Ultrafast All-optical Serial-to-parallel Converter Using a Surface-reflection Optical Switch

Takako Yasui†, Ryo Takahashi, and Naoto Kondo

Abstract

An all-optical serial-to-parallel converter (SPC) is promising for signal processing in high-speed optical packet-switched networks. In this paper, we present a novel scheme for an all-optical SPC (1 to 16) that can handle ultrafast (40-Gbit/s to 1-Tbit/s) asynchronous optical packets. A key device in the converter is an asymmetric Fabry-Perot (AFP) all-optical switch called LOTOS (low-temperature-grown optical switch) operated in a spin-polarization scheme. We have found that the spin-polarized AFP switch needs a different design from the conventional AFP switch and that the optimized spin-polarized AFP switch meets all of the requirements for a many-channel SPC, such as a high switching efficiency, a high on/off ratio, and large tolerances to the incident angle and input signal power.

1. Introduction

To cope with the explosive growth in IP traffic, we must increase link capacities by using wavelength division multiplexing (WDM) while simultaneously increasing the packet transfer speed at nodes. Therefore, research on photonic networks that use optical technologies has become very active. One promising solution is G-MPLS (generalized-multiprotocol label switching) technology, which treats a wavelength as a label. This scheme can reduce transmission delays and significantly increase throughput. It does not, however, use wavelength efficiently. Optical packet switching is a more promising solution because it enables maximum utilization of the bandwidth of a given single channel. The key functions for achieving such future large-capacity optical packet-switched networks include burst-mode synchronization [1], [2], optical label processing [3]-[6] (recognition and swapping), packet compression/decompression [7], 3R regeneration, and buffering [8], [9] for high-speed asynchronous burst-mode optical packets. There has been considerable research on implementing these functions in the optical domain. However, during label recognition, the input label usually refers to a routing table containing many addresses and corresponding route information. This process should inevitably be entrusted to electronics, specifically to large-scale CMOS-based integrated circuits (CMOS: complementary metal-oxide semiconductor). However, high optical packet bit rates will increase the difficulty of using electronic circuits. Several approaches to label coding based on subcarrier multiplexed labels or slow wavelength labels have been demonstrated to overcome the difficulty of label recognition. In a subcarrier transmission scheme, the subcarrier frequency must be much higher than the data bit rate, meaning that higher frequency modulators and receivers are required. On the other hand, in a wavelength label transmission scheme, many wavelengths are required for the labels in WDM networks.

In contrast, a "self-serial-to-parallel" conversion scheme (**Fig. 1**) would make it possible to recognize high-speed serial labels easily by using conventional smart CMOS electronic circuits that consume little power because all the bits of the incoming serial label are automatically converted to slow parallel electrical signals. In this paper, we describe our approach for making an ultrafast all-optical SPC* for label recognition of asynchronous optical packets.

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* SPC: refers to both a serial-to-parallel converter and the process of serial-to-parallel conversion.

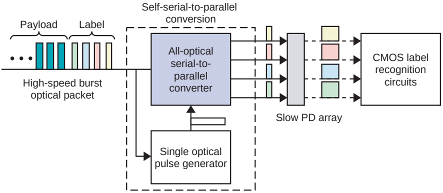


Fig. 1. Label recognition scheme using self-serial-to-parallel conversion.

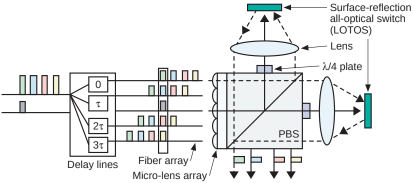


Fig. 2. All-optical serial-to-parallel conversion scheme using surface-reflection all-optical switches.

2. All-optical serial-to-parallel conversion

Several approaches to SPC [10]-[15] have already been demonstrated that use second harmonic generation, wavelength conversion, and four wave mixing. However, no one has managed to find a solution that meets all the requirements, which include operation in the 1.55-μm band, compactness, polarization insensitivity, and low pump power. In this section, we explain the operating principle of our SPC that utilizes a spin-polarization scheme, and describe an asymmetric Fabry-Perot (AFP) ultrafast surface-reflection all-optical switch called LOTOS (low-temperature-grown optical switch) [16], which is a key device for the SPC. We also describe a new design for the spin-polarized AFP switch to improve its various characteristics required for use in SPC.

2.1 Principle

Figure 2 shows the concept of our proposed scheme for all-optical SPC [14]. An incoming optical packet with an N-bit label is split into N packets, which are then coupled into N different delay lines. Each line has a different delay such that the nth line has a delay of (n-1) times the bit separation τ. Then there is a time window that encloses all the bits from 1 to N. The individual optical packets from a fiber array are collimated using a two-dimensional micro-lens array and divided using a polarizing beam splitter (PBS) into two orthogonal, linearly polarized beams whose energies vary according to their polarization. The beams are focused to a spot on each optical switch. Meanwhile, a circularly polarized pump pulse is launched into the center of the PBS and divided into two linearly polarized pulses with the same energy. After being converted into circularly polarized pulses using λ/4 plates, the two pump pulses are also focused to the same spot on each optical switch, and the reflectivity during the time window is increased. As a result, all the bits within the time window are simultaneously output in parallel. Thus, handling the two orthogonal components of the signal pulses at two different switches makes the SPC insensitive to polarization.

The parallel output optical signals are then converted into slow parallel electrical signals using a photodetector array. Here, in order to obtain high contrast for the electrical output signals, an extremely high on/off ratio is required for the optical switch because the residual outputs of the optical pulses outside the time window accumulate in the slow photodetector, resulting in considerable degradation in the contrast ratios of the electrical signals. In our SPC, the on/off ratios are greatly improved by using a spin-polarization scheme as described below [18].

In quantum wells, particularly compressively strained ones, the heavy- and light-hole bands are completely split. Therefore, when a circularly polarized pump pulse is irradiated, only the spin-down (or spin-up) carriers are excited by the pump pulse. The electron transitions bring about excitonic absorption saturation due to phase space filling (PSF) and the Coulomb contribution (plasma screening of the Coulomb interaction and exciton linewidth broadening). The PSF contribution is spin-dependent and is dominant for the excitonic absorption saturation, especially in InGaAs MQWs (multiple quantum wells) because of their small effective mass. Meanwhile, the Coulomb contribution is spin-independent and interacts with any signal light. Under this pumping condition, a linearly polarized signal pulse passing through the MQW changes into a rotated elliptical polarized pulse. This is because the linear polarization is composed of left- and right-hand circular polarizations, and only a component with the same circular polarization as the pump pulse can see the absorption saturation and refractive index change due to the PSF. An oppositely polarized component cannot see the changes at all unless the spin polarization relaxes. In contrast, the signal pulse shows no polarization change without a pump pulse. Therefore, the off-state pulses outside the time window can be completely cut off by the PBS, while the on-state pulses within the time window can pass through the PBS, greatly improving the on/off ratio.

2.2 Ultrafast all-optical switch: LOTOS

Low-temperature epitaxial growth [16]-[18] is a promising method for reducing the absorption recovery time. Various studies have shown that GaAs grown at low temperature (about 200°C) is non-stoichiometric, with about 1% excess arsenic being incorporated during growth as As_{Ga} antisite defects (10^{19}–10^{20} cm^{-3}). These As_{Ga}-related defects contribute to the ultrafast (about 200 fs) trapping of photo-excited electrons. However this GaAs material absorbs light only at wavelengths below 0.9 µm, precluding its use in the 1.55-µm band typically employed by optical communications devices. To overcome this limitation, an attempt was made to grow InGaAs/InAlAs MQW structures by gas-source molecular beam epitaxy (GS-MBE) at low substrate temperatures [18]. The recovery time became faster with decreasing growth temperature, but even the fastest recovery time obtained with a 200°C-grown sample was three orders of magnitude slower than the 200-fs recovery time measured for GaAs grown at the same growth temperature. These results indicate that there are fewer excess As-based deep trap centers in 200°C-grown InGaAs wells than in 200°C-grown GaAs wells [19].

Beryllium doping was then tried in an effort to reduce the recovery time further [18]. The recovery time was reduced by two orders of magnitude as the Be doping level was increased, reaching the sub-picosecond region. However, this degrades the optical nonlinearity because the height of the excitonic absorption peak is reduced. Therefore, we tried two approaches to compensate for the reduced optical nonlinearity. First, we introduced 1% compressive strain into the quantum wells. Compressive strain causes a split between the heavy- and light-hole excitons, which produces clearer excitonic features. In addition, it lowers the density of states in the valence band of the quantum wells, so absorption requires fewer carriers to reach saturation. Second, we introduced a reflection geometry combined with a low-reflectivity distributed Bragg reflector (DBR), namely an asymmetric Fabry-Perot etalon [20], [21] with a low finesse. **Figure 3(a)** shows the device structure of the LOTOS. Nonlinearity in the reflectivity can be greatly enhanced only when the device meets an impedance-matching condition (where the two reflected beams, one from the DBR and one from the Au mirror, have the same amount of energy and are out of phase).

The newly developed saturable absorber with both an ultrafast recovery time and very large optical nonlinearity offers ultrafast surface-reflection all-optical switching. **Figures 3(b)** and **(c)** show the time-resolved reflectivity of the probe pulses (a spin polarization scheme was not utilized here). For the LOTOS with a Be-doping level of 4.3×10^{17} cm^{-3} (LOTOS A), the 1.5-ps optical gate opened with an on/off ratio of more than 20 for a pump pulse energy of 2 pJ. Furthermore, when we increased the Be-doping level to 7.8×10^{17} cm^{-3} (LOTOS B), a response time of 250 fs was obtained with an on/off ratio of 26 for a 10-pJ pump energy.

2.3 Design optimization

Although the spin-polarization scheme enables us

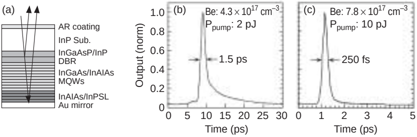


Fig. 3. (a) Device structure of the LOTOS. Time-resolved normalized reflectivity of the probe pulses for (b) a LOTOS with a Be-doping level of 4.3×10^{17} cm^{-3} and (c) a LOTOS with a Be-doping level of 7.8×10^{17} cm^{-3}.

to achieve an extremely high on/off ratio, it reduces the efficiency (on-state reflectivity). Therefore, we numerically investigated the optimum structure of the AFP switch operated in the spin-polarization scheme to obtain high efficiency in addition to a high on/off ratio. The absorption coefficients used in the calculations were estimated experimentally using a 1-µm-thick sample without a DBR, and the extinction ratio of the PBS was assumed to be 1:1000.

Figure 4(a) compares the on/off ratios of AFP switches with and without using a spin-polarization scheme. The AFP switches provide high on/off ratios only when the DBRs meet the impedance-matching condition. Meanwhile, combination with the spin-polarization scheme can improve both the on/off ratios and the DBR fabrication tolerance. Furthermore, it is noted that in the spin-polarization scheme, the output signals exhibit maximum efficiencies at higher DBR reflectivities than under the impedance-matching condition, while maintaining high on/off ratios (**Fig. 4(b)**).

We also investigated the benefits of the spin-polarization scheme to our SPC system. As mentioned above, many parallel beams are focused with various incident angles to a spot on the switch in our SPC system. However, the AFP switch itself provides high on/off ratios only at a fixed incident angle that offers impedance-matching (**Fig. 5(a)**). In contrast, the spin-polarization scheme provides high on/off ratios for a wide range of incident angle. Furthermore, the on/off ratios of the AFP switch degrade sharply with increasing total signal energy due to the absorption saturation caused by the total signal energy focused on the switch (**Fig. 5(b)**). However, with the spin-polarization scheme, the AFP switches, which are designed to have maximum efficiencies, maintain high on/off ratios even when the total signal has the same power as the pump pulse. These results clearly

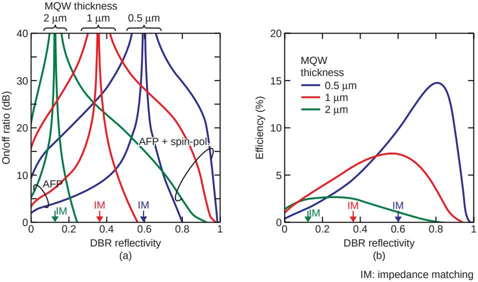


Fig. 4. (a) On/off ratios of AFP swiches with and without a spin-polarization scheme.
(b) Efficiencies of AFP switches with a spin-polarization scheme.

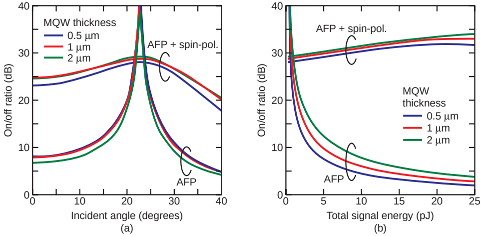


Fig. 5. On/off ratios of AFP switches with and without using a spin-polarization scheme as a function of (a) signal incident angle and (b) total signal energy. The switch is designed to meet the impedance-matching condition at 23°.

indicate that an AFP switch based on a spin-polarization scheme needs a different design from the former switch and is essential for use in multi-channel SPC.

3. Experimental results

3.1 Fiber-based SPC

Figure 6(a) shows a photograph of a fabricated SPC module [14]. It has a fiber array of 18 ports for launching optical packets, which are hexagonally arranged at intervals of 1.5 mm around a central port for a pump pulse. A square λ/4 plate (1.3 mm × 1.3 mm) and a lens array are attached to a cubical PBS (10 mm side). Here, we tested the module operation using an optical switch (LOTOS B). **Figure 6(b)** shows the on/off ratios obtained from an inner and an outer channel as a function of pump energy. 140-fs optical pulses from an optical parametric oscillator with a repetition rate of 82 MHz were divided into pump and signal pulses and launched into the module. The pump pulse was converted to circular polarization by the λ/4 plate, creating spin polarization. Therefore, in the manner mentioned above, with increasing pump energy, the on/off ratios greatly increased almost equally for the inner and outer input signal pulses, reaching about 20 and 30 dB at pump energies of 36 and 98 pJ, respectively. The on-state signal loss was about 16 dB at a pump energy of 98 pJ.

Next, the signal pulse was converted to a 16-bit

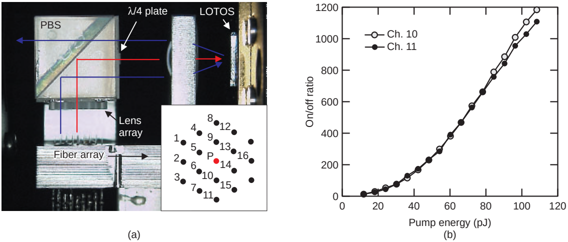


Fig. 6. (a) Photograph of the fabricated module. (b) On/ off ratios obtained for inner channel 10 and outer channel 11 as a function of pump energy.

packet (1011010010110100) with a bit separation of 1 ps (corresponding to 1 Tbit/s) using an optical multiplexer. The optical packet was split into 16 packets, and they were coupled into the ports of the module after they had passed through different delay lines. The delay of each line differed by 1 ps. To make the optical packet parallel, the arrival time of the pump pulse (98 pJ) was fixed at a time window that enclosed all the bits. Each bit signal from the SPC module was converted to a slow electrical pulse using a 1-GHz photodetector and then measured using a sampling oscilloscope. As shown in **Fig. 7**, each bit of the 1-Tbit/s, 16-bit packet was successfully made parallel with a contrast ratio of more than 6 dB, although a small amount of crosstalk was observed from the pump pulse and optical phase-conjugate waves. A higher contrast ratio could be obtained by eliminating this crosstalk. This could be easily achieved by using a pump pulse whose wavelength was different from the signal pulse.

3.2 PLC-based SPC

In the SPC described above, we utilized a fiber array. Therefore, since it was very difficult to obtain accurate delays for each packet by adjusting the fiber lengths, we used 16 variable delay lines in the experiment, which made the whole device rather large. Furthermore, the fiber array must have extremely accurate intervals so that all beams are focused to one spot. Planar lightwave circuit (PLC) technology allows us to monolithically integrate on one chip the 1-to-16 splitter, extremely precise delay lines, and two-dimensionally arranged 45° mirrors with extremely precise intervals. The surface-emitting PLC we used here was designed for parallel conversion of 40-Gbit/s 16-bit optical packets. It is only 32 by 73 millimeters in size, enabling us to make a very compact SPC module. **Figure 8** shows the all-optical SPC using the PLC [15]. The operating principle is the same as mentioned above. The 40-Gbit/s 16-bit incoming optical packets are split into 16 different paths by a PLC and pass through delay lines determined by the bit separation of 25 ps. The 16 split packets are output in a two-dimensional array from the PLC surface by 45° mirrors, and converge to a single point on an all-optical switch (LOTOS A). At this time, the pump pulse irradiates the same point at the time widow for all bits to arrive, and only the pulses within the time window are reflected from the LOTOS and output as parallel optical signals.

Figure 9(a) shows our experimental setup. A 2-ps optical pulse from a fiber laser with a repetition rate of 21 MHz was split into four pulses, which were then converted into four different 40-Gbit/s 16-bit optical packets (A–D) using four different multiplexers. One of the four optical packets was launched into the SPC, and made parallel. **Figure 9(b)** shows an example camera image of the parallel output optical signals of packet B observed using an infrared camera. It can be seen that the packets were successfully converted in

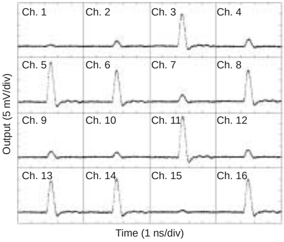


Fig. 7. Output electrical parallel signals.

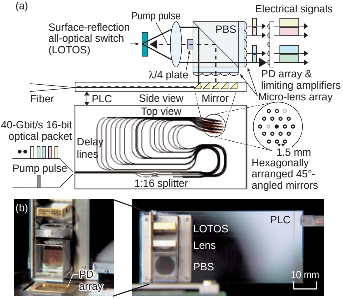
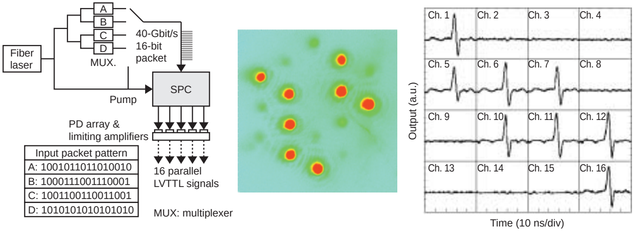


Fig. 8. (a) Configuration and (b) photograph of an all-optical serial-to-parallel converter using a surface-emitting PLC.



(a) (b) (c)

Fig. 9. (a) Experimental setup, (b) camera images of converted parallel optical signals for input packet B, and (c) parallel converted LVTTL electrical signals for input packet B.

parallel with a very high contrast ratio. The parallel output pulses were then converted to LVTTL (low voltage transistor-to-transistor logic) electrical signals (0–3.3 V) using a 16-channel photodetector array and limiting amplifiers. **Figure 9(c)** shows the converted electrical signals for input optical packet B. Other packets were also successfully converted to parallel LVTTL signals. In this experiment, the pulse energies of the pump and the 16-split packets irradiated into the LOTOS were about 20 and 0.25 pJ, respectively. We did not observe any crosstalk in the waveforms after the limiting amplifiers due to their threshold characteristics.

4. Conclusion

We have described a novel scheme for all-optical serial-to-parallel conversion that uses an ultrafast all-optical switch LOTOS made of low-temperature-grown Be-doped strained InGaAs/InAlAs MQWs. We found that when operated in a spin-polarization scheme, an AFP switch with higher DBR reflectivity than that under the impedance-matching condition can provide various advantages indispensable for a many-channel serial-to-parallel converter, such as high switching efficiency, extremely high on/off ratios, and large tolerances to the incident angle and input signal power. Other features are low pump power because all pulses are focused on one spot; compactness due to the two-dimensional arrangement of the inputs and outputs; extensibility of the number of parallel output channels; and polarization insensitivity using two optical switches. We have also demonstrated a 1-Tbit/s, 16-bit all-optical SPC using a fiber-based converter and 40-Gbit/s SPC using a PLC-based converter. Such ultrafast SPCs are promising for highly functional processing of asynchronous high-speed packets because of the availability of conventional smart CMOS circuits.

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