Intelligent photonic switch based on polarization-selective birefringent computer-generated holograms

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We designed and implemented an intelligent reflecting 2 × 1 photonic switch using polarization-selective birefringent computer-generated holograms combined with two polarization modulators. In functional terms, the reflecting switch provides a through path to the output when only one incoming link is transmitting. When both incoming links attempt transmission, the switch turns reflecting, thereby permitting a full exchange of the two incoming streams. The switch can also be set to detect backpropagating beams at its output, to split the beam evenly, and to route the two resulting beams to each of the two inputs. The switch is useful for ultrafast fault-tolerant photonic network applications.

The decomposition of communication functions into layers fostered portability across platforms and permitted the parallel development of protocols, devices, and architectures. With the maturing of networking technology, it seems worthwhile to reexamine networking devices and protocols from a new perspective. Can we migrate higher-layer networking functions directly into the lower layers by developing new devices that bear the most promise for large-scale deployment?

Efficient multiplexers and switches are key to the design of high-speed networks. Both of these functions involve many independent users attempting simultaneous access to one or more links. Contention is inherent in the process, and the manner in which it is overcome determines the efficiency of the overall system. Contention is usually resolved by a careful exploitation of the feedback.[1] The type of feedback available and the fate of contending users are determined by the physical nature of the transmission medium. At times, the contention resolution functions are concentrated in a specialized scheduling device and viewed as being exterior to the switch. In some candidate designs[2,3] the contention resolution device must function at speeds that are a multiple of the rate at which cells must be switched. Thus it is common for the contention resolution device to be the bottleneck, and the topic merits continued scrutiny. Therefore we designed an intelligent device that generates enhanced feedback to permit the downward migration of higher-layer protocols. This high-speed optical implementation is consistent with the overall trend toward third-generation devices with all-optical paths through the switches even though the controls are initially electrical.

In this Letter we report a photonic switch with a novel reflecting property. Stated in functional terms, the reflecting switch is a 2 × 1 switch that provides a through path to the output when only one incoming link is transmitting. When both incoming links attempt transmission, the switch turns reflecting, thereby permitting a full exchange of the two incoming streams. The switch can also be set to detect backpropagating beams at its output, to split the beam evenly, and to route the two resulting beams to each of the two inputs. This is in contrast to commonly used switching structures in which, in the event of a contention, one of the two streams would go through. Clearly, the reflecting switch would perform poorly if used in conventional architectures. Hence, new architectures must be explored with regard to the value of feedback information in the migration of higher-layer networking functions directly into lower-layer devices. The 2 × 1 reflecting switch is composed of two standard 1 × 2 switches wired together appropriately. Of particular interest to us is a high-speed optical implementation of the reflecting switch made by integrating novel polarization-selective birefringent computer-generated holograms (BCGH's) with polarization modulators. A BCGH is a general-purpose diffractive optical element that possesses two independent impulse responses for two orthogonal linear polarizations.[4] The concepts of 1 × 2 and 2 × 2 optical switches with BCGH elements have been demonstrated.[5]

A schematic diagram of the reflecting photonic switch with BCGH elements is shown in Fig. 1. The switch consists of four BCGH elements, two polarization modulators (PM's), a mirror, and a quarter-wave ($\lambda/4$) plate. The BCGH elements are diffractive polarization beam splitters/combiners. Both BCGH1 and BCGH2 transmit straight, vertically polarized light, whereas the horizontally polarized light is de-

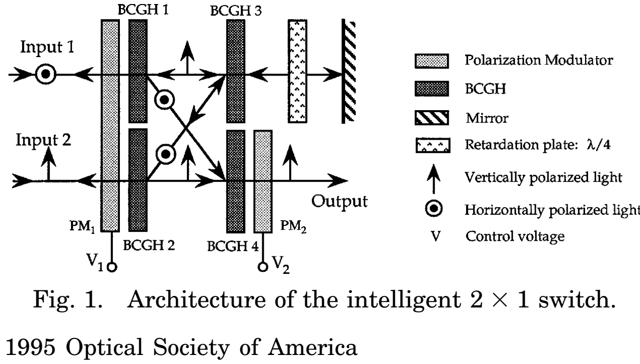

Fig. 1. Architecture of the intelligent 2 × 1 switch.

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Table 1. Truth Table of the Intelligent Switch[a]

PM_1, PM_2	I_1(HP), —	—, I_2(VP)	I_1(HP), I_2(VP)
0, 0	**I_1(HP), —, —**	**I_2(VP), —, —**	I_1(HP) + I_2(VP), —, —
0, 1	**I_1(VP), —, —**	**I_2(HP), —, —**	I_1(VP) + I_2(HP), —, —
1, 0	—, —, I_1(VP)	—, I_2(HP), —	**—, I_2(HP), I_1(VP)**
1, 1	—, —, I_1(VP)	—, I_2(HP), —	**—, I_2(HP), I_1(VP)**

[a]The boldface entries are valid switch outputs.

flected at an angle (Fig. 1). BCGH3 and BCGH4 are identical to BCGH1 and BCGH2, respectively, but are used as polarization beam combiners. BCGH3 also routes the beams reflected from the mirror to either BCGH1 or BCGH2, depending on the polarization of these beams. The fast axis of the $\lambda/4$ plate in the switch is oriented at 45° to the horizontal axis; thereby both horizontally and vertically polarized light will be rotated by 90° on propagation through the $\lambda/4$ plate twice. This switch is useful for distributed control networks, in which a pair of photodetectors (not shown in Fig. 1) may be added to the switch. A small fraction of input signals is deflected into these photodetectors to measure the activity at the inputs and generate the control signals needed to set the state of the switch.

Table 1 summarizes the different states of the switch, in which the boldface entries correspond to the desirable switch settings. The (i, j)th entry in the table specifies the three signals: the switch output, reflection to input node 1, and reflection to input node 2 when the PM's are set as in the ith row and the applied input signals are set as in the jth column. The 1 and 0 in the PM setting column indicate polarization rotation of the incoming light by 90° and 0°, respectively. Note that the switch can also be used to backpropagate by setting the PM's to state $(0, c)$, where c corresponds to a voltage that turns PM_2 into a $\lambda/4$ plate. This setting changes linear polarization to circular, and, consequently, backpropagating signals are sent evenly to both input nodes.

To demonstrate the 2×1 photonic switch we designed and fabricated a four-phase-level BCGH switching element that integrates BCGH1 and BCGH2 side by side. The measured diffraction efficiency of the BCGH element was 26%, and the polarization contrast ratio was 80:1. A pair of such elements was used to construct the intelligent 2×1 photonic switch. The schematic diagram of the experimental demonstration setup is shown in Fig. 2, where a cw Ar^+ laser at $\lambda = 514.5$ nm was used. For identification purposes, two input beams modulated at two different frequencies by two mechanical beam choppers were used to simulate two input channels. A pair of beam splitters and photodetectors (P1 and P2) was placed at the input nodes to permit the detection of the reflected signals. A third photodetector (P3) was used to measure the transmitted output signals. Figure 3 illustrates the oscilloscope traces showing the three detected signals corresponding to the different input combinations and switch settings. In all three photographs the top traces show the signals detected by P3 at the output of the switch; the middle and the bottom traces show the signals reflected to the input nodes 1 and 2, respectively. Figures 3(a) and 3(b) show the results obtained with only one active input to the switch. In contrast, Fig. 3(c) shows the results obtained when both inputs to the switch were active. In this state (PM_1 in state 1) the input signals were not transmitted to the output of the switch; instead they were exchanged and reflected back to the input nodes.

The performance of the 2×1 switch was also evaluated in terms of signal-to-noise ratio (SNR) at the output and input nodes of the switch. The output SNR is the ratio of the light intensities measured by P3 when only one input to the switch is active to that measured by P3 when both inputs to the switch are active. The measured switch output SNR was better than 10:1, and the measured insertion loss was less than 12 dB. The SNR at each input node is the ratio of the reflected signal intensities when both inputs to the switch are active to that when only one input to the switch is active. Both input nodes' SNR's were measured to be symmetric with values of better than 50:1 and insertion losses of less than 25 dB for reflection mode operation. The insertion losses for the reflected beams are in quadratic relation to the insertion losses for the output beam because the reflected beams pass through twice as many BCGH elements. To compensate for this asymmetry we scaled the top traces of Fig. 3 by a factor of 25. Note that better-performance BCGH elements can minimize the overall insertion losses.[4,5]

In the following, we introduce and discuss a multiplexer application that uses a simple binary tree architecture composed of a number of the 2×1 reflecting switches. One of the nodes is a special service control device whose function is outlined below

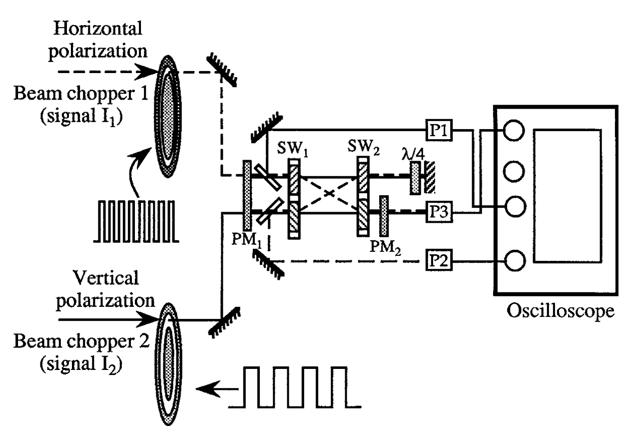

Fig. 2. Schematic of the experimental setup for demonstration of 2×1 reflective optical switch: SW_1, SW_2, switches.

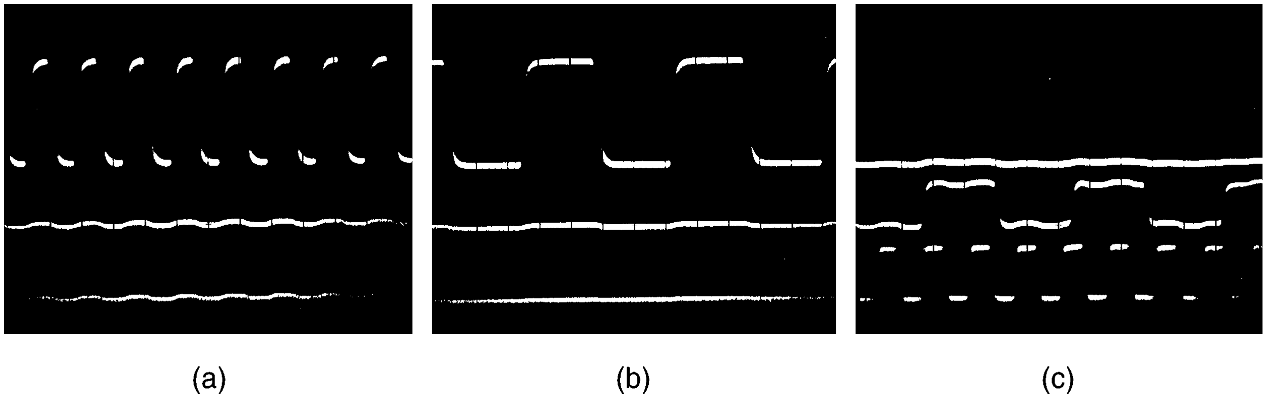

Fig. 3. Oscilloscope traces: (a) only I_1 is active, (b) only I_2 is active, (c) both I_1 and I_2 are active.

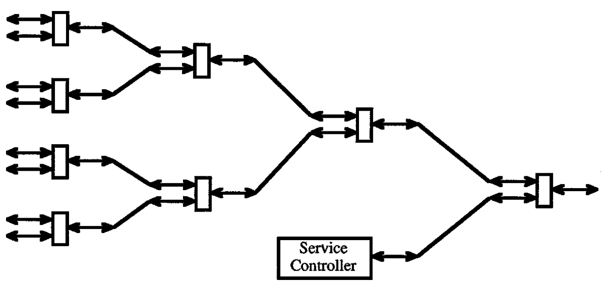

Fig. 4. Multiplexer architecture.

(Fig. 4). The nodes are assumed to generate cells of fixed length for multiplexing. The system is assumed to be cell synchronized and operates in a gated mode. Initially, all nodes transmit their outstanding cell backlogs (including an explicit transmission to indicate no backlog). Because of the reflecting nature of the 2×1 switches this will result in each node of a pair connected to a common switch becoming aware of the other's backlog. At the next step, every alternate node is required to transmit all the backlog information that it is aware of. Continuing this iterative process will result in the rate control module's becoming aware of the backlog of each of the N nodes after $\log N$ steps. This global information can be used to formulate and implement a large number of service policies that might be designed to address various service needs, such as bounds on jitter or delay variability. The broadcast of control information can be initiated by the service control module. In slot ($\log N + 1$) the extra switch at the apex of the tree is set to state (1, 0), and all other nodes desist from transmitting. The first action results in the injection of the broadcast data at the root node for backpropagation. The second action will allow the reflecting switches to sense the backpropagating data and set all subsequent switches to back propagate mode (0, c) as the broadcast information fans out.

The proposed architecture can be shown to be fault tolerant and is versatile enough to permit the embedding of higher-layer control functions. As an example consider the rate control, a transport layer function. It is well known that congestion in high-speed photonic networks can be controlled by regulating the bursty nature of the sources.[1] The service control module can be programmed to schedule transmissions in a manner that ensures that the data rate in a preset sliding window remains below a preset threshold.

Another example of a higher-layer control function that can be migrated is synchronization. We have developed a synchronization procedure that allows pairs of nodes that need to reflect to synchronize their clock offsets. This procedure involves $\log_2 N$ steps. At each step nodes reflect off successively higher layers of the tree. At the end of the procedure each node becomes aware of the offset that it must use when reflecting off any given layer.

In conclusion, we have designed, constructed, and experimentally evaluated a novel type of intelligent 2×1 photonic switch using polarization-selective computer-generated holograms combined with polarization modulators. Application of the switch to implement fault-tolerant multiplexer architecture has been discussed. These preliminary findings suggest that a systematic study of reliability and fault tolerance can be carried out by exploration of the interplay among architecture, protocol, and device level feedback.

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