Clock recovery from NRZ data at 10 Gb/s using SOA loop mirror and mode-locked fiber ring laser based on SOA

Lina Yin (尹丽娜), Guoming Liu (刘国明), Jian Wu (伍 剑), and Jintong Lin (林金桐)

Key Laboratory of Optical Communication and Lightwave Technologies of MOE,
Beijing University of Posts and Telecommunications, Beijing 100876

Received May 27, 2005

All-optical clock recovery from non-return-to-zero (NRZ) data using an semiconductor optical amplifier (SOA) loop mirror and a mode-locked SOA fiber laser is firstly schematically explained and experimentally demonstrated at 10 Gb/s. Furthermore, the pulse quality of the recovered clock is effectively improved by using a continuous-wave (CW) assist light in the gain region of SOA, through which the amplitude modulation is reduced from 57.2% to 8.47%. This scheme is a promising method for clock recovery from NRZ data in the future all-optical communication networks.

OCIS codes: 060.2330, 060.2360, 200.3050, 230.1150.

All-optical clock recovery is one of the most important functions for future all-optical communication networks. Clock recovery from non-return-to-zero (NRZ) format data is known to be rather difficult to implement compared with the return-to-zero (RZ) format data because there is no discretely separated clock frequency component in its modulation spectrum. Therefore, two stages are required for clock recovery from NRZ data (shown in Fig. 1). First, a NRZ-to-PRZ (pseudo-return-to-zero) converter is required to realize clock component extraction, which can be realized by using an additional optical nonlinear element[1−3], such as a semiconductor optical amplifier (SOA), an optical interferometer or a SOA loop mirror. Second, a clock recovery circuit is chosen to accomplish clock recovery from the converted PRZ signal, which can be realized by using the schemes used for clock recovery from RZ data, such as self-pulsating semiconductor laser[4] or mode-locked fiber laser[5] etc.

Among the above-mentioned NRZ-to-PRZ converters, SOA loop mirror is a promising method for integration. There are two basic configurations for SOA loop mirror, one is pump-probe configuration[6], the other is called as simplified configuration. The simplified configuration is not so complex as pump-probe configuration because it does not require another light source and optical pass-band filter[7]. Clock recovery from NRZ data at 2.5 Gb/s has been realized using the simplified configuration[8].

In this paper, clock recovery from NRZ data at 10 Gb/s is firstly successfully realized using the simplified configuration of SOA loop mirror and a mode-locked SOA fiber laser. Furthermore, the unequal amplitude of the recovered clock is effectively improved by using a continuous-wave (CW) assist light.

Figure 2(a) shows the simplified configuration of SOA loop mirror. It consists of a 3-dB coupler with two branches connected with SOA forming a loop. The SOA is placed in the fiber-loop-mirror with a displacement from the midpoint of the fiber loop by adjusting the optical delay line (ODL). A polarization controller (PC) is used to adjust the polarization direction of the signal in the loop. When the original NRZ signal is injected into SOA loop mirror from the input port, it is split into clockwise (cw) and counter-clockwise (ccw) directions by the 3-dB coupler. At the output port, a converted PRZ data signal with the same wavelength as the original NRZ data can be obtained.

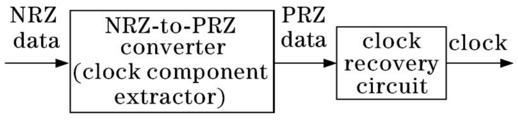

Fig. 1. Schematic of clock recovery from NRZ data.

The principle of conversion from NRZ to PRZ using SOA loop mirror can be explained by using Fig. 2(b). For the sake of simplicity, the waveform distortion (e.g.,

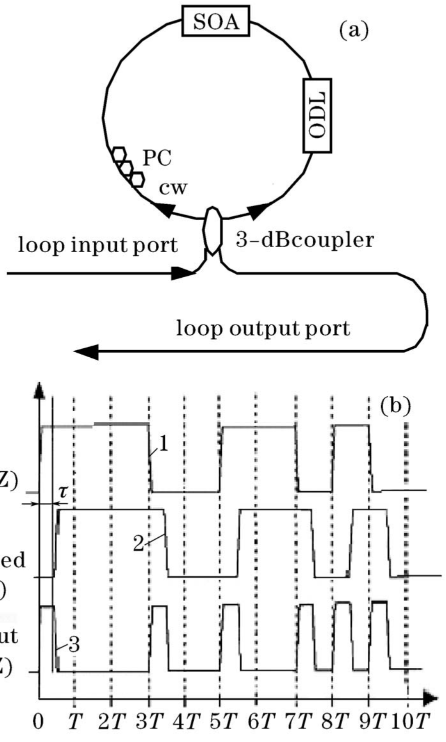

Fig. 2. Simplified configuration of SOA loop mirror (a) and principle of conversion from NRZ to PRZ (b).

an overshoot generated at the leading edge) of NRZ signal caused by the gain saturation effect of SOA is neglected in Fig. 2(b). By adjusting the ODL, the SOA displaces from the midpoint of the loop, then a time difference τ between the cw and ccw beams will generate (shown at curves 1 and 2 of Fig. 2(b)), so the two branches experience different gain and phase evolution at a given time. Therefore, in the 3-dB coupler, interferences between the two beams will occur. For an ideal 50:50 coupler, the output power can be expressed as[9]

$$P_{\text{out}}(t) = \frac{1}{4} G^{\text{cw}}\left(t - t_{\text{d}}\right) P_{\text{in}}\left(t - t_{\text{d}}\right) \times \left[1 + \frac{G^{\text{ccw}}}{G^{\text{cw}}} - 2\sqrt{\frac{G^{\text{ccw}}}{G^{\text{cw}}}} \cos\left(\phi^{\text{cw}} - \phi^{\text{ccw}}\right)\right], \quad (1)$$

where t_{d} is the pulse round trip time in the loop, P_{in} is the input power of the optical signal, $G^{\text{cw}}(\phi^{\text{cw}})$ and $G^{\text{ccw}}(\phi^{\text{ccw}})$ are the gain (phase) experienced by the cw and ccw beams, respectively. The relation between the gain ratio $G_{\text{cw}}/G_{\text{ccw}}$ and the phase difference $\phi^{\text{cw}} - \phi^{\text{ccw}}$ can be expressed as: $\phi^{\text{cw}} - \phi^{\text{ccw}} = -(\alpha/2)\ln(G_{\text{cw}}/G_{\text{ccw}})$, where α is linewidth enhancement factor. Owing to the longer gain recovery time of SOA and the existence of time difference τ between cw and ccw beams, the gains of these two beams experienced in SOA are generally different, therefore, the gain ratio $G_{\text{cw}}/G_{\text{ccw}}$ is not a constant. It can be concluded that the gain ratio $G_{\text{cw}}/G_{\text{ccw}}$ is closely related to the time difference τ. Moreover, $G_{\text{cw}}/G_{\text{ccw}}$ is also affected by the SOA parameters such as carrier lifetime, small signal gain, and saturation gain etc.. Equation (1) shows that an output light generates at the loop output port when the phase difference does not equal to zero, and a maximum output can be obtained when the phase difference is π. The SOA loop mirror acts as an exclusive OR gate, thus, the NRZ data can be converted into PRZ data containing a clock frequency component, as shown at curves of Fig. 2(b). After the clock-enhanced PRZ signal is injected into the clock recovery circuit such as mode-locked SOA fiber laser, clock pulse trains will generate due to cross gain modulation (XGM) of SOA when the mode-locking condition (the data modulation rate is a harmonic of fundamental frequency of the fiber ring laser) is satisfied.

Figure 3 shows the experimental setup of clock recovery from NRZ data. The NRZ data is produced using a tunable CW laser source (HP8168F), whose wavelength is set at 1546 nm, modulated by a LiNbO$_3$ modulator (LN MOD) driven by a synchronous digital hierarchy (SDH) analyzer at 10 Gb/s. The optical power of NRZ data is firstly optimized using an erbium-doped fiber amplifier (EDFA) and an optical attenuator, and then it is injected into SOA loop mirror (NRZ-to-PRZ converter) to realize format conversion from NRZ to PRZ signal. After that, the converted PRZ data signals pass through another EDFA and attenuator in order to adjust the data power, which is applied to modulate the SOA in the cavity. Finally, the PRZ data is injected into a mode-locked SOA fiber laser to realize clock recovery, which includes a SOA, a tunable optical filter, an ODL, two PCs, and a coupler. In the mode-locked fiber ring laser, SOA is a key element for clock recovery, which corresponds to a gain medium and a modulator to provide gain and gain modulation in the cavity. The SOA exhibits 0.5-dB polarization gain dependence, so two PCs are used for performance optimization. A circulator is used for introducing the PRZ data into the cavity. A tunable optical filter is used for selecting wavelength of clock pulses, an ODL is used to precisely adjust the cavity length to obtain clock pulses at the expected repetition rate and a coupler is used for clock output. The pulse waveform and its corresponding radio frequency (RF) spectrum are displayed by using a digital sampling oscilloscope (Agilent 83480A).

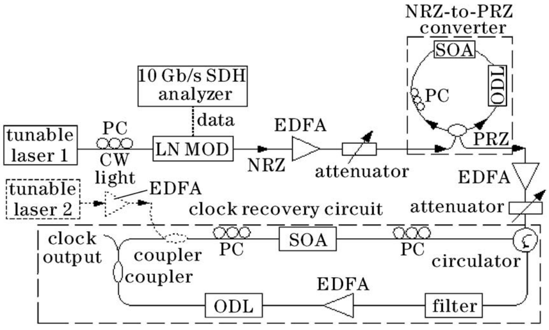

Fig. 3. Experimental setup of clock recovery from NRZ data.

Figure 4 shows the experimental results of clock recovery from NRZ data sequence at 10 Gb/s. Figure 4(a) is the waveform of NRZ data coded with 1011001010111000

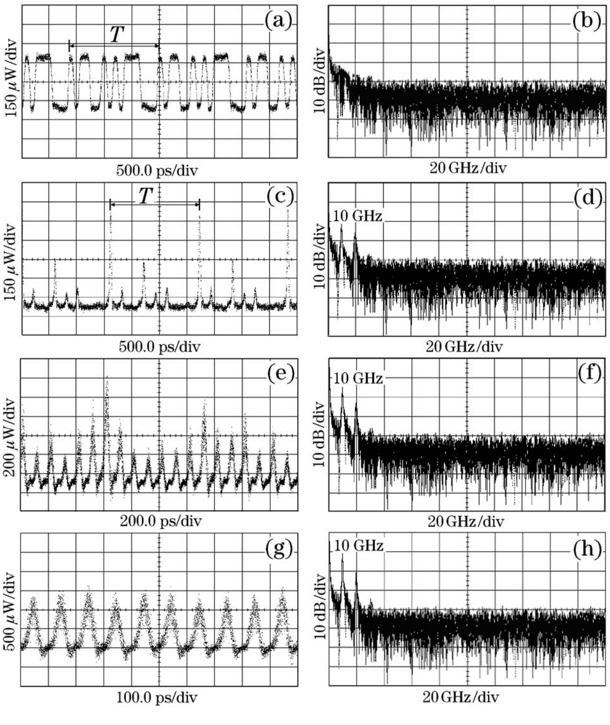

Fig. 4. Clock recovery from NRZ data at 10 Gb/s using SOA loop mirror. (a) Original NRZ data; (b) RF spectrum of NRZ data; (c) converted PRZ data; (d) RF spectrum of PRZ data; (e) recovered clock without CW assist light; (f) RF spectrum of the clock without assist light; (g) recovered clock with CW assist light; (h) RF spectrum of the clock with CW assist light.

(T stands for a coding period). Figure 4(b) shows the corresponding RF spectrum of NRZ data, which is obtained by a fast Fourier transform (FFT) function in the oscilloscope. There is almost no discretely separated clock frequency component at 10 GHz in the input NRZ data. After passing through the SOA loop mirror, the NRZ data is converted into PRZ data. Figure 4(c) shows the converted PRZ data when the average power of the NRZ data injected into the SOA loop mirror is 3.53 dBm, the bias current of SOA (Alcatel1901) in the loop mirror is set at 110 mA, and the time difference between the cw and ccw beams is about 10 ps. As shown in this figure, there is a time delay for the PRZ data compared with the original NRZ data due to its passage through the fiber loop. The PRZ pulses are evidently generated at the leading edge of the NRZ data, but almost no PRZ pulses generated at the trailing edges, which are caused by the fast saturation and slow recovery of SOA[8]. It can be explained in detail as follows: there are gain and phase differences at both the leading and trailing edges owing to the time difference between cw and ccw branches, therefore, an output window will be generated at the corresponding position according to Eq. (1). However, at the leading edges, the steeper slope of the gain and phase changes due to the fast saturation of SOA, as well as a corresponding larger gain will lead to a larger output power. On the contrary, at the trailing edges, the slower changes of the gain and phase due to the slow recovery of SOA, together with a smaller gain will lead to a smaller output, in fact, it is too small to be observed in experiment as shown in Fig. 4(c). Figure 4(c) also shows that there are severe pattern effects in the PRZ data signals, where a high-amplitude pulse generates after a longer consecutive "0", whereas a low-amplitude pulse generates when the consecutive "0" number is fewer due to the longer gain recovery time of SOA.

Figure 4(d) shows the corresponding RF spectrum of the PRZ data. As shown in this figure, after passing through the SOA loop mirror, the clock frequency component at 10 GHz is enhanced by about 12 dB compared with that of the original NRZ data in Fig. 4(b), which is beneficial for further clock recovery. By injecting the converted PRZ data into the mode-locked fiber ring laser, the recovered clock is obtained, whose waveform and RF spectrum are shown in Figs. 4(e) and (f), respectively. The bias current of SOA (IPSAD1501) in the mode-locked fiber ring laser is set at 190 mA and the clock wavelength is 1541 nm. The pulse amplitudes of the recovered clock are severely uneven owing to the pattern effect caused by the longer carrier lifetime of SOA[5,10]. In order to quantify the amplitude differences, a parameter m is defined, which characterizes the amplitude modulation

$$m = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} \times 100\%. \tag{2}$$

The amplitude modulation in Fig. 4(e) is calculated to be about 57.2% using Eq. (2), which is too severe to apply in future optical networks. In order to reduce the pattern effect of the recovered clock, a CW assist light in the gain region of SOA is introduced into the cavity to shorten the effective carrier lifetime of SOA[11−13]. In experiment, the CW assist light is provided by another tunable CW light source (tunable laser2) and a high-gain EDFA (dotted line in Fig. 2), and then injected into the SOA in the laser cavity through a coupler. When the CW assist light with a wavelength of 1545 nm and average power of 14.3 dBm is injected, the recovered clock and the corresponding RF spectrum are shown in Figs. 4(g) and (h). As shown in Fig. 4(g), the pulse quality of the recovered clock is evidently improved and the amplitude modulation is reduced to 8.47%.

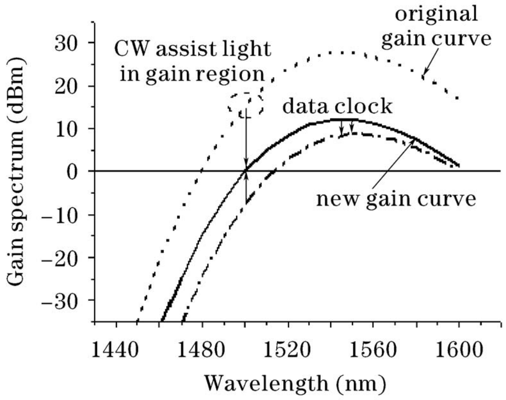

Fig. 5. Principle of optical speedup by CW assist light in gain region.

The principle that CW assist light can reduce the pattern effect of the recovered clock can be further explained as follows (shown in Fig. 5)[11]: when no assist light is used, the carrier lifetime of SOA is usually several hundred picoseconds governed by the spontaneous emission. However, When a CW assist light in gain region is injected, the original gain curve (dotted line) changes due to stimulated emission and build up a new equilibrium (solid line), corresponding to a new transparency wavelength generated at the holding wavelength of CW assist light. When the data signals pass through the SOA and amplified, the carrier density decreases and the gain curve of SOA (solid line) changes towards longer wavelength (dashed line). The assist light shifts into absorption region, creates new carriers, and enhances the gain recovery due to absorption, so the gain curve quickly goes back to the steady state, which leads to the reduction of gain recovery time (i.e., optical speedup), thus the corresponding pattern effect is lower. It is believed that CW assist light is a simple and effective method to reduce the pattern effect for SOA-based all-optical clock recovery and other all-optical signal processing.

In conclusion, all-optical clock recovery from NRZ data is schematically explained and experimentally demonstrated at 10 Gb/s using SOA loop mirror and a mode-locked SOA fiber laser. Using the SOA loop mirror, the clock frequency component at 10 GHz is enhanced by about 12 dB, which is beneficial for further clock recovery. The pulse amplitudes of the recovered clock are severely uneven owing to the pattern effect caused by the longer carrier lifetime of SOA. By using a CW assist light, the pulse quality of the recovered clock is effectively improved, the amplitude modulation is reduced from 57.2% to 8.47%. This scheme is a promising method for clock recovery from NRZ data in the future all-optical communication networks.

This work was supported by the National Natural Science Foundation of China (No. 90401025) and the Key Project of MOE (No. 105036). L. Yin's e-mail address is yinlina_bupt@163.com.

References

1. H. J. Lee, H. G. Kim, J. Y. Choi, and H. K. Lee, Electron. Lett. **35,** 989 (1999).
2. H. K. Lee, J. T. Ahn, M.-Y. Jeon, K. H. Kim, D. S. Lim, and C. H. Lee, IEEE Photon. Technol. Lett. **11,** 730 (1999).
3. W. Hong, D. Huang, F. Cai, and Y. Wang, IEEE Photon. Technol. Lett. **16,** 1116 (2004).
4. Y. Li and G. Li, Electron. Lett. **38,** 892 (2002).
5. K. Vlachos, G. Theophilopoulos, A. Hatziefremidis, and H. Avramopoulos, IEEE Photon. Technol. Lett. **12,** 705 (2000).
6. H. J. Lee and C.-S. Park, Opt. Commun. **181,** 323 (2000).
7. W. Hong and D. Huang, Acta Opt. Sin. (in Chinese) **24,** 781 (2004).
8. M. Yao, H. Tang, M. Fukazawa, J. Zhou, K. Vahala, M. Newkirk, and B. Miller, in *Proceedings of OFC'96* WL11, 177 (1996).
9. M. Eiselt, W. Pieper, and H. G. Weber, J. Lightwave Technol. **13,** 2099 (1995).
10. T. Wang, Z. Li, C. Lou, Y. Wu, and Y. Gao, IEEE Photon. Technol. Lett. **14,** 855 (2002).
11. L. Yin, G. Liu, J. Wu, and J. Liu, Opt. Eng. (to be published).
12. D. M. Patrick and R. J. Manning, Electron. Lett. **30,** 151 (1994).
13. R. J. Manning and D. A. O. Davies, Opt. Lett. **19,** 889 (1994).