All-optical stage of an Omega network

Dan M. Marom, Naim Konforti, and David Mendlovic

All-optical multistage interconnection networks are desirable for overcoming the limitations of optical signal regeneration in switching systems. We present a new implementation of the perfect-shuffle interconnection pattern that is coupled with an all-optical switching element, forming a complete stage of a multistage network. Switching is performed with birefringent calcite crystals and a ferroelectric liquid-crystal device, while interconnection is achieved with a space-semivariant imaging configuration. Cascading the layout allows this system to be used to construct an all-optical multistage interconnection network. An experimental demonstration of the stage is presented. © 1998 Optical Society of America

OCIS codes: 200.4650, 200.2610.

1. Introduction

Free-space optical interconnections provide ultrahigh communication throughputs that could solve the interconnection bottleneck observed in electronic circuit design. Optical components can efficiently perform *fixed* interconnections between a transmitter source and receiver locations, while *reconfigurable* interconnections that are capable of connecting arbitrary source points to different target points require the use of active or switching elements. Reconfigurable interconnections can be performed with minimal switching elements by use of a multistage interconnection network (MIN) architecture.[1] The MIN structure consists of alternating layers of fixed interconnection patterns and arrays of switching modules, usually elementary switches for two signals known as bypass–exchange switches. The Omega network[2] (see Fig. 1) is an example of a MIN with N input signals ($N = 2^m$, where m is an integer) that has $\log_2 N$ stages of $N/2$ bypass–exchange switches and a perfect-shuffle interconnection pattern between them. The Omega network is topologically equivalent[3] to other MIN's such as the banyan and cross-over networks, but the other networks have different interconnection patterns between switching stages, which requires dedicated hardware for each interconnection stage. Mathematically the perfect shuffle can be expressed as

$$k \rightarrow \begin{cases} 2k & \text{if } 0 \leq k \leq N/2 - 1 \\ 2k - N + 1 & \text{if } N/2 \leq k \leq N - 1 \end{cases}, \tag{1}$$

where the input node k ($k = 0, \ldots, N - 1$) is mapped to a new location defined by the permutation.

The perfect-shuffle interconnection pattern has been investigated extensively for use in optical networks because of its simplicity. Most implementations duplicate the input vector and recombine the two copies with a relative shift, keeping the overlapping region that fulfills the perfect-shuffle permutation [expression (1)]. A major disadvantage of this method is a power loss of -3 dB. The optical perfect shuffle can be realized with standard lenses and prisms,[4] interferometer-based setups,[5] space-semivariant lens arrangements,[6] and space-variant dedicated lenslet pairs implemented with diffractive optics.[7] These optical implementations have addressed the interconnection problem between source and target points, where it is usually assumed that the switching element is an optoelectronic device with detectors, modulators, and electronic circuitry. For such an optoelectronic switch any light incident upon the detectors serves as an input signal to the switch, regardless of the propagation direction.

Recently, we investigated a compact all-optical bypass–exchange switch.[8] This switch requires two optical input signals to propagate normal to the switch with an orthogonal polarization state. Thus the perfect-shuffle interconnection preceding the switch array must provide the proper propagation directions for the input signals. We achieve this re-

When this study was performed, the authors were with the Faculty of Engineering, Tel-Aviv University, P.O. Box 39040, Tel-Aviv 69978, Israel. D. M. Marom (dmarom@ucsd.edu) is now with the Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0407.

Received 26 March 1998; revised manuscript received 26 June 1998.

0003-6935/98/296946-05$15.00/0

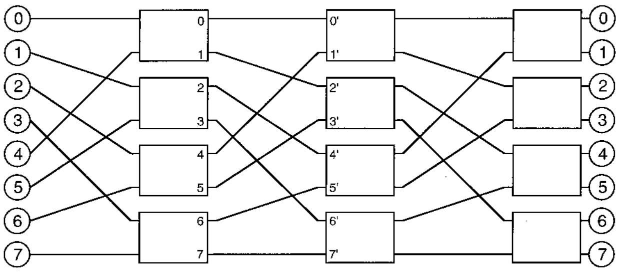

Fig. 1. Omega network for interconnecting eight channels composed of three identical stages each with a perfect-shuffle permutation and four bypass–exchange switches (represented by the rectangular boxes).

quirement by modifying the perfect-shuffle interconnection pattern, making use of the vertical direction and polarization to assist in implementing the one-dimensional perfect shuffle. The optical interconnections are performed by use of a space-semivariant lens imaging system, relieving losses associated with diffractive space-variant elements or the −3-dB power loss from source-duplication techniques. The combination of the modified perfect-shuffle interconnection and the all-optical switches form a power-efficient complete stage of an Omega network. When the complete stage is cascaded $\log_2 N$ times, an all-optical Omega network is formed that is capable of connecting any optical input channel to any output node. The optical signal is never regenerated within the MIN, freeing the system from the limitations inherent to electronic components.

An alternative scheme based on birefringence-customized modular optics has also been proposed.[9] This approach uses calcite crystals for performing both the switching function of the bypass–exchange switch and the perfect-shuffle permutation. Patterned half-wave plates are inserted between calcite crystal slabs for a three-dimensional solid-state module. Because of the large quantities of calcite crystals and half-wave plates this approach requires, its implementation is likely to be too expensive for real-world applications.

Section 2 is a review of our optical bypass–exchange switch. In Section 3 we propose a new implementation of the perfect-shuffle interconnection integrated with our all-optical switch. Experimental results are presented in Section 4, followed by a conclusion in Section 5.

2. Compact, All-Optical Bypass–Exchange Switch

The all-optical bypass–exchange switch[8] is based on polarization switching with the aid of birefringent calcite crystals and a controllable polarization-rotation device. Similar switches based on polarization beam-splitter cubes,[10] total internal reflection at a liquid-crystal interface,[11] and birefringent computer-generated holograms[12] have been reported. The switch either passes both signals in bypass mode or crosses the signals in exchange mode. The first calcite crystal combines the two orthogonally polarized optical beams by the phenomenon of double refraction (see Fig. 2). The state of the switch is controlled by a polarization modulator, in our case a ferroelectric liquid-crystal (FLC) modulator (Fabia Technologies, Israel). In the bypass mode the modulator does not change the state of polarization of the optical signals, and the second calcite crystal separates the two signals at the output. In the exchange mode the modulator rotates the state of polarization of both signals simultaneously, and after the second calcite crystal the two signals have exchanged their location. Half-wave plates are used in the input and the output to adjust the polarization state of the optical signals.

Experimental measurement of the optical switch (Ref. 8) has demonstrated a cross talk of −23 dB. This cross talk was due primarily to imperfect polarization rotation of the FLC device. For a driving voltage of ±10 V dc, switching rates were 1 ms. However, it has been reported that FLC devices can be operated in the 10-μs range.[13] Alternatively, faster electro-optic materials can be used.

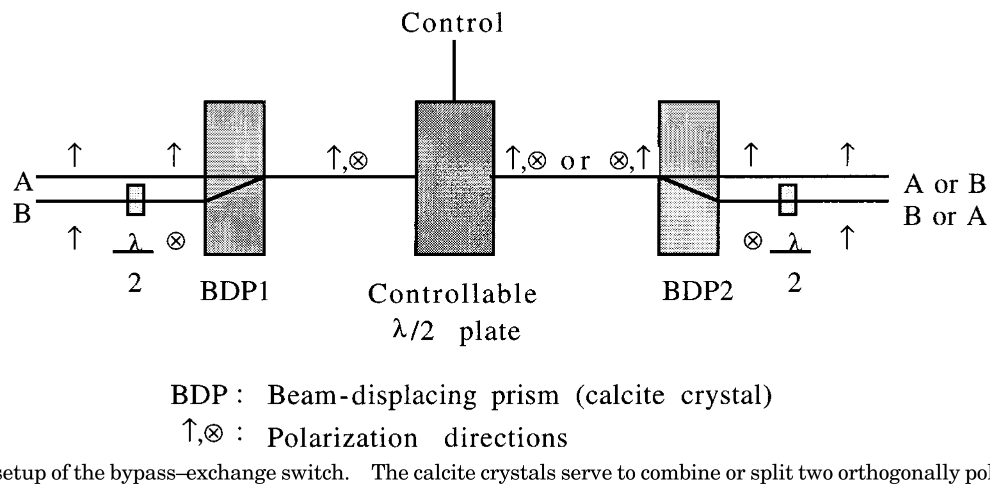

Fig. 2. Optical setup of the bypass–exchange switch. The calcite crystals serve to combine or split two orthogonally polarized beams. A FLC device is used as a controllable half-wave plate to rotate the polarization of both signals.

3. Complete Stage of an Omega Network

A complete stage of an Omega network consists of a perfect-shuffle interconnection pattern followed by an array of bypass–exchange switches. For optimal performance the propagation direction of the optical beams input to our bypass–exchange switch should be normal to the surface of the calcite crystals. The optical perfect shuffles suggested in the past[4–7] do not meet the normal propagation requirement.

In the perfect-shuffle interconnection pattern each half of the input vector undergoes a different linear transformation, as described by expression (1). Our implementation of the perfect shuffle modifies the transformation but retains the same functionality. We maintain the separation of the two halves of the input vector after the transformation because the optical signal beams need to be recollimated. The separation is performed in the vertical direction, making use of the three-dimensional nature of optics. The new transformation can be described as follows:

$$k \rightarrow \begin{cases} (-\Delta y/2,\, 2k) & \text{if } 0 \le k \le N/2-1 \\ (\Delta y/2,\, 2k-N) & \text{if } N/2 \le k \le N-1 \end{cases}, \qquad (2)$$

which describes a transformation from a vector to a matrix form of two rows.

This transformation does not perform the interleaving required by the perfect-shuffle interconnection but rather aligns the two halves with a separation of Δy in the vertical direction. The transformation defined by expression (2) is separable in both the input (along the vector direction) and at the output (in the vertical direction). Therefore the optical implementation of the transformation can be described as two independent imaging systems, side by side. The transformation requires a scaling factor of 2 with shifts in both the x and the y directions. Such a transformation can easily be implemented by use of off-axis lenses. The perfect-shuffle optics segment of Fig. 3 consists of two afocal lens pairs that magnify by a factor of 2 (Galilean telescope) and provide the required shifts in the vertical direction. The spherical lenses have been cut so that they can be placed next to each other.

After passing through the modified perfect-shuffle interconnection, signal pairs that share a common bypass–exchange switch are offset in only the vertical direction. By rotation of the input calcite crystal of the bypass–exchange switch by 90°, the switch will combine signals in the vertical direction while still splitting them in the horizontal direction (see Fig. 3). This feature enables the switch to perform an interlacing function after the switching action. The input calcite crystal provides a displacement equivalent to Δy, whereas the output calcite crystal displaces the beams by the amount required to achieve the interlace. The amount of displacement dictates the crystal's length.

To offset the signal magnification by a factor of 2, which was necessary to double the pitch of the signals but is undesirable for the signals themselves, a space-variant demagnifying telescopic array is introduced into the system (see Fig. 3). The telescopic array maintains the pitch while reducing the signal spot size. It can be implemented by use of a combination of two lenslet arrays or by a holographic telescopic array.[14] Interlacing cannot be accomplished without the demagnifying telescope.

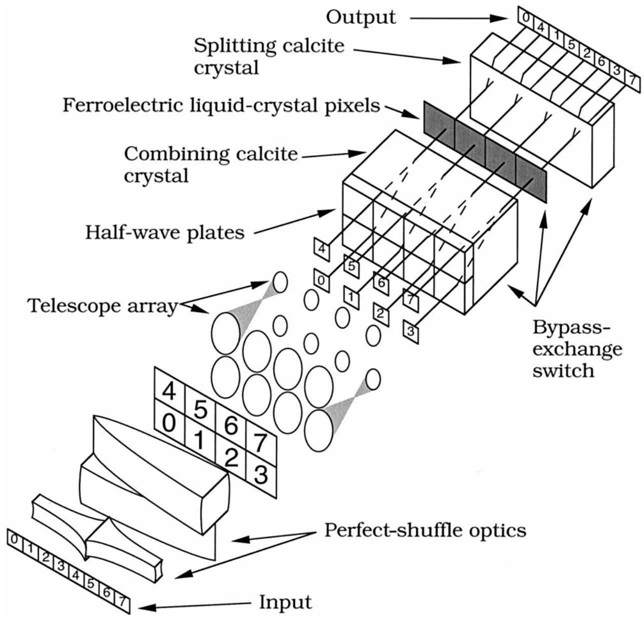

Fig. 3. Optical setup for a complete stage of an Omega network, as described in Section 3. The output signals' locations might vary according to the switch settings.

Let us assume that each signal is a square of dimension $\Delta \times \Delta$, with a pitch Δ (in practice, a fill ratio of less than 1 is required to prevent cross talk). The input vector is of dimension $N\Delta \times \Delta$ (where N is the number of signals). After the modified perfect-shuffle optics, each signal has been magnified and is of dimension $2\Delta \times 2\Delta$ with a pitch 2Δ. The signals are arranged in a rectangle of dimension $N\Delta \times 4\Delta$ (assuming Δy takes on the minimum value of 2Δ). The telescopic array compresses the signals back to dimension $\Delta \times \Delta$ but maintains the pitch of 2Δ. The polarization state of the optical signals is adjusted by permanent half-wave plates such that the lower signal row is orthogonal to the upper signal row. The first calcite crystal displaces the signals by 2Δ in the vertical direction, so the signals overlap for switching purposes. The second calcite crystal horizontally translates by Δ one of the signals after switching, performing the interlace function, and returning all the signals to a vector form, as was the input. The signal that is displaced to the vacant area is dependent on the state of the switch (bypass or exchange). The polarization-adjusting half-wave plates, as described above, are identical in every stage with the exception of the input stage (we assume that the input signals are all identically polarized at the network input, whereas the interlaced output of every stage has an alternating polarization state for each signal).

Because the output of the complete stage is in exactly the same form as the input (signal size, pitch, layout, and polarization), the same setup can be repeated in cascade, building up to an entire MIN.

4. Experimental Results of the Complete Omega Stage

The setup of Fig. 3 was constructed in the laboratory with the following exceptions: (1) The demagnifying telescopic array used to reduce the signal size after magnification was replaced with an amplitude mask that truncates the size of the optical signal back to the original input size. This results in a 25% power efficiency (ratio of the area of a circle to a circle of double diameter). (2) A large FLC cell was used in place of a pixelated device. This prevented individual control of the switch array. Therefore we could simulate only two states in which *all* switches were either in the bypass or the exchange mode.

The input signals were created by an amplitude mask with eight circular apertures to simulate eight input channels. The pitch between signals was 0.55 mm, and the diameter of the apertures was 0.34 mm (for a fill ratio of 62%). The spherical lenses used to perform the perfect shuffle were designed with a computer program (optimized to minimize aberrations), custom made, and cut precisely so that they could be placed next to each other. The operating cw wavelength was 532 nm from a frequency-doubled YAG laser. The light efficiency of transmitted signals was not measured in this experiment but is expected to be limited by only reflection from optical components, which can be minimized with antireflection coatings.

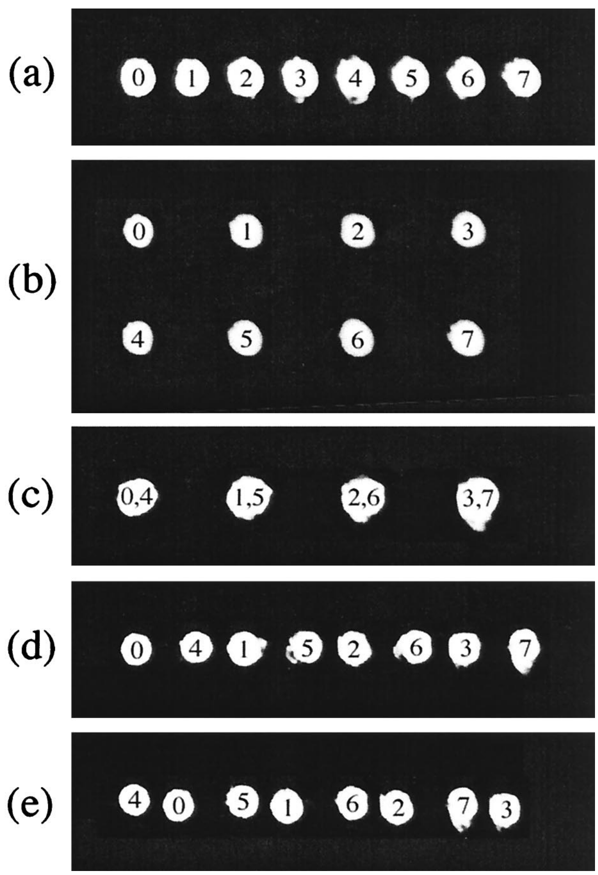

Fig. 4. Experimental images obtained at various locations in the stage: (a) in the input vector, (b) after the modified perfect-shuffle imaging optics and reduction of the signal size by a mask, and (c) after the combination of vertical pairs by the first calcite crystal. Also shown is the output vector at different switch settings: (d) all switches in the bypass mode and (e) on all switches in the exchange mode. Note that the signal labels were added with photoediting software (no further editing was performed).

Figure 4 shows images of the optical signal in various locations in the setup. The input vector [Fig. 4(a)] is divided into two, and the two halves are shifted one above the other, while the pitch has doubled [Fig. 4(b)]. Signal spot sizes appear not to have doubled since the image was taken after the truncating mask. The first calcite crystal combines the vertical pairs [Fig. 4(c)], and the second calcite crystal displaces the signals according to the state of the switches in the array [Figs. 4(d) and 4(e)]. The output vector is in the same layout as the input vector, so this process can proceed $\log_2 N$ times for a complete Omega network. In our experiment the output-channel spacing is not even and depends on the switching state. This probably was due to our calcite crystals, which did not have the exact lengths required, a problem that should not be encountered in industrial design. Cross-talk performance was identical to that measured in our previous experiments and thus was limited by the performance of the polarization-rotation device.

5. Conclusion

We have shown that, by slightly modifying the perfect-shuffle interconnection pattern, we can optically implement the permutation by two independent optical imaging systems that are in proximity to each other. The input and the output signals are in a collimated-light-beam format that is compatible with our all-optical, bypass–exchange switch. The calcite crystals in our all-optical switch combine the signal pairs in the vertical direction and perform the interlacing action required by the perfect shuffle in the horizontal direction after the switching function has been performed by a polarization modulator. The combination of a perfect-shuffle interconnection and a switch array constitutes a complete stage of an Omega network. Cascading this stage by $\log_2 N$ times will create an all-optical MIN.

All-optical switching networks must be highly efficient, as the optical power is not regenerated in the system. The proposed stage does not suffer the -3-dB loss associated with most perfect-shuffle implementations. The only sources of loss in our design are from reflection at the air–glass and the air–calcite interfaces. If we assume that all such interfaces have an antireflection coating that provides 99% power throughput and that the entire calcite-based switch can be packaged as one optical element,[15] then the loss per stage is estimated at -0.44 dB. Thus a seven-stage network sufficient for

128 input signals will have a total switching loss of −3 dB.

The authors acknowledge Fabia Technologies for providing the FLC device. This project is a part of the RODCI (reconfigurable optical device for computer interconnection) Esprit Project 22613 supported by the European Union.

References

1. C.-L. Wu and T.-Y. Feng, "The universality of the shuffle–exchange network," IEEE Trans. Comput. **C-30,** 324–331 (1981).
2. H. S. Stone, "Parallel processing with the perfect shuffle," IEEE Trans. Comput. **C-20,** 153–161 (1971).
3. C.-L. Wu and T.-Y. Feng, "On a class of multistage interconnection networks," IEEE Trans. Comput. **C-29,** 694–702 (1980).
4. A. W. Lohmann, W. Stork, and G. Stücke, "Optical perfect shuffle," Appl. Opt. **25,** 1530–1531 (1986).
5. K.-H. Brenner and A. Huang, "Optical implementations of the perfect shuffle interconnection," Appl. Opt. **27,** 135–137 (1988).
6. A. A. Sawchuk and I. Glaser, "Geometries for optical implementation of the perfect shuffle," in *Optical Computing 1988*, J. W. Goodman, P. Chavel, and G. Roblin, eds., Proc. SPIE **963,** 270–279 (1988).
7. K. S. Urquhart, P. Marchand, Y. Fainman, and S. H. Lee, "Diffractive optics applied to free-space optical interconnects," Appl. Opt. **33,** 3670–3682 (1994).
8. D. M. Marom and D. Mendlovic, "Compact, all-optical bypass–exchange switch," Appl. Opt. **35,** 248–253 (1996).
9. L. Liu and Y. Li, "Free-space optical shuffle implementations by use of birefringence-customized modular optics," Appl. Opt. **36,** 3854–3865 (1997).
10. R. E. Wagner and J. Cheng, "Electrically controlled optical switch for multimode fiber applications," Appl. Opt. **19,** 2921–2925 (1980).
11. R. A. Soref and D. H. McMahon, "Total switching of unpolarized fiber light with a four-port electro-optic liquid-crystal device," Opt. Lett. **5,** 147–149 (1980).
12. A. V. Krishnamoorthy, F. Xu, J. E. Ford, and Y. Fainman, "Polarization-controlled multistage switch based on polarization-selective computer-generated holograms," Appl. Opt. **36,** 997–1010 (1997).
13. T. C. Chieu, J. L. Sanford, and K.-H. Yang, "A high-resolution and high-speed ferroelectric liquid-crystal shutter array print head," IEEE Trans. Electron. Dev. **38,** 1316–1323 (1991).
14. A. W. Lohmann and F. Sauer, "Holographic telescope arrays," Appl. Opt. **27,** 3003–3007 (1988).
15. N. Wang, L. Liu, and Y. Yin, "Cantor network, control algorithm, two-dimensional compact structure and its optical implementation," Appl. Opt. **34,** 8176–8182 (1995).