High speed fiber-based clock enhancement of NRZ data

Tong Wu (武 同) and Kun Qiu (邱 昆)

Key Laboratory of Broadband Optical Fiber Transmission and Communication Networks, UEST of China, Chengdu 610054

Received June 14, 2004

A scheme for all-fiber clock enhancement of non-return-to-zero (NRZ) data based on cross-phase modulation (XPM) effect in nonlinear fibers is proposed and demonstrated in simulation. The simulation results indicate that the clock-to-data ratio of NRZ signals at 64 Gb/s can be increased to 22.94 dB by using this scheme, and the pattern effect in clock enhanced signals is very weak. The ability of high speed operation up to 140 Gb/s of this scheme is also proved in our simulation.

OCIS codes: 060.4370, 060.5060, 060.7140, 070.4560.

All-optical clock recovery circuit is a critical component of optical transparent networks. Several optical techniques for all-optical clock recovery have been proposed[1,2]. Most of these techniques need a return-to-zero (RZ) format signal because it has a strong clock component in its modulation spectrum. For a non-return-to-zero (NRZ) signal, in which the clock component contained is very weak, only a few works have been published, all of them have a preprocessing stage to derive or enhance the clock component in original spectrum. H. K. Lee *et al.* used a NRZ-to-pseudo-RZ converter based on the Mach-Zehnder interferometer (MZI) exclusive-OR (XOR) gate to derive the clock component[3]. H. J. Lee *et al.* used a semiconductor optical amplifier (SOA) followed by a narrow-band grating filter to convert the NRZ signal to pseudo-RZ signal to enhance the clock component[4], the chief of their scheme was to filter out the overshoot at the leading edge of pulses after the SOA. W. Mao *et al.* proposed another clock enhancement scheme using a SOA followed by a narrow-band filter[5], and its use in a clock recovery circuit for NRZ and RZ data was demonstrated[6], they used the self-phase modulation (SPM) effect in SOA and filtered out chirp components at the leading and tailing edge of pulses after SOA.

These schemes have a common shortcoming: they can not apply to NRZ data at high bit rate.

In this paper, we propose a novel scheme for clock enhancement of a high speed NRZ-format signal based on frequency modulation to amplitude modulation (FM-to-AM) conversion by using two segments of nonlinear fiber and band-pass filters, and demonstrate it by numerical simulation. The basis of our scheme is the cross-phase-modulation (XPM) effect in optical fibers.

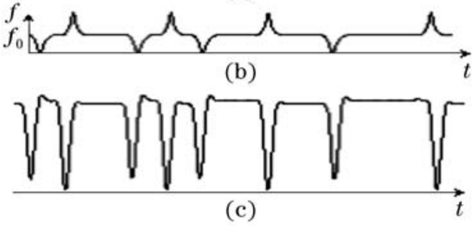

Fig. 1. Concept figure of (a) NRZ pump data, (b) chirps of probe signal produced by XPM, and (c) probe signal after optical filter.

It has been proved that if there are two signals at different frequency transmitted through an optical fiber, the XPM effect between them introduces a variety to both signals in frequency domain and time domain. In detail, when a probe signal and a pump signal are injected in a fiber together, the frequency of the probe signal will be chirped by the pump via XPM: the leading edge and the tailing edge of a pump pulse will impose a red shift and a blue shift of frequency to the probe signal respectively, as shown in Figs. 1(a) and (b). The maximum value of the chirp has a direct proportion to the power of signals.

By using a frequency discriminator such as an optical filter, the frequency modulation can be converted to amplitude modulation[5].

In our scheme, the probe signal is a continuous wave (CW), and the discriminator is an optical band-pass filter. The central frequency of this filter equals to that of the CW. So the slightly chirped components of the CW which caused by the center of pump pulses can pass through; meanwhile, the strongly chirped component of the CW which caused by the leading and tailing edges of pump pulses via XPM will be attenuated. As a result, the CW is holed by the filter according to its frequency shift, as shown in Fig. 1(c). The interval of these holes equals to n times (n is an integer) of the minimum pulse width of the pump signal, which is just the period of the clock signal of NRZ data. Reversing this holed CW signal, we can get a signal with strong clock component. In order to obtain strong enough XPM effect, high injection power is needed in this scheme.

Compared to the scheme exploiting SPM effect in a SOA followed by a frequency discriminator[5], this scheme using XPM effect in an optical fiber would get a speed-advantage because the fiber nonlinearity has a speed-advantage over the semiconductor nonlinearity.

Furthermore, because chirps are produced by the SPM effect in the scheme which using SOA, the filter in it is to split NRZ source data into two part, so the pulses originated from leading edge and the tailing edge of NRZ data have a different power level, which can be found from the waveform picture of it[5]. The great power fluctuation is harmful to further signal processing. In our scheme, thanks to the XPM effect, we can change the amplitude modulation of NRZ data to the frequency modulation of CW, so, it is the CW that is filtered out and the filtered signal pulses should have a uniform power level.

Figure 2 shows our scheme for clock enhancement. It

1671-7694/2005/040193-03 http://www.col.org.cn

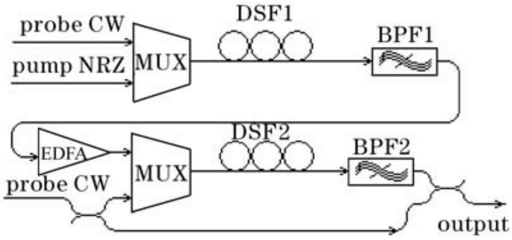

Fig. 2. Scheme for clock enhancement. BPF: band-pass filter; DSF: dispersion shift fiber.

contains two stages, each stage consists of a segment of dispersion shift fiber (DSF) as the XPM medium, of which zero dispersion wavelength is 1535 nm, a band-pass filter and a wavelength divided multiplexing (WDM) multiplexer.

In stage one, a CW at 1537.67 nm is used as the probe signal and NRZ-format data at 1532.18 nm act as the pump signal, after being multiplexed, they are injected into the DSF. Because of XPM effect in DSF, the pump signal introduces frequency chirps to the probe signal just as mentioned above. The band-pass filter in this stage acts as a FM-to-AM converter, which has a central frequency of 1537.28 nm, to convert frequency chirps to amplitude variety of CW probe.

The output of stage one is amplified by an erbium-doped fiber amplifier (EDFA) before being injected into stage two.

Stage two is a reversed wavelength converter using XPM effect in DSF, which will reverse the input signal for further signal processing. In this stage, the probe signal is a CW at 1532.18 nm, splitting into two parts. When the pump signal exists, it will introduce a phase modulation to one part of the probe via the XPM effect. Injecting this phase modulated signal and the other part of the probe into an interference coupler and adjusting the fiber-length, we can obtain a reversed signal.

It must be mentioned that the DSF in this stage should be of polarization maintaining. Because, if the polarizations of the lights in two arms of the coupler are different, the interference is hard to take place. And also, some stabilization electronics are needed to stabilize the working condition of the DSF, such as temperature.

The band-pass filter acts as a wavelength division multiplexing (WDM) demultiplexer to demultiplex the probe signal. The passive optical couplers used in this stage have a split ratio of 3 dB. At the output port of the last coupler, the clock enhanced signal is gotten.

The clock enhancement of NRZ data is simulated and investigated using a commercial software presented by virtual photonics. In simulation, two nonlinear fibers are used as DSFs by setting their zero dispersion wavelength to 1535 nm and two Bessel filters are deployed as the band-pass filter in our scheme. Simulation parameters are given in Table 1.

Table 1. Parameters Used in Simulation

Parameter	Value	Unit
Dispersion Slope	0.086×10^3	ps/(nm^2·km)
Attenuation	0.4×10^{-3}	dB/m^2
Core Area	24×10^{-12}	m^2
Length (DSF1)	500	m
Length (DSF2)	200	m
Nonlinear Index (DSF1)	3.4×10^{-20}	m^2/W
Nonlinear Index (DSF2)	2.4×10^{-20}	m^2/W
3-dB Bandwidth	300×10^9	Hz

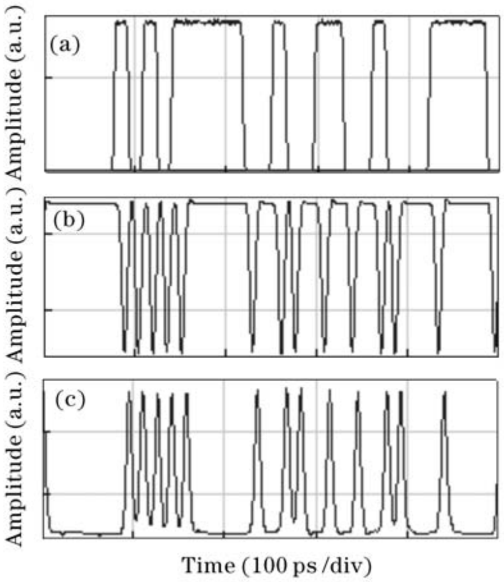

Fig. 3. Waveforms of (a) the original NRZ signal, (b) the output of stage 1 and (c) the clock enhanced signal.

We use a 64 Gb/s NRZ pseudo-random binary sequence (PRBS) signal with a pattern length of $2^{21} - 1$ to investigate the capability of this clock enhancement circuit. Because a high injection power is needed, the PRBS is amplified by an EDFA, and has an average injection power of 21.03 dBm. The probe signal is a CW which has an average power of 17 dBm. Power waveform of the output signal of stage 1 is shown in Fig. 3(b). We can find many holes dug by band-pass filter, their spatial position is relative to the leading and tailing edges of original NRZ signal (Fig. 3(a)), their interval approximately equals to n times of 15.625 ns which is the period of clock signal.

This signal is amplified by an EDFA with a gain of 7 dB and injected into stage 2 with an average power of 22.17 dBm. A CW with 13 dBm average power acts as the probe in this stage. At the output of this stage, the signal with a strong clock component is obtained. Figure 3(c) shows the power waveform of the clock enhanced signal, from which we can see each NRZ pulse to be split into two and there is little pattern effect, the extinction ratio of this signal is about 21 dB. Figure 4 gives the RF spectrum of NRZ data before (Fig. 4(a)) and after (Fig. 4(b)) clock enhancement. Figure 4(b) clearly indicates that the clock-to-data ratio is increased to 22.94 dB, the increase relates to the detuning of the optical frequency from the band-pass filter.

Because XPM is a fast nonlinear dynamic, this circuit can apply to a higher bit rate. In our simulation, it is demonstrated that this circuit can be operated at a bit rate up to 140 Gb/s at the same injection power level

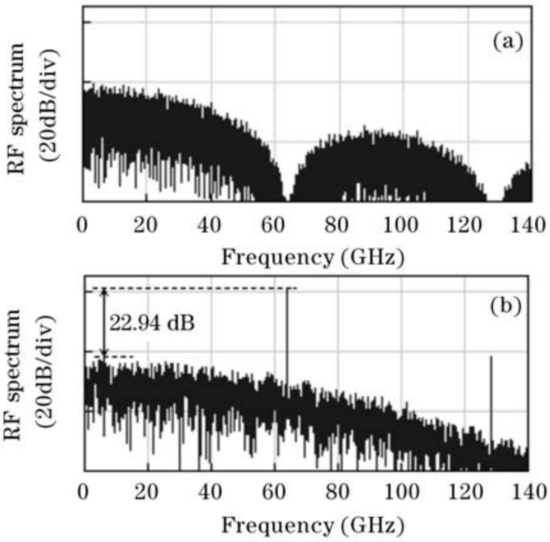

Fig. 4. RF spectra of (a) original NRZ signal and (b) clock enhanced signal.

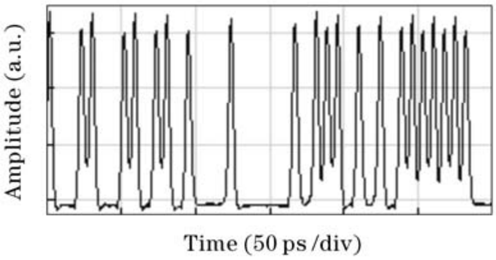

Fig. 5. Power waveform of the clock enhanced signal at 140 Gb/s.

without being modified. Figures 5 and 6 give the power waveform and the RF spectrum of the clock enhanced data at 140 Gb/s, from which some deterioration can be seen: the amplitude of pulses are not equivalent and the extinction ratio is much lower, the clock-to-data ratio we measured from RF spectrum drops to 13.3 dB. But we believe, the deterioration can be avoided by optimizing parameters of fiber and band-pass filter in the scheme.

In general, the scheme we proposed exhibits an excellent performance in clock enhancement of NRZ data at all bit rates below 140 Gb/s in numerical simulation.

A novel scheme for all-fiber optical enhancement of clock signal of NRZ data by using two segments of fiber and two simple band-pass filters was proposed and successfully demonstrated by numerical simulation. The results indicate that the clock-to-data ratio of a NRZ signal at 64 Gb/s can be increased to 22.94 dB by using this scheme and there is little pattern effect in clock enhanced signal.

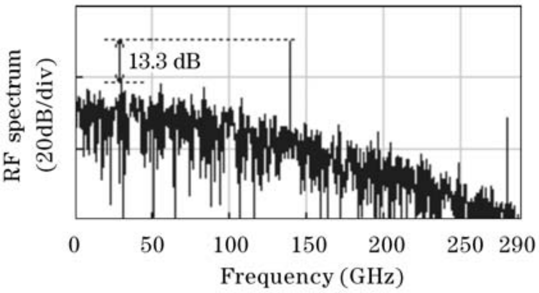

Fig. 6. RF spectrum of the clock enhanced signal at 140 Gb/s.

The application to higher bit rate was also studied by simulation. Without modifying parameters of the circuit, the clock enhancement of 140 Gb/s NRZ data can be achieved. Although, there is some deterioration in clock enhanced signal, we believe those can be avoided by optimizing.

It must be noted that the DSF and the coupler in stage 2 must be of polarization maintaining for effective coherent interference in a real system. And, in order to obtain strong XPM between the probe and the pump signal, high injection power is needed in this scheme.

T. Wu's e-mail address is pegasusme@163.com.

References

1. B. Sartorius, C. Bornholdt, O. Brox, H. J. Ehrke, D. Hoffmann, R. Ludwig, and M. Mohrle, Electron. Lett. **34,** 1664 (1998).
2. K. Vlachos, G. Theophilopoulos, A. Hatziefremidis, and H. Avramopoulos, IEEE Photon. Technol. Lett. **12,** 705 (2000).
3. 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).
4. H. J. Lee, H. G. Kim, J. Y. Choi, and H. K. Lee, Electron. Lett. **35,** 989 (1999).
5. W. Mao, M. Al-Mumin, X. Wang, and G. Li, IEEE Photon. Technol. Lett. **13,** 239 (2001).
6. W. Mao, Y. Li, M. Al-Mumin, and G. Li, IEEE Photon. Technol. Lett. **14,** 873 (2002).