Photonic Switch with Optically Self-Routed Bit Switching

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Self-routing of optical signals through an integrated-optic waveguide modulator using optically processed control is reported. The source encodes destination information in each data bit using optical spread spectrum techniques. The optical controller reads the destination address using an incoherent fiber-optic delay-line correlator, and makes routing decisions in real-time. Switching of 3.125 Mb/s data is experimentally demonstrated, with a spread spectrum chip rate of 100-Mbaud. Extension of this technique to a self-routing NXN switch is discussed

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Photonic switches capable of routing wideband optical signals will be an important element of ultrahigh-capacity fiber-optic networks of the future [1,2]. A photonic switch generally consists of a multistage connecting network—each stage comprising switching devices and controllers—which routes optical information between input and output ports. We restrict our attention here to photonic switching devices which maintain signals in optical form as they traverse the switch. The controllers process address information supplied by the source. This processing can be performed either electronically or optically. The controller output sets up the appropriate switch permutation to route the signal to its destination. This control signal may be either electrical or optical, depending upon whether switching is accomplished by an electro-optic or opto-optic effect.

Photonic switching devices which have been previously demonstrated include 2×2 integrated-optic waveguide switches, controlled electrically [3-5]. Arrays of these 2×2 switching devices have been organized in N×N crossbar configurations [6-9]. Crossbar switch arrays can be further cascaded into photonic switching networks [10]. Recently, optically-controlled photonic switching devices have also been developed [11,12] and are expected to ultimately switch at speeds in excess of 1 THz [13].

Whatever photonic switching device is used, the speed of future photonic switches will be limited not only by the device switching speed, but by the speed of the controller. A severe data flow bottleneck will occur at the controller if electronic processing is used. This bottleneck can be eliminated with optical processing. In switches requiring electro-optic control, the output of the optical processor must be converted to an electrical signal to activate the switch. In future photonic switches employing opto-optic control, this conversion would not be necessary. The speed of such a switch would then be limited by the speed of the optical decision-making process or the speed of the photonic switching device itself.

There have been few proposals of photonic switches with optically-processed control. Haque and Arozullah [14] have proposed that some of the electronic functions in a conventional electronic switch be replaced by their optical or electro-optic counterparts. We propose to improve the performance of photonic switches by developing a novel optical architecture with optically-processed control which could not be implemented with electronic components. Distinguishing characteristics of optical processing include its inherent parallelism and non-interfering nature as well as its high speed [15].

We report the experimental demonstration of a photonic switch using optically self-routed bit switching. This novel architecture exploits the speed of optical processing by encoding each bit with its destination address, using a spread spectrum bandwidth expansion code.

Optically Self-Routed Bit Switching

Three switching techniques are presently in common use. They are circuit switching, message switching, and

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packet switching. A technique referred to as bit switching is employed by our photonic switch. It can be viewed as a special case of packet switching with the packet length limited to one bit. Routing information is subencoded in each bit, and is preserved throughout the routing process. Bit switching combines features of both the datagram and virtual-circuit approach to packet switching.

In bit switching, a routing decision is made at each switching node, as in the datagram approach. This routing decision can be made under centralized or distributed control. Under centralized control, a central processor decides on the "optimal" route of a signal through the switch. This may not be efficient on a bit-by-bit basis. Under distributed control, the processing of the routing decision is carried out by each switching node. Self-routing control is a form of distributed control which allows all bits with the same destination address to follow a preestablished route. The routing decision involves the determination of the destination and therefore of the predetermined route. Self-routing control is more efficient than centralized control for bit switching.

In bit switching, all bits belonging to the same message follow the same route and arrive in the order they have been sent, as in the virtual-circuit approach. Therefore, sequencing is assured while eliminating the need for a route setup phase, along with the required overhead bits.

Bit switching is also well suited for real-time traffic, eliminating the need for flow control. Though bit switching increases the processing burden at each node, this burden can be relieved by optical processing.

Real-Time Optical Control

The photonic switch proposed in this paper consists of a photonic switching element and an optical controller, as shown in Fig. 1. If the photonic switch is electro-optic, then a photodetector/preamplifier combination is also required to convert the optical controller output into an electrical gating signal. The optical controller processes the address information supplied by each input data bit, and sets up the required switch permutation to route the bit to its destination.

To self-route each data bit in real time, the controller must be able to accept a new input address in a time τ that is less than or equal to the bit interval T:

$$\tau \leq T \qquad (1)$$

At ultra-high bit rates, electronic processing would not be sufficiently fast to satisfy (1), resulting in a data flow bottleneck at the input to the switch. With optical processing, τ can be decreased substantially, increasing the allowable throughout 1/T of the switch.

Once all the physical mechanisms for decreasing τ have been exhausted, if (1) is still not satisfied, then parallel processing or pipelining can be used to further reduce τ. By connecting a system of K processors in parallel, and sequentially allocating the input data to the individual processors, a K-fold increase in performance is obtained. However, it may be inconvenient to replicate the processing units K times, and to sequentially allocate the data to the K individual processors. Alternatively, a K-fold increase in performance is also obtained by forming a systolic pipeline, which partitions the processing into a sequence of K discrete processing stages, each of duration τ_i. If (1) is satisfied for $\tau_i = \tau$ in each stage of the pipeline, then there is no data flow bottleneck.

As shown in Fig. 1, the controller can be divided into two stages: a linear processing stage and a nonlinear processing stage. A linear matched filter consisting of fiber-optic delay-lines can recognize the destination address of each data bit, as discussed in the next section. The maximum delay-line length, and consequently the processing time of the linear filter, is T, which satisfies (1). The linear filter output is threshold-detected by a nonlinear optical logic element. To avoid a data flow bottleneck in the pipeline, (1) requires that

$$t_{nl} \leq T, \qquad (2)$$

where t_{nl} is the full-width half-maximum of the impulse response of the non-linear element.

If the switch is electro-optic, then opto-electronic conversion of the optical controller output is required. It is assumed that the photodetector and preamplifier used for this purpose have bandwidth greater than 1/2T and introduce negligible propagation delay.

Switching requires synchronization between the control signal and the arrival of the information signal at the switch. An optical delay of length t_d is therefore required at the switch input, to match the time for the pipe to fill, that is,

$$t_d = \sum_{i=1}^{k} \tau_i \qquad (3)$$

Summing the linear and nonlinear processing times, the required delay length is

$$t_d = T + t_{nl}. \qquad (4)$$

If (2) and (4) are satisfied, then the pipeline generates a control signal in synchronism with the arrival of the data bit at the input to the switch. Though the pipeline introduces a propagation delay t_d in the switch, no data flow bottleneck occurs since switching is carried out in real time.

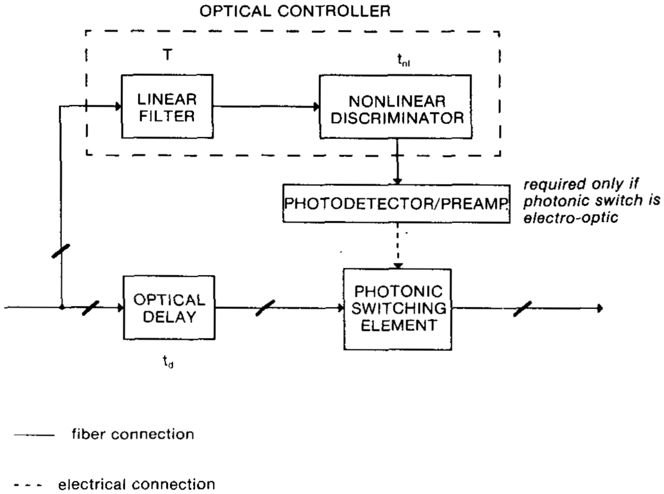

Fig. 1. Self-routing Photonic Switching Architecture. The Slash Indicates Multiple Connections.

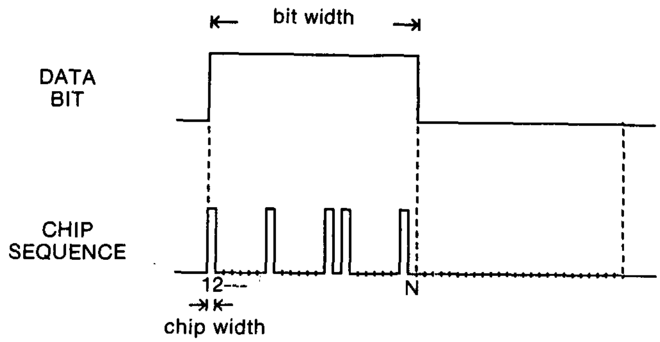

Fig. 2. Encoding of a Data Bit with a Spread Spectrum Chip Sequence. Number of Chips N = 25. Number of 1's P = 5.

Self-Routed Bit Switching with Spread Spectrum

We have investigated spread spectrum code division multiple access (CDMA) as a technique for coding each bit with its destination address.

Each CDMA bit is encoded with a waveform s(t) that corresponds to a code sequence of N chips, representing the destination address of that bit (Fig. 2). An optical matched filter correlates its own stored address f(t) with the received signal s(t). The controller output r(t) is

$$r(t) = \int_{-\infty}^{+\infty} s(z)\, f(t-z)\, dz. \qquad (5)$$

If the signal is to be switched (that is, the switch is to be set in the cross state), then s(t) = f(t), and (5) represents an autocorrelation function (for example, Fig. 3a). If the signal is not to be switched (the switch is to be set in the bar state), then s(t) $\neq$ f(t), and (5) represents a cross-correlation function (such as, Fig. 3b). To maximize the discrimination between the signal to be switched and all other signals at the controller, it is necessary to maximize the peak of the autocorrelation function and minimize the standard deviation of the cross-correlation function. This is accomplished by selecting a set of orthogonal code sequences. Increasing the processing speed, by using optical processing, allows a reduction in chip width and an increase in N. Increasing N yields an increase in the number of orthogonal sequences, and consequently, in the number of assignable addresses.

The set of code sequences that will yield adequate discrimination between the auto- and cross-correlation functions, depends on the nature of the correlation process used. A fundamental difference exists between optical correlation and conventional electronic correlation. Conventional electronic correlation can be based on electrical delay-lines which coherently combine tapped signals [16]. Though optical signals can also be processed coherently, this is not practicable at the present time, owing to the high frequency of the optical carrier. A more feasible optical correlation technique employs fiber-optic delay-lines which incoherently combine tapped signals [17]. This results in a simple summation of optical power.

Thus conventional codes (for example, Gold codes), which exhibit good orthogonality properties with

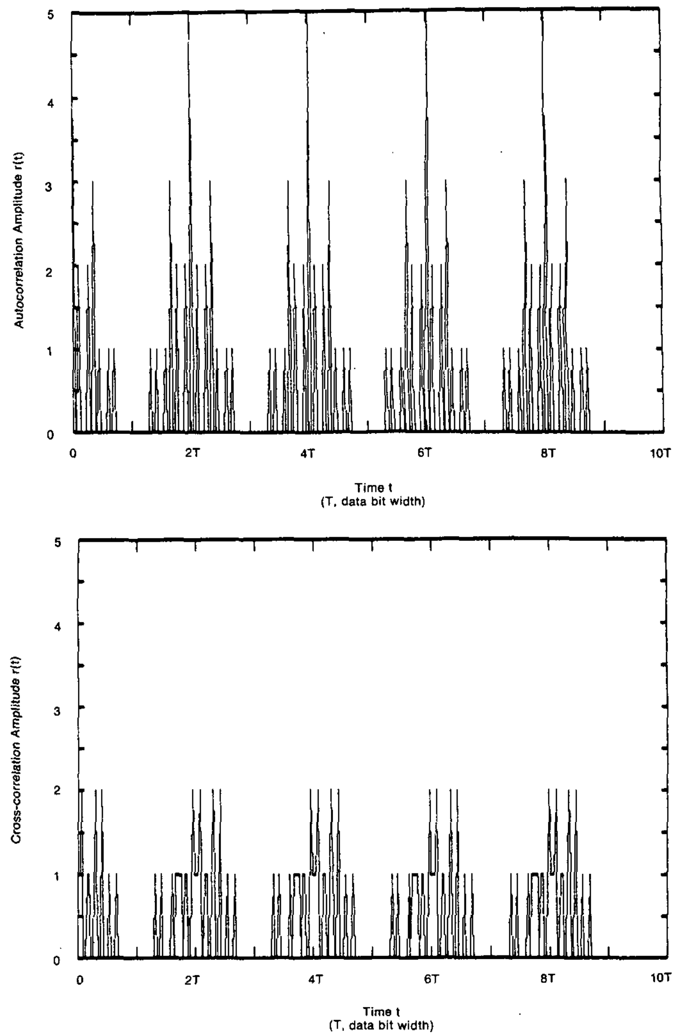

Fig. 3. Optical Processing Performed on a Prime Code Sequence with N=32, P=5 (7 Padding Zeros are Added at the End of the Original Code Sequences). The Data Pattern is 1010101010., a) Autocorrelation Function. b) Cross-correlation function.

conventional coherent correlation are not suitable here. It has been determined that the set of prime code sequences exhibits good orthogonality properties with incoherent optical correlation, [18]. These code sequences have length $N=P^2$ and are generated from prime sequences of length P, with P a prime number. The number of 1's in the code sequence, and therefore the peak of the autocorrelation function equals P. On the other hand, the cross-correlation peak equals the maximum number of coincidences of 1s in all shifted versions of any two code sequences. This maximum value does not exceed 2, independent of P. The prime code sequences have been chosen to represent destination addresses in the following experimental demonstration of optically self-routed bit switching.

Experiment

Setup

The experimental setup is shown in Fig. 4. A 3GHz $LiNbO_3$ integrated-optic waveguide modulator is used as an optical switching element. This modulator is of the

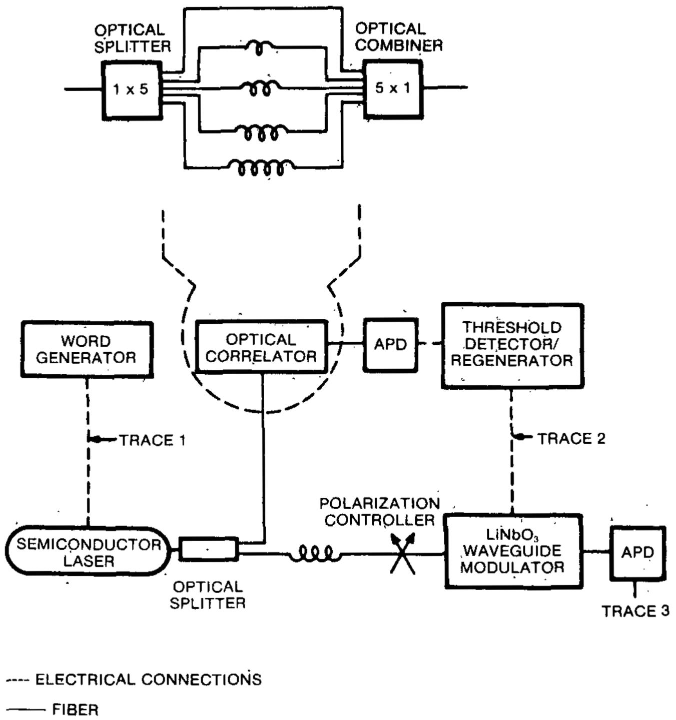

Fig. 4. Setup of the Self-routed Bit Switching Experiment.

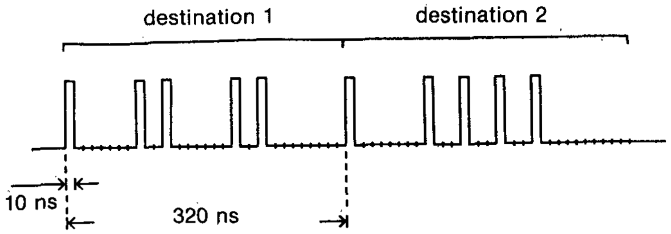

Fig. 5. Orthogonal Spread Spectrum Code Chip Sequences Used in the Experiment. Destination 1: 1000000010010-0000001001000000000; Destination 2: 1000000001000100-0100010000000000. The Last 7 Zeros in Both Sequences Were Added for Experimental Convenience.

Mach-Zehnder interferometric type, with one optical input and one optical output. It is expected that our results will directly apply to a 2X2 directional coupler switch as well. However, a 2X2 electro-optic switch is designed to be in the cross state when no bias is present, and to change to the bar state when a bias is applied. Thus, the detection of an autocorrelation peak would cause the switch to change from the cross to the bar state. This is the opposite of the desired effect, since we want the autocorrelation function to contain the switching information. This situation can be remedied by using negative logic to control the switch.

Two alternating spread spectrum sequences of length N=32 are produced by a word generator (seven zeros were added to the original code sequence to get N=32, a more convenient sequence length to use in the experimental setup). Sequence 1 (corresponding to destination 1) is contained in positions 0 to 31, and sequence 2 (corresponding to destination 2) is contained in positions 32 to 63. The two alternating spread spectrum chip sequences used in the experiment are shown in Fig. 5. The transmitted signal is composed of the superposition of a 1010... data pattern transmitted to destination 1 and a 0101... data pattern transmitted to destination 2. The chip rate is 100-Mchips/s and the data rate is 3.125-Mbs. It should be noted that the auto- and cross-correlation functions shown in Fig. 3 were calculated for the actual code sequences and data pattern used in the experiment.

The word generator drives a 100MHz, 830-nm semiconductor laser transmitter. The output of the laser is coupled into a single-mode 8-μm-core fiber optic splitter that directs the encoded data to both the integrated-optic modulator and the optical controller.

A three-turn fiber optic polarizer [19] is used to linearly polarize the light that is then coupled into the 5-μm-wide titanium-indiffused waveguide of the integrated-optic modulator. Input and output fibers are coupled to the waveguide using micropositioners for holding and alignment.

The optical controller is an incoherent fiber-optic delay-line correlator with tap winding lengths matched to the positions of pulses in sequence 1 (Fig. 6). The output of the correlator is converted to an electrical signal using a 100MHz silicon avalanche photodetector/preamplifier combination. Threshold detection of the autocorrelation peak is performed by triggering a 250MHz pulse generator, which in turn generates a 320-ns, 5-V switching pulse with a +2−V dc offset. The dc offset maximizes the extinction ratio of the modulator. The output of the pulse generator is connected to the electrical gating input of the modulator.

A length of fiber matched to the routing processing time of the controller is inserted between the splitter and the optical input of the modulator. This delay ensures that the signal to be switched does not arrive at the modulator before the switch is appropriately set, as mentioned previously.

Results

The results of the demonstration of optically self-routed bit switching are shown in Fig. 7. The alternating electronic spread spectrum sequences at the word generator output are shown in Fig. 7a, trace 1. Sequence 1 generates an optical autocorrelation function at the output of the fiber-optic correlator (Fig. 7b), which triggers a 320-ns electrical switching pulse at the pulse

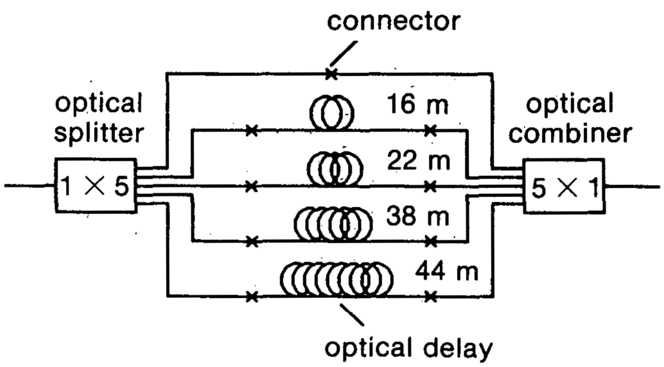

Fig. 6. Fiber-optic Correlator Corresponding to Destination 1.

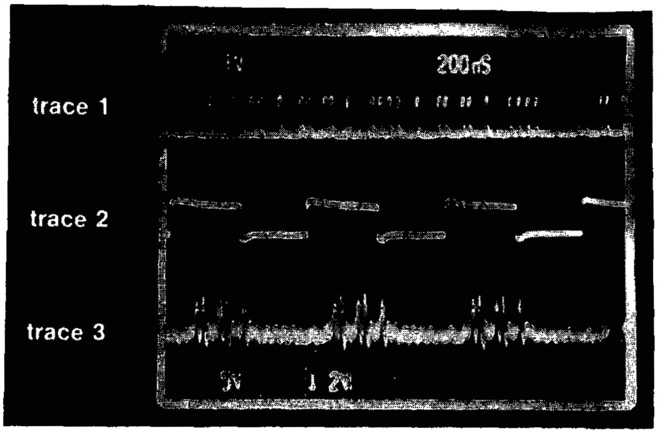

Fig. 7a. Demonstration of Self-routing Optical Data. Trace 1: Alternating Electronic Chip Sequences 1 and 2. Trace 2: 320-ns Gating Pulses. Trace 3: Self-switched Chip Sequence 1.

generator output (Fig. 7a, trace 2). This switching pulse opens the modulator so that sequence 1 passes through. Sequence 2 generates a cross-correlation function at the output of the fiber-optic correlator, which does not generate a switching pulse. The modulator does not open and sequence 2 does not pass through the modulator. The modulator output is shown in Fig. 7a, trace 3. A modulation extinction ratio of 5:1 is achieved as seen by the portion of sequence 2 detected in the "*off*" state of the switch (Fig. 7a, trace 3).

Applications

A bit switching technique has been experimentally demonstrated which would not be practicable without the fast routing capability of optical processing. Real-time self-routing of spread spectrum subencoded bits has been performed. This technique provides several improvements in network performance, as described below.

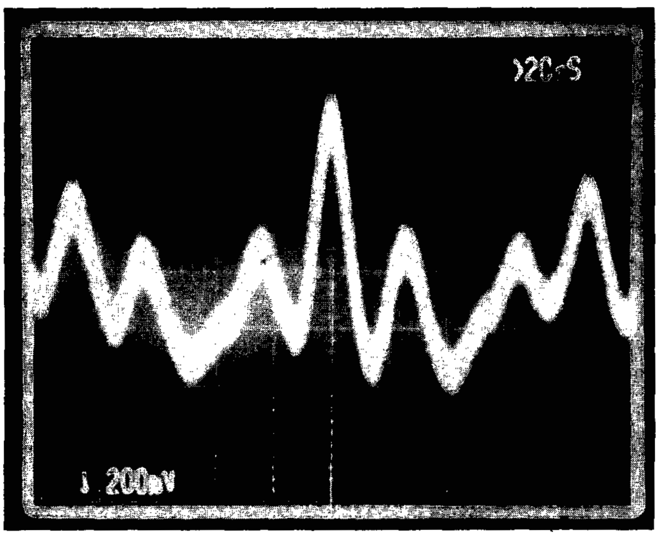

Fig. 7b. Autocorrelation Function for Chip Sequence 1 as Detected at the Output of the Correlator.

Bit switching provides the flexibility of routing data with different bit rates. Before transmission, the lower bit rate data is sampled once per bit interval and a pulse of width equal to the highest rate bit is generated. This provides uniformity of pulse width at the switch input and permits the self-routing of different data types using the same optical processing elements.

The decentralized optical control of a 2×2 switching element can be readily extended to an N×N strictly nonblocking crossbar switch. Such crossbar switches offer a high degree of flexibility, at the expense of requiring N^2 switching elements. As seen in Fig. 8, each input is processed by a set of destination correlators $C_1,...,C_N$, corresponding to the N distinct code sequences. An autocorrelation peak at the output of the k^{th} correlator in the i^{th} row will switch data from input row I_i to output column O_k.

Since the spread spectrum destination code is preserved throughout the routing process, synchronized signals can be self-routed in successive switch stages. At each stage, similar routing processing as previously described is required.

Permitting signals on different input ports to be switched to the same output port without collision is a distinct advantage of spread spectrum bit switching. This is achieved by permuting the order of the correlators in successive rows, so that no two correlators are alike in any column. In this configuration, signals with the same destination address in different input rows are encoded with orthogonal spread spectrum sequences. Since the orthogonal sequences are distinguishable when superimposed, signals on different input ports of the crossbar switch can be switched asynchronously to the same output port without collision. To switch multiple inputs to the same output, the crossbar switch must

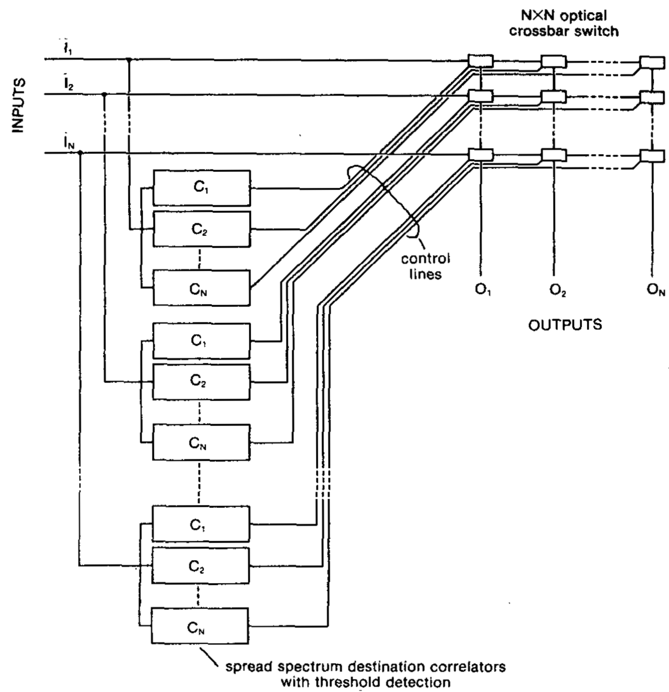

Fig. 8. Extension of the Spread Spectrum Self-routing Control Technique to an N×N Optical Crossbar Switch.

allow only a fraction of the input signal to be switched. This might be achieved by controlling the switching bias voltage. The fact that bits to the same destination are encoded differently requires that each destination be able to recognize more than one sequence. It also renders the routing in subsequent stages more complex.

An application of switching multiple inputs to the same output is the integration of services. Various services (such as, voice, data, video) arriving at distinct input ports of the N×N switch, but destined for the same user, can be switched to the same output port without collision.

Though we have confined our discussion of N×N switching to the crossbar configuration, it is expected that this technique will be applicable to other configurations (for example, tree, Benés network, . . .) as well [20]. It is expected that the real-time self-routed bit switching technique developed here can be easily extended to other switching techniques, such as packet switching. Finally, destination encoding is not restricted to spread spectrum. Other address encoding techniques that are suitable for all-optical processing, such as time-division multiplexing, will be investigated in the future.

References

[1] P. R. Prucnal, M. A. Santoro, S. K. Sehgal, and I. P. Kaminow, "TDMA fibre-optic network with optical processing," *Electron. Letters*, vol. 22, no. 23, pp. 1218-1219, 1986.

[2] Paul R. Prucnal, Mario A. Santoro, and Sanjay K. Sehgal, "Ultrafast all-optical synchronous multiple access fiber networks," *IEEE Jour. on Selected Areas in Comm.*, vol. SAC-4, no. 9, pp. 1484-1493, 1986.

[3] R. C. Alferness, "High-speed optical switches for single-mode lightwave communications," *Proc. IEEE GLOBECOM '84*, vol. 2, paper 26.2, pp. 874-877, 1984.

[4] R. A. Becker, "Broad-band guided-wave electrooptic modulators," *IEEE Jour. of Quantum Electronics*, vol. QE-20, no. 7, pp. 723-727, 1984.

[5] L. Thylén, A. Djupsjöbacka, B. Lagerström, and P. Svensson, "High speed $LiNbO_3$ integrated optics modulators and switches," in *Integrated Optical Circuit Engineering, Proc. of SPIE 517*, pp. 249-257, 1985.

[6] R. A. Becker and W. S. C. Chang, "Electrooptical switching in thin film waveguides for a computer communication bus," *Applied Optics*, vol. 18, no. 19, pp. 3296-3300, 1979.

[7] H. S. Hinton, "A nonblocking optical interconnection network using directional couplers," *IEEE GLOBECOM '84*, vol. 2, paper 26.5, pp. 885-889, 1984.

[8] A. Neyer, W. Mevenkamp, and B. Kretzschmann, "Nonblocking 4 × 4 switch array with sixteen X-switches in $Ti:LiNbO_3$," *IGWO '86 Tech. Digest*, paper WAA2, p. 4, 1986.

[9] P. Granestrand and L. Thylen, "Strictly nonblocking 8 × 8 integrated-optic switch matrix in $Ti:LiNbO_3$," *IGWO '86 Tech. Digest*, paper WAA3, pp. 4-5, 1986.

[10] Ron A. Spanke, "Architectures for large nonblocking optical space switches," *IEEE Jour. of Quantum Electronics*, vol. QE-22, no. 6, pp. 964-967, 1986.

[11] A. Lattes, H. A. Haus, F. J. Leonberger, and E. P. Ippen, "An ultrafast all-optical gate," *IEEE Jour. of Quantum Electronics*, vol. QE-19, no. 11, pp. 1718-1723, 1983.

[12] H. M. Gibbs, "Optical switching: controlling light with light," in *Optical Bistability: Controlling Light with Light*, chapter 5, Academic Press, Inc., Orlando, FL, 1985.

[13] P. W. Smith, "On the physical limits of digital optical switching and logic elements," *Bell System Tech. Jour.*, vol. 61, no. 8, pp. 1975-1993, 1982.

[14] T. Haque and M. Arozullah, "A microprocessor and optoelectronics based packet switch for satellite communications," *Proc. IEEE ICC'81*, vol. 1, paper 15.3, pp. 82-86, 1981.

[15] Alan Huang, "Optical switching computers," *Proc. IEEE GLOBECOM '84*, vol. 2, paper 26.8, pp. 903-906, 1984.

[16] K. P. Jackson, S. A. Newton, B. Moslehi, M. Tur, C. C. Cutler, J. W. Goodman, and H. J. Shaw, "Optical fiber delay-line signal processing," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-33, no. 3, pp. 193-209, 1985.

[17] M. A. Santoro and P. R. Prucnal, "Asynchronous fiber optic LAN using CDMA and optical correlation," *Proc. of the IEEE*, in press.

[18] P. R. Prucnal, M. A. Santoro, and T. R. Fan, "Spread spectrum fiber-optic local area network using optical processing," *Jour. of Lightwave Tech.*, vol. LT-4, no. 5, pp. 547-554, 1986.

[19] H. C. Lefevre, "Single-mode fibre fractional wave devices and polarization controllers," *Electron. Letters*, vol. 16, no. 20, pp. 778-780, 1980.

[20] Alexander A. Sawchuk and B. Keith Jenkins, "Dynamic optical interconnections for parallel processors," in *Optical Computing, Proc. of SPIE 625*, pp. 143-153, 1986.

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