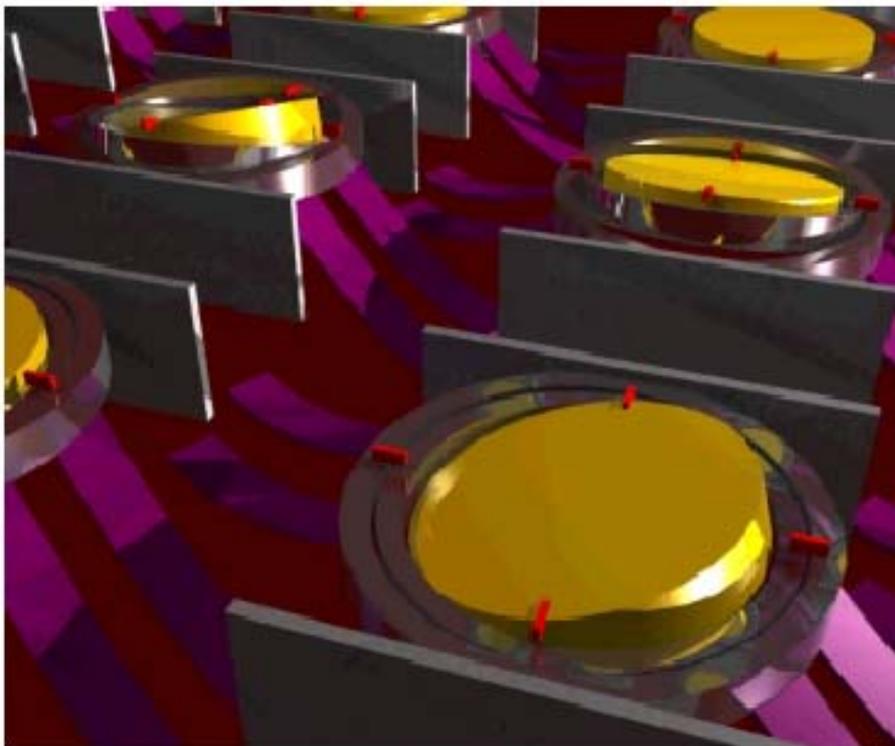


Figure 6-5: 2-axis motion of MEMs OCX mirror^[12]

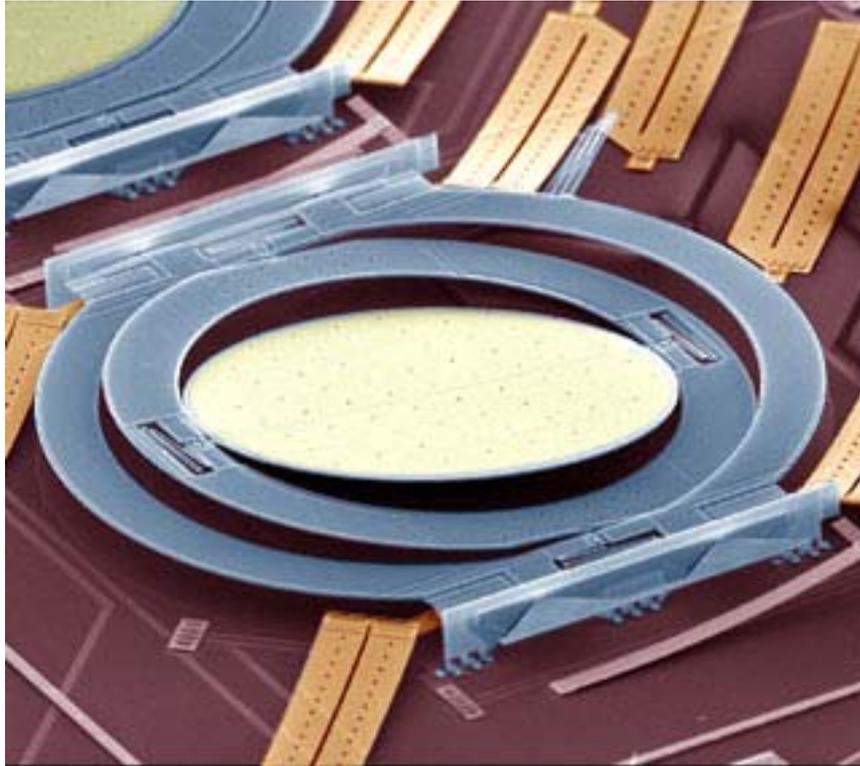


Figure 6-6: Single MEMs mirror for OCX^[13]

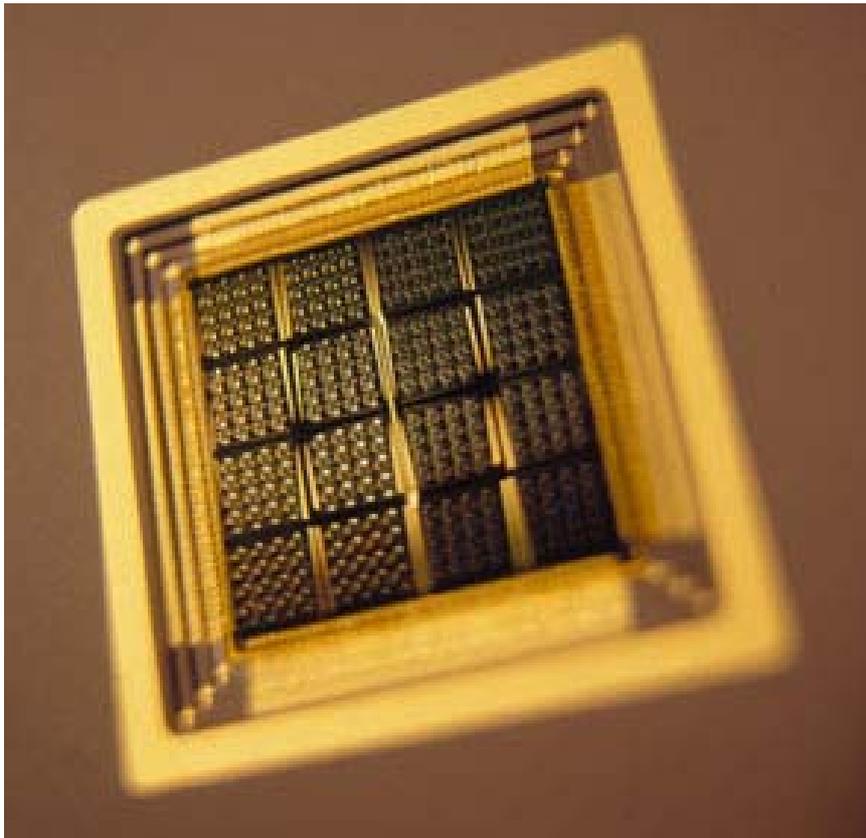


Figure 6-7: 256x256 OXC switching array^[14]

7 Sources

No.	Source	Figure or Text
[1]	Jeff Hecht	Text - City of Light, 1999
[2]	Lucent Technologies	Picture „MEMs“
[3]	C. Marxer, C. Thio, M.-A. Gretillat, O. Anthamatten, R. Baettig, B. Valk, P. Vogel and N. F. de Rooij	"Vertical Mirrors Fabricated By Deep Reactive Ion Etching For Fiber Optic Switching Applications", IEEE Journal of Micro Electro Mechanical Systems, vol. 6, no. 3, Sept. 1997.
[4]	C. Marxer, N. F. de Rooij, Univ. of Neuchâtel, Switzerland.	"2x2 Fiber Optic Switch"
[5]	Spectraswitch.	"Wave-Walker 1'2 Optical Switch"
[6]	Agilent Tech. Inc.	"Photonic Switching Platform"
[7]	NTT Electronics Corp.	"Thermo-Optic Switches"
[8]	M. Hoffman, P.Kopka, and E. Voges	"Thermooptical digital switch arrays in silica on silicon with defined zero voltage state", IEEE Journal of Lightwave Technology, vol. 16, no. 3, March 1998, pp. 395–400.
[9]	Lynx Photonic Networks	Text
[10]	Digilens Inc.	"Photonic Chips for the 21th Century"
[11]	A. J. Agranat, G. Bartal, J. Krupnic, B. Pessah, D. Sadot,	"The Electroholographic Optical Switch", white paper Trellis Photonics
[12]	Lucent Technologies	Picture : "2-axis motion of mems OCX mirror"
[13],[14]	Lucent Technologies	Both pictures

8 Information about document

Version

Last modification

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Homepage

History

Initial document

Version

1.0

1.0

30. Jan. 2003

Refer to chapter „sources“,

All others : Roland Lenz

<http://www.2cool4u.ch/>

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