State of the Art of Optical Switching Technology for All-Optical Networks

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Abstract: - All-optical switching fabrics will be a significant breakthrough in order to relieve the capacity bottleneck of electronic-switched networks. These devices allow switching traffic directly in the optical domain, avoiding the need of several optical-to-electrical-to-optical conversions. In this paper, the state of the art of optical switching fabrics is reviewed, by outlining the main technologies that are under development. Moreover, some possible applications and performance data are summarized, based on a market analysis that we carried out in the latest months. We believe that this review is valuable to researchers envisaging new all-optical switching network architectures for telecommunications networks of the future.

Key-Words: - optical communication, Internet, switching, acousto-optic, holography, thermo-optic, optical amplifiers.

1 Introduction

Telecommunication networks are demanding a dramatic increase of capacity, mostly due to the exponential growth of IP traffic. To this aim, considerable research is devoted to design an optical network layer, in order to relieve the capacity bottleneck of electronic-switched networks.

A *single* optical fibre offers a potentially huge transmission capacity: just in the III wavelength window, 5 or 10 THz are there to be mined, if only we could be able to exploit such tremendous bandwidth with adequate technology. Recently, optical Dense Wavelength Division Multiplexing (DWDM) has been developed, which made available commercial systems providing impressive transmission capacities.

Unfortunately, switching is still performed mostly by electronics. The extension of optics from transmission to switching is thus the second step needed. In this context, all-optical switching fabrics play a central role and will be a significant breakthrough on this way. These devices allow switching directly in the optical domain, avoiding the need of several optical-electrical-optical conversions.

In this paper, the state of the art of optical switching fabrics is reviewed, by outlining the main technologies that are under development to realize these devices. Finally, some possible applications and performance data are summarized, based on a market analysis that we carried out in the latest months. Therefore, a snapshot on the state of the art of optical switching devices is provided indeed. We believe that this review is valuable to researchers envisaging new all-optical switching network architectures for telecommunications networks of the future.

2 Optical Switching Technologies

Most solutions for all-optical switching are still under study. Given the wide range of possible applications for these devices, it seems reasonable to foresee that there will not be a single winning solution. In fact, different technologies feature different performance, for example in terms of scalability, switching speed, insertion loss, cross-talk.

In the following subsections, we will provide a detailed review of optical switches based on different technologies.

2.1 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 fibres [1][2]. As far as medium- and large-size switching fabrics are concerned, micro-mirrors can be arranged into two-dimensional or three-dimensional arrays [3]. In these switches, mirrors are steered in order to deflect light beams properly. Small-size switches can be also made, as shown in Fig. 1.

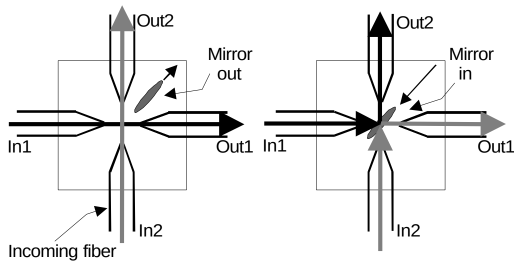

Fig. 1: Scheme of a MEMS 2×2 switch.

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 32×32 are already available and can be used as basic building blocks, in single-stage architecture, to scale up to 256 ports.

2.2 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 1×2 Liquid-Crystal (LC) optical switch structure is shown in Fig. 2 [4][5]. 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.

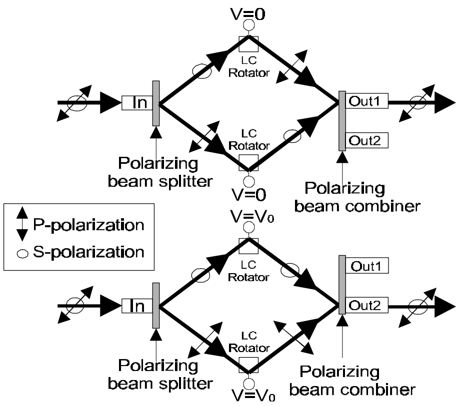

Fig. 2: Scheme of 1×2 liquid-crystal optical switch.

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.

2.3 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 32×32 and 16×32 subsystems [6], which can be connected in a multistage Clos architecture to scale the number of ports up to 512.

2.4 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, as shown in Fig. 3, 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].

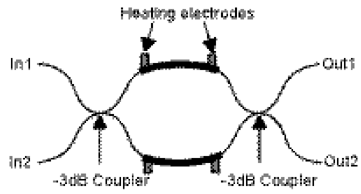

Fig. 3: Scheme of 2×2 interferometric switch.

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) 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.

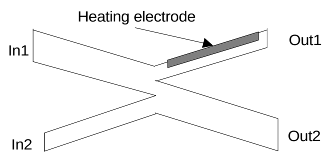

Fig. 4: Scheme of 2×2 digital-optical switch.

2.5 Liquid-Crystals-in-Polymer Switches

This solution, proposed by Digilens Inc. [10], is used to make small size switches. A 1×2 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. 5a). 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 (Fig. 5b).

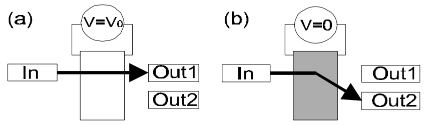

Fig. 5: Scheme of 1×2 liquid-crystals-in-polymers switch.

2.6 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 pre-stored holograms in order to deflect properly light beams.

In both states of the switch, the output beams are diffracted beams. As shown in Fig. 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. Multistage configurations can be designed from arrays of 2×2 switches to scale the number of ports up to 256.

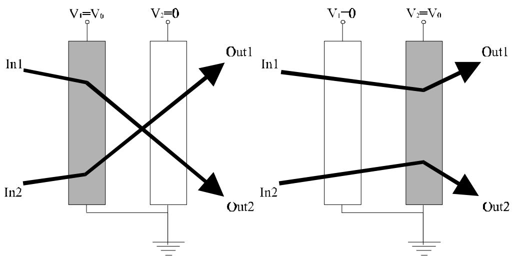

Fig. 6: Scheme of 2×2 electro-holographic switch.

2.7 Acousto-Optic Switches

The operation of these devices is based on the acousto-optic effect. This effect consists in the variation of the refractive index of a medium, caused by the mechanical strains accompanying the transit of a surface acoustic wave. This wave can set up a diffraction grating within the medium. The grating pace can be such to modify the polarization of an optical signal travelling through the medium.

A 2×2 switch is obtained using a polarizing beam splitter, which separates the TE and TM components that are then routed through two distinct waveguides [12]. If there are no resonance phenomena along the waveguides, the polarization of light is unchanged and the signals are recombined at the first output port (BAR state, Fig. 7a). If an acoustic wave is present, TE and TM components vary their polarization and the signal is directed to the second output port (CROSS state, Fig. 7b).

If the incoming signal is multi-wavelength, it is even possible to switch selectively different wavelengths off the beam, as it is possible to have several acoustic waves in the material, having different frequencies, at the same time.

Only small size (1×2 and 2×2) switches are produced [13], but is thought that this technology can be used to build also large-size switching fabrics (up to 256 ports).

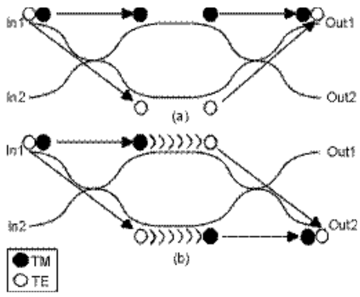

Fig. 7: Scheme of 2×2 acousto-optic switch.

2.8 Semiconductor-Optical-Amplifiers Switches

Semiconductor Optical Amplifiers (SOA) are all-optical amplification devices, which have been already used in a wide range of applications. To switching purposes, they can be arranged as shown in Fig. 8 [14]. In this structure, SOAs are used as gates that let the signals pass through or that stop them, depending on the state required.

An interesting characteristic of SOA switches is that they allow amplification of the travelling signals, thus making possible to restore signal level, besides routing.

Alcatel SA followed a similar scheme as that depicted in Fig. 8, to build their 4×4 SOA switches [15].

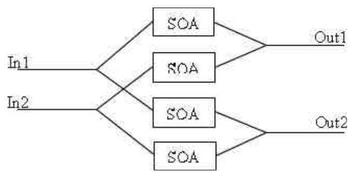

Fig. 8: Scheme of 2×2 SOA switch.

3 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, 2×2 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.

4 Characteristic and Performance Data

Table 1 reports some performance data of optical switches, from references cited previously: the wavelength range (l), insertion loss (IL), cross-talk attenuation (a_{xtalk}), polarization-dependent loss (P_{pol}), power dissipation (P_{diss}) and switching time (t_s) are reported. Moreover, 1×2 LC-in-polymers, 32×32-bubbles and 16×16-interferometric switches feature P_{diss}=50 mW, P_{diss}=25 W and P_{diss}=20 W, respectively.

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

(1) extinction ratio

Table 1: Performance data of optical switches.

We notice that all systems, but SOA and electro-holographic switches, feature switching times in the ms range. This may probably make MEMS switches the most attractive solution for most applications where non-wavelength selective switches are required, due to the poor cross-talk and high insertion losses of the other swtiches.

For optical packet switching, the only two technologies that may be considered are electro-holographic and SOA switches. While the former ones are probably more attractive as far as scalability is concerned, the latter ones are faster and allow the amplification of incoming signals. Finally, for such applications as add-drop multiplexing or signal monitoring where wavelength selection is required, any solution may be acceptable, because performance data of wavelength-selective switches are comparable.

5 Conclusions

In this paper, the current state of production of optical switching fabrics was reviewed, by outlining the main technologies that are under development. Some possible applications and performance data were also summarized, based on a market analysis that we carried out in the latest months, thus providing a valuable support to researchers envisaging new all-optical switching network architectures.

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