Recent Progress in Optical Switching Device Technologies in NTT

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Abstract

There have been several important developments in photonic networks based on wavelength division multiplexing in response to the explosive growth of Internet and broadband network services. Since optical processing systems such as optical cross-connects and optical add-drop multiplexers are essential for photonic networks, there is a strong need for optical switching devices, which will be key components of these systems. This paper gives an overview of NTT's recent progress in low-loss and highly reliable optical switches fabricated by technologies based on planar-lightwave circuits, the oil-latching interfacial-tension variation effect switch, and three-dimensional micro-electro-mechanical systems mirrors.

1. Introduction

The rapid and global spread of the Internet and broadband network services is accelerating the growth of optical communications networks. Photonic networks based on wavelength division multiplexing (WDM) systems is playing a key role in increasing the capacity and flexibility of these communications networks. The first WDM networks were point-to-point transmission systems and the signals were processed electrically in the system nodes after optical-electrical (OE) conversion. Today, a very attractive research topic is next-generation photonic networks, where many point-to-point dense wavelength division multiplexing (DWDM) transmission systems are connected and optical signals are processed without OE/EO conversion at the nodes [1]. Such networks require optical cross-connect (OXC) and optical add/drop multiplexing (OADM) systems. Key devices for these systems are large-scale integrated space division optical switches.

This paper outlines recent trends of optical switching devices and gives an overview of NTT's activities concerning low-loss and highly reliable optical switches using planar-lightwave circuits (PLCs), the oil-latching interfacial-tension variation effect switch (Olive), and three-dimensional micro-electro-mechanical systems (MEMS) mirrors. The individual switches are described in more detail in the subsequent three papers.

2. Configuration of OXCs and OADMs using optical switch devices

NTT has already developed a new extended signaling and traffic engineering method for a multilayer (photonic and electrical) router based on generalized multiprotocol label switching (GMPLS), as reported at SUPERCOMM 2001 [1]-[4]. It consists of an IP-router, a wavelength router, and a GMPLS-router manager and offers both IP (Internet protocol) packet switching and wavelength-path switching capabilities. In the router, the wavelength paths, known as optical label switched paths (OLSPs), are set and released in a distributed manner based on the functions provided by GMPLS. Therefore the router lets us create the optimum network configuration by considering the IP and photonic network resources in a distributed manner. The OXC in the router, which establishes both optical cross connection and long-haul WDM transmission functionalities, is constructed using the delivery-and-coupling switch (DC-SW) architecture shown in Fig. 1. The 8×16 (8 input and 16 output ports) cross-connect switch (Fig. 1(b)) consists of 128 1×2 PLC-switches and 16 8×1 optical couplers. The DC-SW architecture enables us to

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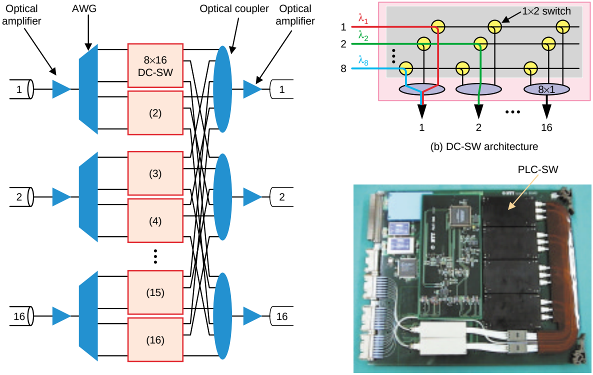


(b) DC-SW architecture

(a) 8×16 fiber port system architecture

(c) 8×16 DC-SW sub-board

Fig. 1. Delivery-and-coupling optical switch.

reduce the number of switch elements in the router by using couplers as multiplexers and to fabricate an inexpensive practical router.

If we can manufacture a low-cost N×N type matrix optical switch with low loss and high reliability, we can easily achieve a wavelength-path cross-connect by allocating a different wavelength to each port of the switch. The operation of the unit switches composing a matrix optical switch is outlined in Table 1. A digital optical switch has a matrix arrangement consisting of 1×2 or 2×2 unit switches. Each switch has two states and acts like an on-off shutter. An input optical signal can be switched to any desired output port by operating a unit switch at a specific intersec-

Table 1. Basic structure of large-scale matrix optical switch.

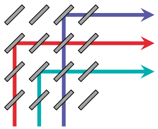
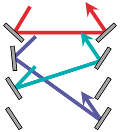
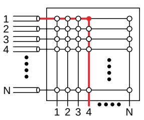
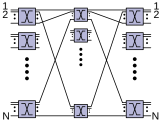
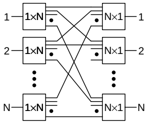
Type	Digital optical switch	Analog optical switch
Architecture		
Characteristics	Matrix arrangement of 2×2 unit switches	Free-space optical transmission
Number of switches	Number of unit switches increases exponentially as the number of input and output ports increases.	Number of unit switches increases in proportion to the number of input and output ports.
Issues	Path dependence of insertion loss	Stable operation and reliability
Examples	PLC-switch, bubble reflection switch, electronic switch	3D-MEMS mirror

Table 2. Configuration of large-scale matrix switches using small-scale digital optical switches.

Type	Crossbar	3-stage Clos	2N 1×N
Architecture			
Number of switches	N^2	approx. $6N^{1.5}–3N$	N (N–1)

tion. Highly reliable digital switches with a small matrix-scale such as 1×16 and 16×16 PLC switches are commercially available [5], [6]. However, they are disadvantageous in terms of both optical loss and the cost of large-scale switch fabrication, because the required number of unit switches increases geometrically. If we consider N input fibers and N output fibers, the total number of mirrors required is equal to N^2. An analog optical switch can be created using a free-space transmission structure, such as a three-dimensional (3D) MEMS mirror optical switch (see section 3.6). A 3D MEMS array operates by steering beams of light in an analog fashion in 3-dimensional space. For N fibers in and N fibers out the total number of mirrors needed is 2N and the distance that the light travels does not increase as quickly with the port count as it does for two-dimensional (2D) configurations. Therefore, a 3D-MEMS mirror optical switch is much more suitable for fabricating large-scale devices. The characteristics of a large-scale prototype optical switch (about 1000×1000) have already been reported [7]. Further work is required on the design of systems for mirror control and free-space optical transmission to ensure that analog optical switches operate stably.

A method for designing large-scale matrix switches using small-scale digital switches is shown in Table 2. When an N×N crossbar matrix optical switch is fabricated with a digital optical switch, the value of N in one switch chip is often limited to a few tens. Multi-chip arrangements of the three-stage (Clos[*1]) switch-fabric architecture and/or the 2N 1×N type switch enable us to overcome this limit and fabricate large-scale (100×100 or more) optical switches easily. The number of unit switches for a 3-stage Clos is less than that for the crossbar type above 32×32, although the crossbar type has fewer unit switches when the scale is smaller.

*1 Named after C. Clos of AT&T Bell Labs.

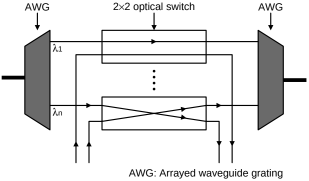


Fig. 2. Basic structure of OADM system.

Figure 2 shows the basic arrangement of an OADM system, which consists of an optical multiplexer/demultiplexer (MUX/DEMUX) and 2×2 switches. In an OADM system, the number of 2×2 switches should match the number of WDM transmission wavelengths.

3. Optical switch devices

There have already been reports of the design and fabrication of several kinds of optical switch device [8]. Table 3 summarizes the characteristics of these devices. They can be roughly categorized into two types depending on whether they use optical waveguides or free-space transmission. The optical waveguide type can be subdivided according to the structure of the switch unit: Mach-Zehnder interferometer (MZI), Y-branch waveguide, bubble reflection, moving optical fiber, and semiconductor optical amplifier (SOA) types. The free-space transmission type uses a 2D or 3D MEMS mirror.

NTT is proceeding with the research and development of the MZI, Y-branch waveguide, and bubble

Table 3. Characteristics of optical switch devices.

Type	Switching principle		Base technology	Characteristics
Optical waveguide	Mach-Zehnder Interferometer	TO effect	Silica waveguide, Heater as phase shifter	Reliable, Simple driving circuit
		Electric current injection	Semiconductor optical waveguide	Short switching time of less than 1 µs
	Y-branch waveguide and TO effect		Polymer optical waveguide, Thin film heater	Small wavelength dependence, Simple driving circuit
	Bubble reflection	Bubble generation	Bubble generating liquid, Silica optical waveguide	Short switching time of less than 1 ms, Small wavelength dependence
		Bubble movement	Oil, Silica optical waveguide	Self-latching, Low wavelength dependence, Small power consumption
	Moving optical fiber		Silica optical fiber, Magnet	Small wavelength dependence, Small polarization dependence, Self-latching
	Optical adsorption of SOA		SOA	Short switching time of less than 1 ns, Works as an amplifier
Free-space transmission	Micro-mirror reflection	2D-MEMS	Si process	Small wavelength dependence, Small polarization dependence,
		3D-MEMS	Si process	Good for mass production, Small wavelength dependence, Small polarization dependence

NTT's activities

reflection type optical waveguide switch technologies. A maximum switch scale of about 32×32 ports can be fabricated in a single chip. Figure 3 shows the basic structure of each switch unit. NTT is also examining the 3D-MEMS mirror optical switch as a technology that enables the fabrication of large-scale optical switch chips with over 100×100 ports.

3.1 MZI type optical switch

Figure 3(a) shows the basic structure of an MZI type 2×2 optical switch element. Two 3-dB directional couplers are connected by a pair of arms. Each arm includes a phase shifter that can introduce a difference in optical path length ΔL between the two arms by changing the refractive index of the waveguide. There are two main choices for implementing the phase shifters: a thin film heater that utilizes the thermo-optic (TO) effect or an electrode that injects electric current. At NTT, we have been developing TO switch devices using silica-based PLC technology since the 1980s [9]. Although silica-based PLC is essentially a passive device, it can be used to make an optical switch by combining the TO effect and an interferometer configuration. In a PLC switch, the refractive index of one arm waveguide is increased by the thin film heater. The optical path length difference ΔL between the two arms is designed to be either zero (symmetric-MZI) or a half-wavelength (asymmetric-MZI). The MZI can be in the cross-state, in which an optical signal is guided from input port 1 to output port 3 when ΔL is zero, or in the bar-state, in which an optical signal is guided from input port 1 to output port 4 when ΔL is a half-wavelength. By varying the refractive index of one waveguide arm of the MZI using the TO effect, we can change ΔL by half a wavelength, and thus change the switch state. Typical temperature increases at the core and the heater are 15 and 40°C, respectively. The switching power is 0.35 to 0.45 W for an MZI. The switching time is 1 to 3 ms, which is sufficient for OXC and OADM systems. Figure 4 shows the progress that has been made in optical circuit integration and power consumption in PLC switches. We have already fabricated a practical 16×16 optical switch module and prototype switch chips up to 1×128 and 32×32. Moreover, we successfully performed a fundamental test on the operation of a 128×128 switch subsystem, consisting of 2N 1×N switch modules and over 16,000 optical fibers [10]. The results show that the multichip arrangement is effective for constructing large-scale N×N switching subsystems. The high power consumption of the previous PLC switch, which was its greatest disadvantage, has been significantly reduced to about 1/10 of its former value of 45 mW by using heat insulating grooves [11]. A total power consumption of only 1.4 W is expected for a 16×16 matrix switch with this low power technology.

One of the most important advantages of PLC switches is their high reliability. Using eight arrayed 2×2 switch modules for OADM systems, we carried

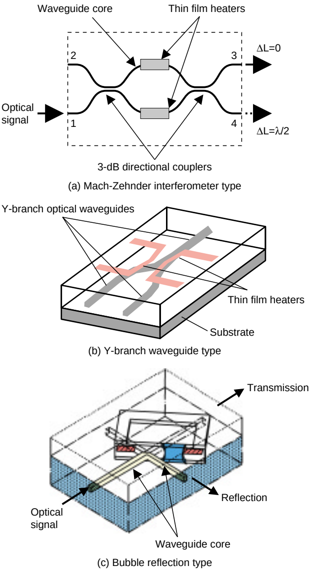


Fig. 3. Unit structure of optical waveguide type switch devices developed in NTT.

out a long-term reliability test that included six types of storage test: heat-damp, high-temperature, low-temperature, heat-cycle, vibration, and impact tests, in accordance with Telcordia*2 standards [12]. There were no problems such as drift of the optimum operating point, change in heater resistance, or deterioration in loss or extinction ratio during the 5000-hour test. We also encountered no problems when operating the heater at 65°C or in mechanical tests. These results show that silica-based PLC switch modules are highly reliable. The next paper, “Recent Advances in Optical Switches using Silica-based PLC Technology,” describes the PLC switch in more detail.

The electron-injection type MZI optical switch is fabricated on a substrate made of a semiconductor such as Si. Switching is achieved by injecting an electric current into the electrode to control the refractive index of the waveguide arm. A high switching speed of less than 1 μs can be expected, although there are stability problems due to changes in the optical transmittance caused by the injected electric current. Moreover, the high refractive index of core materials such as Si makes it necessary to improve the optical fiber connection method to reduce the connection and return losses.

3.2 Y-branch waveguide type optical switch

Polymers have large TO coefficients (more than ten times that of SiO_2). This enables us to develop a Y-branch waveguide type optical switch. Figure 3(b) shows the basic structure of a 1×2 switch. When one arm is heated to reduce its refractive index, the optical output appears only in the other arm. This switch is independent of wavelength in principle, which is one of its advantages over the MZI type.

NTT has developed 2×2 and 1×8 optical switches using newly synthesized silicone resin and polyimide resin as the optical waveguide materials [13]. In the 1×8 switch, we achieved low power consumption of 360-450 mW, on/off ratio of 40 dB, insertion loss of 3 dB, and polarization-dependent loss of 0.3 dB. The switching times obtained from the pulse response characteristics for a 90%-rise and 90%-fall were 6.0 and 3.4 ms, respectively, and there was no deterioration in the switch characteristics after 10^7 switching operations. Moreover, we confirmed that simultaneous switching of wavelengths in the 1.3 and 1.55 μm bands was possible.

3.3 Bubble reflection type optical switch

This type of switch consists of intersecting optical waveguides that have partially fluid-filled grooves at each waveguide intersection. Optical switching is achieved by controlling two optical states: the transmission state and the reflection state. An optical signal passes straight through the groove when it is filled with fluid that has the same refractive index as the waveguides (the transmission state). In contrast, the signal is reflected into an intersecting waveguide at the groove wall by total internal reflection when there is a bubble in the groove (the reflection state). There are two main methods based on using bubbles. In one, air bubbles are generated in liquid by using technolo-

*2 http://www.telcordia.com/

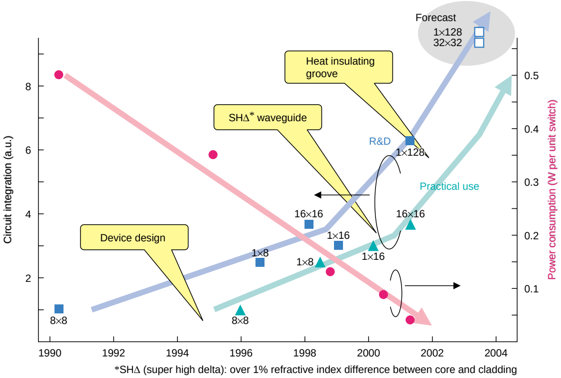


Fig. 4. Progress in optical circuit integration and power consumption in PLC switch devices.

gy originally developed for inkjet printers [14]. In the other, heat is used to move a bubble in a partially fluid-filled groove [15].

NTT has developed an optical switch called the oil-latching interfacial-tension variation effect switch (Olive). Figure 3(c) shows its basic structure. The interfacial tension of the air-liquid interface is reduced by heating. This allows the liquid in the groove to move toward the opposite side of the groove. The liquid is held there by capillary pressure, which is determined by the width of the groove. This means that the switch only consumes power to change state: each state is maintained stably without power, a useful property called self-latching. Olive has exhibited a low insertion loss (below 3 dB in a 1×8 optical switch), a high extinction ratio (>50 dB), low crosstalk (<–50 dB), and wavelength insensitivity (±0.5 µm). The switch chip size is about 10 mm×10 mm. Recently, the switching time was reduced from about 50–100 ms to less than 10 ms by using new basic technologies designed to lower the viscosity of the liquid and shorten its traveling distance. The third paper in this issue, "High-speed Switching Operation in a Thermocapillarity Optical Switch for Application to Photonic Networks," provides further details.

3.4 Moving optical fiber type optical switch

This type of optical switch works by physically moving optical fibers, for example by using magnets [16]. These switches are self-latching but have a low operating speed of about 10 ms, so they might be suitable for situations where switching is infrequent or need not be fast, such as setting up optical transmission paths in a telephone exchange for new service subscribers. However, this approach is not suitable for high-density mounting because each switch must be magnetically shielded.

3.5 SOA type optical switch

Optical switching can also be achieved by changing between two states of a semiconductor optical amplifier (SOA): SOA-on with high optical transparency and SOA-off with high optical absorbance. The SOA response time is very fast: on the order of nanoseconds. Moreover, SOAs can compensate for loss by amplifying the signals [17]. However, the switch is currently impractical because the SOA still has many technical problems and the fabrication technology is immature.

3.6 MEMS mirror reflection type optical switch

A 2D-MEMS mirror works as a digital optical switch. Some manufacturers have already marketed a

16×16 switch and reported its optical properties and reliability [18]. The matrix switch arrangement is a crossbar; the optical loss varies with the selected input and output ports because of the difference in optical path length. Eliminating the path length dependence of the insertion loss is an important issue in the fabrication of a large-scale switch system.

A 3D-MEMS mirror operates as an analog optical switch. Because the number of unit switches increases only linearly in proportion to the number of input and output ports, the 3D-MEMS mirror should be more suitable for use in fabricating a large-scale switching system than a digital optical switch. Moreover, since the path length dependence of the insertion loss is lower in the 3D-MEMS than in the 2D-MEMS, there is no need to apply techniques to cancel out the loss differences between the selected input and output ports.

For a free-space transmission type switch such as 3D-MEMS, it is important to stabilize the mirror against optical and mechanical stress to reduce any loss change caused by vibration and temperature changes in the system. Stability is also improved by shortening the free-space transmission path length, but this requires a high tilt angle, high processing accuracy, and appropriate electrostatic drive voltages for the mirrors. NTT's MEMS-mirror arrays are single crystal silicon integrated with high-aspect ratio torsion springs, and are tilted two-dimensionally by electrostatic force. The prototype switching module with 100-channel optical fiber input/output has a low coupling loss of 4.0 dB and a switching time of 3 ms. The fourth paper in this issue, "Development of a Large-scale 3D MEMS Optical Switch Module," provides more details.

4. Future of optical switch devices

Figure 5 summarizes the integration scale at the chip level and the switching time of various optical switch devices. The integration scale is limited by the substrate size because chips are fabricated on, for example, silicon substrates. Moreover, waveguide loss, electrode density, and heat dissipation are important parameters in chip design. In general, the maximum integration scale in a single chip is about 32×32 for optical waveguide type switches. The switching time ranges from the millisecond order (for the TO effect and bubble reflection) to the nanosecond order (for the SOA type). In contrast, a large-scale matrix switch of over 100×100 with a millisecond-order switching time can be fabricated in one chip using the 3D-MEMS free-space transmission type switch.

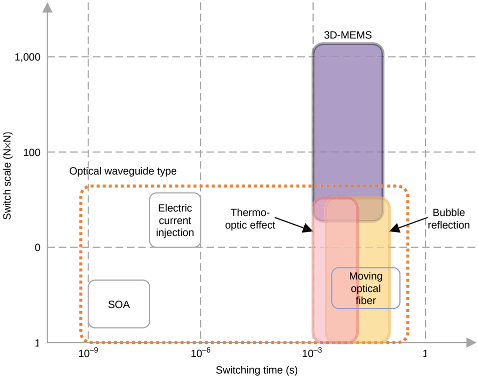


Fig. 5. Switch scale and switching time of various optical switch devices.

The optical switch devices described in this paper have both merits and demerits, so one should select the best switch according to the situation. After the announcement of a large-scale free-space transmission optical switch using 3D-MEMS mirrors by Lucent Technologies in 1999, the research goal has been to develop a 1000×1000 switch. However, from the practical point of view, an important target is to make a smaller OXC (e.g., with 32 wavelengths on 8 or 16 lines) that provides high reliability at a low cost. In addition, high-speed switching devices will be necessary if we are to develop next-generation switching technology such as optical burst switching and optical packet switching.

5. Conclusion

This paper outlined recent trends related to optical switching devices and introduced the principles of and experimental results for devices fabricated at NTT. Some devices have excellent characteristics and will enable us to design large-scale optical switching systems. Of course, further research and development that considers not only device performance but also reliability and total cost, including both fabrication and maintenance, will be necessary when applying these devices to optical cross-connects and optical add/drop multiplexers. Moreover, it is important to develop all-optical systems that eliminate the optical-electrical-optical conversion required for electrical switches.

References

[1] K. Sato, N. Yamanaka, Y. Takigawa, M. Koga, S. Okamoto, K. Shiomoto, E. Oki, and W. Imajuku, “GMPLS-based photonic multilayer router (Hikari Router) architecture: an overview of traffic engineering and signaling technology,” IEEE Commun. Mag., Vol. 40, pp. 96-101, Mar. 2002.

[2] S. Okamoto, M. Koga, H. Suzuki, and K. Kawai, “Robust photonic transport network implementation with optical cross-connect,” IEEE Commun. Mag., pp. 94-103, Mar. 2000.

[3] Y. Yamabayashi, M. Koga, and S. Okamoto, “Autonomously controlled multiprotocol wavelength switching network for Internet backbones,” IEICE Trans. Commun., Vol. E83-B, pp. 2210-2215, 2000.

[4] M. Koga, A. Watanabe, T. Kawai, K. Sato, and Y. Ohmori, “Large-capacity optical path cross-connect system for WDM photonic transport network,” IEEE J. Sel. Areas Commun., Vol. 16, pp. 1260-1269, Sep. 1998.

[5] M. Okuno, T. Watanabe, T. Goh, T. Kominato, T. Shibata, T. Kawai, M. Koga, and Y. Hibino, “Low-loss and high-extinction ratio silica-based 1×N thermo-optic switches,” Tech. Dig. OECC/IOOC 2001, Sydney, Australia, MD5, July 2001.

[6] T. Shibata, M. Okuno, T. Goh, M. Yasu, M. Itoh, M. Ishii, Y. Hibino, A. Sugita, and A. Himeno, “Silica-based 16×16 optical matrix switch module with integrated driving circuits,” Tech. Dig. OFC’2001, Anaheim, California, U.S.A,. WR1, March 2001.

[7] D. Bishop, C. R. Giles, and G. Austin: “The Lucent LamdaRouter: MEMS technology of the future here today,” IEEE Commun. Mag., Vol. 40, pp. 75-79, 2002.

[8] Y. Yamabayashi, “Optical switching devices and systems,” IEICE Technical Report, 102, PS2002-14, 2002 (in Japanese).

[9] M. Okuno, A. Sugita, T. Matsunaga, M. Kawachi, Y. Ohmori, and K. Katoh: “8×8 optical matrix switch using silica-based planar lightwave circuit,” IEICE Transactions on Electronics, Vol. E76-C, No. 7, pp. 1215-1223, 1993.

[10] T. Goh, H. Takahashi, T. Watanabe, M. Kobayashi, T. Shibata, M. Ishii, S. Sohma, Y. Abe, M. Okuno, and Y. Hibino, “Scalable 128×128 optical switch system composed of planar lightwave circuit and fiber sheet for optical crossconnect,” ECOC 2002, Copenhagen, Denmark, Sep. 2002.

[11] S. Sohma, T. Goh, H. Okazaki, M. Okuno, and A. Sugita: “Low switching power silica-based super high delta thermo-optic switch with heat insulating grooves,” Electron. Lett., Vol. 38, No. 3, pp. 127-128, 2002.

[12] M. Okuno, “Highly integrated PLC-type optical switches for OADM and OXC systems,” Tech. Dig. OFC’2003, Tu1, Atlanta, Georgia, U.S.A., Mar. 2003.

[13] S. Toyoda, N. Ooba, T. Kitoh, T. Kurihara, and T. Maruno, “Thermo-optic switch and wavelength tunable filter using polymer waveguides,” Proc. SPIE, Vol. 4532, pp. 62-72, 2001.

[14] J. E. Fouquet, S. Venkatesh, M. Troll, D. Chen, P. W. Barth, and H. F. Wong, “Compact scalable fiber optic cross-connect switches,” LEOS Summer Topical Meeting, Vol. 59, 1999.

[15] M. Makihara, M. Sato, F. Shimokawa, and Y. Nishida, “Micromechanical optical switches based on thermo-capillarity integrated in waveguide substrate,” J. Lightwave Technol., Vol. 17, No. 1, pp. 14-18, 1999.

[16] S. Nagaoka, “Compact latching-type single-mode-fiber switches fabricated by a fiber-micromachining technique and their practical applications,” IEEE Journal of Selected Topics in Quantum Electronics, Vol. 5, No. 1, pp. 36-45, 1999.

[17] K. Kato, “10-Gb/s Photonic cell switching with hybrid 4×4 optical matrix switch module on silica based planar waveguide platform,” OFC’98, PD3-1, pp. 437-439, 1998.

[18] P. De Dobbelaere, K. Falta, L. Fan, S. Gloeckner, and S. Patra, “Digital MEMS for optical switching,” IEEE Commun. Mag., Vol. 40, pp. 88-95, 2002.

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