All-optical Modulation Format Conversion from NRZ to RZ Using SOA and Optical Bandpass Filter Converters*

XIE Yi-yuan, ZHANG Jian-guo, ZHAO Wei, YAN Shuang-yi, XIE Xiao-ping, LIU Yuan-shan

(State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China)

Abstract: An all-optical non return-to-zero (NRZ) to return-to-zero (RZ) modulation format converter using single semiconductor optical amplifier (SOA) and an optical band-pass filter (OBPF) was proposed. By adopting the ultra-fast SOA model associated with optical system software, the 10 Gbit/s NRZ-to-RZ format conversion was successfully demonstrated with simulation. The proof-of-the-principle experiment at 10 Gbps was also demonstrated using the test SOA and OBF converter. The result shows that the BER is 1.0×10^{-9} when the power of RZ is −15 dBm, which are well coincidence with simulated results.

Key words: Non return-to-zero (NRZ); Return-to-zero (RZ); Semiconductor optical amplifier (SOA); Optical band-pass filter (OBPF)

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0 Introduction

All-optical signal processing is a promising technology to remove optical-to-electric (O/E) and electric-to-optical (E/O) converters in future all-optical networks. A large number of researches have been focused on all-optical signal regeneration and processing, which helps overcoming accumulation of signal degradation[1]. To complete all-optical networks, there would be a need for a wide variety of all-optical signal processing techniques such as optical 3R regeneration, wavelength conversion, optical label processing, and modulation format conversion[2-5].

Future all-optical networks are likely to be a hybrid of wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) networks by adopting the advantages of both technologies[6]. The evolving trends in optical networking-propelled by the ever-increasing bandwidth demands—indicate a future leaning toward dense wavelength tributaries (>100 closely spaced channels), increased line rates (>40Gbit/s), longer transparency lengths (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 in recent years[7].

The RZ pulses have been widely used in optical fiber communication systems and optical networks, including RZ format transmission, optical time-division multiplexing, optical code-division multiple access, and optical packet generation. For example, RZ formats rather than non return-to-zero (NRZ) formats have been applied in long-haul fiber transmission systems to extend transmission distance due to a possible higher tolerance to many fiber transmission impairments. The NRZ format is spectrally efficient and thus is better suited for dense wavelength division multiplexing (DWDM) system. Thus, All-optical format conversion between non return-to-zero (NRZ) and return-to-zero (RZ) will become an important interface technology in future for connecting the DWDM access and metro networks to the ultra-fast OTDM long-haul networks[8-9]. Recently, various demonstrated schemes have been proposed to realize NRZ-to-RZ format conversion, such as using an injection-locked Fabry-Perot laser diode[10-11], using nonlinearity of semiconductor optical amplifier[12], and using nonlinearity of optical fiber[13]. The reported injection locking technologies were with low bit rate due to the directly modulated source. The nonlinearity of optical fiber is attractive in format conversion due to its ultra-fast nonlinear response[14]. However, a long interaction length is required in order to

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Tel: 029-88887615 Email: xieyiyuan1000@126.com

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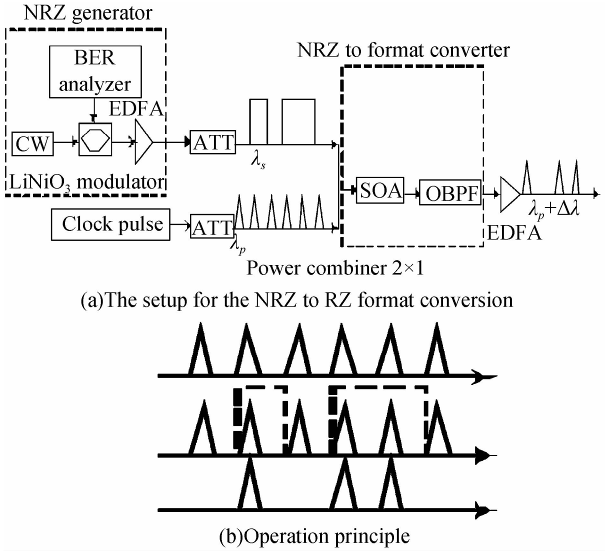
obtain sufficient nonlinear effects. The use of Semiconductor Optical Amplifier (SOA) as the nonlinear medium has received considerable attention in terms of small footprint, high nonlinearity, and optical integration. But a large number of studies focus on the principle and simulation[6]. To the best of the authors' knowledge, this paper is the only one that reports data format conversions from NRZ to RZ with transmission experiments at the bit rate of 10 Gbps base on single SOA and OBF.

In this paper, the experimental setup and operation principle is presented, and results is discussed.

1 Principle of operation

Fig. 1(a) shows the schematic diagram of the proposed modulation format converter. The basic configuration consists of a SOA and an OBPF. The SOA-OBPF converters convert a NRZ data signal to a RZ signal by using the cross phase modulation (XPM) in SOA. The SOA is used as the nonlinear medium and the OBPF as the spectral filtering. The incoming NRZ data signal with wavelength λ_s is combined with the synchronized clock pulse as the control signal, and then launched into the SOA. The pulse-width of the clock signal is picosecond scale, typically 1.5ps, to achieve sufficient XPM-induced spectral broadening to the NRZ data signal. The OBPF extract the sideband spectrum with its central wavelength is $\lambda_s+\Delta\lambda$, $\Delta\lambda$ is the filter detuning from the NRZ central wavelength. Therefore, NRZ data signals can be converted to RZ data signals. The theory of the scheme is similar to the non-inverted wavelength conversion base on the setup of the SOA and OBPF. Fig. 1 (b) shows the operation principle for format conversion. The input clock pulse will drive the phase of NRZ signal to change periodically. If the NRZ data signal is "1", the converted signal will output at bit "1" because the non-inverted wavelength conversion, otherwise, the converted signal will output bit "0" since the input NRZ data signal is "0". So the format conversion from NRZ to RZ can be obtained. To explain the intrinsic mechanism of the scheme, a potent SOA model should be developed to predict the SOA operation. For analyzing the SOA, we divide the SOA into M sections as shown in Fig. 2 and use following rate equation of the carrier density to calculate the carrier density variation



EDFA: doped erbium fiber amplifier; OBPF: optical band-pass filter; CW: continuous wave; ATT: optical variable attenuation

Fig. 1 The NRZ to RZ format conversion

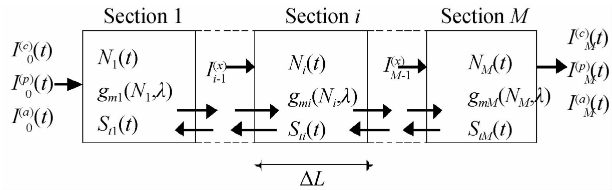


Fig. 2 Numerical model using the rate equation of the carrier density

during the time corresponding to the propagation of fields in each of the divided sections of the SOA[5,15].

$$\frac{\mathrm{d}N_i}{\mathrm{d}t}=\frac{J}{qd}-\frac{N_i}{\tau_i}-\sum_{x=\mathrm{c,p,a}}\frac{g_{\mathrm{m}_i}^{(x)}\cdot I_i^{(x)}}{E^{(x)}}-g_{\mathrm{m}}^{\mathrm{ASE}}S_{t_i} \qquad (1)$$

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 $x(=c, p$ and $a)$ denotes the control, probe and assist light, respectively. In Eq. (1), the first term on the right-hand side represents the increase in 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[5,16],

$$I_{\mathrm{av}_i}^{(x)}=I_i^{(x)}\frac{\exp(g_i\Delta L)-1}{g_i\Delta L} \qquad (2)$$

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

$$g_i=\Gamma g_{\mathrm{m}_i}-\alpha \qquad (3)$$

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[5, 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 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

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

The nonlinear phase change, arising from carrier density-induced changes in the refractive index, is given by[16]

$$\varphi_i=\frac{\pi\Delta L\Gamma g_{m_i}}{2\alpha_1\lambda^{(x)}}\Delta\bar{n}_N \quad (8)$$

Where $\Delta\bar{n}_N$ is the rate of change of refractive index in the active region with carrier concentration.

2 Results and dicussion

In NRZ to RZ format conversion scheme, the simulation parameters are listed in Table 1, the experimental parameters are listed in Table 2.

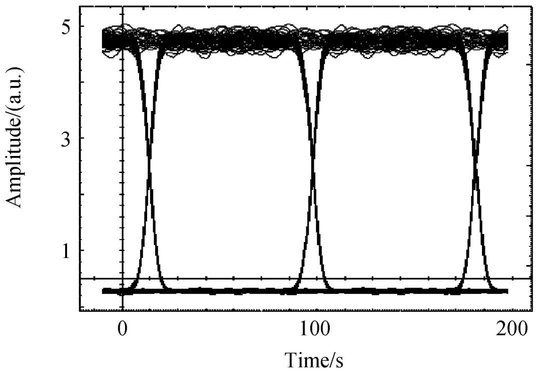
We simulate the format conversion from NRZ to RZ, as shown in Fig. 3. The eye diagrams and spectrum of NRZ are shown in Fig. 3(a) and (c). The original NRZ signal is synchronized to the clock signal and modulated at 10 Gb/s to form $2^{31}-1$ pseudo random binary sequence (PRBS) signal, whose wavelength is 1 540 nm. The power of input NRZ signal is 0 dBm. The input control signal is 10 GHz clock pulse train at 1 552 nm with 1. 5 ps pulse-width. The power of input clock signal is 5 dBm. When the NRZ signal and the clock signal are simultaneously launched into the SOA, the spectrum of NRZ signal will be changed due to XPM effect induced by the control signal. When the detuning $\Delta\lambda$ is 0. 5 nm, the eye diagrams and spectrum of converted RZ are shown in Fig. 3 (b) and (d).

Table 1 Simulation parameters

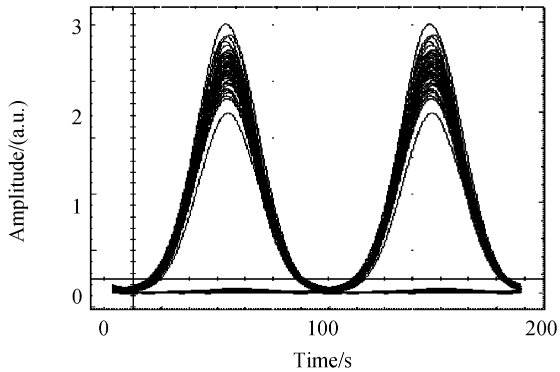
Parameter	Value
Wavelength of NRZ signal	1 540 nm
Wavelength of clock singal	1 552 nm
Bit rate	10 Gb/s
Injected current I	500 mA
Bandwidth of the fliter	0. 5 nm
Small signal gain	25 dBm
Polarization dependent saturated gain	0. 5 dB
Saturation output	6 dBm
Gain peak wavelength	1 560 nm
3 dB spectrum bandwidth	50 nm
Saturated gain recovery time	25 ps

Table 2 Experiment parameters

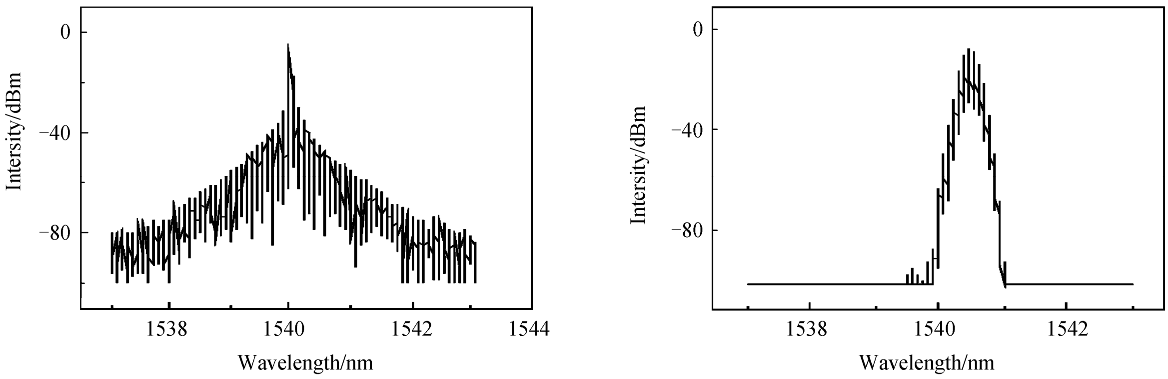
Parameter	Value
Wavelength of NRZ signal	1 539. 9 nm
Wavelength of clock singal	1 552 nm
Bit rate	10 Gb/s
Injected current I	300 mA
Bandwidth of the fliter	0. 3 nm
Small signal gain	30 dB
Polarization dependent saturated gain	0. 5 dB
Saturation output	6 dBm
Gain peak wavelength	1 560 nm
3 dB spectrum bandwidth	50 nm
Saturated gain recovery time	25 ps



(a)The eye diagrams of NRZ



(b)The eye diagrams of converted RZ



(c)The spectrum of NRZ (d)The spectrum of converted RZ

Fig. 3 Simulation results of the format conversion from NRZ to RZ

Fig. 4 shows the Bit Error Rate (BER) with the proposed system for NRZ to RZ format conversion. The simulation result shows that the BER is 1.0×10^{-9} when the power of NRZ is −29.5 dBm. So we can find the BER of the novel scheme for NRZ to RZ format conversion using single SOA and optical band-pass filter is very lower.

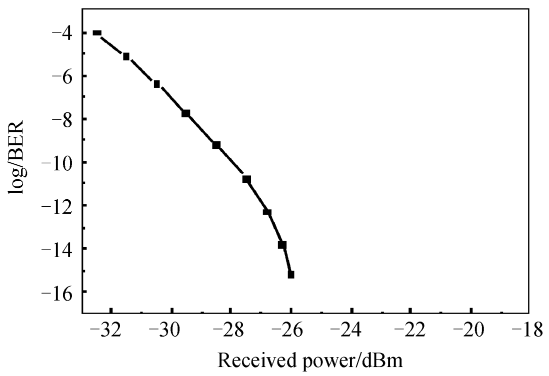
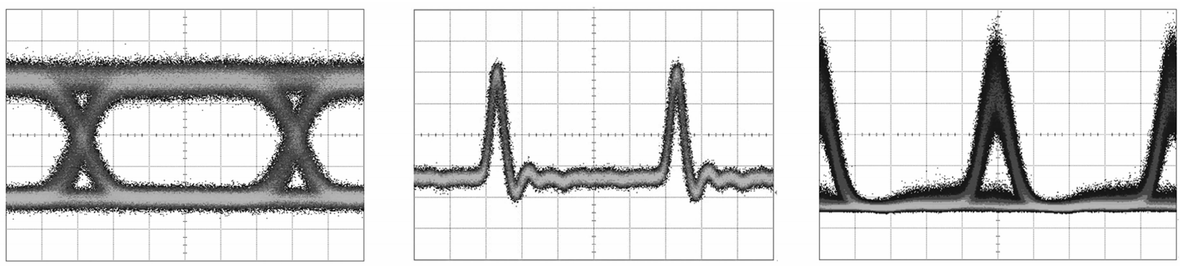


Fig. 4 The BER for the NRZ to RZ format conversion in simulation

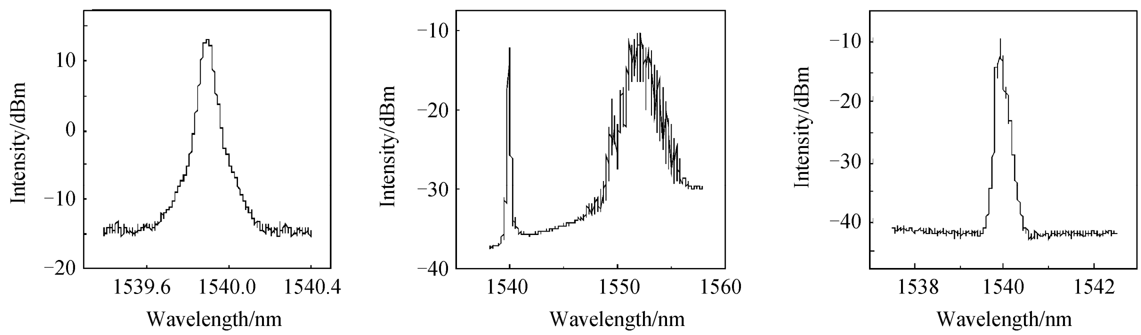
We used the setup which is shown in Fig. 1 and according the simulation results. The experiment results shows in Fig. 5. The input clock signal is 10 GHz at 1 552 nm with 1.5 ps pulse width, whose eye diagrams is shown in Fig. 5 (b). The power of input clock signal is 4.68 dBm. The original NRZ signal modulated at 10 Gbps to form $2^{31}-1$ pseudo random binary sequence (PRBS) signal, whose wavelength is 1 540 nm. The eye diagram is shown in Fig. 5(a). The power of input NRZ signal is 1.05 dBm. The converted RZ is shown in Fig. 5(c).

The spectra of the input NRZ signal, the clock signal, pass SOA and the converted RZ signal are shown and analyzed in Fig. 6.



(a)The eye diagram of input NRZ signal (b)The eye diagram of input clock signal (c)The eye diagram of RZ signal

Fig. 5 Measured NRZ to RZ conversion of PRBS ($2^{31}-1$)



(a)The spectrum of NRZ (b) The spectrum of NRZ and clock signal pass the SOA (c) The spectrum of RZ.

Fig. 6 Measured spectra of the format conversion

The input signal is 10 Gbps pulse train at 1 540 nm,whose spectrum is shown in Fig. 6(a). As shown in Fig. 6(b), the solid lines represent the spectra of NRZ signal and the clock signal pass the SOA. Fig. 6(c) shows the spectrum of the converted RZ signal.

Fig. 7 shows the BER with the proposed system for NRZ to RZ format conversion in experiment. The result shows that the BER is 1.0×10^{-9} when the power of RZ is -15 dBm. When the power of NRZ is over -12 dBm, the BER is 0. The experiment results are well coincidence with simulated results.

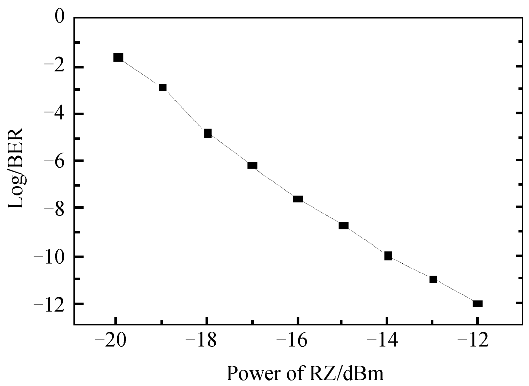


Fig. 7 The BER for the NRZ to RZ format conversion in experiment

3 Conclusion

In this paper, we have proposed and experimentally demonstrated an all-optical modulation format conversion scheme from NRZ to RZ using single SOA-OBPF converter. Simulation results accord with experimental results very well at 10 Gbit/s. The BER of the scheme from NRZ to RZ format conversion is very lower. Our proposed scheme has advantages as follow: 1) simple implementation; 2) high speed operation; 3) low BER of the system. Even though the further study on the conversion penalty should be done before applying to the real system, this modulation format conversion will become a key technique at the gateway node interfacing MAN and WAN in the future all-optical networks.

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基于半导体光放大器和光滤波器的全光非归零码到归零码的转换

解宜原，张建国，赵卫，延双毅，谢小平，刘元山
（中国科学院西安光学精密机械研究所 瞬态光学与光子技术国家重点实验室，西安 710119）

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摘　要：利用半导体光放大器模型和仿真软件对全光非归零码到归零码的变换进行了数值仿真．在仿真结果的基础上，实现了基于半导体光放大器和光滤波器的10 Gbps的全光非归零码到归零码的变换试验．试验结果显示在RZ码输入功率为－15 dBm时，该变换的误码率为1.0×10^{-9}．

关键词：非归零码；归零码；半导体光放大器；带通光滤波器

XIE Yi-yuan received M. S. degree from College of Science of Southwest Jiaotong University in 2006. Currently, he is working toward the Ph. D. degree at State Key Laboratory of Transient Optics and Photonics, Xi′an Institute of Optics & Precision Mechanics, Chinese Academy of Sciences, and his research interests focus on optical burst switching and high-speed optical communication systems, WDM optical networks, and related topics.