Penalty-Free Error-Free All-Optical Data Pulse Regeneration at 84 Gb/s by Using a Symmetric-Mach–Zehnder-Type Semiconductor Regenerator

Yoshiyasu Ueno, Shigeru Nakamura, and Kazuhito Tajima

***Abstract*—Penalty-free data-pulse regeneration at 84 Gb/s was achieved down to an error rate level of 1×10^{-11} by using a data pattern length of $2^{31}-1$. A symmetric-Mach–Zehnder-type all-optical polarization-insensitive semiconductor regenerator was used.**

***Index Terms*—3R, all-optical, interferometric, jitter, Mach–Zehnder, regeneration, semiconductor, ultrafast.**

I. Introduction

ULTRAFAST optical time-division multiplexing (OTDM) technology, whose bandwidth is not limited by that of electronic devices, is attractive because it leads to more flexible packet networks. Several types of all-optical devices, such as demultiplexers [1]–[5], wavelength convertors [6]–[10], and 3R regenerators [10]–[12], have been proposed and demonstrated. All of these devices in these reports are based on the symmetric-Mach–Zehnder (SMZ)-type interferometric semiconductor switch structure and its mechanism [1], which enables these devices to form a rectangular-like switch window with an ultrafast response time (rise and fall times). The response time is not limited by the slow semiconductor carrier lifetime because the interference cancels out carrier-recovery-induced components. Error-free demultiplexing from 168 to 10 Gb/s has been successfully demonstrated [5].

For 3R-renegeration or wavelength-conversion of ultrahigh bit-rate OTDM data pulses at over 40 Gb/s, not only the impulse response but also the device's repetition rate must be ultrafast. In addition, the devices must follow input data patterns. To date, the SMZ mechanism has been proved to work at repetition rates up to 168 Gb/s [8]–[10], where an ultranarrow switch window width of 1.5 ps was still observed. The input-data pattern-induced effect is suppressed either by the input clock pulses [10], [11] or by the input continuous-wave light [6], [9].

The 3R regeneration (reamplifying, reshaping, and retiming) is an important function for realizing OTDM systems because of their shorter time frame and their larger pulse-quality degradation due to the nonlinear effects in silica fibers. Recently, all-optical 3R regeneration at up to 84 Gb/s, where the regenerators exhibit power penalties of 3–4 dB, has been demonstrated [10], [12]. In this work, we reduced the penalty at 84 Gb/s to almost zero at an error rate of 10^{-11} with a data pattern length of $2^{31}-1$.

Manuscript received October 25, 2000; revised February 8, 2001. This work was supported by the New Energy and Industrial Technology Development Organization, under the management of the Femtosecond Technology Research Association.

The authors are with the Photonic and Wireless Devices Research Laboratories, NEC Corporation, Tsukuba, Ibaraki 305-8501, Japan (e-mail: y.ueno@ieee.org).

Publisher Item Identifier S 1041-1135(01)03745-4.

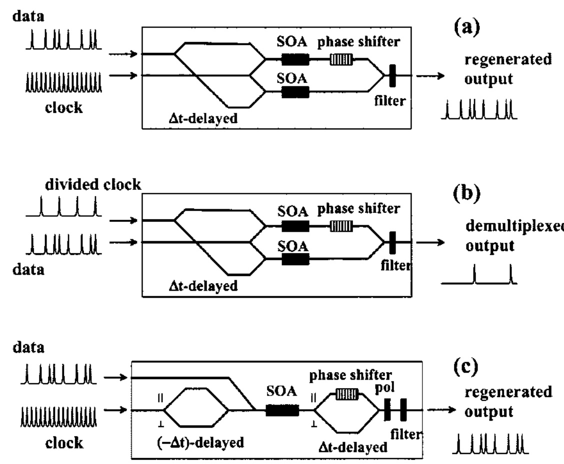

Fig. 1. SMZ-type all-optical device structures: (a) 3R regenerator scheme with SMZ structure, (b) demultiplexer scheme with SMZ structure, and (c) 3R regenerator scheme with PD-SMZ structure.

II. Device Structure

Fig. 1(a) shows a schematic structure of the SMZ-type 3R regenerator [11]. Only the input scheme is different, but the structure is exactly the same as the SMZ demultiplexer [see Fig. 1(b)] used in [1], [4], and [5]. Each time a data pulse triggers the regenerator, the regenerator all-optically forms a rectangular switch window and passes a copropagating clock pulse that coincides with the window (Fig. 2). Thus, input data pulses are replaced with retimed clean data pulses.

In this work, we used an optional SMZ structure, that is, a polarization-discrimination SMZ (PD-SMZ) structure [see Fig. 1(c)] that was originally proposed in [2] and has been used as both demultiplexers [2], [3] and regenerators [10], [12]. This structure needs only one semiconductor optical amplifier (SOA) and its interference is inherently stable (because of the coaxial pulse propagation). The SMZ mechanism works for this device as well [2]. Each data pulse induces a nonlinear

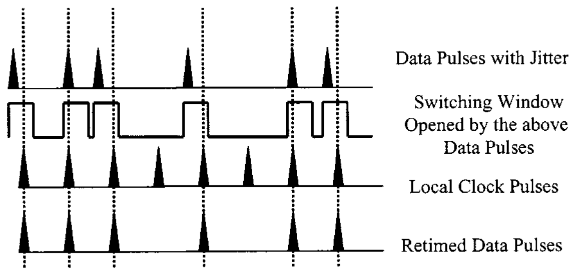

Fig. 2. All-optical 3R regeneration.

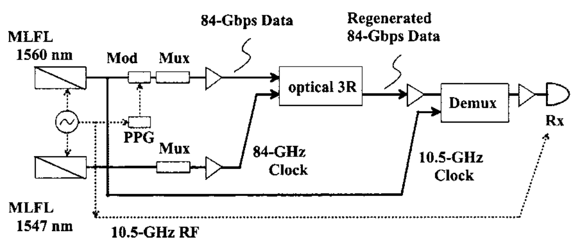

Fig. 3. Experimental setup.

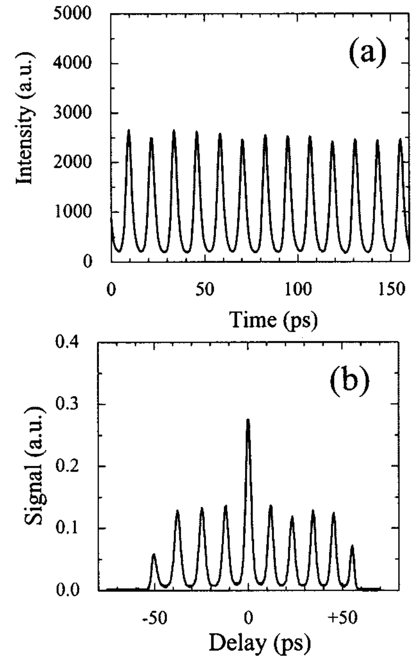

Fig. 4. 84-Gb/s data pulses at the input: (a) averaged image with a streak camera and (b) autocorrelation trace.

refractive-index change in the SOA. Each clock pulse is split into two components in the first MZ interferometer (MZI) and passes through the SOA. When the two components are recombined at the second MZI output, they interfered either destructively or constructively depending on if the clock pulse arrives with a data pulse or not. In this work, the two MZIs were built with calcite crystals and other classical optical components [3], [10] and lens-coupled to the pigtailed fibers of a polarization-insensitive SOA module. The birefringency of the two calcite crystals (6.2 ps) determines the width of the rectangular switch window. A Babinet–Soleil phase shifter for adjusting the interference phase bias was inserted into the second MZI.

III. Experimental Setup

Fig. 3 shows our experimental setup. The 84-Gb/s 1560-nm pseudorandom data pulses were generated with a mode-locked fiber ring laser (Pritel Inc.) synchronized to a 10.5-GHz external RF clock, a 10-GHz lithium niobate modulator, and three stages of fiber multiplexers. The base frequency of 10.5 GHz was chosen so that our 82-MHz streak camera was subharmonically synchronized. The 84-GHz 1545-nm clock pulses were generated with another synchronously mode-locked fiber laser and multiplexers.

The pattern length of the 10.5-Gb/s data was set to $2^{31}-1$, where each pattern includes a 30-consecutive-“0” pattern. When the delay times in multiplexing the 10.5-Gb/s data to 84 Gb/s data are too short (as in [10]) to separate the consecutive-“0” patterns from each other, the multiplexed 84-Gb/s data includes even 200-consecutive-“0” patterns. Such patterns can induce too large pattern-induced effects for the clock pulses to suppress, with temporarily increasing the average carrier density in the SOA. For separating (decorrelating) the 30-consecutive-“0” patterns at 84 Gb/s, we used delay times much longer than those in the previous reports. The delay times (fiber lengths) for the three multiplexer stages were chosen to be 25, 50, and 100 ns (5, 10, and 20 m). The minimum delay time was still much shorter than the 10.5-GHz pattern length (0.2 s) but was long enough to separate the 2.9-ns-long 30-consecutive-“0” patterns from each other.

Despite the long delay fibers inside the multiplexers, we obtained stable 84-Gb/s data pulses with uniform peak heights, uniform spacings, and a short pulsewidth (see Fig. 4). The center peak in Fig. 4(b) is two times higher than the other peaks because of the mark ratio of 50% of the random pulses. The pulsewidths of the data and clock pulses measured at the SOA input with an autocorrelator were 2.1 ps and 2.8 ps, respectively.

The average powers of the data and clock pulses coupled to the SOA chip inside the regenerator were -4 dBm (9 fJ/pulse) and $+2$ dBm, respectively. For measuring the error rate of the regenerated 84-Gb/s pulses, a hybrid-integrated SMZ all-optical demultiplexer in Fig. 1(b) [5] and a commercial 10-GHz receiver system were used.

IV. Results and Discussion

Fig. 5(a) shows the regenerated 84-Gb/s waveforms observed with a streak camera. As seen in the inset, the typical extinction ratio of the regenerated pulses was larger than 17 dB. As shown in Fig. 5(b), 30-GHz sampling after the all-optical demultiplication indicates a clear eye opening.

Fig. 6(a) shows the error rate of the regenerated-and-demultiplexed 10.5-Gb/s data pulses as a function of the delay time for the 84-Gb/s data pulses with respect to the 84-GHz clock pulses. A timing jitter of ± 1 ps (± 8% of the 84-GHz time frame) increases the error rate by a factor of only 10. This jitter-tolerence will be improved by optimizing the switch window shape.

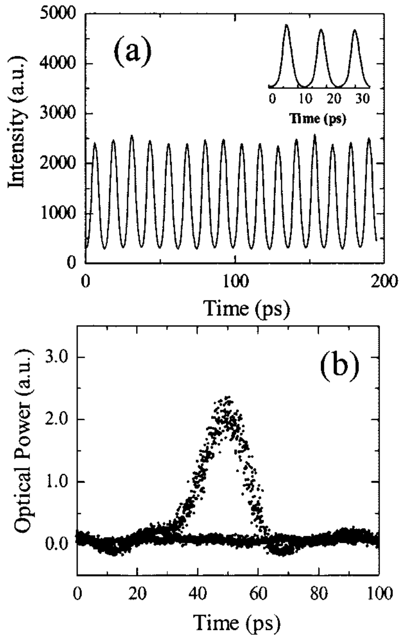

Fig. 5. Regenerated data pulses: (a) streak camera images of the regenerated 84-Gb/s pulses and (b) eye diagram of the regenerated-and-demultiplexed 10.5-Gb/s pulses.

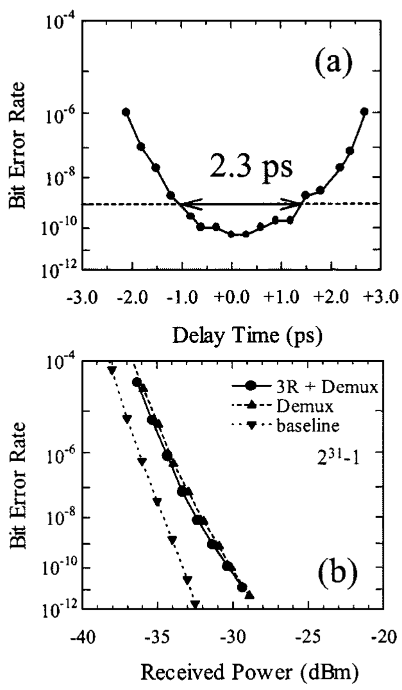

Fig. 6. Error rates of the regenerated pulses.

The solid curve in Fig. 6(b) shows the bit error rate for the regenerated-and-demultiplexed 10.5-Gb/s data pulses as a function of the optical power received by an Er-doped fiber preamplifier in front of the 10-GHz receiver. It should be noted that the error rate was almost insensitive to the input data pulse's polarization.

The dashed curve in Fig. 6(b) shows the error rate for 10.5-Gb/s data pulses directly demultiplexed from the 84-Gb/s data pulses without regeneration, as a reference (the dotted curve shows the baseline of our 10-GHz detection system). As shown, the power penalty of the 3R regeneration alone is negligibly small down to an error rate of 10^{-11}. We attribute this improvement in the power penalty to the above-mentioned data multiplexer. These results indicate that the optical signal-to-noise ratio of the regenerated 84-Gb/s data pulses with a pattern length of $2^{31}-1$ is as high as that of the input clock pulses.

V. Summary

We have achieved penalty-free error-free data-pulse regeneration at 84 Gb/s, for the first time, with a data pattern length of $2^{31}-1$, where an all-optical inherently polarization-insensitive 3R regenerator with a PD-SMZ structure was used. Tolerence to the input timing jitter was also discussed and clearly demonstrated.

References

[1] K. Tajima, "All-optical switch with switch-off time unrestricted by carrier lifetime," *Jpn. J. Appl. Phys.*, vol. 32, pp. L1746–L1749, Dec. 1993.

[2] K. Tajima, S. Nakamura, and Y. Sugimoto, "Ultrafast polarization-discriminating Mach–Zehnder all-optical switch," *Appl. Phys. Lett.*, vol. 67, pp. 3709–3711, Dec. 1995.

[3] S. Nakamura, Y. Ueno, and K. Tajima, "Ultrafast (200-fs switching, 1.5-Tb/s demultiplexing) and high-repetition (10 GHz) operations of a polarization-discriminating Symmetric Mach–Zehnder all-optical switch," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1575–1577, Nov. 1998.

[4] K. Tajima, S. Nakamura, Y. Ueno, J. Sasaki, T. Sugimoto, T. Kato, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki, and T. Sasaki, "Hybrid integrated Symmetric Mach–Zehnder all-optical switch with ultrafast, high extinction switching," *Electron. Lett.*, vol. 35, pp. 2030–2031, Nov. 1999.

[5] S. Nakamura, Y. Ueno, K. Tajima, J. Sasaki, T. Sugimoto, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki, and T. Sasaki, "Demultiplexing of 168-Gb/s data pulses with a hybrid-integrated Symmetric Mach–Zehnder all-optical switch," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 425–427, Apr. 2000.

[6] B. Mikkelsen, K. S. Jepsen, M. Vaa, H. N. Poulsen, K. E. Stubkjaer, R. Hess, M. Duelk, W. Vogt, E. Gamper, E. Gini, P. A. Besse, H. Melchior, S. Bouchoule, and F. Devaux, "All-optical wavelength converter scheme for high speed RZ signal formats," *Electron. Lett.*, vol. 33, pp. 2137–2139, Dec. 1997.

[7] Y. Ueno, S. Nakamura, K. Tajima, and S. Kitamura, "3.8-THz wavelength conversion of picosecond pulses using a semiconductor delayed-interference signal-wavelength converter (DISC)," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 346–348, Mar. 1998.

[8] Y. Ueno, S. Nakamura, and K. Tajima, "Ultrafast 168 GHz 1.5 ps 1 fJ symmetric-Mach–Zehnder-type all-optical semiconductor switch," *Jpn. J. Appl. Phys.*, vol. 39, pp. L806–L808, Aug. 2000.

[9] Y. Ueno, S. Nakamura, H. Hatakeyama, T. Tamanuki, T. Sasaki, and K. Tajima, "168-Gb/s OTDM wavelength conversion using an all-optical SMZ-type switch," in *Dig. 26th Eur. Conf. Optical Communications (ECOC 2000)*, Munich, Germany, Sept. 3–7, 2000, pp. 13–15.

[10] S. Nakamura, Y. Ueno, and K. Tajima, "Error-free all-optical data pulse regeneration at 84 Gbps and wavelength conversion at 168 Gbps with symmetric Mach–Zehnder all-optical switches," in *Dig. Optical Amplifiers and Applications*, Quebec, Canada, July 9–12, 2000, Paper PD4-1.

[11] L. Billes, J. C. Simon, B. Kowalski, M. Henry, G. Michaud, P. Lamouler, and F. Alard, "20 Gbit/s optical 3R regenerator using SOA based Mach–Zehnder interferometer gate," in *Dig. 23rd Eur. Conf. Optical Communications (ECOC '97)*, vol. 2, Edinburgh, U.K., Sept. 22–25, 1997, pp. 269–272.

[12] A. E. Kelly, I. D. Phillips, R. J. Manning, A. D. Ellis, D. Nesset, D. G. Moodie, and R. Kashyap, "80 Gb/s all-optical regenerative wavelength conversion using semiconductor optical amplifier based interferometer," *Electron. Lett.*, vol. 35, pp. 1477–1478, Aug. 1999.