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All-Optical Bit-Rate Flexible NRZ-to-RZ Conversion Using an SOA-Loop Mirror and a CW Holding Beam

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All-optical non-return-to-zero (NRZ) -to- return-to-zero (RZ) data-format conversion has been successfully demonstrated using a semiconductor optical amplifier in a fiber-loop mirror (so-called SOA-loop mirror) with a continuous-wave (CW) holding beam. The converted RZ signal after pulse compression has been used to create a 40 Gb/s OTDM (Optical Time Division Multiplexing) signal. Here is proposed an NRZ-to-RZ conversion method without any additional optical clocks, unlike conventional methods based on optical AND logic. In addition, it has the merit of operating at various bit-rate speeds without any controlling device. Moreover, it has a simple structure, and it can be used for all-optical bit-rate-flexible clock recovery.

Keywords : All-optical data format conversion, Non-return-to-zero (NRZ), Return-to-zero (RZ), wavelength division multiplexing (WDM), Optical time division multiplexing (OTDM)
OCIS codes : (060.0060) Fiber optics and optical communications; (060.4510) Optical communications

I. INTRODUCTION

Future all-optical networks are mainly based on two promising techniques, based on Wavelength Division Multiplexing (WDM) and Optical Time Division Multiplexing (OTDM) technologies [1, 2]. These approaches would essentially use two standard data formats, (return-to-zero (RZ) and non-return-to-zero (NRZ)). Generally, the RZ format relies on the bit-interleaving method, and is preferred in ultrafast OTDM networks. The NRZ format, on the other hand, has a lower bandwidth requirement, with higher timing jitter tolerance than the RZ format. Therefore, a conversion between these two data formats becomes necessary in linking and interfacing ultrafast OTDM networks with low-speed WDM networks [1, 2]. In this paper, an NRZ-to-RZ conversion method is proposed for an ultrafast OTDM channel multiplexed from low speed WDM channels while maintaining optical transparency.

An appreciable number of all-optical data-format conversions have been reported, including semiconductor optical amplifier (SOA) gain compression [1, 2], a monolithically integrated Michelson interferometer (MI) employing SOAs [3], an SOA/fiber grating wavelength converter [4], a nonlinear optical loop mirror (NOLM) with SOA [5-7, 15], cross-phase modulation (XPM) and/or four-wave-mixing (FWM) in a nonlinear photonic crystal fiber [8] or a Mach-Zehnder interferometer (MZI) employing SOAs [9], and a Fabry-Perot (FP) laser diode with dual-wavelength injection locking [10, 17]. Currently, research has been extended to all-optical format conversions between on-off keying (OOK) and phase-shift keying (PSK) [11, 12].

In this paper, all-optical NRZ-to-RZ conversion is proposed and experimentally demonstrated at various bit rates. It is cascaded with an optical time-interleaved circuit to make a 40 Gb/s OTDM channel. Previously an NRZ-to-RZ converter [5, 6, 14, 15] using an SOA in a fiber-loop mirror (i.e., an SOA-loop mirror) was reported, but the method proposed in this paper has a different operating principle compared to that previous NRZ-to-RZ converter. In this study, a continuous-wave (CW) holding beam is used to reduce the gain recovery time of the SOA [16, 17] to help in obtaining symmetric RZ pulses converted at the

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rising and falling edges of an input NRZ signal. Conventional NRZ-to-RZ conversions [1, 2, 7] are commonly performed using the optical AND logic operation for NRZ signal input and an optical clock. In contrast, the proposed NRZ-to-RZ conversion method requires only NRZ signal input, thus making its structure very simple, with no need for a dedicated circuit to synchronize an optical clock with the bit rate of the input. Therefore, the input NRZ signal is directly converted to an RZ signal, without any optical clock.

II. PRINCIPLE OF OPERATION

For this NRZ-to-RZ conversion, the same structure as in the prior literature [5, 6, 14, 15] is employed, but the principle is different. A CW holding beam is used to reduce the gain recovery time of the SOA, yielding symmetric RZ pulses with the same width and shape at the rising and falling edges of the input NRZ signal, at any bit rate. The NRZ-to-RZ converter scheme used in this paper is shown in the dashed box ‘A’ of Fig. 1. It is based on a nonlinear optical-loop mirror using an SOA (i.e., an SOA-loop mirror). This has been used often as an ultrafast switching device in OTDM networks [13], but in this paper it acts as a bit-rate-flexible NRZ-to-RZ converter. To the best of our knowledge, this is the first report of such a bit-rate-flexible converter using an SOA-loop mirror.

The terms *x(t)* and *y(t)* denote respectively the input and output data signals of the electric fields for the NRZ-to-RZ converter. The terms *cw(t)* and *ccw(t)* are used to denote signal propagation in *clockwise* and *counterclockwise* directions, respectively, in the loop mirror. The input NRZ signal *x(t)* in Fig. 1 enters the fiber loop through WDM coupler 1. Because the SOA is located at a displacement of $\tau/2$ from the midpoint of the fiber loop, the *ccw(t)* beam experiences a phase-changing effect at a time τ later than the *cw(t)* beam. The transmitted intensity *y(t)* is given in Eq. (1) below [13]:

$$y = I_{in}\big(a^2 G_{cw} + (1-a)^2 G_{ccw} \\ - 2a(1-a)\sqrt{G_{cw}G_{ccw}}\cos\theta_{diff}\big), \tag{1}$$

Where I_{in} is the input intensity, a is the coupling coefficient of the TDC, G_{cw} and G_{ccw} are the gains of the SOA for *cw* and *ccw* beams, respectively. θ_{diff} (= θ_{cw} - θ_{ccw}) is the phase difference between the *cw* and *ccw* beams. The time τ is set to be less than *T/2* (where *T* is the signal period), to extract pulses at the rising and falling edges of the input NRZ signal *x(t)*, while τ was set to T ($\tau \leq T$) in previous experiments [6, 14]. The operational timing diagram is illustrated in Fig. 2. The gain and phase for *cw(t)* and *ccw(t)* beams depend simul-

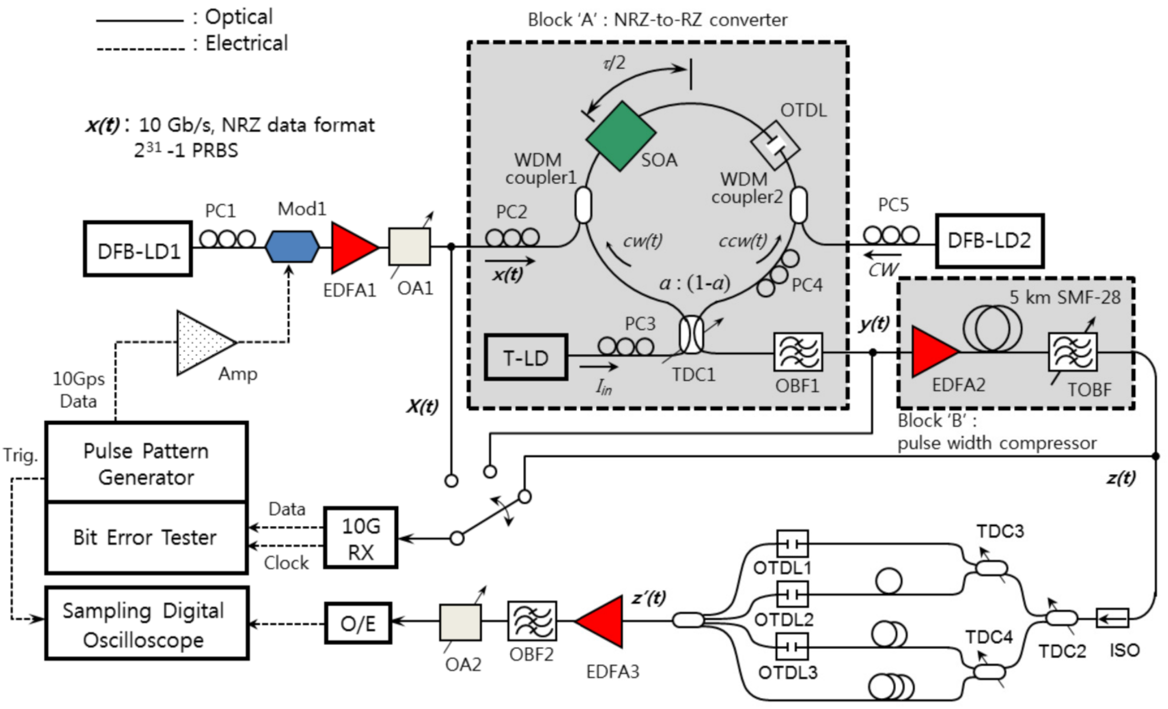


FIG. 1. Experimental setup for testing the proposed NRZ-to-RZ conversion. PC: Polarization Controller; EDFA: Er-doped Fiber Amplifier; OA: Optical Attenuator; SOA: Semiconductor Optical Amplifier; T-LD: Tunable Laser Diode; TDC: Tunable Directional Coupler; OTDL: Optical Tunable Delay Line; OTGF: Optical Tunable Grating Filter; OBF: Optical Bandpass Filter; Mod: Modulator.

taneously on the intensity of the input NRZ signal *x(t)*. The gain profiles of the *cw(t)* and *ccw(t)* beams produced by the cross-gain modulation (XGM) of the SOA in the loop mirror are shown in Figs. 2(b) and 2(c). To investigate the phase relationship, phase values are denoted above each gain profile. The values, such as 0 and π, indicate the cross-phase modulation (XPM) -induced phase shift that the *cw(t)* and *ccw(t)* beams experience due to the NRZ input *x(t)*. Here the gain at the falling edge of the NRZ input typically shows slow recovery (dotted lines in Figs. 2(b) and 2(c)). Due to the long carrier lifetime in the SOA, the generated RZ pulse *y(t)* becomes wider and out of time (the dotted line in Fig. 2(d)). However, the effective carrier lifetime of the SOA can be shortened by using a CW holding beam, and thus the SOA gain-recovery time is reduced. Hence, to mitigate the effect of slow gain recovery, a CW holding beam [16, 17] as shown in Fig. 1 is used. The holding beam's wavelength can be set for either the gain [16, 17] or the transparency region [16]. The experiments in this paper have used the gain-region wavelength, i.e. a CW holding beam of 1555.4 nm, closer to the SOA's gain peak, so that it can cause a larger effect on the data signals. For faster gain recovery, the counter-propagating configuration [16] between NRZ data signal and CW holding beam is applied.

For simplicity, we set the TDC coupling coefficient a to 1/2. We also assume that when the input signal *x(t)* is high, the gain of the *cw(t)* beam is the same as that of the *ccw(t)* beam due to the XGM effect of the SOA, i.e. $G_{cw,high} = G_{ccw,high}(G_{high})$, and when the input is low $G_{cw,low} = G_{ccw,low}(G_{low})$,. This assumption can be applied to regions I, IV, V, and VIII in Fig. 2. In addition, the XPM of the SOA induces a phase difference $\theta_{diff} = 0$ between $I_{in}G_{cw,high}$ (or $I_{in}G_{cw,low}$) and $I_{in}G_{ccw,high}$ (or $I_{in}G_{ccw,low}$). Therefore, the output *y(t)* of the SOA-loop mirror becomes 'zero', based on Eq. (1). On the other hand, regions II, III, VI, and VII have different gains and phases, as shown in Figs. 2(b) and (c). Thus the output *y(t)* has a certain amount of power. The outputs at points 'A' ($\theta_{diff} = \pi$) and 'B' ($\theta_{diff} = -\pi$) of Fig. 2 become maximal and can be described by the following:

$$y_A = y_B = \frac{1}{4} \times I_{in}\left(G_{low} + G_{high} + 2\sqrt{G_{low}G_{high}}\right) \quad (2)$$

y_A and y_B have the same value but alternate phases, as shown in Fig. 2(d). The RZ pulses have red-chirped components at both the rising and falling edges of the input NRZ signal, with a characteristic typical of modified duobinary signals [6]. Pulse compression is applied to the red-chirped RZ components, to reduce pulse width. The final RZ signal *z(t)* is produced as shown in Fig. 2(e). The NRZ-to-RZ conversion is conducted without any controlling devices, as long as $\tau < T/2$. In other words, a bit-rate-flexible conversion can be achieved, requiring no extra optical clock. As reported in a previous article [6, 14], the converted output *y(t)* also has the value from exclusive-OR (XOR) logic applied to the input *x(t)* with the delayed signal *x(t+T)*. In practice, because line coding such as a scrambling technique is usually used, the original data can be easily recovered by a modified descrambling.

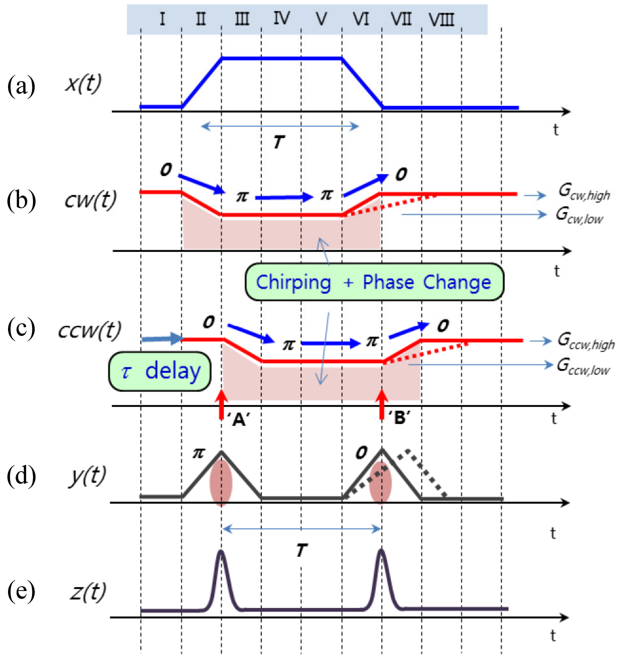


FIG. 2. Operational principle of the NRZ-to-RZ format conversion. τ is set to be less than $T/2$, unlike in previous reports [6, 14].

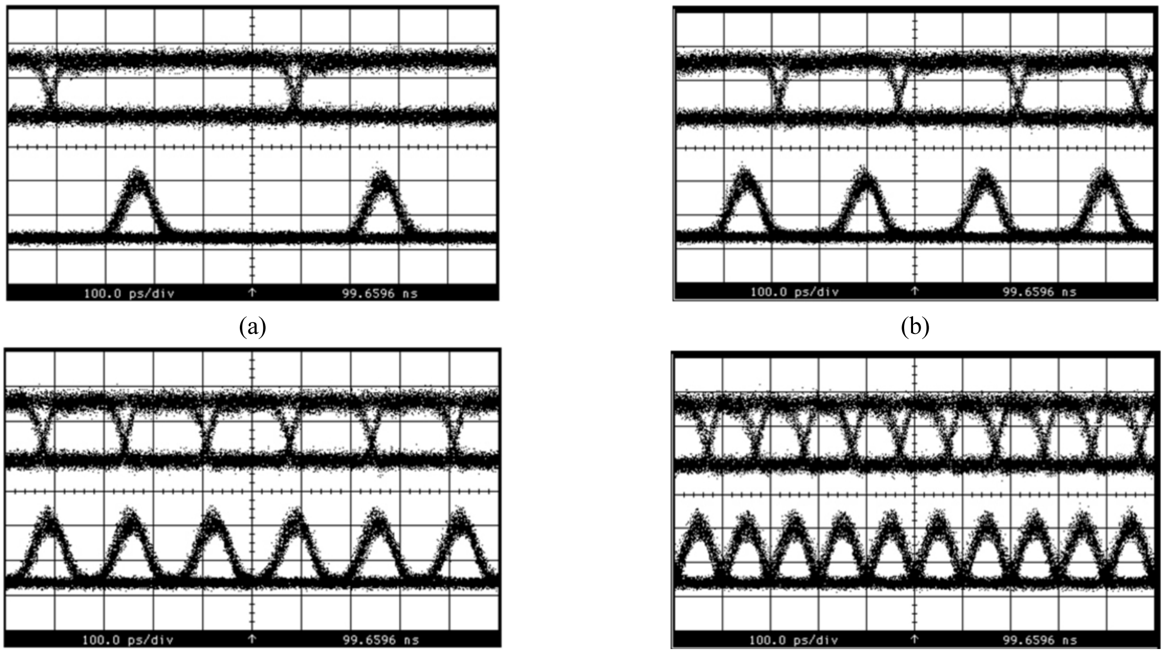
III. EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 1, where dashed boxes 'A' and 'B' depict an NRZ-to-RZ converter and a pulse compressor respectively. A pulse compressor [18] was used to reduce the pulse width of the converted RZ signal for a 40 Gb/s OTDM signal through a bit-interleaving technique. For NRZ-to-RZ conversion, the previously developed SOA-loop mirror [5, 6, 14, 15] was used. It consisted of a TDC1, an OTDL, a PC4, and an SOA. A $LiNbO_3$ optical Mach-Zehnder modulator (Mod1), driven by a pulse pattern generator (PPG), was used to generate a 10 Gb/s 2^{31}-1 pseudorandom bit sequence (PRBS) data stream in NRZ format at 1557.8 nm. The NRZ input signal *x(t)* was fed into the SOA-loop mirror through the WDM coupler1. For RZ data generation, the continuous-wave beam I_{in} at 1550 nm, generated by a tunable laser diode (T-LD), entered one arm of the SOA-loop mirror, as shown in Fig. 1. The SOA used in this experiment was 1000 μm long and nearly polarization insensitive (typically ~0.6 dB), with a low-tensile-bulk separate-confinement heterostructure. The SOA arrival-time difference τ was set at ~45 ps; τ should set to be less than *T/2* (maximum τ) to extract pulses at the rising and falling edges of the input NRZ signal *x(t)*. On the other hand, the minimum τ can be determined from the sum of rise and fall times for a converted RZ pulse. The measured rise and fall times were 22.5 ps and 22.8 ps respectively, so to get a high-speed RZ signal (minimum $\tau = 22.5+22.8 = 45.3$ ps). The τ is set by the OTDL in Fig. 1, which controlled in integer precision.

The SOA current was 195 mA, and the coupling coefficient α of TDC1 was adjusted to 0.45. The CW holding beam (DFB-LD2 in Fig. 1), with 0.5 dB m at 1555.4 nm to reduce gain-recovery time of the SOA, entered the other arm of the SOA-loop mirror through the WDM coupler2. The power of the CW holding beam was manually increased from -25 to 2.0 dB m to find the optimum power. Without the CW holding beam the shape of the converted RZ pulses was imperfect, due to the slow gain recovery at the falling edge of the input NRZ signal [6]. By injecting the optimum power of ~0.5 dB m into the SOA, symmetrical RZ pulses were achieved, as shown in Fig. 3.

Eye diagrams of input NRZ signals and the NRZ-to-RZ converted signals at bit rates of 2, 4, 8, and 10 Gb/s are shown in Figs. 3(a), (b), (c), and (d) respectively. NRZ-to-RZ conversions were successful at various bit rates, even when the bit rate was continuously changed from 0.5 Gb/s to 10 Gb/s without any control. Previous studies [6] have shown that the NRZ-to-RZ converted signal has better transmission performance than a conventional RZ signal, in spite of the imperfect rising and falling edges of the converted signal (due to different principles, compared to those in this paper). Such better performance might be coming from the two red-chirped RZ components and the modified duobinary contained in the converted RZ signals.

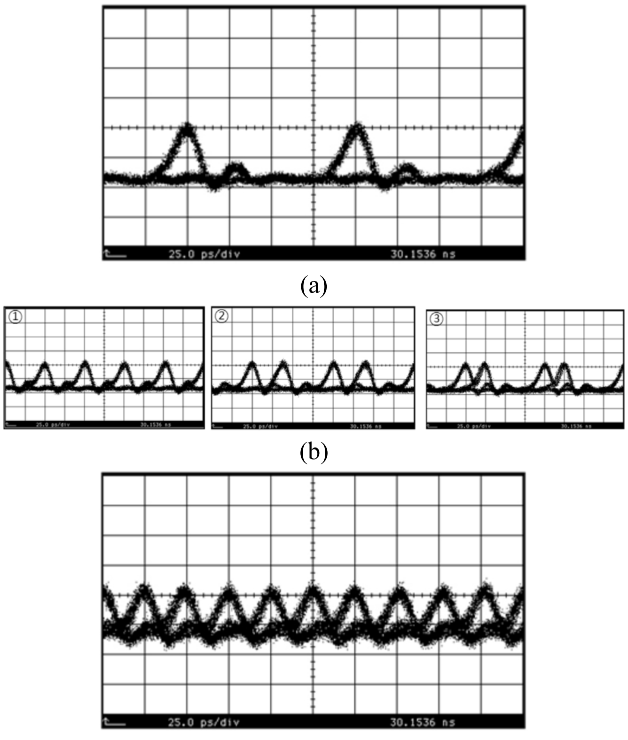
The pulse width of the converted RZ signal was ~54 ps, which had to be reduced for the 40 Gb/s OTDM signal. To do that, a pulse-compression method used in a previous report [18] was employed. A standard optical fiber that can provide anomalous group-velocity dispersion for wavelengths around 1.5 μm was used for chirped pulse compression (red chirped light is slower than blue). The fiber compressor consisted of a narrow-bandwidth optical grating filter TOGF (bandwidth 0.25 nm at -3 dB; JDS FITEL TB9226) and ~5 km of SMF-28 fiber with the dispersion parameter of 17.7 ps/(km nm) at 1560 nm, as shown in the dashed block 'B' of Fig. 1. The output *z(t)* of the compressed RZ pulse with pulse width of ~18 ps is shown in Fig. 4(a). To test the feasibility of bit interleaving for a 40 Gbps OTDM signal, the distance between two compressed RZ pulses was decreased from 50 to 25 ps, as shown in-①-③ of Fig. 4(b). Even when the distance was close to 25 ps, the eye still seemed to be clear, regardless of the slight beating noise. The bit-interleaved 40 Gb/s OTDM signal is shown in Fig. 4(c). Due to the limited experimental environment, the bit error rate (BER) was not measured. However, reasonable BER performance is expected. Instead of measurements for the 40 Gb/s signal, the BERs for the input NRZ signal, the NRZ-to-RZ converted signal, and the compressed RZ signal are shown in Fig. 4. While the optical power penalty of the NRZ-to-RZ conversion was -2.73 dB, the compressed RZ signal had a power penalty of -0.75 dB



(a) (b)

(c) (d)

FIG. 3. Measured eye diagrams (100.0 ps/div) for the input RZ signal and the NRZ-to-RZ converted signal, at (a) 2 Gb/s, (b) 4 Gb/s, (c) 8 Gb/s , and (d) 10 Gb/s bit rates.



(a)

(b)

(c)

FIG. 4. Measured eye diagrams (25.0 ps/div) for (a) the compressed RZ signal after NRZ-to-RZ conversion, (b) the bit-interleaved signal according to the distance between two compressed RZ pulses (① 50 ps, ② 37 ps, ③ 25 ps), and (c) the bit-interleaved 40 Gb/s OTDM signal.

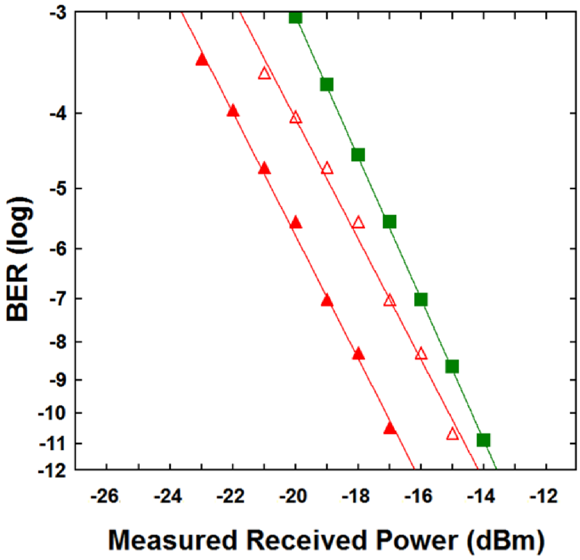


FIG. 5. Measured BER curves for the NRZ input signal (■), the NRZ-to-RZ converted signal (▲), and the compressed RZ signal (△) at a bit rate of 10 Gb/s.

compared to the injected NRZ signal. A negative power penalty signifies an increase in receiver sensitivity; this is only possible due to the format conversion from NRZ to RZ.

IV. CONCLUSION

A new, all-optical bit-rate-flexible NRZ-to-RZ data-format conversion was experimentally demonstrated in this study. A CW holding beam was used to obtain symmetric RZ pulses converted at the rising and falling edges of an input NRZ signal, by reducing the gain-recovery time of the SOA. The proposed method can be applied to all-optical bit-rate-flexible clock recovery, as previous reported in [14]. With compressed pulses from the converted RZ signal, it is feasible to produce a 40 Gb/s OTDM signal, without using any additional optical clock, due to the red-chirped RZ signal formed by the proposed NRZ-to-RZ converter using an SOA-loop mirror. The compressed RZ signal had a pulse width of ~18 ps, whereas that of the original converted RZ was ~54 ps. The proposed NRZ-to-RZ conversion penalty was found to be -2.73 dB with the input NRZ signal, whereas the optical-power penalty for the compressed RZ conversion was -0.75 dB. The proposed NRZ-to-RZ conversion method can be used as a key piece in linking and interfacing all-optical OTDM and WDM networks.

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