All-optical nonreturn-to-zero to return-to-zero format conversion with wavelength conversion using an electro-absorption modulator

Zhixin Chen, Jian Wu, Kun Xu, and Jintong Lin
Beijing University of Posts and Telecommunications, Key
Laboratory of Optical Communication and Lightwave
Technologies of MOE, P.O.Box 55, Beijing, China, 100876
E-mail: czx.bupt@gmail.com

Abstract. Simultaneous all-optical nonreturn-to-zero (NRZ) to return-to-zero (RZ) format conversion and wavelength conversion in an electroabsorption modulator (EAM) based on cross-absorption modulation (XAM) at 10 Gbit/s is demonstrated. The impact of the bias voltage of EAM and the input NRZ data signal power on the performance of converted RZ signals is studied. The maximum extinction ratio (ER) of converted RZ signals is about 12.08 dB. By tuning the wavelength of input NRZ signals from 1550 to 1570 nm, negative power penalty with a range of −0.9 to −0.2 dB is observed for converted RZ signals. Thus, error-free all-optical simultaneous format and wavelength conversion using EAM is reported, in a setup that has not been demonstrated in the past. © *2007 Society of Photo-Optical Instrumentation Engineers.*
[DOI: 10.1117/1.2766938]

1 Introduction

Format conversion between nonreturn-to-zero (NRZ) and return-to-zero (RZ) and wavelength conversion are key technologies in future all-optical networks. In the past few years, several format conversion schemes have been demonstrated using semiconductor optical amplifiers,[1] Injection-locked laser diodes,[2] semiconductor optical loop mirrors,[3] and self-starting electroabsorption modulator (EAM)-based OEO (EAM-OEO).[4] Meanwhile, many wavelength conversion schemes have been proposed, such as using a Mach-Zehnder interferometer (MZI),[5] periodically poled lithium-niobate (PPLN),[6] and Sagnac loops.[7] However, few simultaneous format conversion and wavelength conversion technologies have been reported so far.[8,9] In this work, we demonstrate a novel all-optical format conversion and wavelength conversion based on cross-absorption modulation (XAM) effect in an electroabsorption modulator (EAM). Compared with the complex structure of the reference,[4] this scheme only needs an EAM without OEO conversion. Meanwhile, the advantages of using EAM as a nonlinear switching medium are fast recov-
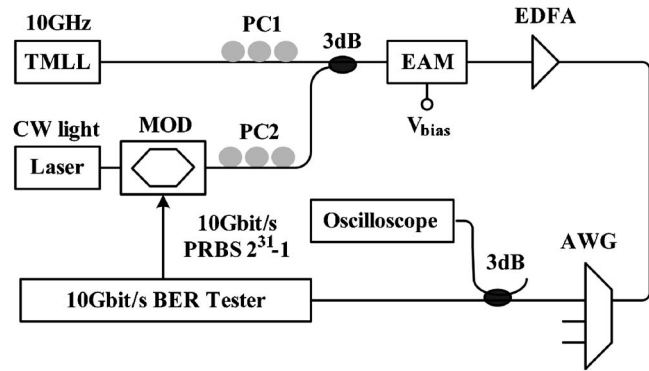
Fig. 1 Experimental setup

ery time and the ability to be integrated with other semiconductor components.[10] Using this scheme, error-free all-optical format conversion and wavelength conversion is realized at 10 Gbit/s in a single EAM.

2 Experimental Setup and Principle

The experimental setup is shown in Fig. 1, which is composed of a tunable mode-locked laser (TMLL), a LiNbO₃ modulator, a continuous-wave (cw) laser, a commercial quantum well EAM (OKI-OM5642W-30B) with maximumum input peak power of 13 dBm, two polarization controllers (PCs), and an arrayed-waveguide grating (AWG). Driven by a 10-GHz clock signal from a patten pulse generator, the TMLL generates 10-GHz, 2-ps full-width half maximum (FWHM) pulses at 1545.5 nm. The 10-Gbit/s 2^{31}-1 PRBS NRZ data signal is generated by modulating the 1550-nm cw light with the LiNbO₃ modulator. The high-power 10-Gbit/s NRZ data signal and the low-power 10-GHz clock signal are simultaneously coupled through a 3-dB coupler into the EAM, which is under reverse bias voltage. The insertion loss and the polarization dependence loss of the EAM are about 6 and 0.2 dB, respectively. The format and wavelength converted output from the EAM is amplified by an erbium-doped fiber amplifier (EDFA), and fed into an AWG filter with 0.41-nm bandwidth. In this setup, the reverse bias voltage of EAM is set at 2.75 V. Two PCs are used for performance optimization. The eye waveforms are displayed by a wide-bandwidth oscilloscope (Agilent 86105A) with a 20-GHz optical module.

The principle of format and wavelength conversion with this scheme can be explained by the XAM effect in EAM. As high intensity NRZ data signals and weak-power clock signals are simultaneously launched into the EAM, more carriers are generated in the active region of the EAM due to the high intensity NRZ data signal. The increase of carriers leads to a temporary reduction of absorption coefficient of EAM and consequently the low-power clock signal in EAM experiences a smaller attenuation. In other words, the EAM serves as an AND gate with the NRZ data signal and the clock signal as inputs, and the resulted signal at clock signal wavelength as an output. As the AWG singles out the clock signal wavelength, the NRZ data signal is converted into a RZ signal at a converted wavelength. Thus all-optical wavelength conversion and format conversion is realized in an EAM.
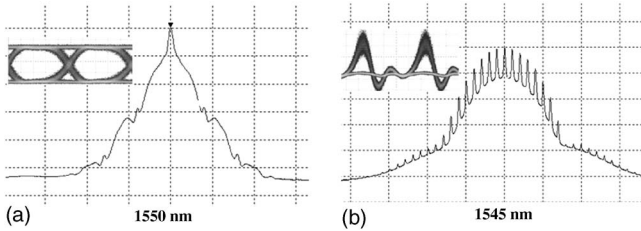
Fig. 2 (a) Eye diagram and spectrum of the 10-Gbit/s NRZ data signal. (b) Eye diagram and spectrum of the 10-Gbit/s RZ data signal after wavelength and format conversion (20 ps/div)

3 Experimental Results and Discussion

Figure 2 shows the results of format and wavelength conversions. The wavelengths of the NRZ data signal and clock signal are 1550 and 1545.5 nm, respectively, and the corresponding values of average power are 11 and −0.56 dBm. Figure 2(a) shows the eye diagram and the spectrum of the 10-Gbit/s NRZ data signal, and the extinction ratio (ER) of input NRZ signal is about 12.4 dB. Figure 2(b) presents the eye diagram and the spectrum of the 10-Gbit/s RZ data signal after format and wavelength conversions. It can be seen from the figure that the eye diagram of the converted RZ signal is relatively clearly opened and with a high ER of 12.08 dB. However, a slight pattern effect is seen on the mask of the eye diagram, possibly due to a finite carrier absorption recovery time of EAM.

The effect of the bias voltage and input NRZ data signal power on the format and wavelength converted signal is investigated in this experiment. The wavelength of the NRZ data and clock signals is 1550 and 1545.5 nm, respectively. The power of the clock signal is fixed at −0.56 dBm, and the input average power for the NRZ data signal is adjusted from 8 to 11 dBm. The reverse bias voltage of EAM is tuned from 1.95 to 3.00 V in the experiment. Figure 3 shows the extinction ratio (ER) of converted RZ signal as a function of the bias voltage under different NRZ data signal power. With the increase of reverse bias voltage, the ER first increases and then gradually decreases. The ER
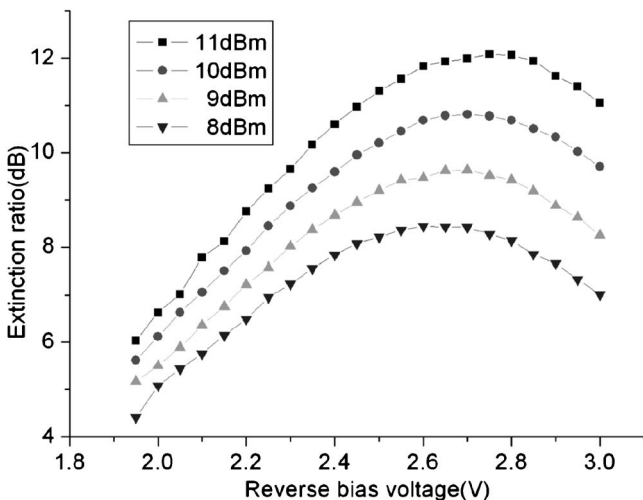

Fig. 3 ER of converted RZ signal as a function of the bias voltage of EAM with NRZ signal data power as a parameter.
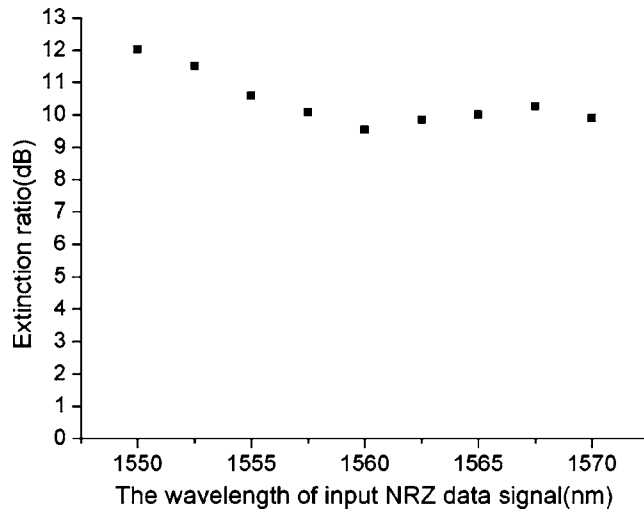

Fig. 4 ER of converted RZ signal under different wavelengths of input NRZ data signals.

reaches its maximum at a certain bias voltage. It also can be seen from Fig. 4 that with the increase of NRZ data power, the ER of converted RZ signal correspondingly increases and the bias voltage for the maximal ER is different. As the power of the NRZ data increases from 8 to 11 dBm, the maximal ER also increases from 8.44 to 12.08 dB, and the reverse bias voltage of EAM for maximal ER is changed from 2.6 to 2.75 V. This result can be explained as follows. When a data signal is injected, carriers will be generated in the active region of the EAM. At low bias voltages, the high power of the data signal is enough to achieve complete absorption saturation for logical 1 of the input signal, and the maximum XAM-induced extinction ratio available increases with the increase of reverse bias voltages. But as the bias voltage increases, the carriers are swept out of the waveguide faster and the accumulated carriers in the waveguide are reduced. Thus the carrier effect on the absorption coefficient is reduced, the optical saturation power increases, so the absorption is not "saturated" fully for logical 1 of data signals at these high bias reverse voltages. Thus, with the increasing of the bias voltage, the transmission increment between logical 0 and logical 1 induced by XAM effect reduces, and the ER of converted RZ signal becomes smaller gradually.[11,12] Meanwhile, the higher data power is, the higher the ER of converted RZ signal under the same bias voltage. Therefore, the higher the power of input data signals, the stronger XAM effects in the EAM. So the ER of converted RZ signals becomes bigger gradually. Also, the higher data power can produce more carriers in waveguides, so they required more reverse voltage to achieve the maximum ER of converted RZ signals. Thus, for the different data power, the bias voltage for the maximal ER is different.

For realizing broadband wavelength conversion, the input power of NRZ data signal and the reverse bias voltage of EAM are optimized to 11 dBm and 2.75 V, respectively. To testify the available range of wavelength conversion, the wavelength of input NRZ signal is tuned rather than the clock signal. This is because the wavelength of the clock signal makes it difficult to achieve a dynamic adjustment in the experiment. The ER of converted RZ signal in a broad
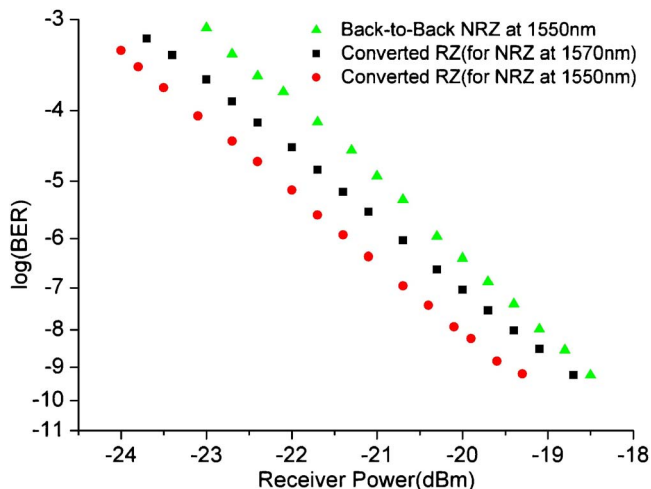
Fig. 5 BER measurements of the back-to-back input NRZ signal at 1550 nm and converted RZ signal at 1545.5 nm when the wavelength of the input NRZ data signal is 1550 and 1570 nm, respectively.

wavelength range is shown in Fig. 4. It is found that as the NRZ data signal wavelength tunes from 1550 to 1570 nm, the ER of converted RZ signal varies in the range of 12.08 to 9.90 dB. The result is consistent with the following fact that the absorption of EAM for longer wavelength data signals decreases[13] and then weakens the XAM-induced effect, which causes to the decreasing of the ER of the converted RZ signal.

The performance of the wavelength and format conversion was accurately evaluated by measuring bit error rate (BER). The BER measurement results are summarized in Fig. 5. In the experiment, the difference of back-to-back BER results is very minor between the input NRZ signal at 1550 nm and that at 1570 nm. The experimental result for NRZ signals only at 1550 nm is plotted. Error-free results were obtained with small negative power penalty from -0.9 to -0.2 dB (BER$=10^{-9}$) in this wavelength range. This improvement is partly attributed to the inherently better sensitivity of RZ signal compared to NRZ signals, and the pulsewidth of converted RZ signal is relatively narrow, because the narrow pulse from TMLL is used in the experiment. Even so, the negative power penalty of less than 1 dB is achieved across the whole 20-nm wavelength span, which shows error-free BER all-optical operation.

4 Conclusions

Simultaneous all-optical NRZ-RZ format and wavelength conversions by employing a simple EAM based on XAM for the first time at 10 Gbit/s is experimentally demonstrated. The experimental results indicate that with the increase of reverse bias voltage, the ER first increases and then gradually decreases at the fixed input NRZ data signal power. Thus the ER reaches its maximum at a certain bias voltage. Meanwhile, with the increase of NRZ data power, the ER of converted RZ signal correspondingly increases and the bias voltage for the maximal ER is different. The maximum extinction ratio (ER) of converted RZ signal is about 12.08 dB. By tuning the wavelength of input NRZ signal from 1550 to 1570 nm, negative power penalty with a range of -0.9 to -0.2 dB (BER$=10^{-9}$) is observed for converted RZ signal. Error-free BER all-optical operation of format and wavelength conversions using EAM is reported at 10 Gbit/s.

References

1. L. Noel, X. Shan, and A. D. Ellis, "Four WDM channel NRZ to RZ format conversion using a single semiconductor laser amplifier," *Electron. Lett.* **40**, 620–621(2004).
2. C. W. Chow, C. S. Wong, and H. K. Tsang, "All-optical modulation format conversion and multicasting using injection-locked laser diodes," *J. Lightwave Technol.* **22**, 2386–2392 (2004).
3. C. G. Lee, Y. J. Kim, C. S. Park, H. J. Lee, and C. S. Park, "Experimental demonstration of 10-Gb/s data format conversions between NRZ and RZ using SOA-loop-mirror," *J. Lightwave Technol.* **23**, 834–841 (2005).
4. J. Lasri, P. Devgan, V. S. Grigoryan, and P. Kumar, "Multiwavelength NRZ-to-RZ conversion with significant timing-jitter suppression and SNR improvement," *Opt. Commun.* **240**, 293–298 (2004).
5. W. Idler, K. Daub, G. Laube, M. Schilling, P. Wiedemann, K. Dutting, M. Klenk, E. Lach, and K. Wunstel, "10 Gb/s wavelength conversion with integrated multiquantum-well-based 3-port Mach-Zehnder interferometer," *IEEE Photonics Technol. Lett.* **8**, 1163–1165 (1996).
6. I. Cristiani, V. Degiorgio, L. Socci, F. Carbone, and M. Romagnoli, "Polarization-insensitive wavelength conversion in a lithium niobate waveguide by the cascading technique," *IEEE Photonics Technol. Lett.* **14**, 669–671 (2002).
7. S. L. Jansen, H. Chayet, E. Granot, S. B. Ezra, D. den van Borne, P. M. Krummrich, D. Chen, G. D. Khoe, and H. De Waardt, "Wavelength conversion of a 40-Gb/s NRZ signal across the entire C-band by an asymmetric sagnac loop," *IEEE Photonics Technol. Lett.* **17**, 2137–2139 (2005).
8. L. Xu, B. C. Wang, V. Baby, I. Glesk, and P. R. Prucnal, "All-optical data format conversion between RZ and NRZ based on a Mach-Zehnder interferometric wavelength converter," *IEEE Photonics Technol. Lett.* **15**, 308–310 (2003).
9. T. G. Silveira, A. Teixeira, G. Tosi Beleffi, D. Forin, P. Monteiro, H. Furukawa, and N. Wada, "All-optical conversion from RZ to NRZ using gain-clamped SOA," *IEEE Photonics Technol. Lett.* **19**, 357–359 (2007).
10. S. Kodama, T. Shimizu, T. Yoshimatsu, K. Yoshino, T. Furuta, and H. Ito, "Ultrafast optical sampling gate monolithically integrating a PD and EAM," *Electron. Lett.* **40**, 696–697 (2004).
11. N. Cheng, "Optical modulation and wavelength conversion using electroabsorption modulator,' PhD Thesis, Queen's University, Canada (2003).
12. Y. F. Yang, C. Y. Lou, J. J. Wang, L. Huo, and Y. Z. Gao, "Experimental study of NRZ format wavelength conversion using electroabsorption modulator," *Opt. Commun.* **15**, 571–576 (2006).
13. T. Yoshimatsu, S. Kodama, K. Yoshino, and H. Ito, "100-gb/s error-free wavelength conversion with a monolithic optical gate integrating a photodiode and electroabsorption modulator," *IEEE Photonics Technol. Lett.* **17**, 2367–2369 (2005).