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All-Optical RZ to NRZ Format Conversion Using Single SOA Assisted by Optical Band-Pass Filter *

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We propose a novel all-optical format conversion from the return-to-zero (RZ) to the non-return-to-zero (NRZ) based on single semiconductor optical amplifier (SOA) and optical band-pass filter (OBF). We demonstrate the proof of the principle experiment at 10 Gbps by using the test SOA and OBF converter. The format conversion can be achieved with output extinction ratio of 11.51 dB. The BER is 5.5×10^{-9} *when the power of NRZ is* -10 *dBm. The proposed scheme is robust and potential for applications in optical networks.*

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Future all-optical networks are likely to be a hybrid of wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) networks by combining the advantages of both technologies.[1,2] The evolving trends in optical networking propelled by ever-increasing bandwidth demands indicate a future leaning toward dense wavelength tributaries (> 100 closely spaced channels), increased line rates (> 40 Gbit/s), longer transparency length (regeneration spans), and improved flexibility. To release the potential of optical transmission systems and achieve higher transmission capacity, a lot of research on novel modulation formats other than traditional non return-to-zero (NRZ) and return-to-zero (RZ) has been carried out in recent years. The RZ format is widely employed in OTDM networks as it has large tolerance to fibre nonlinearities in spite of the dispersion induced effect, and the NRZ format is specially efficient and thus is better suited for the dense wavelength division multiplexing (DWDM) system. Thus, modulation format conversion will become an important interface technology for future optical networks that will include different formats.[3]

So far, reports have demonstrated different techniques of realizing all-optical format conversions between RZ and NRZ. Recently, the format conversion from NRZ to RZ has been demonstrated, such as using an injection-locked Fabry–Perot laser diode,[4,5] using nonlinearity of semiconductor optical amplifier,[6,7] and using nonlinearity of optical fibre.[8,9] The format conversions from carrier-suppressed return-to-zero (CS-RZ) to the NRZ is proposed and demonstrated with a temperature controlled all fibre delay interferometer (DI) and narrow-band filters.[10] However, the all fibre delay interferometer is required. In this DI one arm is temperature controlled to change the refractive index. The other arm has a time delay, thus change the phase difference. This control is difficult.

In this Letter, we propose a novel format conversion scheme from RZ to NRZ using single SOA and optical band-pass filter. The SOA act as a nonlinear element to broaden the spectrum of input RZ signal due to the cross gain modulation (XGM) and the cross phase modulation (XPM) effect, and the OBF is used to extract the special spectrum from the broadened spectrum.[11,12] Our system is robust in term of the simple structure.

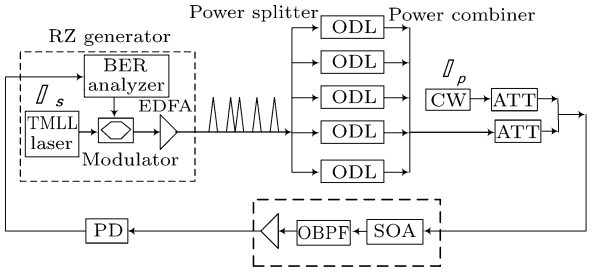


Fig. 1. Experimental setup for the RZ to NRZ format conversion. SOA, semiconductor optical amplifier; EDFA, doped erbium fibre amplifier; OBPF, optical band-pass filter; CW, continuous wave; ATT, optical variable attenuation; PD, photo-detector.

The experimental setup for our RZ to NRZ format conversion is shown in Fig. 1, which consists of an SOA, five optical delay line (ODL) and a band

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filter. The format converter made up of the SOA as nonlinear medium and the OBF as spectral filtering. In our experiment, the RZ generator system is used to generate input 10 Gb/s RZ signal at the centre wavelength of 1550.97 nm. The signal power can be controlled by the followed erbium doped fibre amplifier (EDFA) and the attenuator (ATT). The pulse-width of the signal is pico-second-scale, typically 1.5 ps. The signal pulse is preprocessed by the system formed by one power splitter, one power combiner, five ODL. Our proposed preprocessing system has a time delay Δt about 20 ps in each arm corresponding to about 4.2 mm fibre length difference. The signal power can be controlled by the followed ATT. The signal pulse and the probe light whose central wavelength is 1559.68 nm pass the power combiner, and then are launched into the SOA. The RZ signal and the probe light achieved sufficient the XGM and the XPM effect induced spectral broadening. The input power of signal and probe light can be adjusted by the EDFA and the ATT. The subsequent OBF then extracts the sideband spectrum with its central wavelength $\lambda_p+\Delta\lambda$ about 1559.36 nm, where $\Delta\lambda$ is the difference between the central wavelength of probe light and the central wavelength of NRZ. As we know, the converted signal will keep in probe light if the filter detuning is properly chosen. The principle is similar to the wavelength conversion based on the configuration of the SOA and OBF. Simply speaking, our scheme for RZ to NRZ format conversion can also act as wavelength conversion. The results can be analysed by the optical spectrum analyser (OSA) and the oscillograph. The bit error ratio (BER) can be measured by the error analyser (EA).

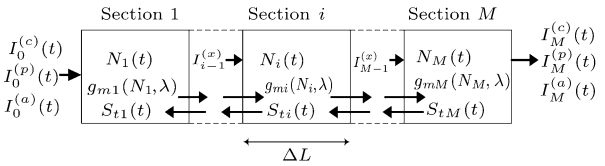


Fig. 2. Numerical model using the rate equation of the carrier density.

To explain the intrinsic mechanism of the scheme, a potent SOA model should be developed to predict the SOA operation. For analysing the SOA, we divide the SOA into M sections as shown in Fig. 2 and use the following rate equation of the carrier density to calculate the carrier density variation during the time corresponding to the propagation of fields in each of the divided sections of the SOA:[13,14]

$$\frac{dN_i}{dt} = \frac{J}{qd} - \frac{N_i}{\tau_i} - \sum_{x=c,p,a} \frac{g_{mi}^{(x)} \cdot I_i^{(x)}}{E^{(x)}} - g_m^{\mathrm{ASE}} S_{t_i}, \quad (1)$$

where N is the carrier density, J is the injection current density, d is the active layer thickness, τ is the carrier life time, g_m is the material gain, I is the injected light intensity, E is the photon energy, S_t is the average amplified spontaneous emission, q is the electron energy, subscript i is the number of section, superscript $x = (c, p \text{ and } a)$ denotes the control, probe and assist light, respectively. In Eq. (1), the first term on the right-hand side represents the increase of carrier density by current injection, while the second, third and fourth terms represent the decreasing carrier density due to spontaneous emission, stimulated emission, and amplified spontaneous emission (ASE), respectively. From Ref. [15], we have

$$I_{av_i}^{(x)} = I_i^{(x)} \frac{\exp(g_i \Delta L) - 1}{g_i \Delta L}, \quad (2)$$

where I_{av_i} is the average incident light intensity into the section i, ΔL is the section length, and

$$g_i = \Gamma g_{m_i} - \alpha, \quad (3)$$

is the net optical gain in section i, Γ is the confinement factor, and α is the material loss. The gain spectrum is assumed to be parabolic and the material gain is thus approximated to be[3,17]

$$g_{m_i} = \alpha_1(N_i - N_0) - \alpha_2(\lambda - \lambda_{p_i})^2, \quad (4)$$

where α_1 and α_2 are the gain constants, N_0 is transparency carrier density, λ represents the wavelength, and λ_p is the wavelength at gain peak given by[3]

$$\lambda_{p_i} = \lambda_0 - \alpha_3(N_i - N_p), \quad (5)$$

where α_3 is also a gain constant and N_p is the carrier density at λ_p. The injected light $I_{i+1}(t)$ into the section $i+1$ is obtained from the light $I_{i+1}(t-1)$ injected into the adjacent section I multiplied by the optical gain $G(N_i, \lambda)$ of the section i at the preceding time $t-1$, as[3]

$$I_{i+1}^{(x)} = G_i^{(x)}[N_i(t-1), \lambda^{(x)}] \cdot I_i^{(x)}(t-1), \quad (6)$$

where

$$G_i(x)(N_i, \lambda^{(x)}) = \exp[g(N_i, \lambda^{(x)}) \cdot \Delta L] \cdot I_i^{(x)}(t-1). \quad (7)$$

The nonlinear phase change, arising from carrier density-induced changes in the refractive index, is given by[14]

$$\phi_i = \frac{\pi \Delta L \Gamma g_{m_i}}{2\alpha_1 \lambda^{(x)}} \Delta n_N, \quad (8)$$

where Δn_N is the rate of change of refractive index in the active region with carrier concentration.

In our scheme, we take the experimental parameters as listed in Table. 1. The simulation results are show in Fig. 3. The experimental results are shown in Figs. 4–6.

According to the previous analysis, based on the

model of Mecozzi and Mørk associated with the intraband mechanism we simulate the format conversion from RZ to NRZ, as shown in Fig. 3.[16] The input signal is 10 Gb/s pulse trains at 1550.97 nm with 1.5-ps-pulse-width 4.98 dBm peak power, whose eye diagram is shown in Fig. 3(a). The original RZ signal modulated at 10 Gb/s to form $2^{31}-1$ pseudo random binary sequence (PRBS) signal. Figure 2(b) is the eye diagram converted NRZ.

Table 1. Experimental parameters.

Parameter	Value
Wavelength of signal pulse	1550.97nm
Wavelength of probe light	1559.68nm
Bit rate	10Gb/s
Injected current I	300mA
Bandwidth of the filter	0.3nm
Small signal gain	30dB
Polarization dependent saturated gain	0.5dB
Saturation output	6dBm
Gain peak wavelength	1560nm
3dB spectrum bandwidth	50nm
Saturated gain recovery time	25ps

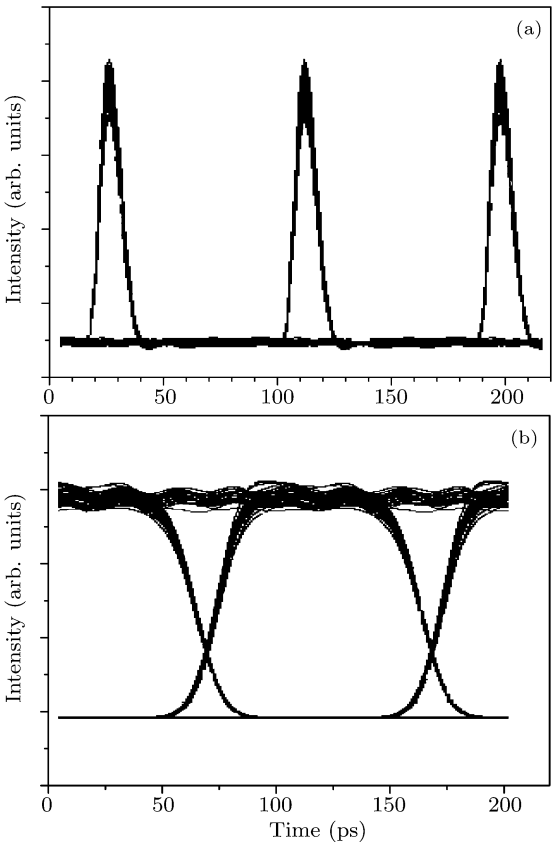


Fig. 3. Simulation results of the format conversion: (a) the eye diagram of RZ signal, (b) the eye diagram of NRZ signal.

Figure 4 shows the experimental results for the conversion of the RZ signal modulated at 10 Gb/s to form $2^{31}-1$ PRBS signal. The generated RZ pulses are modulated and become an RZ format data stream. Figure 4(a) is the eye diagram of input RZ. Figure 4(b) is the eye diagram of converted NRZ. The converted NRZ signals show clear and open eyes, with little ripple on the top. No additional noise and the pattern effect can be found. The output extinction ratio (ER) is over 11 dB. We can see that the experimental results are in agreement with the simulation results very well at 10 Gb/s. The spectra of the input RZ signal, the probe light, the signal and probe light after SOA and the converted NRZ signal are shown and analysed in Fig. 5.

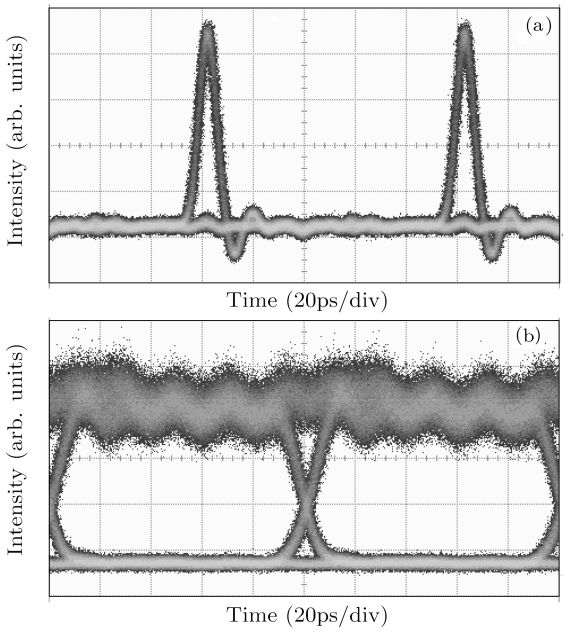


Fig. 4. Measured RZ-to-NRZ conversion of PRBS ($2^{31}-1$): (a) the eye diagram of RZ signal, (b) the eye diagram of converted NRZ signal.

The input signal is 10 Gbps pulse train at 1550.97 nm, whose spectrum is shown in Fig. 5(a). As shown in Fig. 5(b), the solid line represents the spectra of the probe light. RZ signal and the probe light lunched into the SOA, the RZ spectrum will be broadened and the spectra of the probe light will be changed due to the XGM and the XPM effect. Figure 5(c) shows the spectra of the probe light pass the SOA with RZ signal. When the central wavelength of the filter is 1559.36 nm, the spectrum of the converted NRZ signal is shown in Fig. 5(d).

Figure 6 shows the bit error rate (BER) with the proposed system for RZ to NRZ format conversion. The result shows that the BER is 5.5×10^{-9} when the power of NRZ is -10 dBm. When the power of NRZ is over -4 dBm, the BER is 0. Thus we can find that the BER of the novel scheme for RZ to NRZ format conversion using single SOA and optical band-pass filter is very much lower.

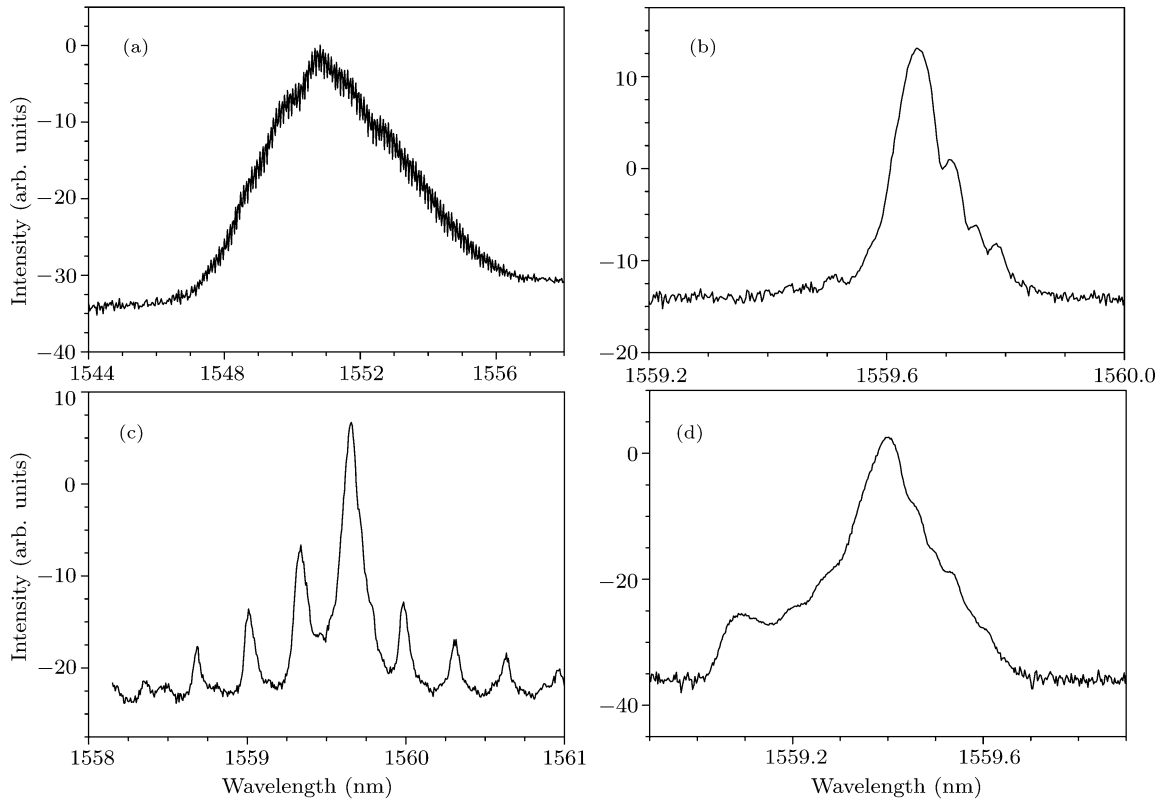


Fig. 5. Measured spectra of the format conversion: (a) the spectrum of RZ, (b) the spectrum of probe light, (c) the spectrum of probe light pass the SOA, (d) the spectrum of NRZ.

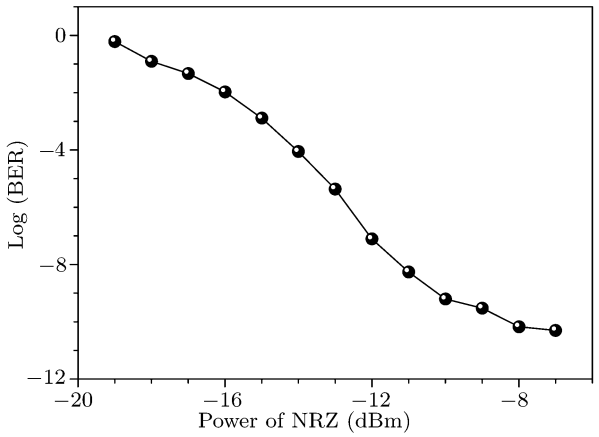


Fig. 6. BER for the RZ to NRZ format conversion.

In summary, we have proposed a novel all-optical format conversion from RZ to NRZ based on single SOA, OBPF and the preprocessed system which includes one power splitter, one power combiner, five ODLs. The converted NRZ signal can be achieved with ER of about 11dB. The BER of the novel scheme from RZ to NRZ format conversion is very lower. When the power of NRZ is over −4 dBm, the BER is 0. Our proposed scheme has advantages as follows: (1) simple implementation, (2) high speed operation, (3) easy to reach high ER, and (4) low BER.

References

[1] Norte D and Willner A E 1995 *IEEE Photon. Technol. Lett.* **7** 1354
[2] Winzer P J and Chandrasekhar S 2003 *Electron. Lett.* **39** 859
[3] Yan L S, Nezam S M R M, Sahin A B, McGeehan J E, Luo T, Yu Q and Willner A E 2005 *J. Lightw. Technol.* **23** 1063
[4] Chow C W, Wong C S and Tsang H K 2002 *Opt. Commun.* **209** 329
[5] Chang Y C, Lin Y H, Chen J and Lin G R 2004 *Opt. Express* **12** 4449
[6] Lee C G, Kim Y J, Park C S, Lee H J and Park C S 2005 *J. Lightwave Technol.* **23** 834
[7] Huang C M, Yu K C, Chang Y C and Lin G R 2006 *OFC JThB33* (California)
[8] Yu J, Chang G K, Barry J and Su Y 2005 *Opt. Commun* **248** 419
[9] Dong J, Zhang X, Xu J and Huang D 2007 *Opt. Express* **15** 2907
[10] Yu Y, Zhang X and Huang D 2007 *Opt. Express* **15** 5693
[11] Martinez J M, Ramos F and Marti J 2004 *Electron. Lett.* **40** 894
[12] Mishina K, Nissanka S, Maruta A, Mitani S, Ishida K, Shimizu K, Hatta T and Kitayama K 2007 *Opt. Express* **15** 7774
[13] Asghari M, White I H and Penty R V 1997 *J. Lightw. Technol.* **15** 1181
[14] Kawaguchi H 1987 *Opt. Quantum Electron.* **19** 1
[15] Connelly M J 2002 *Semiconductor Optical Amplifiers* (Dordrecht: Kluwer)
[16] Mecozzi A and Mørk J 1997 *J. Opt. Soc. Am.* B **14** 761