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A Survey of Photonic Switching Systems

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Abstract

Data transmission by optical means has been widely studied, the technology is well-developed, and fiber optic transmission systems have been widely deployed. On the other hand, recent developments in photonics technology have led to its possible implementation in communication switching, the natural mode of operation for optical data transmission. This paper reviews emerging photonic switching technologies that may be expected to become the basic components of future communication switching systems. As in conventional technology, in photonics, the switching function is implemented by dividing and multiplexing a signal in one of the three domains: space, time, or wavelength, or frequency. Technological limitations alter the performance of these three multiplexing systems, so that the system of choice will depend on the technological advancements achieved in each of the three categories, as well as theoretical considerations. This survey paper summarizes the advantages and limitations of existing and upcoming candidate technologies for photonic switching in each of the three categories.

1. Introduction

Recently, the employment of photonics technology for commercial communication switching systems has become a viable possibility from a technological standpoint, although many researchers believe rapid advancements in speed, scale of integration, and cost of electronic systems make absolute comparisons of full-scale systems in terms of price and performance necessary. Although optical fibers can easily be used for information transmission with the advantages of their broadband capabilities, the challenge in a communication network is to perform the operations of switching, routing, flow and congestion control, conflict resolution, and other related data processing functions optically, without changing the signal into electrical form. Switching stands as the most fundamental of these network functions, and is the first target for introducing new technology based on optical processing. In contrast to electrons, photons do not interact and therefore photonic switching will not suffer from the capacitive and inductive limitations of electronics, enabling higher switching speeds. In addition, switching data optically in an existing optical plant avoids electrical to optical and optical to electrical conversions, and may be more cost effective. Candidate optical devices for meeting this goal can be arranged into two classes. The devices in the first class, called *relational devices,* perform a simple mapping between the inputs and the outputs. This mapping does not depend on the signal or data inputs, it is only a function of the control signals to the device. This way, the information entering and flowing through the device cannot change the current relation between the inputs and the outputs. Although relational devices can support very high bit rate channels, they are not suitable for packet switching as they cannot read and respond to packet headers. In *logic devices,* the data incident on the device control the state of the device since they sense and respond to individual bits of information. The maximum bit rate that can be handled by a logic device is limited by its optical switching speed. The challenge in optical device research for communication switching is to match the low optical switching speeds of logic devices with the extremely high bit rates that can be supported in optical fibers.

Another classification can be based on the multiplexing technique employed in switching. In *space division switching,* the goal is to direct information from one physical path to another physical path or to several other physical paths with minimum blocking. These switches have no memory. As only optical matrix switches are used, they can be easily fabricated. Their disadvantage is the limited number of input and outputs that can be supported, and the difficulty of performing routing. In *time division switching,* a signal is interleaved in time with other signals, and switched by changing its location within an information frame, i.e., its time slot. The signal is subsequently reassembled to reconstruct the original at the destination. Time division switches are composed of multiplexers and demultiplexers, and optical memories for the time slot exchanger. Although successfully implemented electrically, this is a very difficult technique to implement optically, because of the lack of high-speed optical memories. In *wavelength division switching,* the signals to be switched are modulated onto optical carriers whose wavelengths are determined by control signals. These switches use multiplexers and demultiplexers, wavelength converters, and variable wavelength filters. They have the advantage of large switching capacity. In this case, the challenge is to build light sources or optical filters whose carrier or center frequency can be changed very rapidly. This last item has been the subject of active research in many laboratories around the world. Only recently, devices meeting moderate performance objectives have been reported, and incorporated into laboratory experiments for wavelength division multiplexing research.

In the following three sections, we will describe components for these three kinds of switching techniques. It should be noted that the devices in one category are not necessarily exclusive to that category, for example, many space switches are employed in time division switching. Also, some components, such as optical amplifiers, light emitting diodes (LEDs), and photodiodes are common to all techniques. It should also be noted that time division switching and wavelength division switching can be implemented in a distributed manner to realize optical communication networks.

This brief survey is only a short introduction to the subject. To the interested reader, we suggest one of the several paper collections, such as [1]–[4], books [5], [6], or conference proceedings [7]–[21].

2. Space Division Switching

2.1. Mechanical Switches

These switches physically deviate or guide the incoming signal to its outgoing path(s). There are several approaches which have been proposed to accomplish this task such as the moving fiber, rotating mirror, moving glass block, and moving prism methods [22]. As an example, Figure 1 shows an illustration of the moving fiber method. In this switch, a mechanical force, which can be generated by an electrically activated solenoid, moves an incoming fiber to one of two positions, causing it to couple to one of the two corresponding outgoing fibers. This simple device can actually be implemented, and is practical, however, the mechanical nature of the switch limits its size and robustness to changes in the environment. As in all mechanical switches, or more generally, as in all relational devices, the moving fiber switch can support very high throughputs, in the order of Mbits/sec to Gbits/sec, and have negligible crosstalk. They can also be made with very low insertion loss (a small fraction of a dB) and a repetitively low loss over thousands of switching cycles. On the other hand, they have very low switching speeds, in the order of milliseconds. Also, to suffer minimum loss of signal in the "connect" position, it is essential to have as good an alignment of the two fibers as possible [23], [24], which limits the robustness of the switch to environmental changes.

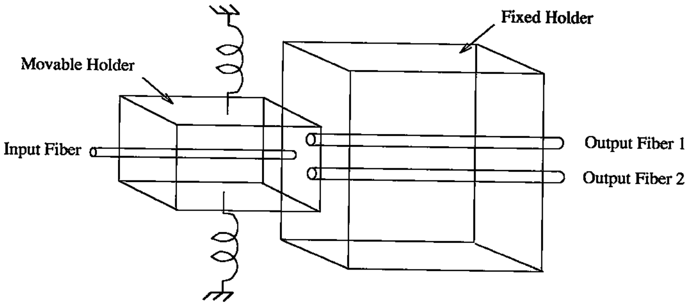

Figure 1. A Moving Fiber Switch.

2.2. Directional Coupler Switches

A directional coupler is an electro-optic device that can be used as a 2×2 photonic switch. This device can be put into two different states as shown in Figure 2 by using the control input. In a directional coupler, two optical waveguides are brought close together to allow energy from one waveguide to couple to other. This coupling occurs because of the overlap in the evanescent fields of the waveguides. Figure 3 shows the physical layout of a directional coupler [25]. To force the directional coupler to change state, i.e., to go from the crossover (cross) state to the straight-through (bar) state or vice versa, an electric field must be applied to the electrodes placed over the waveguides in the coupling region [26], [27]. This electrical control limits the switching speed of this device. A good application of the directional coupler switch is a protection switch. A protection switch is placed at the end points of a long haul transmission link, and used to switch transmission to preallocated capacity when a failure is detected in the link. This spare capacity is typically a physically separate link, together with the line cards connecting the link to the switching fabric. Since the only time a protection switch will need to be reconfigured is when a failure occurs in a transmission link or the line card, which is a rare event, one has a switching situation in which high bit rates need to be carried with moderate reconfiguration rate requirements [28].

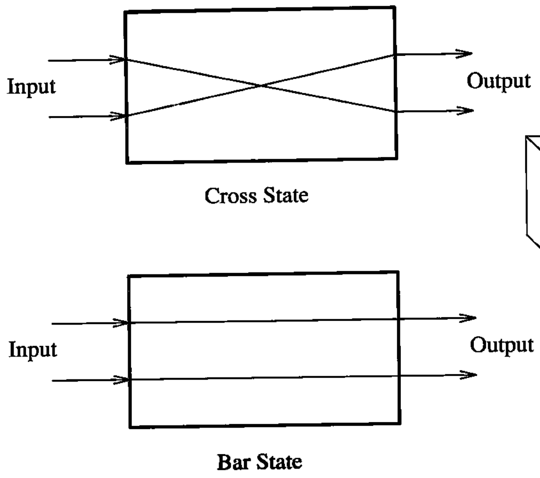

Figure 2. Two States of A Directional Coupler.

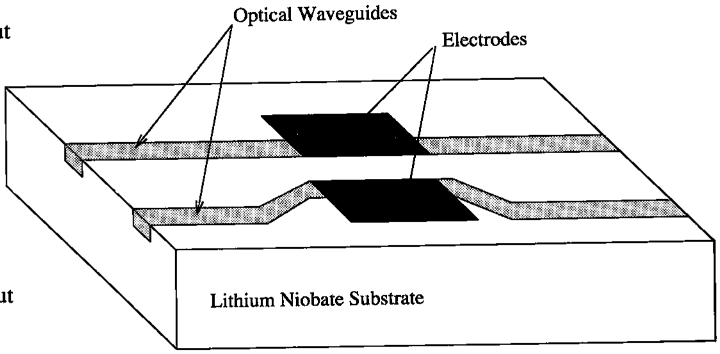

Figure 3. A Directional Coupler Space Division Switch.

In a similar way to mechanical switches, the main advantage of directional couplers is the ability to transmit high data rates, with their main disadvantage being the low reconfiguration rates, limited by the electrical control speed. Furthermore, large scale integration is not practical due to the long physical length requirement of each directional coupler and the high degree of crosstalk between adjacent channels. An even more serious problem with conventional directional coupler based systems is their limitation to a single polarization. These are not compatible with available low-loss single-mode fibers which do not preserve linear polarization. For a single applied voltage, different polarizations view unequal electro-optic coefficients, and low channel crosstalk is not possible. This last problem is solved by using Ti-diffused $LiNbO_3$ waveguides [29], [30], [31]. With the Ti : $LiNbO_3$ technology, best characteristics in matrix size and insertion loss have been achieved, and integration of directional couplers to produce switches with size larger than 2×2 has become possible [32], [33]. Currently, in many countries, one of the candidates to implement the backbone of a wide area lightwave communication network is using optical fibers as transmission links, and the Ti : $LiNbO_3$ technology to build cross connect switches. Like a protection switch, a cross connect switch is reconfigured infrequently, in the order of a few reconfigurations per day, depending on the slowly varying traffic patterns.

2.3. Internal Reflection Waveguide Switches

By using total internal reflection in directional couplers, some of their limitations can be overcome. For total internal reflection, either the injection carrier induced refractive index change or the electric field induced refractive index change is used. Their advantage over directional couplers is the small length cross sections and, high speed switching which can be achieved in a multi quantum well structure type [23], [34]. For example, an InGaAsP/InP optical switch which is of less than 1 mm is currently available [35], whereas a directional coupler switch is typically an order of magnitude longer. Furthermore in [36], an intersectional waveguide optical switch using the quantum confined Stark effect of a 1.6 μm GaInAs/InP quantum well structure was given.

2.4. Gate Matrix Switches

The advantage of this type of switches is their ability to perform point-to-multipoint switching and signal amplification. They are also applicable to both single mode and multimode fiber systems. Electrical switches with electrical-to-optical and optical-to-electrical transforms, laser diode switches which are based on simulated emission and absorption in a laser diode, and photoconductor switches belong to this class [23].

2.5. Optically Activated Optical Switching

In this kind of switches an optical control signal causes another optical signal to switch between two paths. They allow switching at very high speeds. An example is shown in Figure 4. An optical cavity is formed by placing two almost totally reflecting mirrors back-to-back. If the spacing between the mirrors is an even multiple of quarter wavelength of the optical signal, the device will act as a transparent window. If the spacing is equal to an odd multiple of quarter wavelength, it will act as a reflecting device. The device can be switched from one mode to the other by changing the spacing of the mirrors. This is accomplished by placing an optically nonlinear material in the space between the mirrors, and by changing the optical properties of this material by applying an optical control signal. These devices are known as Fabry-Perot filters. Fabry-Perot filters possess resonance properties with controllable resonance frequencies, and therefore they are also used in wavelength division multiplexing networks [37]. Recently several investigations have been focused on this area, such as [38], [39].

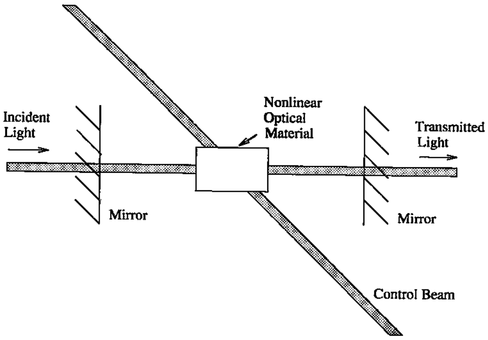

Figure 4. A Nonlinear Optical Switch.

2.6. Holograms

Holograms can also be used as matrix switches where the incident lightwave is modified and redirected , i.e., the hologram is the space division switch [40]. A representation of how a hologram may be used for switching is shown in Figure 5. Here, the basic idea is to exploit the parallelism in space, making the hologram implement the photonic wires interconnecting optical gates. In this figure, M_1 and M_2 are mirrors, which are used by the map present on the hologram to interconnect the inputs and outputs of the optical logic devices. Holograms can result in very large space-bandwidth products, but their practical implementation as an optical space division switch is yet to be demonstrated in the laboratory [40].

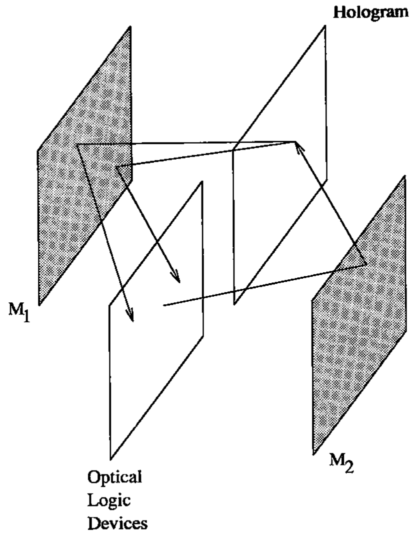

Figure 5. Hologram Used as an Optical Space Division Switch.

2.7. Spatial Light Modulators

A spatial light modulator (SLM) is a two-dimensional array of optical modulators. These operate independently of each other and can individually modulate the incident light. They can operate in either analog or digital fashion, and are available in many technologies such as the magnetooptic effect, liquid crystal, deformable mirrors, and GaAs quantum wells. The control is achieved electrically. Figure 6 shows how to implement a photonic switch using an SLM.

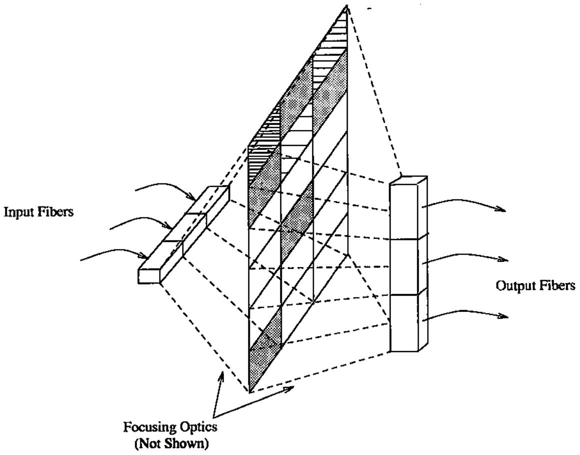

Figure 6. Spatial Light Modulator Used as a Nonblocking Crossbar Interconnection Network.

The inputs are aligned to associate each fiber with a unique column of the SLM. A lens system spreads the inputs vertically onto the SLM . The SLM is designed such that, by blocking or passing light in each pixel, the system implements a nonblocking crossbar interconnection network. The advantage of such a system, as in all relational devices, is the high bit rates that can be supported, while the disadvantage is the low reconfiguration speeds due to electrical control. Among most recent approaches are Si thin films on lead, lanthanum, zirconate, titanate (PLZT) substrates [41], and hybrid Si/GaAs inverted Fabry-Perot cavities [42].

3. Time Division Switching

Optical memories, which are optical logic devices, are essential to construct optical time division switching networks. There are two kinds of optical memories: *optical fiber delay lines* and *optical bistable devices.*

The first experiment in optical time division switches using optical fiber delay lines and directional coupler switch matrices was reported in 1983 [28]. A typical time division switch, or a time slot exchanger, of this kind is shown in Figure 7. In this figure, the input time slots are directed to fiber-delay lines where they recirculate until needed at the output. The time delay created by the fibers must be equal to the duration of the time slot. Recently, a flexible photonic switching system using fiber-delay lines has been demonstrated in [43].

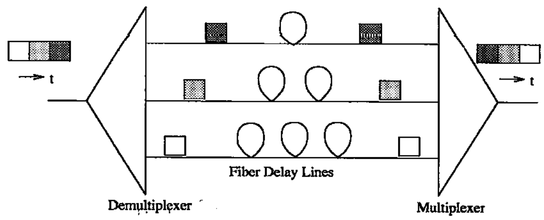

Figure 7. An Optical Time Division Switching System Using Fiber Delay Lines as Optical Memory.

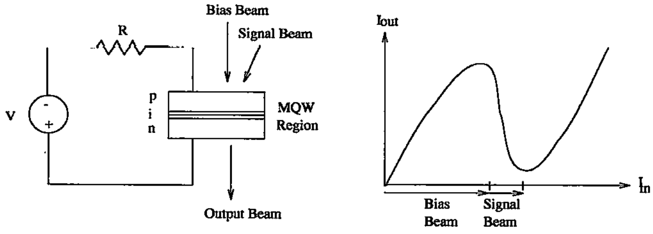

Figure 8. The Self-Electro-Optic Effect Device.

Optical bistable devices exhibit two distinct light transmission states. When both states can exist for the same input power, the device will exhibit optical hysteresis. Many types of optical bistable devices are being explored for constructing optical memories [44]. In an intrinsic device all operations can be realized with the light signal. Typically, it consists of a pair of mirrors between which a nonlinear medium is placed, as in the Fabry-Perot filter. On the other hand, a hybrid device comprises an electro-optic light intensity modulator with a feedback voltage proportional to the optical output power. A bistable light diode (LD) and a non-linear Fabry-Perot etalon (NLFP) are intrinsic, whereas a self-electro-optic effect device (SEED) and monolithically integrated bistable device consisting of optoelectronic feedback circuits are hybrid [40]. The SEED and the NLFP have received considerable attention in the past few years [45], [46], [47], [48], [49]. The SEED is an electrooptical device that requires both optical and electrical energy [50], [51]. The NLFP is an all-optical device in that all energy required to switch the device is supplied optically. By exploiting the parallelism present in the optical domain, both of these devices can be fabricated into two-dimensional arrays. A functional diagram of the SEED is shown in Figure 8. It is a p-i-n diode with a multi quantum well (MQW) material in the intrinsic region. The SEED relies on the changes in optical absorption that can be induced by electric fields perpendicular to the thin semiconductor layers in quantum well materials. Combining this effect with optical detection leads to optical bistability, that is, one gets an optical device with hysteresis. The electric field is induced by a resistor in series with a reverse-biased voltage source. If, instead of this resistor, one uses another quantum p-i-n diode in series, the resulting device acts as a bistable optical memory element as shown in Figure 9. This device can be operated in a mode with individual set and reset capabilities, and complementary outputs as an SR latch, as shown in Figure 10. This device, known as the symmetric SEED, or the S-SEED, is an optical memory element, and forms the basis of the first optical digital computer [52].

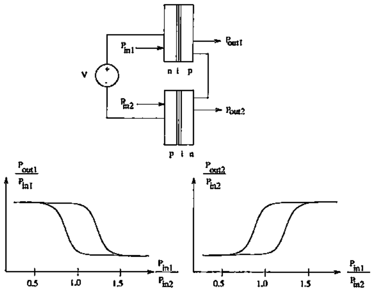

Figure 9. The Symmetric Self-Electro-Optic Effect Device.

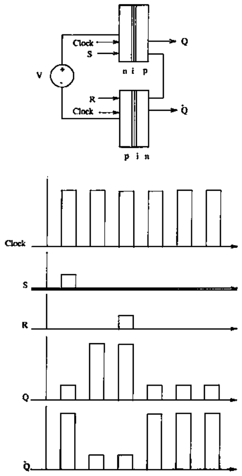

Figure 10. The Symmetric Self-Electro-Optic Effect Device Operated as an Optical SR-latch.

The second device that is widely used is the NLFP. This device exploits reflection instead of absorption to control the bias beam. A functional diagram of a NLFP is shown in Figure 11. In Figure 11, on the left, the NLFP is shown without a signal beam, in which case the device acts as a transparent window. When an incident signal is present, the NLFP changes its state, and the bias beam is reflected.

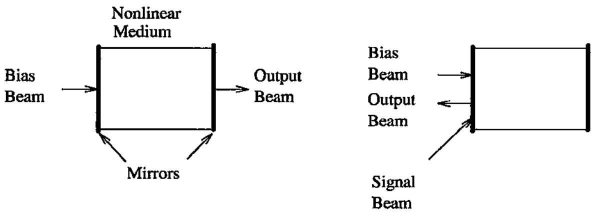

Figure 11. The Nonlinear Fabry-Perot Etalon.

4. Wavelength Division Switching

Wavelength division switching is a promising technique for switching electrical data in optical media without intermediate optical to electrical conversion. It can be implemented as a network, or as a photonic switch. The technique is known by the generic name wavelength division multiplexing (WDM). As shown in Figure 12, each electrical source modulates a light source corresponding to this input (or corresponding to its destination). All the optical energy is summed by a device known as a star coupler, and then physically split to be processed at the destination. Each destination uses a filter in tandem with a detector to recover the data destined for it. As will be described below, the methods of wavelength multiplexing and demultiplexing are relatively straightforward. The challenge is in building fast (frequency agile) lasers or tunable filters. Another implementation makes use of the heterodyning concept, and is known as coherent reception, shown in Figure 13. In this case, the processing at the destination is optical to electrical conversion and envelope detection by a photodetector. The electrical output signal is at microwave frequencies. Then, the detection is accomplished by means of well-known microwave methods.

In this section, we describe the currently available devices for wavelength multiplexing and demultiplexing, wavelength translation, and the tunable optical filters.

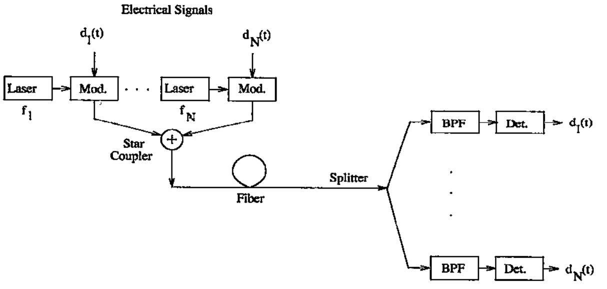

Figure 12. Wavelength Division Multiplexing Block Diagram.

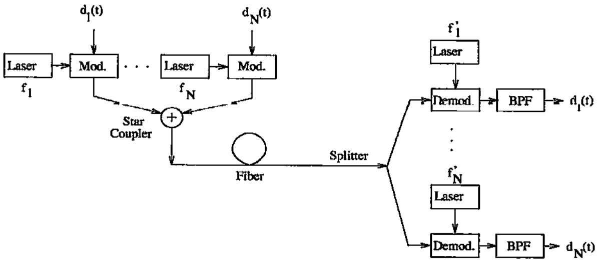

Figure 13. Wavelength Division Multiplexing by means of Coherent Detection.

4.1. Wavelength Multiplexers and Demultiplexers

Optical wavelength multiplexing and demultiplexing devices are generally classified into two types: *wavelength-selective* and *wavelength-nonselective*. The wavelength-selective type is further classified into two types: *passive* and *active*. The passive type includes angularly dispersive devices, dielectric thin-film filters, hybrid devices, and planar waveguides. The active type includes multiwavelength light sources (LD, LED) and multiwavelength photodiodes. The wavelength-selective type is primarily important for the wavelength division multiplexing (WDM) system because the WDM system makes use of principles based on the combination and selection of light beams of different wavelengths.

4.1.1. Angularly Dispersive Devices

Angularly dispersive devices can multiplex or demultiplex many channels using only one angularly dispersive element, such as a prism or grating. The idea is to differentiate signals in space by using diffraction, i.e., different wavelengths travel at different directions as in the case of light going through a prism. At present, the diffraction grating is primarily being used as the angularly dispersive element. The grating can be obtained by mechanical means, or by etching a single-crystal silicon. The silicon grating is superior as it provides freedom, high efficiency, and stable surface. Figure 14 shows a Littrow type silicon grating [53]. In this demultiplexer, the incoming light is collimated by the lens and then angularly dispersed by the silicon grating. Then the different wavelengths pass through the lens and are focused to their corresponding fibers. By using this type of grating, up to 20 channels with a wavelength spacing of 40 nm can be handled [53]. This device is reciprocal, and can also be used as a multiplexer. There are several other implementations reported [23].

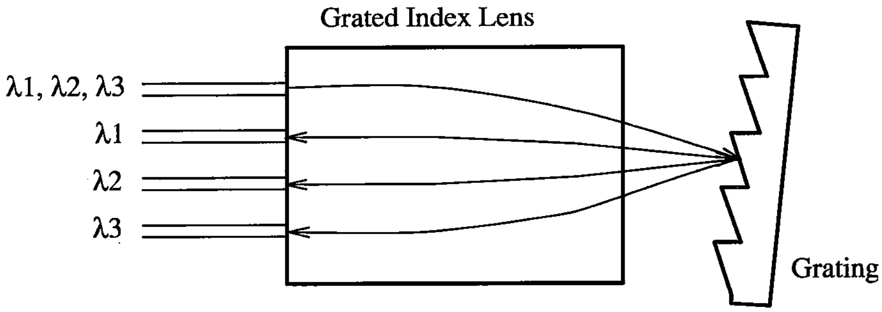

Figure 14. Littrow Type Silicon Grating.

4.1.2. Dielectric Thin-Film Filter Type Device

This device makes use of the wavelength selective characteristics of a dielectric thin-film filter (DTF), and can be considered as an optical bandpass filter (BPF) which lets the desired wavelength pass, and suppresses the others. It contains high and low refractive-index films in alternating layers, making the DTF to have a frequency selective characteristic. Figure 15 shows a typical example of a DTF device. It is a multireflection BPF type. All the filters used have different passband wavelengths, i.e., the center wavelength of the first filter is λ_1, that of the second filter is λ_2, and so on. When the wavelengths in the range $\lambda_1 - \lambda_6$ are applied from the input fiber, they are collimated by the graded index (GRIN) rod lens to form parallel beams and enter the first filter. Due to the characteristics of this filter, wavelength λ_1 is transmitted through the filter, while others are reflected and enter the second filter. The second filter passes λ_2, and reflects the remainder. By continuing this process, all of the originally multiplexed wavelengths can be separated [23].

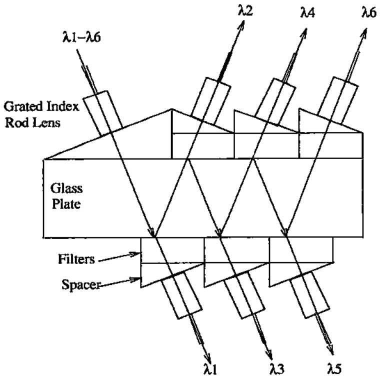

Figure 15. Multi-Reflection Type DTF.

4.1.3. Hybrid Type Devices

The gratings can demultiplex a large number of channels, and the DTFs are efficient multiplexers. Hybrid type devices combine a grating and a DTF, and therefore have the advantages of both devices.

4.1.4. Planar-Waveguide Type Devices

These devices are constructed by incorporating a planar waveguide and a planar diffraction grating. They are applicable only to single-mode WDM systems because they have a planar waveguide for single mode operation. They are inferior to grating type or the DTF type devices mentioned previously. However, the advantages of planar technology, such as reproducibility, batch fabrication, incorporation of complex optical circuits into photomasks, and ease of alignment with connecting fibers makes them desirable [2].

4.2. Wavelength Converters

Wavelength converters are necessary to switch the wavelength in WD optical switching systems. For the conversion of optical wavelength, second harmonic generation and parametric effects can be used in some cases. But a large optical power is needed for this purpose. On the other hand, wavelength tunable laser diodes are more practical for the wavelength conversion process.

Four families of tunable lasers exist: thermal tuning, mechanical tuning, injection-current tuning, and acoustooptic tuning [37]. Thermal tuning of single frequency lasers is limited to about ± 1 nm of bandwidth and very slow changes, in the order of milliseconds. Mechanically tuned lasers have a much broader tuning range. The principal drawback of these lasers is the limited tuning speed due to the mechanical movements required for tuning. There are a variety of semiconductor lasers tuned by adjusting the injection current in one or more sections of the lasers. These devices have the fastest tuning times, in the order of nanoseconds, but the tuning range is limited to about 10 nm. Another form of a tunable laser is an external-cavity semiconductor laser with an electronically tunable filter within the cavity. Such lasers have been demonstrated with both acoustooptic and electrooptic tunable filters. The tuning time of acoustooptic laser is limited by the acoustic velocity in the filter and it is in the order of microseconds. The tuning ranges can vary from 7 to 83 nm [53].

4.3. Tunable Optical Filters

Tunable filters are classified into three categories: passive filters, active filters, and tunable optical amplifiers. The passive filter category is composed of those basically passive wavelength-selective components which can be tuned by adjusting some mechanical element of the filter, such as mirror position or resolution. Similar to mechanical switches, they have high losses and low tuning speed. In the active filter category, there are two filters based upon wavelength-selective polarization transformation by either electrooptic or acoustooptic means. A filter bandwidth of approximately 1 nm can be achieved by this kind of filters. They have higher tuning speeds. Tunable optical amplifiers are made tunable by simply adjusting the injection current. The resolution of this kind of filters is about 0.25 $\mathring{A}$ and switching times are in the order of several nanoseconds [23]. Recently, a ZnS etalon filter using multilayer dielectric coatings which can be tuned about 0.4 $\mathring{A}$ has been demonstrated [54]. This filter can roughly be tuned to a desired channel by adjusting its angle, and then locked to the transmitter signal by varying the temperature.

In passing, we would like to mention that a recent breakthrough in device technology made the implementation of photonic networks and switching systems more likely: the Erbium doped fiber amplifier [55]. This technology provides compact high-gain optical amplifiers that can be incorporated into long haul connections or switching systems when attenuation impairments are severe. The high gain-bandwidth products of these amplifiers make the implementation of WDM systems with more stations and over longer distances feasible.

5. Conclusion

In this paper, we have attempted to give a brief review of emerging photonic switching technologies for future communication switching systems. Recent research indicates that these devices may replace their electronic counterparts in the future. However, in order for practical systems to be built, further developments in optical devices such as optical memories, gates, wavelength converters, wavelength tunable lasers and filters, and high speed switching devices are required. Feasibility of this technology for actual implementation depends on its cost compared to the cost of its electronic counterparts exhibiting similar performance. Recent advances in electronics point to a competitive thread against producing cost effective photonic systems in near future. Nevertheless further development in photonic devices is expected to close this gap in the coming decades. In particular, as the need for speed and capacity increases, electronics will reach its fundamental limits, and photonic solutions will become more attractive. In addition, device research for photonic switching systems will provide substantial potential for development in other fields of electrical engineering such as optical computing and optical information processing.

6. Acknowledgement

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References

[1] H. S. Hinton and J. E. Midwinter, *Photonic Switching,* IEEE Press, New York, 1990.

[2] T. K. Gustafson and P. W. Smith, *Photonic Switching,* Springer-Verlag, Berlin, 1988.

[3] Special Issue on Photonic Switching, *IEEE Communications Magazine,* Vol. 25, May 1987.

[4] Special Issue on Photonic Switching, *IEEE Journal on Special Applications in Communications,* Vol. 6, August 1988.

[5] H. A. Elion and V. N. Morozov, *Optoelectronic Switching Systems in Telecommunications and Computers,* Marcel Dekker, New York, 1984.

[6] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics,* Wiley, New York, 1991.

[7] *Proceedings of the Symposium on Optical Computing,* Los Angeles, California, January 1986. SPIE Proceedings, Vol. 625.

[8] *Proceedings of the First Topical Meeting on Photonic Switching,* Incline Village, Nevada, March, 1987. Springer Series in Electronics and Photonics, Vol. 22, Springer-Verlag.

[9] *Proceedings of the Symposium on Nonlinear Optical Materials,* Hamburg, Germany, September 1988. SPIE Proceedings, Vol. 1017.

[10] *Proceedings of the OSA Topical Meeting on Photonic Switching,* Salt Lake City, Utah, March 1989. OSA Proceedings, Vol. 3.

[11] *Proceedings of the Symposium on Materials for Optical Switches, Isolators, and Limiters,* Orlando, Florida, March 1989. SPIE Proceedings, Vol. 1105.

[12] *Proceedings of the Symposium on Nonlinear Optical Materials II,* Paris, France, April 1989. SPIE Proceedings, Vol. 1127.

[13] *Proceedings of the Workshop on Coherent Optical Communications and Photonic Switching,* Tirrenia, Italy, September 1989. Elsevier, 1990.

[14] *Proceedings of the Symposium on Nonlinear Optical Materials and Devices for Photonic Switching,* Los Angeles, California, January 1990. SPIE Proceedings, Vol. 1216.

[15] *Proceedings of the Symposium on Nonlinear Optical Materials III,* The Hague, The Netherlands, March 1990. SPIE Proceedings, Vol. 1273.

[16] *Proceedings of the International Topical Meeting on Photonic Switching,* Kobe, Japan, April, 1990. Springer Series in Electronics and Photonics, Vol. 29, Springer-Verlag.

[17] *Proceedings of the Workshop on Photonic Networks, Components and Applications,* Montebello, Canada, October, 1990. World Scientific, 1991.

[18] *Proceedings of the Symposium on Optically Activated Switching,* Boston, Massachusetts, November 1990. SPIE Proceedings, Vol. 1378.

[19] *Proceedings of the International Topical Meeting on Photonic Switching,* Salt Lake City, March 1991. OSA Proceedings, Vol. 8.

[20] *Proceedings of the Symposium on Nonlinear Optics III,* January 1992. SPIE Proceedings, Vol. 1626.

[21] *Proceedings of the Symposium on Optically Activated Switching II,* Los Angeles, California, Ja. SPIE Proceedings, Vol. 1632

[22] S.F. Su, L. Jou, and J. Lenart, "A Review on Classification of Optical Switching Systems," *IEEE Communications Magazine,* Vol. 24, pp. 50–55, May 1986.

[23] M. Sakaguchi, and K. Kaede, "Optical Switching Device Technologies," *IEEE Communications Magazine,* Vol. 25, pp. 27–31, May 1987.

[24] P. Hale, "Mechanical Optical-Fiber Switch," *Electronics Letters,* Vol. 12, p. 388, June 1976.

[25] H. S. Hinton, "Photonic Switching Using Directional Couplers," *IEEE Communications Magazine,* Vol. 25, pp. 16–25, May 1987.

[26] M. Papuchon, Y. Combemale, X. Mathieu, D. B. Ostrowsky, L. Reiber, A. M. Roy, B. Sejourne, and M. Werner, "Electrically Switched Optical Directional Coupler: Cobra," *Applied Physics Letters,* Vol. 27, pp. 289–291, September 1975.

[27] H. Kogelnik and R. V. Schmidt, "Switched Directional Couplers with Alternating $\Delta\beta$," *IEEE Journal of Quantum Electronics,* Vol. QE-12, pp. 396–401, July 1976.

[28] H. S. Hinton, "Photonic Switching Fabrics," *IEEE Communications Magazine,* Vol. 29, pp. 71–89, April 1990.

[29] R. C. Alferness, "Polarization-Independent Optical Directional Coupler Switch Using Weighted Coupling," *Applied Physics Letters,* Vol. 35, pp. 748–750, November 1979.

[30] R. V. Schmidt and R. C. Alferness, "Directional Coupler Switches, Modulators, and Filters Using Alternating $\Delta\beta$ Techniques," *IEEE Transactions on Circuits and Systems,* Vol. CAS-26, pp. 1099–1108, December 1979.

[31] L. McCaughan, "Low-Loss Polarization-Independent Electrooptical Switches at $\lambda = 1.3$ μm," *IEEE Journal of Lightwave Technology,* Vol. LT-2, pp. 51–55, February 1984.

[32] P. Granestrand, B. Stoltz, L. Thylen, K. Bergvall, W. Doldissen, H. Heinrich, D. Hoffmann, "Strictly Nonblocking 8×8 Integrated Optical Switch Matrix," *Electronics Letters,* Vol. 22, pp. 816–818, July 1986.

[33] H. Nishinoto, M. Iwasaki, S. Suziki, and M. Kondo, "Polarization Independent $LiNbO_3$ 8×8 Matrix Switch," *IEEE Photonics Technology Letters,* Vol. 2, pp. 634–637, September 1990.

[34] J. A. Cavailles et al. "First Digital Optical Switch Based on InP/GaInAsP Double Heterostructure Waveguides," *Electronics Letters,* Vol. 27, pp. 699–700, 1991.

[35] S. Sakano, H. Inoue, H. Nakamura, T. Katsuyama, and H. Matsumara, "InGaAsP/InP Monolithic Integrated Circuit with Laser and Optical Switch," *Electronics Letters,* Vol. 22, pp. 594–596, 1986.

[36] K. Shimomura et al. "Low-Drive Voltage Intersectional Waveguide Optical Switch Using GaInAs/InP MQW Structures," *IEEE Photonics Technology Letters,* Vol. 4, pp. 359–362, 1992.

[37] C. Bracket, "Dense Wavelength Division Multiplexing Networks: Principles and Applications," *IEEE Journal on Selected Areas in Communications,* Vol. 8, pp. 948–962, August 1990.

[38] K. Hu et al., "All Optical Photonic Switches Using Integrated Inverted Asymmetric Fabry-Perot Modulators and Heterojunction Phototransistors," *IEEE Photonics Technology Letters,* Vol. 4, pp. 263–266, 1992.

[39] K. Kirayabashi and T. Kurokawa, "Tunable Wavelength Selective Demultiplexer Using a Liquid Crystal Filter," *IEEE Photonics Technology Letters,* Vol. 4, pp. 737–740, 1992.

[40] H. S. Hinton, "Architectural Considerations for Photonic Switching Networks," *IEEE Journal on Selected Areas in Communications,* Vol. 6, pp. 1209–1226, August 1988.

[41] M. Jin et al., "Bonding of Si Thin Films to PLZT Substrates for SLM Applications," *Proc. OSA Topical Meeting on Spatial Light Modulators and Applications,* STuB2, Palm Springs, March 1993.

[42] A. R. Tanguay et al., "Hybrid Silicon/Gallium Arsenide Inverted Fabry-Perot Cavity MQW Spatial Light Modulators," *Proc. OSA Topical Meeting on Spatial Light Modulators and Applications,* STuB3, Palm Springs, March 1993.

[43] R. M. Fortenberry et al., "Photonic Fast Packet Switch with Gain," *Proc. OSA Topical Meeting on Photonic Switching,* ThA2, Salt Lake City, March 1991.

[44] D. Jager (Ed.), High Speed Phenomena in Photonic Materials and Optical Bistability, *Proc. SPIE,* Vol. 1280, 1990.

[45] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegman, T. H. Wood, and C. A. Burrus, "Novel Hybrid Optically Bistable Switch: The Quantum Well Self-Electrooptic Effect Device," *Applied Physics Letters,* Vol. 45, pp. 13–15, July 1984.

[46] D. A. B. Miller, D. S. Chemla, T. C. Damen, T. H. Wood, C. A. Burrus, A. C. Gossard, and W. Wiegman, "The Quantum Well Self-Electrooptic Effect Device: Optoelectronic Bistability and Oscillation, and Self-Linearized Modulation," *IEEE Journal of Quantum Electronics,* Vol. QE-21, pp. 1462–1476, September 1985.

[47] D. A. Miller, J. E. Henry, A. C. Gossard, and J. H. English, "Integrated Quantum Well Self-Electrooptic Effect Device: 2 × 2 Array of Optically Bistable Devices," *Applied Physics Letters,* Vol. 49, pp. 821–823, September 1986.

[48] A. L. Lentine, H. S. Hinton, D. A. B. Miller, J. E. Henry, J. E. Cunningham, L. M. F. Chirovsky, "Symmetric Self-Electrooptic Effect Device: Optical Set-Reset Latch," *Applied Physics Letters,* Vol. 52, pp. 1419–1421, April 1988.

[49] S. D. Smith, "Optical Bistability, Photonic Logic, and Optical Computation," *Applied Optics,* Vol. 25, pp. 1550–1564, May 1986.

[50] C. Park et al., "A Novel Optically Bistable Multiple-Quantum-Well Phase Modulator," *IEEE Photonics Technology Letters,* Vol. 4, pp. 1225–1227, 1992.

[51] A. L. Lentine et al., " Integrated Self Electro-Optic Effect Device Photonic Switching Nodes," *Proc. OSA Topical Meeting on Photonic Switching,* ThC4, Salt Lake City, March 1991.

[52] M. E. Prise, M. M. Downs, F. B. McCormick, S. J. Walker, and N. Streibl, "Design of an Optical Digital Computer," *Optical Bistability-IV,* pp. C2-15–C2-18, 1988.

[53] H. Ishio, J. Minowa, and K. Nosu, "Review of Status of Wavelength Division Multiplexing Technology and Its Application," *IEEE Journal of Lightwave Technology,* Vol. LT-2, pp. 448–463, 1984.

[54] Y. C. Chung, "Temperature Tuned ZnS Etalon Filters for WDM Systems," *IEEE Photonics Technology Letters*, Vol. 4, pp. 600–602, 1992.

[55] E. Desurvire, J. R. Simpson, and P. C. Becker, "High Gain Erbium-Doped Traveling Wave Fiber Amplifier," *Optics Letters*, Vol. 12, pp. 888–890, 1987.

Foton Anahtarlama Sistemleri Üzerine Bir Araştırma

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Özet

Son yıllarda fiber optik sistemlerindeki çalışmalara da bağlı olarak optik iletişim teknolojisinde önemli ilerlemeler kaydedilmiştir. Bu gelişmeler optik iletişimde doğal olarak kullanılması beklenen foton anahtarlama sisteminin gündeme gelmesine neden olmuştur. Bu bildiride, gelecekte iletişim sistemlerinin önemli bir parçası olması beklenen foton anahtarlama sistemleri hakkında genel bir bilgi verilecektir. Şimdiki elektronik teknolojisinde olduğu gibi foton anahtarlamada da, anahtarlama işlemi gelen sinyalin uzay, zaman ya da frekans alanında bölünüp çoğullanmasıyla gerçekleşmektedir. Bu üç çoğullama sisteminden hangisinin kullanılacağı ise hem teknolojik hem de kuramsal gelişmelere bağlıdır. Bu bildiri , bu üç sistem çerçevesinde foton anahtarlama konusunda yapılan çalışmalar ve gelişen teknoloji konusunda bilgi vermektedir.