Optical Switching Technology Comparison: Optical MEMS vs. Other Technologies

Xiaohua Ma, Beijing University of Posts and Telecommunications
Geng-Sheng (G. S.) Kuo, National Chengchi University

Abstract

Optical switching technologies are very crucial to future mobile broadband all-optical IP networks. Many different optical switching technologies are currently available or under development. The main purpose of this article is to conduct performance comparisons on optical switching technologies in terms of basic performance, network requirements, and system requirements based on a literature survey.

Introduction

With the advances in IP networks and optical communications, all-optical IP networks have become a core topic in the communications industry. Optical switches are an essential ingredient in the optical networks to perform switching functionalities. Optical switching technologies will play a key role in the future mobile broadband all-optical IP networks. Due to the emergence of generic multiprotocol label switching (GMPLS) protocol standards and new technologies, the future IP networks will have the standardized signaling control functions in the lower layer to impact all optical switching technologies. Understanding and mastery of optical switching technologies is a must to achieve the required functionalities and expected performance. Therefore, it is necessary to compare the different optical switching technologies in terms of basic performance, network requirements, and system requirements for better understanding and mastery.

The purpose of this article is to conduct performance comparisons of the optical switching technologies in terms of basic performance, network requirements, and system requirements based on a survey of the literature. The technologies include optical microelectromechanical systems (MEMS)-based switching, thermal optical switching, electro-optic switching, and acousto-optic switching technologies. Due to space limitations, very high-level comparison results are reported in this article, and only 15 references are listed. The organization of the rest of the article is as follows. We describe the different optical switching technologies. We report the performance comparison results. Finally, conclusions are made.

Optical Switching Technologies

Optical MEMS-Based Switch

Optical MEMS are miniature devices with optical, electrical, and mechanical functionalities at the same time, fabricated using batch process techniques derived from microelectronic fabrication [1]. Optical MEMS provide intrinsic characteristics for very low crosstalk, wavelength insensitivity, polarization insensitivity, and scalability [1]. Optical MEMS-based switches are distinguished in being based on mirrors [2], membranes, and planar moving waveguides. The former two are free-space switches; the latter are waveguide switches.

Thermal Optical Switch

Thermal optical switches are based on waveguide thermo-optic effect or thermal phenomena of materials. Their main advantages are polarization-insensitive operation and switching speed on the order of a millisecond. Switches based on waveguide thermo-optic effect are called thermo-optic switches (TOSW), which can use well-established planar lightwave circuit (PLC) technology [3]. They are divided into two basic types: digital optical switches (DOSs) and interferometric switches. Another kind of thermo optic switch is based on thermal effects of materials, such as thermo-capillarity optical switches [4], thermally generated bubble-type switches, and thermo optic switches using coated microsphere resonators [5].

Electro-Optical Switch

Electro-optical switches realize optical switching functions by using electro-optic effects, which offer relatively faster switching speed. Main types are $LiNbO_3$ switches [6], SOA-based switches [7], liquid crystal switches [8], electroholographic (EH) optical switches [9], and electronically switchable waveguide Bragg gratings switches [10]. The first two are among

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the oldest optical switches; the others are new types of electro-optic switches.

The $LiNbO_3$ switch is based on the large electro-optic coefficient of $LiNbO_3$ [6]. One of its main applications is a 2 × 2 directional coupler based on interference, whose coupling ratio is regulated by changing the refractive index of the material in the coupling area [11]. The main weak points of the switch are high insertion loss and high crosstalk [11]. Another application is a digital optical switch (DOS) based on mode evolution, which has a step-like switch response to applied voltage [6]. PLZT is a material with a higher electrooptic coefficient than $LiNbO_3$ [12]. Hence, PLZT electrooptic DOSs are of very good overall switch performance. Here, SOA-based switches refer to current-controlled optical switches, where some SOAs used as gates are turned OFF-ON by controlling the bias currents [7]. New types of semiconductor switches are based on Mach-Zehnder interferometers (MZI) or multimode interference couplers (MMI) [13]. Comparing the two types, MMI has many advantages in switching speed, extinction ratio (ER), device size, and so on.

Liquid crystal (LC) switches are based on controlling the polarization of the light by electo-optic effect. The electro-optic coefficient in LC is much higher than in LiNbO3, which makes LC one of the most efficient electro-optic materials. LC holographic optical switches have advantages of constant insertion losses when the number of channels is increased, and adaptive alignment to correct fabrication and alignment errors. EH optical switches are based on control of the reconstruction process of volume holograms by externally applying an electric field [9]. Electronically switchable waveguide Bragg gratings switches are a cross between LC and EH switches, which is based on holographic polymerized polymer/liquid crystal composites.

Opto–Optical Switch

Opto-optical switches realize switching functions relying on the intensity-dependent nonlinear optic effect (which is ultrafast) in optical waveguides, such as two-photon absorption, lightwave self action (which induces optical phenomenon of self phase modulation, SPM) and the Kerr effect (which induces optical phenomena of four wave mixing, FWM, and cross phase modulation, XPM). They are also called optically controlled switches or all-optical switches. There are two main types: optical fiber-based switches [11] and semiconductor-based switches. Semiconductor-based all-optical waveguide switches have many important issues to be considered before practical applications: low operating power, ultrafast operation, high extinction ratio, room temperature operation, and polarization-independent operation.

Acousto–Optic Switches

Acousto-optic switches are based on the acousto-optic effect in crystals such as TeO_2, in which ultrasonic waves are used to deflect light.

Performance Comparison

The following performance parameters of optical switching technology are considered in this article. The definitions of the performance parameters are highlighted.

Basic Performance

Insertion loss: The insertion loss [2] of optical switching technology is defined as the optical power loss when optical signals pass through the optical switch, consisting of coupling loss, waveguide propagation loss, and excess loss. When designing a network according to optical power budget, optical switches and their cascading impact network performance greatly. Furthermore, insertion loss limits the scalability of optical switches and increases system cost.

Switching speed: The switching speed is defined as the time period from the moment the command is given to the switch to change state to the moment the insertion loss of the switched path achieves more than 90 percent of its final value [2]. According to switching applications, the switching time is divided into three levels: multimillisecond order for protection application, nanosecond order for packet switching application, and picosecond order for bit-level optical time-division multiplexing (OTDM) application.

Crosstalk: Crosstalk is the ratio of the power leaked to the wrong output and the power correct output, used to measure the signal interference between channels. Low crosstalk and high extinction ratio indicate small signal interference or high signal quality. Typically, the crosstalk value is around 40 or 50 dB.

Polarization-dependent loss: Polarization sensitivity is used to measure polarization dependence. When it is very high, it harms transmission reliability, and increases monitoring and dynamic compensation requirements.

Wavelength dependency.

Bit rate and protocol transparency: The ability gives more flexibility in configuring networks. Service providers can switch the whole utilization operation window fiber capacity, or part of it, for more efficient bandwidth and traffic management, and own 1300–1600 nm.

Operation bandwidth.

Network Requirements

Multicast: Multicast can provide powerful connection capability and save many resources. It has become an important parameter for measuring optical switches.

Switching device dimension: Switching fabric dimension/switching matrix size reflects the switching capability of an optical switch. The demand for optical switches is based on the location of optical switches in the optical network. Small-scale optical switches are ideal for a variety of per-channel applications, such as small channel count programmable optical add-drop multiplexers (OADMs) and protection switches. Large matrix switches are typically deployed at backbone networks where a large number of wavelengths or fibers converge.

Scalability: Easy scalability is essential to form larger $N \times N$ switches from smaller orders for applications.

Nonblocking: Nonblocking means the flexibility to route or reroute any input channel to any unoccupied output channel, if needed. The blocking problem in large-scale or cascaded switches is more obvious than in smaller optical switches. In general, optical switches need to be strict-sense nonblocking, which does not disturb existing connections.

System Requirements

Stability/reliability: Given the number of terabits per second the device can switch, reliability is extremely important for optical switching applications. To meet stringent communications standards, switches must meet specified environment requirements for temperature variations, vibration, and humidity.

Repeatability: Port-to-port repeatability refers to all paths across the switching fabric being of identical length.

Size.

Power consumption/driving voltage: High power consumption increases a system's cost, and associated heat dissipation increases a system's ambient temperature.

Temperature feature.

Cost.

All the above parameters are interdependent. When cas-

Switch type	Performance	Insertion loss	Switching speed	Crosstalk	Polarization dependent loss (PDL)	Wavelength dependency	Transparency at 1550 nm optical window
Optical MEMS (Free space)	[2] Mirror/gap-closing electrostatic actuator	< 1.7 dB (8 × 8) < 3.1 dB (16 × 16)	7 ms	≤ –50 dB	0.25 dB	No	Very good
	[14] Micro-optical fiber switch for a large number of interconnects using a deformable mirror (1 × N)	2~3 dB	Submillisecond	≤ –30 dB	Low	No	Very good 10 µm around 1.55
(Waveguide)	[15] 1 × 2 MOEMS switch based on silicon–on–insulator and polymeric waveguides	~0.5 dB (theoretical)	32~200 ns	≤ –32 dB 35 dB (Isolation)	Low	No	Good 1250~1650 nm
	[1] Silica on silicon technology by LETI	1.5 dB (1 × 2) 2 dB (1 × 8)	< 1 ms (1 × 2) < 1 ms (1 × 8)	≤ –42 dB (1 × 2) ≤ –52 dB (1 × 8)	< 0.5 dB (1 × 2) < 0.3 dB (1 × 8)	No	Good 1250~1650 nm
Thermal optical switch	Fully packaged polymeric four arrayed 2 × 2 DOS	3.5~4.0 dB (total)	< 5 ms	≤ –30 dB	0.2~0.7 dB	No	Good C band 1.3 and 1.5 wavelength window
	[3] Silica–based MZI interferometric switch	7.3 dB (16 × 16) 1 dB (2 × 2) 7.4 dB (8 × 8)	< 4.1 ms 4.9 ms (<200 µs was reported)	60.7 dB (extinction ratio) > 30 dB 50.4 dB	0.11 dB Low	Yes	Good 1500–1610 nm (extinction ratio > 40 dB) covering C and L bands
	PLC thermooptical switch (DC–SW) (based on 1 × 2 MZI)	12.8 dB (8×16) (average)	13.8 ms	≤ –25 dB on/off 57.8 dB (average)	Low	Yes	Good 1500–1610 nm
	[4] Thermocapillarity optical switch	0.11 dB (transmission loss) < 1.3 dB (reflection loss) 4 dB (for shortest path) 10 dB (for the longest path)	6 ms (room–temperature)	≤ –60 dB (15~25°C)	Low	No	Good 1500–1610 nm or whole window
	[5] Thermooptical switch using coated microsphere resonators	Exceptionally low	The order of 100 ms	Very high $Q > 10^8$	Low	Very wavelength sensitivity (ultradense wavelength channel)	Good 1550 nm window
	Bubble–actuated switch	0.07 dB (transmission loss per crosspoint) 2.9 dB (fiber to fiber reflection losses) 4.5 dB per 32 × 32 unit	1 ms (switch off time reduced to 100 µs)	≤ –70 dB (per crosspoint)	< 0.1 dB	No	Very good

Table 1 continued next page

Switch type \ Performance		Insertion loss	Switching speed	Crosstalk	Polarization-dependent loss (PDL)	Wavelength dependency	Transparency at 1550 nm optical window
Electrooptic switch	[6] Ti : $LiNbO_3$ DOS 1×2	4dB (1×2) (Fiber-to-fiber losses)	On-off 5 ns frequency: several hundred megahertz	Crosstalk suppression > 45 dB	Independent	No	Good 1520-1570nm
	[12] PLZT DOS 1×2 8×8	5 dB mainly fiber coupling loss 1 dB/cm propagation loss	20 ns frequency: 10 MHz	≤ −22 dB ≤ −40 dB	Independent	No	Good
	[7] SOA-based switch	0 dB	200 ps (10 ps was forecast)	≤ −12 dB	Dependent but (< 1 dB) can be realized		
	[13] Semiconductor space switch based on MMI couplers	< 1.5 dB	< 120 ps	≤ −20 dB	Dependent but low value can be realized	Yes	So so
	[9] Eelectroholographic (EH) optical switch (1×2)	0.5 dB (per switching operation)	< 10 ns	Crosstalk is avoided by management and monitoring	Very low	Yes	Good 1.3um and 1.5um work windows
	[8] Liquid crystal optical switch (2×2) NLC (nematic liquid crystal) FLC (ferroelectric liquid crystal)	< 1 dB < 2 dB	ms (NLC) 35.3 µs (FLC)	≤ −35 dB (NLC) ≤ −34.13 dB (FLC)	0.2 dB 0.5 dB (the worst case value)	Yes	Very good C band
	Liquid crystal holographic switch 1×8 3×3	< 10 dB 19.5 dB	ms	−30 dB (typical) > −40 dB (typical)	Low	Yes	Very good
	[10] Electronically switchable waveguide Bragg gratings switch (2×2)	< 1 dB	10~50 ns	Unkown	Very low	Yes	Good 100 nm around 1.55 µm
Acousto-optic switch	Acousto-optic switch	< 4 dB (1×2) overall	300 ns	32 dB (extinction ratio)	Very low	Yes	Good 1.55 µm

TABLE 1. Basic performance comparison.

cading optical switches, the performance of all the optical switches affects that of the network. A good system should have advantages of low insertion loss, low crosstalk, low switching power, polarization and wavelength independence, and insensitivity against switching bias and working temperature.

Optical switches based on mirrors/gap-closing electrostatic actuators [2] have very low insertion loss and crosstalk, but their switching speeds are medium, on the order of 1 ms. A $1 \times N$ free-space optical switch with a fiber bundle, a macro-lens, and a deformable/adaptive mirror based on an optical MEMS membrane [14] has a higher switching speed, submillisecond, but higher insertion loss and crosstalk, which are believed to be independent of the number of ports. From Table 1, the switching speed of free-space switches is medium, on the order of 1 ms, which is suitable for protection and restoration in the optical layer with no frequent change of connection states. Planar waveguide switches based on silica on silicon (SOS) technology [15] or silicon on insulator (SOI) [1] are highlighted, where polymeric optical waveguides are postprocessed onto the mechanical structure. The former has the advantages of integrated optics and mechanical actuation; the latter is developed for low switching actuation and very high speed on the order of 1 ns. These switches all have very good transparency at a 1.55 µm operation window.

Optical MEMS switches based on tilting micromirrors [2] cannot realize the drop-and-continue function, which is very important for implementing multicast in the optical layer, and cannot realize optical power assignment, which is cru-

Switch type \ Performance		Multicast	Switch dimension	Scalability	Nonblocking	Application
Optical MEMS switch (free space)	[2] Mirror/gap-closing electrostatic actuator	No	8 × 8 16 × 16 32 × 32 uo to 512 × 512	Good	Yes	High capacity backbone network or OXC
	[14] Micro-optical fiber switch for a large number of interconnects using a deformable mirror (1 × N)	No	1 × N (N can be a very large number)	Good but not flexible	Yes	OXC
(waveguide)	[15] 1 × 2 MOEMS switch based on silicon-on-insulator and polymeric waveguides	Yes	1 × 2	Limited	Yes	Small scale switch or OADM
	[1] Silica on silicon technology by LETI	Yes	1 × 2 1 × 8 2 × 2	Limited	Yes	Small scale switch or OADM
Thermal optical switch	Fully packaged polymeric four arrayed 2 × 2 DOS	No	2 × 2	Limited	Yes	Small scale switch or OADM
	[3] Silica-based MZI interferometric switch	No	2 × 2 8 × 8 16 × 16	Good	Strictly	for practical large-scale switch
	PLC thermooptic switch (DC-SW)	Multicast Broadcast	8 × 16 8 × 8 256 × 256	Very good modularity and scalability	Strictly	Medium scale matrix, promising for large-scale matrix
	[4] Thermocapillarity optical switch	No	2 × 2 8 × 8 16 × 16 N × N (N can be a large number)	Good	Strictly	Large scale matrix
	[5] Thermooptical switch using coated microsphere resonators	No	1 × 2	Unknown	Unknown	Promising for ultradense WDM channel network. (The greatest impediment to the use of microsphere resonators in practical devices has been the difficulty of efficiently coupling light into and out of the spheres.)
	Bubble-actuated switch	No	32 × 32	Good	Strictly	Large scale matrix

Table 2 continued next page

cial for management and control functions. In order to realize these functions they need to cooperate with other optical devices to form proper optical switching architecture. Optical switches based on moving mirrors have good scalability and can easily realize large switch dimensions. Free-space switch matrices are very suitable for large-scale nonblocking optical crossconnects, and are applied to backbone networks and large switching services. Optical MEMS switches based on SOI [15] or SOS [1] can realize power assignment between ports. They are very suitable for small-scale applications.

In general, optical MEMS switches need high driving voltage and have high power consumption. They have limited stability due to moving influence. Port-to-port repeatability is still a problem in large switches based on mirrors, because light may have to travel varying distances between ports. However, optical MEMS-based switches have advantages of mechanical stability and low cost.

CONCLUSIONS

Based on the literature surveyed, performance comparisons of

Switch type	Performance	Multicast	Switch dimension	Scalability	Nonblocking	Application
Electrooptic switch	[6] Ti : $LiNbO_3$ DOS 1 × 2	No	1 × 2	Limited	Potentially	Moderate sized switch matrices switch
	[12] PLZT DOS	No	1 × 2 8 × 8	Limited	Yes	Small scale switch or OADM
	[7] SOA based switch	Multicast and broadcast	1 × 4 1 × 8	High modularity and scalability	Yes	Small scale switch or OADM
	[13] Semiconductor space switch based on MMI couplers	No	2 × 2	Potentially good.	Yes	Small scale switch or OADM or packet switching
	[9] Electroholographic (EH) optical switch (1 × 2)	Yes	1 × 2 2 × 2 240 × 240	High suitable for switch with many thousands of ports	Strictly	OXC competes with 3D MEMS on scalability but is better suited for switching individual wavelengths rather than groups of wavelengths.
	[8] Liquid crystal switch	No	2 × 2 64 × 64 Benes OXC at most 80 input ports	Good in theory, but vendors are developing modest size (80-wavelength maximum) devices	Yes/strictly	OADM
	Liquid crystal holographic switch	No	1 × 8 3 × 3	Good	Strictly	OADM protection and restoration
	[10] Electronically switchable waveguide Bragg gratings switch (2 × 2)	Yes	2 × 2 cascading small-scale switch	good cascading small-scale switch	Strictly	OADM
Acousto-optic switch	Acousto-optic switch	Yes	1 × 2 Small-scale	Bad	Strictly	Wavelength selective switch

TABLE 2. Performance comparison of network requirements.

optical switching technologies have been conducted. Very high-level comparison results have been documented in the three tables. Based on comparisons, we obtain that each optical switching technology has unique performance characteristics specific to the utilized optical phenomena. It might be a crucial way to integrate some technologies together to achieve a better solution for optical switching. Furthermore, it is very clear that the optical switching is a very hot topic attracting many research efforts. Optical MEMS-based switching technology might be one of the most promising approaches at this moment. It is very obvious that many new technologies on optical switching might be created in the near future. And, due to the impact of nanotechnology, some innovative approaches to optical switching might emerge in the future.

Acknowledgment

This work was supported by the National High Technology Research and Development Project of the People's Republic of China under Grant 2002AA122032.

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Switch type \ Performance		Actuation voltage/ power dissipation	Size speed	Stability/ reliability	Repeatability	Temperature feature	Cost
Optical MEMS switch	[2] Mirror/gap-closing electrostatic actuator	(A few microwatts) ≤ 50 V	Hundred microns per unit/footprint Module 10 cm	More than a year on over 4000 (typical) switch elements and <37 FIT (failure over 1 billion operating hours)	Low (16 × 16)	−40°C~85°C	Low
	[14] Micro-optical fiber switch for a large number of interconnects using a deformable mirror (1 × N)	< 190 V	Multi mm × mm × mm	Medium	Medium	−40°C~85°C	Low
	[15] 1 × 2 MOEMS switch based on SOIr and polymeric waveguides	3~20 V	1600 μm	Medium	Medium	−40°C~85°C	Low
	[1] SOS technology by LETI	<70 V	2 mm	Medium	Medium		Low
Thermal optical switch	Fully packaged polymeric four arrayed 2 × 2 DOS	250 mW	45×12 mm^2 (4 arrayed 2 × 2)	High	Medium	Temperature control needed	Low
	[3] Silica-based MZI interferometric switch	0.85W (per unit) ×16 = 13.6 W 90 mW (2 × 2) 1.4 W (8 × 8)	$165 \times 160 \times 23$ mm^3 (8 × 8) (the module size including cooling fin) 85×85 mm^2 (8 × 8) (on a 4-in silicon wafer	High	High	Temperature control needed	Low Promising commercialized
	PLC thermooptic switch (DC-SW) (based on 1 × 2 MZI)	0.55 W	330×300 mm^2 (8 × 16)	High	Medium	Temperature control needed	Promising commercialized
	[4] Thermocapillarity optical switch	0.15 W (2 × 2) self-latching	16×16 mm^2 (2×2) 23×23 mm^2 (16×16)	High Over 10 million switching operations	Low	Temperature control needed below the decomposition temperature about 170°C. Optical characteristics, such as transmission loss and crosstalk, could not be degraded by a lot of switching operations.	Promising commercialized
	[5] Thermooptical switch using coated microsphere resonators	405 nm laser 10^4 mW/cm^2	250 μm (diameter)	Potentially good, no moving parts	High	Temperature control or in a sealed package	Low
	Bubble-actuated switch	25 W		Potentially good, no moving parts	Low	Temperature control needed	Low

Table 3 continued on next page

Switch type \ Performance		Actuation voltage/ power dissipation	Size	Stability/ reliability	Repeatability	Temperature feature	Cost
Electro-optic switch	[6] Ti : LiNbO3 DOS (1 × 2)	18 V	3-in	High	High	Simple	Low
	[12] PLZT DOS (1 × 2) (8 × 8)	10 V	About 12 mm 36 mm	High	High	Simple	Low
	SOA based switch	200 mA	$25 \times 5 \times 3$ mm^3	Medium	High		Because of XGM, it is still not commercialized.
	[13] Semiconductor space switch based on MMI couplers	About 10 V	490×11 μm^2	High	High		Unknown
	[9] Electroholographic (EH) optical switch (1 × 2)	So so. Trellis's 240 × 240 port switch consumes less than 300 W. High voltages are required, placing demands on the electronic supply equipment.	1.5×1.5 mm^2 (per KLTN switch unit)	Potentially good; no moving parts.	Good		Not disclosed
	[8] Liquid crystal	Very low (lower than MEMS)	mm^3	High	High	Do not need temperature control	Relatively low
	Liquid crystal holographic switch	Multi-volt	<1 mm × 1 mm	High	High		Unknown
	[10] Electronically switchable waveguide Bragg gratings switch (2 × 2)	Typically 50 mW	Unknown	Potentially good; no moving parts	Unknown		Potentially low cost because a single device performs the function of two or more in alternative technologies.
Acousto-optic switch	Acousto-optic switch (1 × 2)	200 mW	2.5 cm long	Potentially good; no moving parts	Unknown		Very high/ too expensive

TABLE 3. Performance comparison of system requirements

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BIOGRAPHIES

XIAOHUA MA is with National Key Laboratory of Switching and Networking Technology at Beijing University of Posts and Telecommunications, China.

GENG-SHENG (G.S.) KUO (gskuo@ieee.nccu.edu.tw) is with National Chengchi University, Taipei, Taiwan.