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RESEARCH ARTICLE

Optical signal processing based on semiconductor optical amplifier and tunable delay interferometer

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Abstract In this paper, several applications in all-optical signal processing based on a semiconductor optical amplifier (SOA) and variable delayed interferometers (DIs) have been experimentally demonstrated. Wavelength converter based on a nonlinear polarization switch (NPS) and a DI is proposed and presented for the wavelength conversion of nonreturn-to-zero (NRZ) signals. An all-optical nonreturn-to-zero to return-to-zero (NRZ-to-RZ) format converter with tunable duty cycles is achieved by the DI with variable delays. The 40 Gb/s reconfigurable optical OR/NOR gate in a single SOA, followed a tunable optical bandpass filter (OBF) and a DI, optical 2R regeneration using an SOA-DI are investigated. It is found that this combinative realization of filters has been endowed with great flexibility and quality for 40 Gb/s optical logic and 2R regeneration.

Keywords all-optical signal processing, semiconductor optical amplifier, delayed interferometer, wavelength conversion, format converter, 2R regeneration

1 Introduction

Optical signal processing is a key technology for high-speed and large-capacity optical network in the future [1–4]. Optical signal processing based on semiconductor optical amplifier (SOA) has attracted considerable research interest benefitting from its advantages of simple structure. However, the quality of converted signal is degraded due to the pattern effect induced by the slow gain recovery time of SOA. To overcome this influence subsequent optical red-shifted filtering has been used to mitigate the pattern effect [4–9]. Delayed interferometer (DI) has also been used to improve the performance of SOA-based wavelength converter (WC) [10–12]. In this paper, we report a novel WC for nonreturn-to-zero (NRZ) systems using an SOA-based nonlinear polarization switch (NPS) and a DI. The high quality of the converted signal out of the NPS-DI WC is confirmed by negative power penalty after transmission over a 25 km standard single-mode fiber (SMF). By a DI with variable delays, we demonstrate an all-optical nonreturn-to-zero to return-to-zero (NRZ-to-RZ) format converter. 40 Gb/s reconfigurable optical OR/NOR gate in a single SOA followed a DI and a tunable optical bandpass filter (OBF) are proposed and demonstrated. In this scheme, the reconfiguration between the OR and NOR gate can be simply achieved by adjusting parameters of both the DI and the OBF. Finally, all-optical regeneration based on SOA-DI configuration is investigated. The blue-shifted optical filtering technique is used to mitigate the impact of pattern effects at a bit rate of 40 Gb/s 2R regeneration.

2 Results and discussion

2.1 All-optical WC for NRZ systems based on NPS-DI

Since the DI is considered to be effective when narrow input pulses are used, it is mainly applied in return-to-zero (RZ) systems. Although WCs based on NPS and DI have been demonstrated respectively, little attention has been paid to the possible contributions from DI to improve the performance of SOA-based WC for NRZ systems. In this work, a novel WC for NRZ systems is proposed and demonstrated using an SOA-based NPS and a DI. Figure 1 shows the experimental setup of the proposed WC based on the NPS-DI configuration. A continuous-wave (CW) light at 1543.86 nm is generated by a distributed feedback (DFB) laser diode and modulated at a Mach-Zehnder modulator (MZM) by a 10 Gb/s NRZ pseudorandom bit

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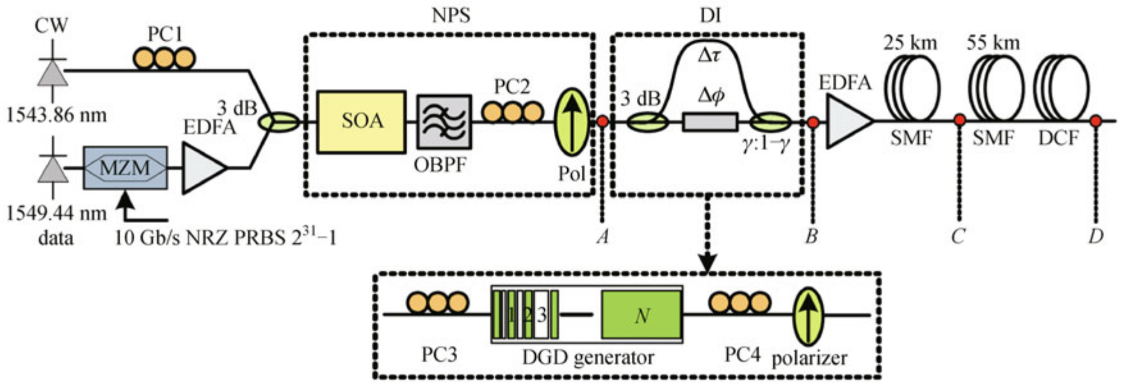
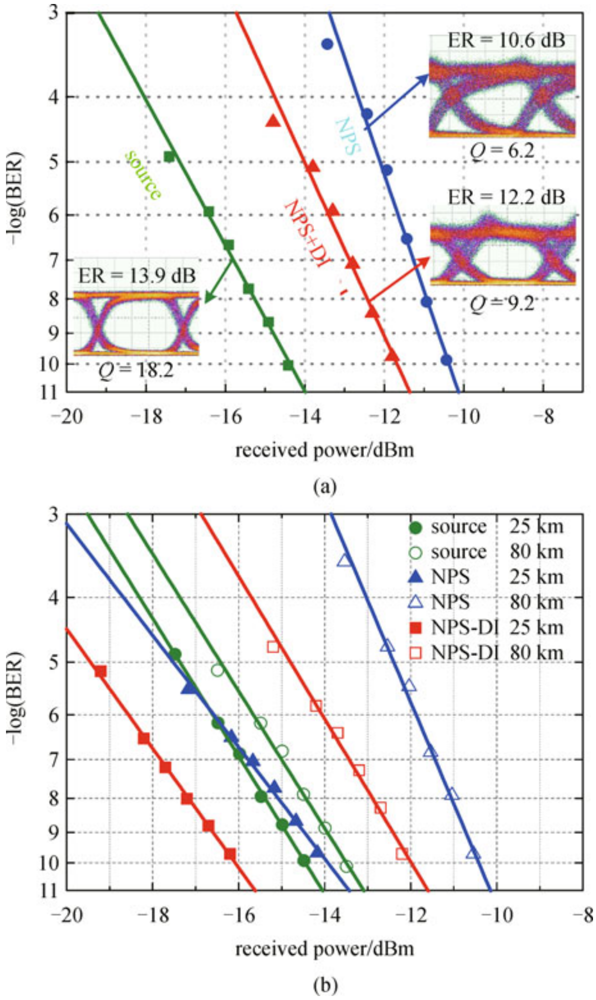


Fig. 1 Experimental setup of WC for NRZ systems

sequence (PRBS) with a word length of $2^{31}-1$. The generated NRZ signal at 1549.44 nm and another CW probe light are injected to an SOA via a 3-dB coupler. The bias current of the SOA is 250 mA. The input power of the CW probe and the data signal are −0.8 and 4.8 dBm, respectively. The proposed WC consists of a conventional SOA-based NPS and a DI. Two polarization controllers (PCs) combined with a polarizer (Pol) are used to achieve the NPS function, which is based on the birefringence effect in the SOA. An optical bandpass filter with a 3 dB bandwidth of 1 nm is inserted at the output of the SOA to block the data signal and suppress the amplified spontaneous emission (ASE) generated by the SOA. To improve the signal quality, we incorporate a DI at the output of the NPS. The DI used in the experiment consists of two PCs, a polarizer, and a variable differential group delay (DGD) element. The DI can be reconfigured by changing the value of the variable DGD element which provides the time delay between the two arms of the DI. To examine the signal quality, the converted signals are transmitted through 80 km dispersion-managed fiber link composed of 80 km SMF and a dispersion compensation fiber (DCF).



(a)

(b)

Fig. 2 (a) BER curves of back-to-back signal and wavelength converted signals using NPS and NPS-DI; (b) BER results of source and converted signals at the output of NPS and of NPS-DI after transmission

Eye diagrams of the input and converted signals are shown in the insets of Fig. 2(a). The input signal has an extinction ratio (ER) of 13.9 dB and a Q-factor of 18.2, respectively. After the NPS, the signal quality is degraded by the pattern effect, which is induced by the slow gain recovery time of the SOA. The eye diagram of the converted signal presents slow rising and falling edges. The ER and Q-factor of the converted signal is only 10.6 dB and 6.2, respectively, which results in a power penalty of 4 dB at a bit-error-ratio (BER) of 10^{-9}. The transmission performance of the converted signals is also investigated to evaluate the signal quality. The BER results of the source and converted signals after transmission are shown in Fig. 2(b). The receiver sensitivity of the source after transmission over 25 km SMF without dispersion compensation is improved due to the small chirp of the modulator. The converted signal out of NPS-DI has a positive chirp across the converted signal, which is opposite to that of the SMF. As a result, the converted NRZ signal is compressed and evolved into an RZ-like waveform after transmission through 25 km of SMF, leading to improvement of the receiver sensitivity. In addition, the suppression of the pattern effects also enhances the transmission performance of the NPS-based converted signal, and therefore a negative power penalty of -1.5 dB is obtained. For the transmission over 80 km dispersion-managed fiber link, the power penalty of the NPS-based converted signal is 3.2 dB, and is improved to 1.5 dB for the converted signal out of the DI due to the signal reshaping by the detuned filtering of the DI.

2.2 Regenerative format converter based on SOA-DI

Figure 3 shows the experimental setup of the NRZ-to-RZ format conversion. A 10 GHz optical pulse train at 1543.86 nm is generated by modulating a CW light using a lithium niobate phase and an intensity modulator and then passing through a section of dispersion compensation fiber. The 10 GHz optical pulse train is compressed by a comb-like dispersion profiled fiber (CDPF) and then multiplexed to 40 GHz using an optical fiber based optical time-division multiplexing OTDM multiplexer (MUX) and amplified using an erbium doped fiber amplifier (EDFA). A 10 Gb/s NRZ signal at 1549.44 nm with PRBS of $2^{31}-1$ and the optical pulse train are synchronized by a microwave phase shifter and injected together to an SOA via a 3-dB coupler. The bias current of the SOA is 250 mA. The work principle of this format conversion is similar to the SOA-DI-based non-inverted wavelength conversion, in which the CW light is used as probe light instead of the NRZ signal. When passing through the SOA, the pump RZ optical pulses modulate the gain and the refractive index of the SOA, and imposed sufficient cross-phase modulation as well as cross-gamin modulation on the NRZ signal. The DI can be considered as a notch filter for translating the phase modulation of the NRZ signal into the intensity modulation. Thus, a converted RZ signal can be obtained at the output of the DI. For the SOA-DI configuration, the width of the switching window, which is decisive to the pulse width of the converted RZ signal, is mainly governed by the time delay of the DI. Converted signals of different duty cycles can be obtained by using different time delays provided by the variable DGD element of the DI. After the format conversion, the RZ signal is transmitted over 80 km of SMF to evaluate the real performance of the signal in the practical optical communication systems.

In the experiment, the delay between the two arms of the DI is set to be 10.2, 15 and 19.7 ps respectively. The corresponding BER performance and the eye diagrams of the converted signals are shown in Figs. 4(a)–4(c). The converted signals have different pulse widths which increase monotonely with the time delays of the DI. The ER of the converted signals are 13.84, 14.55 and 14.87 dB, respectively, and the receiver sensitivity are -18.3, -19.5 and -19.2 dBm at a BER of 10^{-9}, which corresponds to negative power penalties of -3.7, -4.9 and -4.6 dB. It is noted that the appropriate time delay is chosen. By the way, if the optical power is optimized for each converted signal, the sensitivity difference among the converted signals could be reduced. For practical applications, the format converter should accommodate to a relatively large input power dynamic range of the RZ optical clock. In the experiment, the influence of the average power of the optical pulses on the performance of the format conversion is investigated by changing the optical power from 3 to 7 dBm with the delay between the two arms of the DI fixed at 15 ps. These BER results and high ERs as a function of input optical power indicate that, the format conversion performance is insensitive to the power fluctuation of the optical pulses. Figure 5 shows the BER performance and the eye diagrams of the converted signal before and after the transmission over 80 km of SMF. Although the timing jitter of the converted signal after transmission is increased, the eye diagram is widely opened and shows no obvious waveform distortion. The power penalty of the transmission is less than 0.9 dB. It should be emphasized that the obtained power penalty of the transmission could be reduced further if narrower OBPF would be used for the suppression of the out-of-band ASE noise. For the 40 Gb/s applications, the format conversion is performed using a 40 GHz optical pulse train as an RZ optical clock to sample the 10 Gb/s NRZ signal as shown in Fig. 1. The delay of

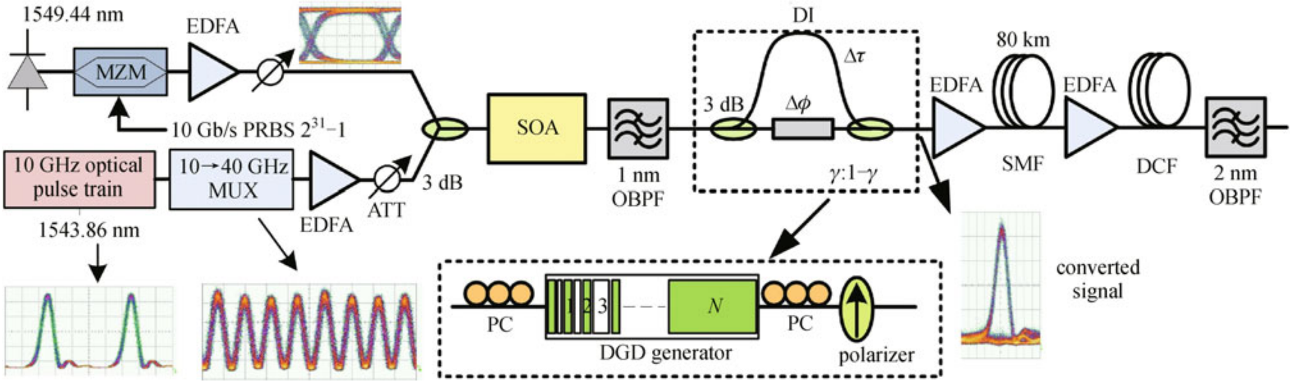


Fig. 3 Experimental setup of NRZ-to-RZ format conversion

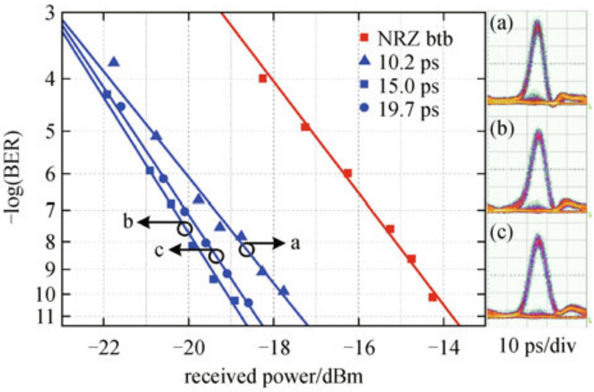


Fig. 4 BER performance and eye diagrams of converted signal with different DI delays. (a) 10.2 ps; (b) 15 ps; (c) 19.7 ps

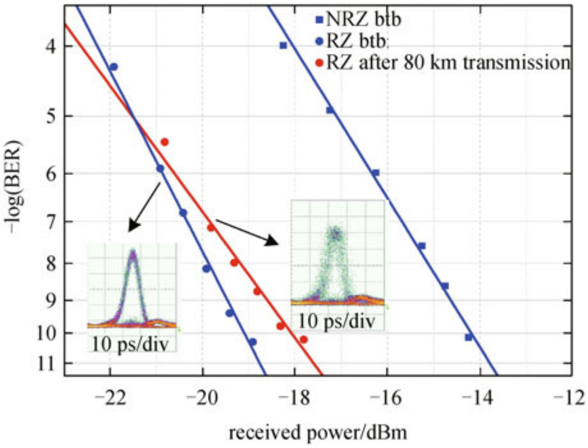


Fig. 5 BER performance and eye diagrams of converted signal before and after transmission

the DI is set to 6.7 ps. The average power of the NRZ signal and the optical pulses are −4.35 and 6.42 dBm, respectively. In the optical spectrum a pure spectrum with 10 GHz tone is found for a 40 GHz optical pulse train.

2.3 High-performance all-optical OR/NOR logic gate in a single SOA with delay interference filtering

Schematic diagram of the setup for the reconfigurable logic gate is shown in Fig. 6; the bandwidth of tunable OBF is 1.3 nm. The power splitting ratio between the two arms of the DI and the phase offset are changed by control of the PCs. Two data streams at 40 Gb/s, namely data A and data B, are generated by multiplexing 10 Gb/s signals with a PRBS of length $2^{31}-1$.

Wavelengths of data A and B are both 1538.9 nm, and that of the probe light is 1549.8 nm. After amplified to 5, 5 and 2 dBm, data A, data B and the probe are coupled into the SOA, which is running under a pump current of 300 mA. The logic gate operation is based on the gain saturation and phase modulation of optical signals in the SOA. Data A and B induce an intensity modulation on the CW probe via cross-gain modulation (XGM), and a phase shift via cross-phase modulation (XPM) in the SOA.

To produce high-performance OR outputs, it is important that the tunable OBF is detuned from the probe carrier in order to balance the extracted powers of the red and blue chirps. In the setup, it is centered at 1548.7 nm. The relative time delay in the DGD generator for the OR configuration is 7.93 ps, which stands for a period of the DI filter of 126 GHz. The profile of the DI is deliberately adjusted to suppress the probe carrier but relatively enhance both chirped sidebands. For the NOR gate, the DI and the OBF are running under a different status. We hence are able to turn the configuration for an OR gate into an NOR gate by simply adjusting the OBF, the DGD generator, and the two PCs.

Figure 7 shows waveforms and eye diagrams for input data and output signals. Figures 7(a) and 7(b) are data streams A and B before entering the SOA. We also compare two OR outputs with different operational setups. Figure 7(c) shows the results from an OR gate with only a DI, in which outputs of dramatically fluctuate and the extinction ratio (ER) deteriorates to only 6.5 dB. This is understandable because a single DI cannot filter out enough blue-chirped sidebands with smaller pattern effects to balance the red-chirped sidebands with larger pattern effects. Thus, more red-shifted sidebands will lead to thick eyelids and deteriorated eye diagram. In this sense, a detuning filter is dispensable for improving output signals. Figure 7(d) is the results from the OR gate with the complete pulse reshaping filter. Detuning the OBF leads to eye diagram amelioration and ER improvement to 8.5 dB. Experimental results for the NOR gate are shown in Fig. 7(e). Waveforms of this NOR gate output fluctuate a little, and the ER exceeds 7.5 dB. So far the operational conditions we propose in this paper are proved feasible, and outputs remain high quality.

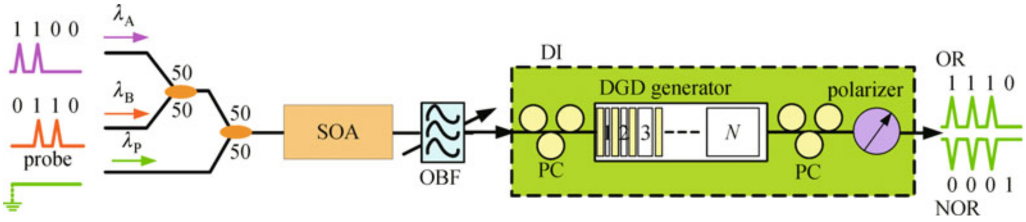


Fig. 6 Experimental setup of reconfigurable logic gate

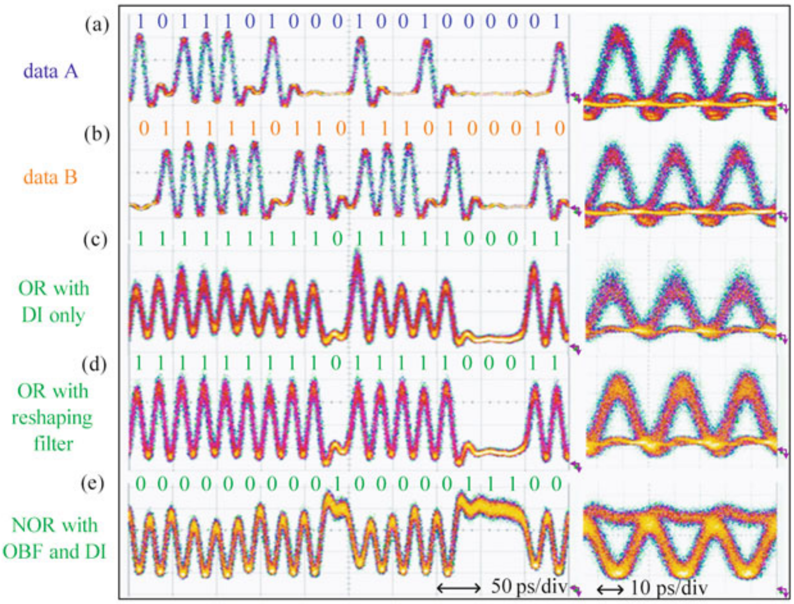


Fig. 7 Waveforms and eye diagrams for input data and logic outputs. (a) A; (b) B; (c) OR gate with DI only; (d) OR gate with pulse reshaping filter; (e) NOR gate

2.4 All-optical 2R regeneration

A novel all-optical 2R regenerator based on SOA-DI configuration is proposed and demonstrated. The scheme of the SOA-DI optical gate is described in Fig. 3. In the experiment, 10 Gb/s degraded signal and another CW probe light are injected to an SOA via a 3-dB coupler. An OBF with a 3 dB bandwidth of 1 nm is inserted at the output of the SOA to remove the data signal and suppress the ASE generated by the SOA. BER results and the eye diagrams of the degraded signal and the regenerated signal have been shown in Fig. 8. The sensitivities at a BER of 10^{-10} are measured for both the degraded signals and the regenerated signals. Bit-error rate improvement has also been achieved using the 2R regenerator. Moreover, the potential of this scheme for the application of 40 Gb/s is demonstrated by a 40 Gb/s degraded signal. The eye diagrams of the 40 Gb/s degraded signal and the corresponding regenerated signals have been presented in Fig. 9. As shown in Fig. 9(e), the 40 Gb/s regenerated signal with only DI has the intensity noise. By setting the filter offset to be −0.83 nm, the blue-shifted optical filtering technique is used to mitigate the impact of pattern effects at a bit rate of 40 Gb/s. Figure 9(f) shows the eye diagram of the regenerated signal with clear and wide eye-opening.

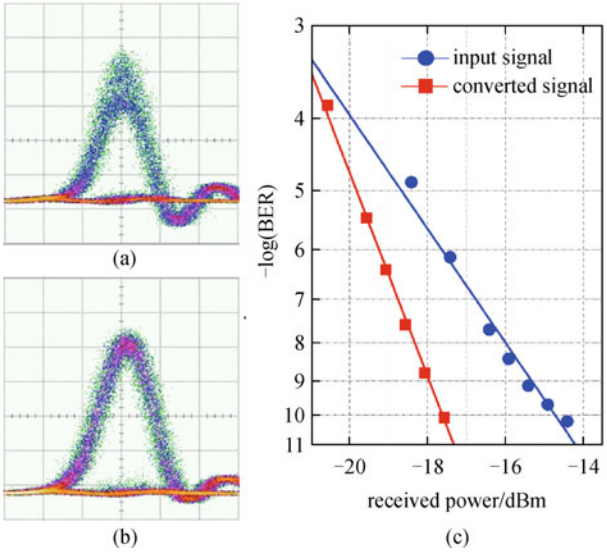


Fig. 8 Eye diagrams. (a) Degraded signal; (b) after 2R; (c) BER performance

3 Conclusions

We have demonstrated a simple, robust all-optical signal processing based on an SOA and following DI. The quality of the WC of NRZ signal can be greatly improved by incorporating a DI after the conventional NPS. Due to the reshaping effect of DI, the power penalty of the NPS-based WC signal is reduced by 2 and 1.5 dB at a BER of 10^{-9} after transmission over 25 km of SMF and 80 km of dispersion-managed fiber link, respectively. 10 Gb/s all-optical format conversion from NRZ to RZ has negative power penalty of −4.8 dB. The converted RZ signal is successfully transmitted over 80 km of SMF with a small power penalty of 0.9 dB. The potential of this scheme for

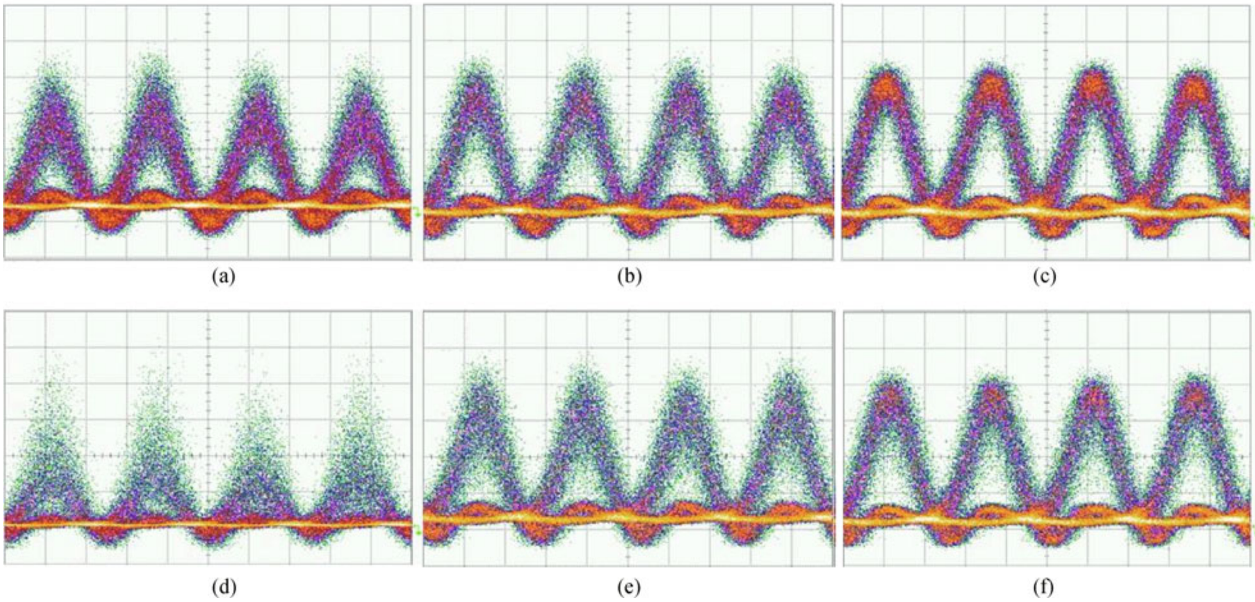


Fig. 9 Eye diagrams. (a) and (d) Input degraded signals; (b) and (e) after 2R signals with DI only; (c) and (f) with blue-shifted optical filtering

40 Gb/s system is also demonstrated. We have experimentally demonstrated an all-optical reconfigurable logic gate at 40 Gb/s based on a combinational method of filtering. Because of the implementation of a pulse reshaping filter, the ER, pulse shape, and eye diagram of the logic gate outputs turn out to be comparable with the inputs. Finally, 2R regeneration based on SOA-DI configuration is investigated. The blue-shifted optical filtering technique is used to mitigate the impact of pattern effects at a bit rate of 40 Gb/s.

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