

40 Gbps All-Optical 3R Regeneration and Format Conversion with Related InP-Based Semiconductor Devices

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We report an experimental demonstration of 40 Gbps all-optical 3R regeneration with all-optical clock recovery based on InP semiconductor devices. We also obtain all-optical non-return-to-zero to return-to-zero (NRZ-to-RZ) format conversion using the recovered clock signal at 10 Gbps and 40 Gbps. It leads to a good performance using a Mach-Zehnder interferometric wavelength converter and a self-pulsating laser diode (LD). The self-pulsating LD serves a recovered clock, which has an rms timing jitter as low as sub-picosecond. In the case of 3R regeneration of RZ data, we achieve a 1.0 dB power penalty at 10^{-9} BER after demultiplexing 40 Gbps to 10 Gbps with an electro-absorption modulator. The regenerated 3R data shows stable error-free operation with no BER floor for all channels. The combination of these functional devices provides all-optical 3R regeneration with NRZ-to-RZ conversion.

Keywords: Mach-Zehnder interferometer, semiconductor optical amplifier, wavelength converter, clock recovery, 3R regeneration, self-pulsating, format conversion.

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I. Introduction

High-speed all-optical communication systems are expected to operate with all-optical 3R (retiming, reshaping, and reamplification) regeneration to repair signals that are degraded due to accumulated transmission noise caused by erbium-doped fiber amplifiers (EDFAs), fiber non-linear effects, group velocity dispersion, polarization mode dispersion, and cross-talk. It provides enhanced transparency, scalability, and flexibility in optical networks [1]. There have been several 3R regeneration schemes based on semiconductor optical amplifiers (SOAs), electro-absorption (EA) modulators, and highly nonlinear fiber [2]-[4]. Most of them are for 40 Gbps applications in which all-optical regeneration has an advantage in speed [5]; however, electrical regeneration has gradually overcome this speed limit [6]. Consequently, all-optical 3R regeneration schemes could potentially enable better performance in very high bit rate applications.

In general, it is not easy to accomplish 3R regeneration with non-return-to-zero (NRZ) format data because of the difficulty of clock extraction from the NRZ format. There are several reported methods to extract a clock component from NRZ data [7]-[11]. A good approach is to use a single SOA and a narrow-width tunable optical band-pass filter (OBPF). Gain depletion causes overshooting at each leading edge of NRZ data in an SOA, and these overshooting components can be filtered out with a narrow OBPF due to chirp. Then, the output of the filter shows the pseudo return-to-zero (PRZ) format which has the clock components. The extracted clock signal is dramatically

improved when format converted signal is injected into the multi-section laser diode (LD) with a distributed feed-back (DFB) reflector (Henceforth, a multi-section LD with a DFB reflector will be referred to as a self-pulsating LD). Previous studies on 3R regeneration have demonstrated optical-electrical-optical (OEO) conversion techniques or complex structures in 40 Gbps NRZ systems [12], [13]. Recently, all-optical 3R regeneration in a 40 Gbps NRZ system has been successfully demonstrated using an EA modulator and SOA [14]. However, the recovered clock in this scheme uses a phase lock loop-based electrical clock recovery circuit. In this paper, we successfully demonstrate an all-optical 3R regeneration with 40 Gbps RZ data and an all-optical format data conversion at 10 Gbps and 40 Gbps without any OEO conversion, which can perform NRZ-to-RZ format conversion with all-optical clock recovery. In order to achieve 3R regeneration, we use a Mach-Zehnder interferometric wavelength converter (MZ IWC) for 2R regeneration (reshaping and re-amplification) and a self-pulsating LD for clock recovery (retiming).

II. 10 Gbps NRZ-to-RZ Format Conversion with All-Optical Clock Recovery

We achieved all-optical 3R regeneration using the MZ IWC and a clock recovery module with 11.727 Gbps pseudorandom bitstream (PRBS) NRZ data. The structures of the devices used in this experiment were reported in [15] and [16]. Figure 1 shows the schematic diagram of the experimental setup, where the 2R regenerator [15], [17] and the clock recovery module are combined together. The output of the DFB laser at a wavelength of 1550 nm is modulated by an external modulator at an 11.727 Gbps PRBS NRZ with a pattern length of $2^{31}-1$. Then, the PRBS NRZ data is divided using a 3 dB fiber coupler to simultaneously accomplish a 2R regeneration and clock recovery. Figure 2 shows the clock recovery module using a self-pulsating LD. The module consists of an SOA, an OBPF1 with narrow bandwidth, two EDFAs, an OBPF2, an optical variable attenuator, a polarization controller, an optical circulator, and a self-pulsating LD [16], [18].

From the NRZ signal power, 3 dB enters into the clock recovery module. To obtain the clock components from the

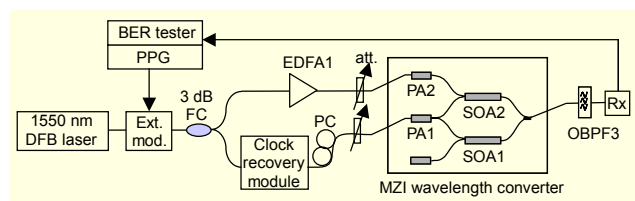


Fig. 1. Experimental setup for all-optical format conversion.

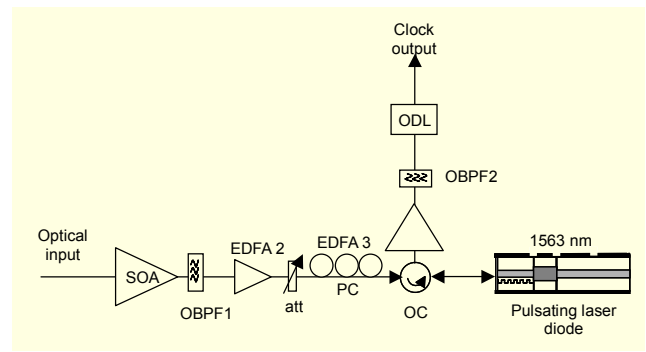


Fig. 2. Clock recovery module using a self-pulsating LD (OC: optical circulator, ODL: optical delay line, PC: polarization controller, and att: attenuator).

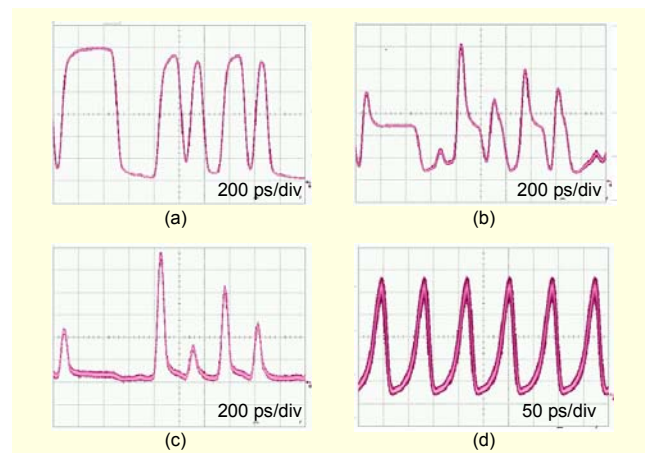


Fig. 3. Sampling oscilloscope traces: (a) input NRZ, (b) overshoot after SOA, (c) PRZ, and (d) recovered clock.

NRZ input data stream, we use the PRZ generator, which is composed of an SOA and a narrow bandwidth-grating filter [9]. The PRZ data extracted from the NRZ data is injected into the DFB section via an optical circulator after its power and polarization are controlled. Then, the free-running pulsation locks to the frequency of 11.727 GHz. The optical clock outputs from the optical circulator are measured using a sampling oscilloscope and an RF spectrum analyzer after they are filtered by an OBPF. The center wavelength of the extracted clock signal is 1558 nm. Figure 3 shows the oscilloscope traces of the input NRZ (a), after SOA (b), PRZ data (c), and the recovered clock (d). The signal after SOA has an overshoot at the leading edge of one bit due to the self-phase modulation of the SOA [9]. The PRZ signal can be extracted using the narrow optical bandpass grating filter as shown in Fig. 3(c). In the experiments, although NRZ data causes an rms timing jitter of 2 ps and severe intensity fluctuation, the extracted clock has an rms timing jitter of approximately 1 ps as shown in Fig. 3(d).

Figure 4 shows the RF spectra of the input PRBS NRZ data,

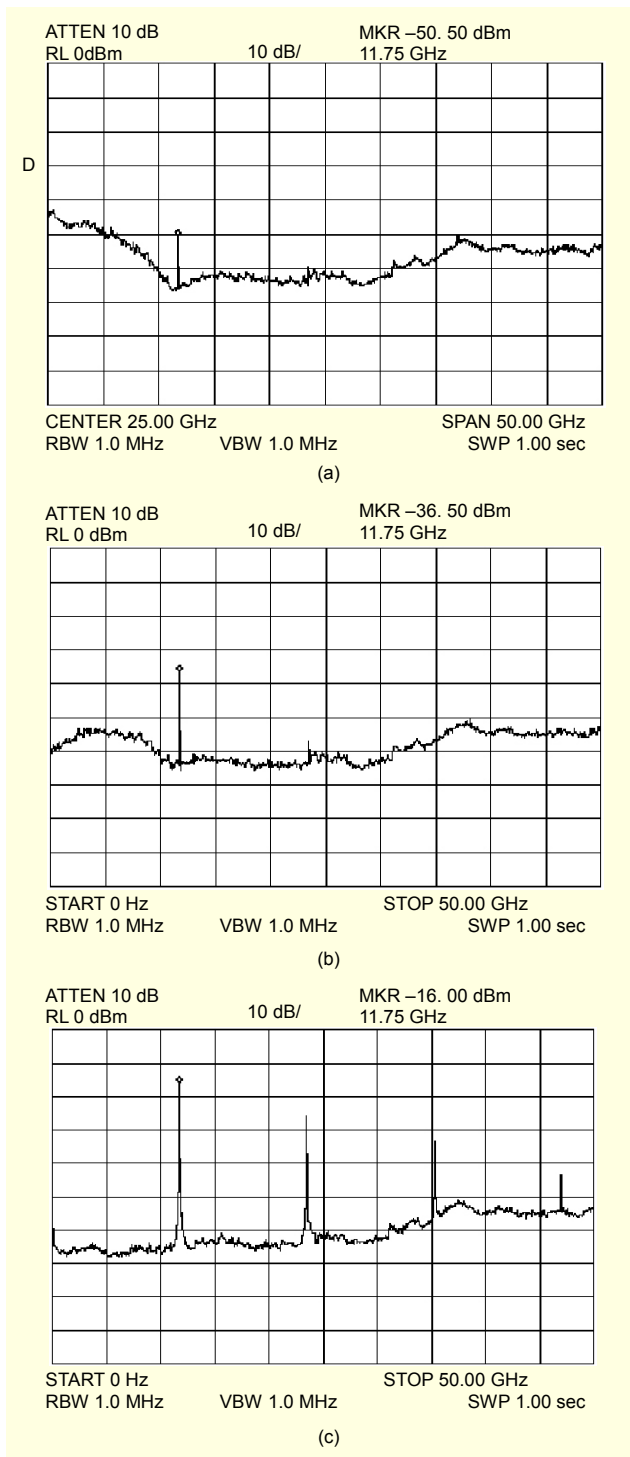


Fig. 4. (a) RF spectra of the input PRBS NRZ data, (b) PRZ signal, and (c) recovered clock (span: 0 to 50 GHz).

the PRZ signal, and the recovered clock. There is wide spectral spreading from DC to 10 GHz as shown in Fig. 4(a). Also, the RF power of the NRZ PRBS signal is lower than that at low frequency around DC. However, as shown in Fig. 4(b), the RF power of the PRZ signal was enhanced more than 20 dB

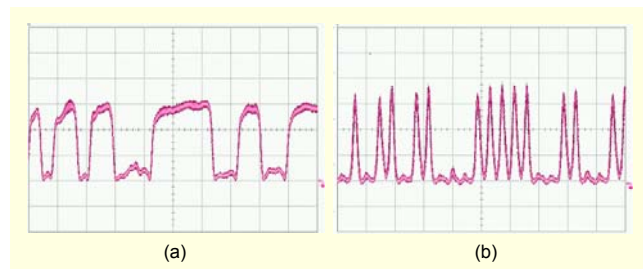


Fig. 5. Sampling oscilloscope traces of (a) input PRBS NRZ data and (b) output of the format converted RZ data (horizontal: 200 ps/div).

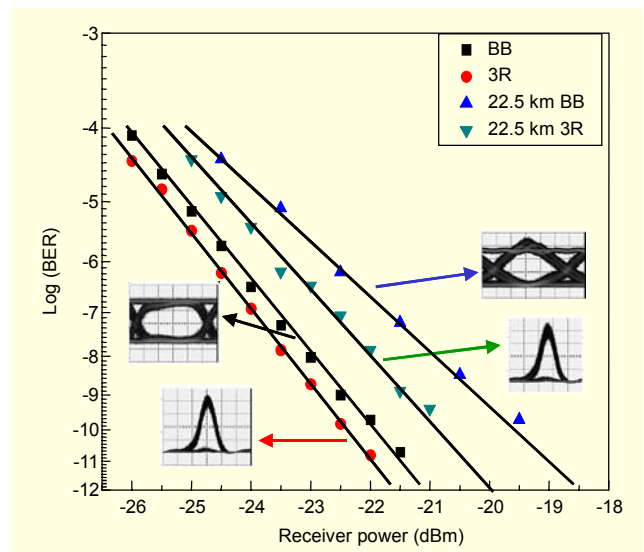


Fig. 6. BER performance of the 10 Gbps data format conversion (Insets: eye diagrams).

compared to the RF power at low frequency around DC. The clock-enhanced PRZ data was then injected into the DFB section through an optical isolator. Figure 4(c) shows the RF spectrum of the recovered clock output from the optical circulator. Wide background noise almost disappears and there is only a strong RF component at 11.727 GHz.

The other divided NRZ signal power was amplified by EDFA and injected into one side of the MZ IWC. The recovered clock was passed through the OBPf and an optical delay line to synchronize with input NRZ data and then injected into the center of the MZ IWC. After synchronizing the input NRZ and clock signal, we obtained the 3R regenerated RZ data by the AND gate between the input NRZ and extracted clock signal. The outputs were analyzed by a sampling oscilloscope, an RF spectrum analyzer, and a bit error rate (BER) measurement system.

Figure 5 shows sampling oscilloscope traces of the input PRBS NRZ data and the output of the format converted RZ signal corresponding to the input NRZ data, which shows

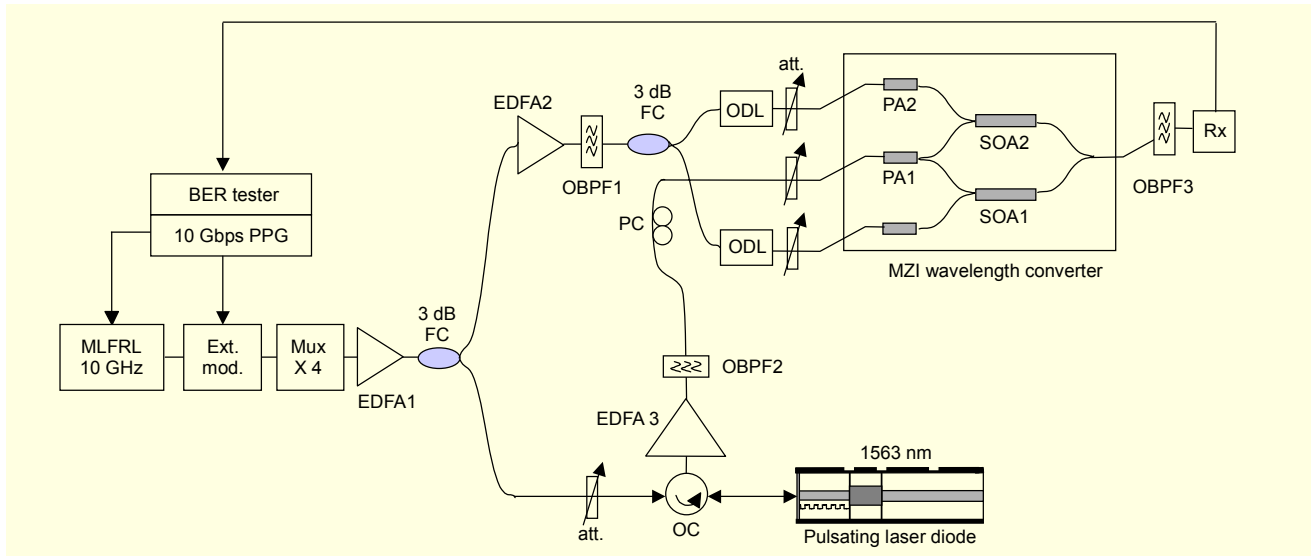


Fig. 7. Schematic diagram of the experimental setup for the 40 Gbps all-optical 3R regeneration.

10110110001111100110011. The results of BER versus received optical power measurements are shown in Fig. 6. The all-optical format conversion incurs almost no power penalty for back-to-back (BB) input NRZ data. The BER performance shows a 1 dB negative power penalty for the input NRZ data after 22.5 km single-mode fiber (SMF) transmission. The insets of Fig. 6 show the eye diagrams for each BER curve. The extinction ratios of the BB and the format converted data were 14.8 dB and 14.1 dB respectively, and the rms timing jitter of the format converted data was approximately 1 ps. After 22.5 km SMF transmission, the extinction ratio was almost the same as that of the BB data. The rms timing jitter of the input NRZ data was around 5.6 ps, but the timing jitter after format conversion was around 1.5 ps. There was improvement with format conversion even though the extinction ratio was high. The negative power penalty, which shows the increase of the receiver sensitivity, is due to the change of the data format. The format converted RZ data shows stable error-free operation with no error floor.

III. 40 Gbps 3R Regeneration of RZ and NRZ-to-RZ Format Conversion

This section describes the 3R regeneration of the RZ data format and an NRZ-to-RZ format conversion at 40 Gbps. Figure 7 shows the schematic diagram of the experimental setup for the 40 Gbps all-optical 3R regeneration, where the 2R regenerator and the clock recovery module are combined. The signal pulses were generated by a mode-locked fiber laser at 9.953 Gbps with a 3 ps pulse width. They were then externally modulated by a LiNbO₃ Mach-Zehnder modulator with 2^7-1 PRBS data and optically multiplexed up to 39.812 Gbps.

The center wavelength of the mode-locked fiber laser was 1546 nm. The 3 dB divided signal power of the 40 Gbps RZ data entered the clock recovery module. The RZ data was injected into the DFB section of the pulsation LD via an optical circulator after its power was controlled. Then, the free-running pulsation locked to the frequency of 39.812 GHz. The optical clock outputs from the optical circulator were filtered by an optical band-pass filter and then were measured using a sampling oscilloscope and an RF spectrum analyzer. The other divided RZ signal was amplified by the EDFA and injected into the two arms of the MZ IWC through the 3dB fiber coupler and optical delay lines. The recovered clock was passed through the optical band pass filter and was then injected into the center of the MZ IWC. After adjusting the time delay between two arms, we achieved the 3R regeneration for the RZ PRBS data [19]. The time delay between the two arms was about 12 ps, which implies a switching window of the MZ IWC device.

Figure 8 shows the sampling oscilloscope traces of the 40 Gbps input data, 3R regeneration, and its 4 demultiplexed channels. The demultiplexed signals were measured using a conventional 65 GHz sampling oscilloscope with a precision time-based module. Figure 9 shows the BER performance for the 40 Gbps 3R regeneration after demultiplexing 40 Gbps to 10 Gbps with an EA modulator. The BER curve of the BB signal at 9.953 Gbps is also shown for comparison. The four demultiplexed channels show almost the same BER performance. The power penalty at 10^{-9} BER for all 4 channels was around 1 dB compared to the BB signal. The power penalty is believed to be due to the amplified spontaneous emission noise of the data signal. The regenerated 3R RZ signals show stable error-free operation with no BER floors for

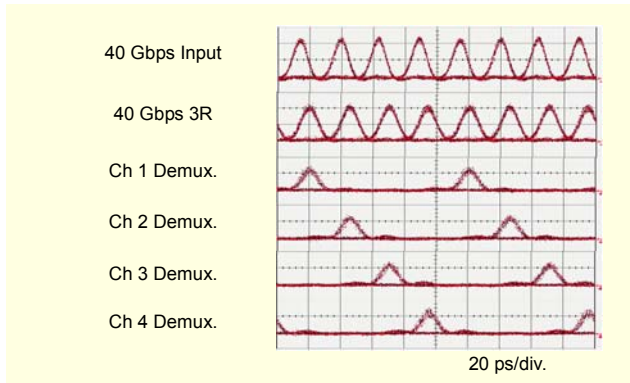


Fig. 8. Sampling oscilloscope traces of the 40 Gbps input data, 3R regeneration, and its demultiplexed channels.

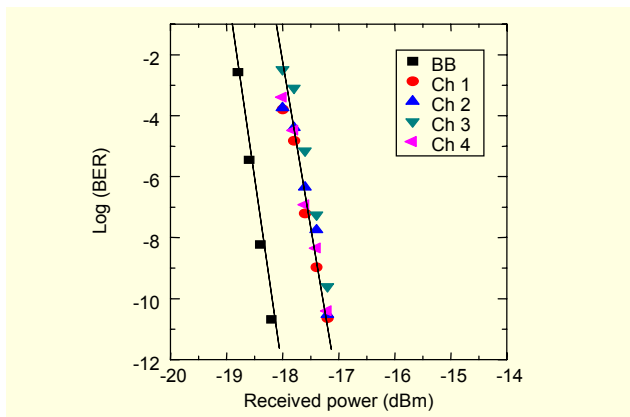


Fig. 9. BER performance of the 40 Gbps 3R regeneration.

all channels.

Next, we present the NRZ-to-RZ format conversion with all-optical clock recovery at 40 Gbps. It is difficult to extract a clock component from a 40 Gbps NRZ format data signal. In the experiment, the operation scheme is similar to the 10 Gbps NRZ-to-RZ format conversion except this experiment uses two optical delay lines. Figure 10 shows the schematic diagram of the experimental setup for the 40 Gbps all-optical NRZ-to-RZ format conversion with 3R regeneration. The setup is almost the same as that shown in Fig. 7, except this setup uses a PRZ generator, which is composed of an SOA and a narrow bandwidth grating filter. In the experiment, the PRZ data extracted from the 40 Gbps NRZ signal was injected into the DFB section of the self-pulsating LD via the optical circulator. Then, the clock was recovered from the NRZ PRBS data. The outputs were analyzed with a sampling oscilloscope and an RF spectrum analyzer.

Figure 11 shows the eye diagrams for all-optical 40 Gbps NRZ-to-RZ format conversion. The eye diagram of input 40 Gbps NRZ data and its recovered clock are shown in Fig. 11(a) and (b), respectively. The extinction ratio of the NRZ input data is 12.05 dB. The extracted clock shows an rms timing jitter of around 900 fs, even though there are dots around the clock signal. Figure 11(c) shows the output of the RZ data with format conversion. The extinction ratio of the NRZ-to-RZ format converted output was 9.41 dB. In the case of NRZ-to-RZ format conversion, it was not possible to

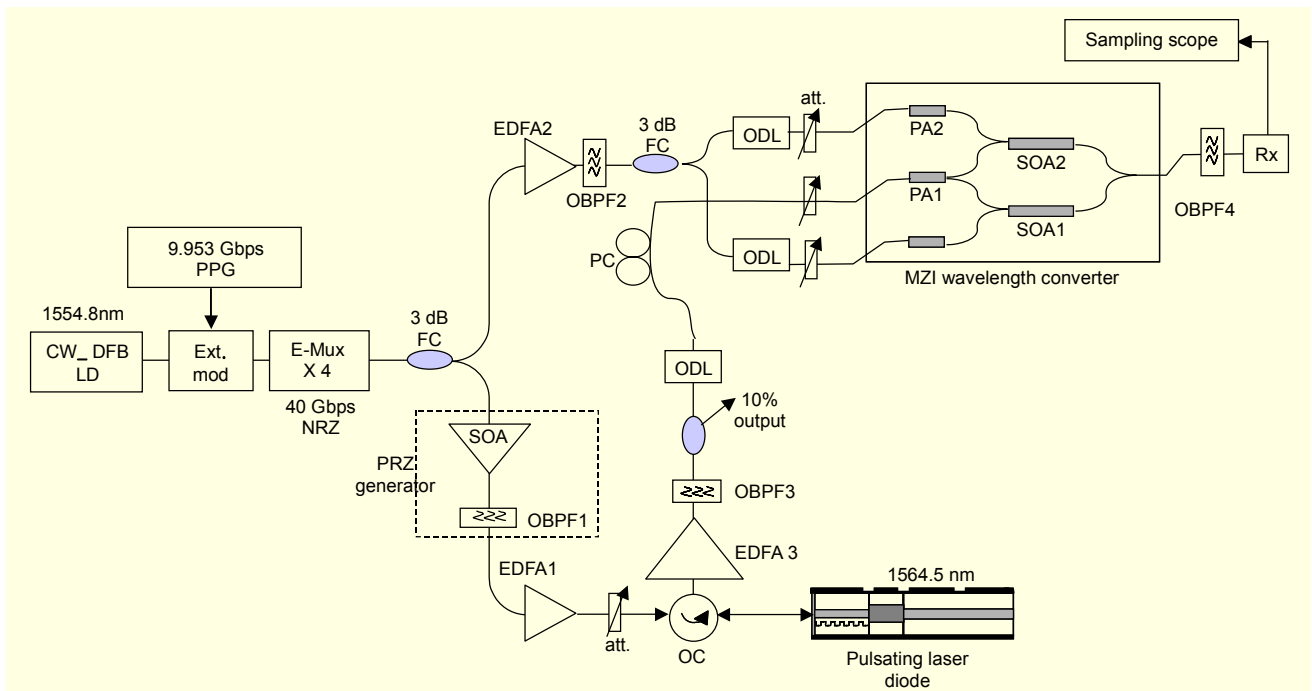


Fig. 10. Schematic diagram of the experimental setup for 40 Gbps all-optical data format conversion with all-optical clock recovery for NRZ input data.

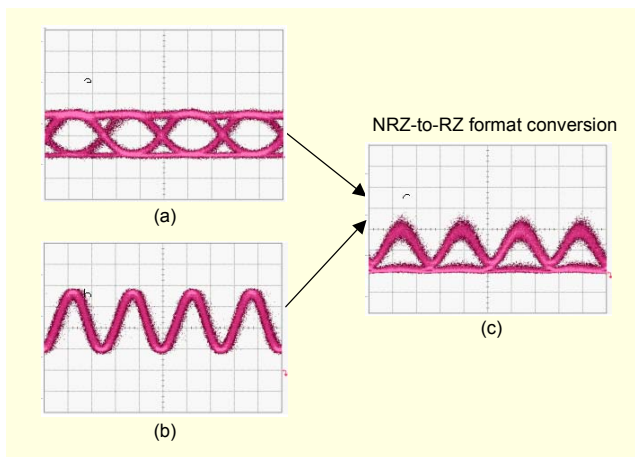


Fig. 11. Sampling oscilloscope traces of (a) 40 Gbps NRZ input data, (b) recovered clock, and (c) NRZ-to-RZ format converted data.

measure the BER because the EA modulator for 40 to 10 Gbps demultiplexing showed too much insertion loss after measuring the BER for 40 Gbps RZ 3R regeneration.

IV. Conclusion

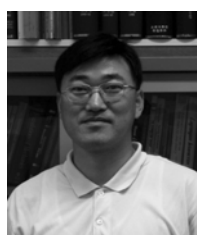
We have demonstrated 40 Gbps all-optical 3R regeneration with RZ data format using an MZ IWC and a self-pulsating LD. Stable error-free 3R regeneration with 1 dB power penalty at 40 Gbps was achieved. Moreover, the data format conversion from NRZ PRBS data was achieved at 10 Gbps and 40 Gbps. It provided an NRZ-to-RZ conversion through all-optical 3R regeneration. In the case of data format conversion, the BER performance incurred a 1 dB negative power penalty for the degraded input NRZ data and almost no power penalty for back-to-back input NRZ data. This is due to the change of the data format, which increases the receiver sensitivity. The combination of our newly designed devices provides all-optical 3R regeneration.

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