

Optical sampling system using periodically-poled lithium niobate waveguide and nonlinear polarization rotation mode-locked fiber laser

Jian LI, Aiying YANG (✉), Lin ZUO, Junsen LAI, Yunan SUN

School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2012

Abstract A novel design of optical sampling system has been developed by using sum-frequency generation (SFG) in a periodically-poled lithium niobate (PPLN) waveguide and using passive mode-locked fiber laser pulses as optical sampling pulses. The system achieved high temporal resolution and high sensitivity using a 30 mm length PPLN with quasi phase match period of 19.3 μm and 151 fs sampling pulses which were generated by passive mode-lock fiber laser based on nonlinear polarization rotation (NPR). Clear eye-diagram of 10 Gbit/s non-return-to-zeros (NRZ) pseudorandom binary sequence (PRBS) optical signal were successfully reconstructed by this system.

Keywords periodically-poled lithium niobate (PPLN), optical sampling, nonlinear polarization rotation (NPR) fiber laser, sum-frequency generation (SFG)

1 Introduction

With the development of high-speed optical communications, optical sampling technology has become the most promising method of diagnosing high-speed optical data greater than 100 Gb/s. Optical sampling based on optical nonlinearity is a promising method for evaluating ultra-high-speed optical transmission systems and optical processing devices because of its high temporal resolution. With the nonlinear effect of sum-frequency generation (SFG) in nonlinear crystal, optical sampling systems have achieved optical signal greater than 100 Gb/s eye diagram recovery [1,2]. The most important component in optical sampling system is the sampling devices, which can be divided into two categories according to their different effects. The first category is based on second-order

nonlinear effects, such as KTiOPO_4 (KTP) [2–4], organic crystal (AANP : 2-adamantylammo-5-nitropyridme) [1] and the periodically poled lithium niobate waveguide (PPLN) [5–12]. Optical samples are generated by SFG or quasi-phase match. The second category is based on third-order nonlinearity (Kerr effect); Kerr effect can be used to generate a variety of nonlinear effects and and-gate function, such as four-wave mixing effects in fibers [13,14] and semiconductor optical amplifier (SOA) [15,16], cross-phase modulation in SOA [17,18]. The SFG efficiencies in KTP, AANP are in the order of $10^{-2}\%/W$ or less. The experiments needed more sensitive detector and require optical amplifiers for signal and sampling pulses. But PPLN with quasi-phase-match (QPM) SFG would offer advantages of much higher efficiencies, larger flexibility for signal and sampling wavelengths and lesser sensitive detector, which reduced the difficulty of the electrical detection and increased the SNR of sampled signal. So in this paper, we present design and experimental demonstration of a PPLN device for efficient picoseconds optical sampling.

2 Principles

2.1 Optical sampling

All-optical sampling system includes sampling pulse source, sampling devices, optical detector and samples acquisition and processing section, shown in Fig. 1.

The input data stream at bit rate B is launched into the sampling device with a train of very short sampling pulses, which was generated by nonlinear polarization rotation (NPR) fiber laser. The repetition frequency of the sampling pulse is f_s . They are related by

$$f_s = (B - \Delta f) / M, \quad (1)$$

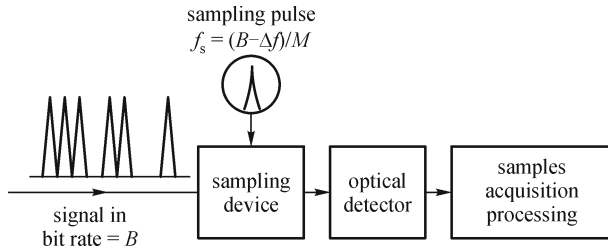


Fig. 1 Principle of optical sampling

where Δf is offset frequency and M corresponds to the bit-rate reduction factor. In the time domain, it is more convenient to express the offset frequency in terms of a corresponding time step Δt , given by

$$\Delta t = \frac{\Delta f}{Bf_s} = \frac{1}{f_s} - \frac{M}{B}. \quad (2)$$

In the samples acquisition and processing section, the coarse Δt is calculated by Fourier transform and accurate one is followed by a high-precision iteration, which can make the time error less than 0.01% bit period [19].

2.2 PPLN SFG

Considering the process of SFG, a signal wave of wavelength λ_s and sampling pulses of wavelength λ_p are coupled together into the PPLN. At or near the QPM condition, the power of SF light is proportional to the product of signal power and sampling pulses power. Then, the PPLN acts like an optical and-gate function and the sampling pulses are the openers. For λ_s and λ_p are both in 1550 nm band, the SF wave in or near 775 nm can be easily detected by Si-PIN.

In the condition of continuous-wave lights inputs, the SF light power can be given approximately by

$$P_{\text{SFG}} = \kappa^2 P_p P_s L^2 \left\{ \frac{\sin(\Delta L)}{\Delta L} \right\}^2, \quad (3)$$

$$\Delta = \pi \left(\frac{n_e(\lambda_{\text{SFG}})}{\lambda_{\text{SFG}}} - \frac{n_e(\lambda_p)}{\lambda_p} - \frac{n_e(\lambda_s)}{\lambda_s} - \frac{1}{\Lambda} \right).$$

Subscripts SFG, p and s represent the converted SF light, the pump and the signal, respectively. L is the length of PPLN, Λ denotes the PPLN QPM grating period, n_e means the wavelength-dependent extraordinary refraction index of lithium niobate and λ is the wavelength. According to Eq. (3), in order to obtain high SFG efficiency, the PPLN QPM grating period Λ should be designed to satisfy

$$\Lambda = \left[\frac{n_e(\lambda_{\text{SFG}})}{\lambda_{\text{SFG}}} - \frac{n_e(\lambda_p)}{\lambda_p} - \frac{n_e(\lambda_s)}{\lambda_s} \right]^{-1}, \quad (4)$$

when Eq. (3) is satisfied, the SF power is maximized. So in the optical sampling system for 1550 nm band, $\Lambda = 19.3 \mu\text{m}$ and $L = 30 \text{ mm}$ has been fabricated. Under that condition, the 3 dB bandwidth of SFG in PPLN is

approximate 0.85 nm as shown in Fig. 2. In the same time of SFG, weak second-harmonic generation (SHG) may also be generated, which plays role of noise to SFG detector. By making large separation between λ_s and λ_p , this noise can be minimized. When $\Delta\lambda = |\lambda_s - \lambda_p|$ is larger than 5 nm, the SHG can be neglected according to Fig. 2.

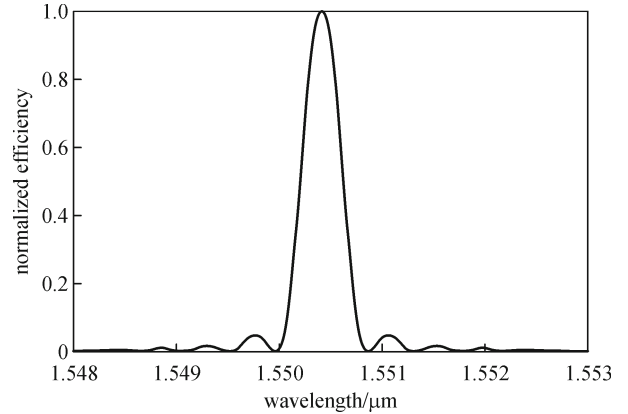


Fig. 2 Normalized SFG efficiency versus wavelength under 62°C

Other effects of PPLN, such as pulse broadening in the dispersive waveguide and walk-off between the input and SF pulses are not considered in this paper, because they are small enough to be neglected.

2.3 NPR passive mode-locked fiber laser

Basic scheme of NPR passive mode-locked fiber laser is shown in Fig. 3. After the polarization dependent isolator (PD-ISO), the light became line polarized and the following polarization controller (PC1) changed it into elliptically polarized. Then, two orthogonal components were amplified by the erbium-doped fiber and had different nonlinear phase shift produced by self-phase modulation and cross-phase modulation in fiber cavity, which changed the polarization states of the light. Carefully adjusting PC2

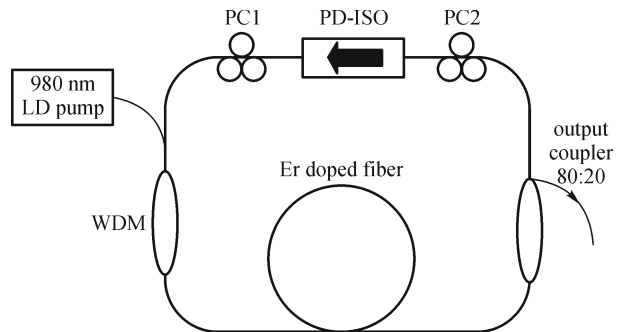


Fig. 3 Scheme of NPR passive mode-locked fiber laser. WDM: wavelength division multiplexer; LD: laser diode

made the center of the pulses go through the PD-ISO. The edge of the pulses would be cut. After many cycles, the pulses became ultra-short and stable.

Figure 4 is the optical spectrum of the sampling pulses from NPR mode-locked fiber laser. The center wavelength is 1557.7 nm, flat bandwidth is 16.8 nm and Fourier-transform pulses width is 151 fs. The repetition rate of the sampling pulses is 29.31 MHz.

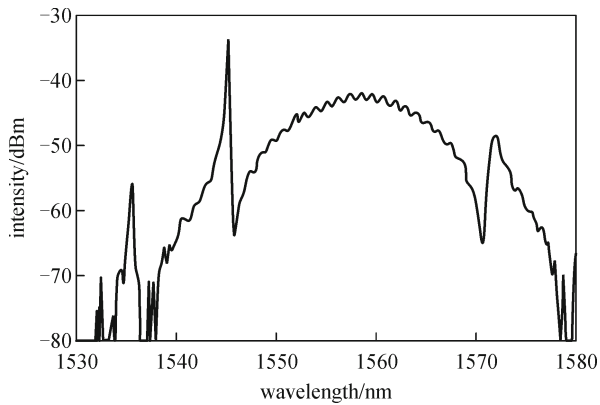


Fig. 4 Spectrum of NPR fiber laser output pulses

3 Experiments

Block diagram of optical sampling experimental system is shown in Fig. 5. The femtoseconds sampling pulses generated by NPR fiber laser went through an optical coupler (90:10). In which 10% power of the pulses was detected by low bandwidth InGaSn detector as a clock

trigger to analog to digital converter board and other 90% power went into a tunable filter, which is a band-pass filter with center wavelength of 1557 nm, 3 dB bandwidth of 0.5 nm. The filtered pulses combined with 10 Gbit/s non-return-to-zeros (NRZ) pseudorandom binary sequence (PRBS) optical signal were amplified by erbium doped fiber amplifier (EDFA) and launched into PPLN. The 10 Gbit/s optical signal was generated by 10 Gbit/s NRZ PRBS source driving Mach-Zehnder modulator (MZM) transmitter with a distributed feedback laser (DFB) centered at 1544 nm, which made the separation of signal and pulse source almost 13 nm. With this large separation, the SHG light would be minimized according to PPLN SFG efficiency band in Fig. 2. For making high SFG efficiency, carefully adjusting PC and setting the oven to the desired temperature of PPLN were carried. The optical signal was sampled as SFG light, and was detected with a Si amplified photodiode (PDA10A). The Si-PIN had responsivity of 0.5 A/W with 10^3 V/A gain, bandwidth of 150 MHz. Then, detected optical signal was converted into an electrical signal and the electrical signal was converted into a digital signal by AD (ADS822E) and processed by Field-Programmable Gate Array (FPGA).

The real system in lab was shown in Fig. 6. Eye-diagram was reconstructed by FPGA and visualized on liquid crystal display (LCD) screen.

4 Results

Spectrum of filtered NPR fiber laser and 10 Gbit/s NRZ PRBS optical signal was shown in Fig. 7 and the spectrum of output SFG light could be seen in Fig. 8. The efficiency of SFG is 1%, which is much higher than other

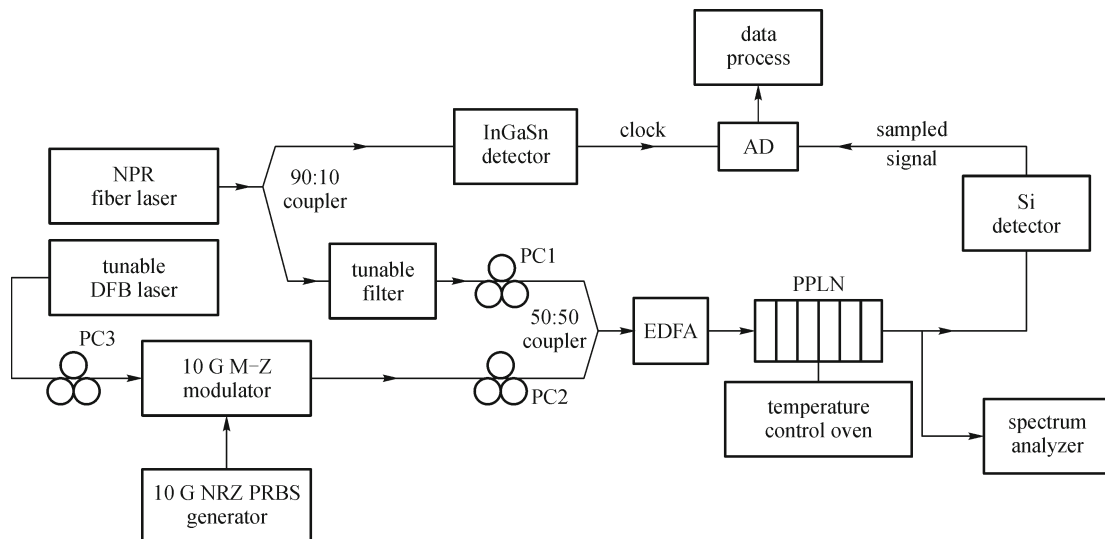


Fig. 5 Block diagram of optical sampling system

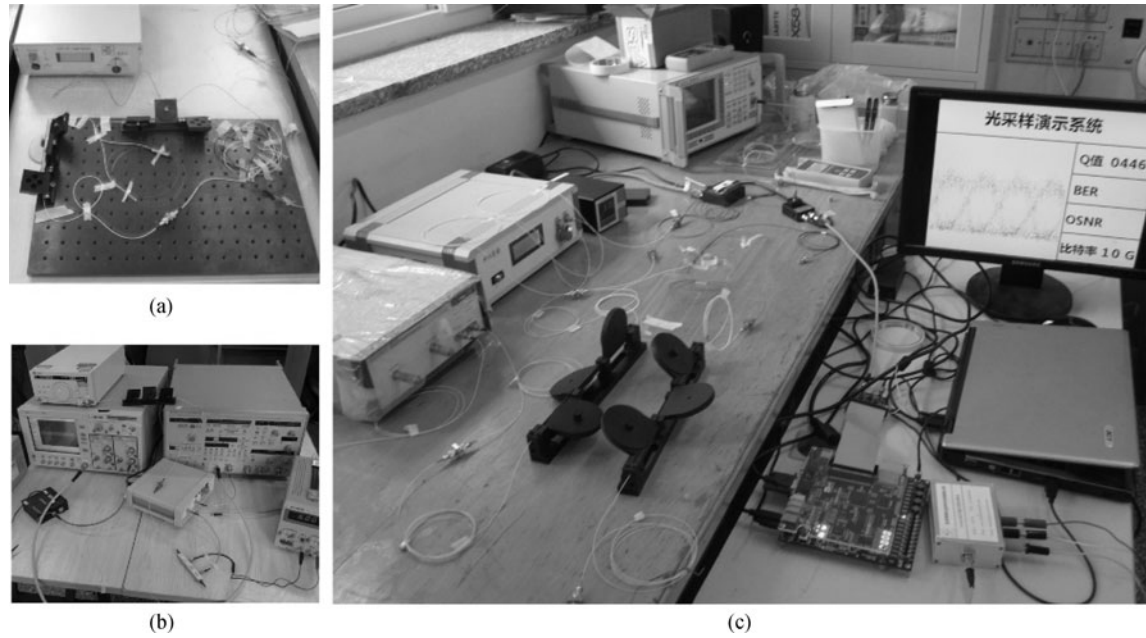


Fig. 6 Whole optical sampling system in lab. (a) NPR fiber laser; (b) 10 Gbit/s PRBS NRZ optical signal generator; (c) PPLN optical sampling system

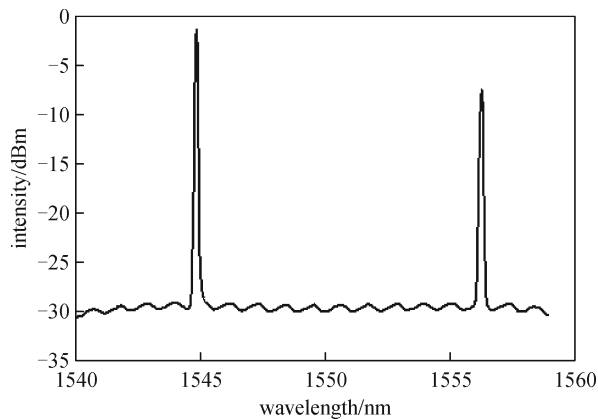


Fig. 7 Spectrum of signal and sampling pulses

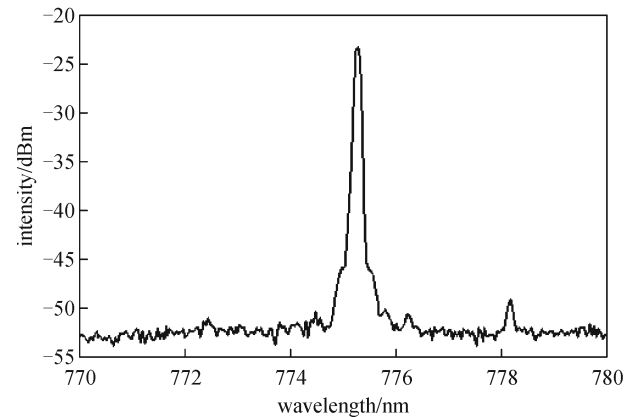


Fig. 8 Spectrum of SFG light

crystal. From Fig. 8, the lower peak at 778 nm is the SHG light of NPR fiber laser, which was almost 30dB lower than SFG and could be neglected. The power of signal light was less than 1 mW, which proved the system was very sensitive and low demanding for signal power.

Figure 9(b) shows reconstructed eye-diagram of 10 Gbit/s NRZ PRBS($2^{31}-1$) optical signal using our PPLN optical sampling system. Compared with Fig. 9(a) which is detected by high speed oscilloscope (Agilent 86110A), the reconstructed one was quite accurate once the system was turned on, the clear eye-diagram was maintained during the system operation period.

5 Conclusions

10 Gbit/s NRZ PRBS optical signal eye-diagram is clearly measured through optical sampling based PPLN and NPR fiber laser. The system has a wide operating wavelength range for data signal, which is more than 20 nm, and a low requirement for the power of data signal less than 1 mW. Furthermore, the sampling process is instantaneous. The results show that PPLN based optical sampling systems have the performance advantages for direct monitoring and evaluation of ultrahigh bit-rate optical communication systems.

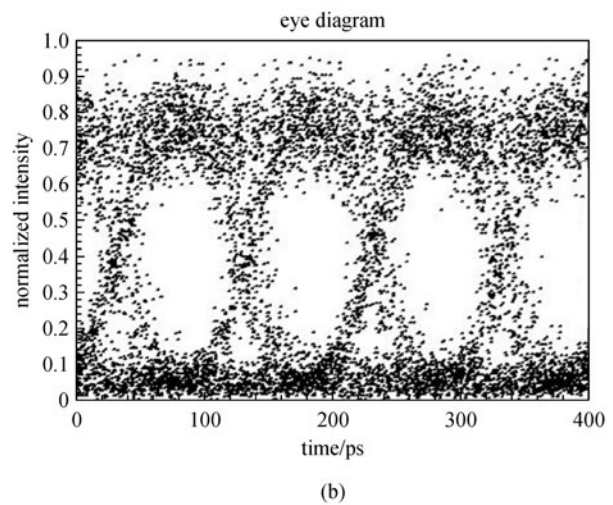
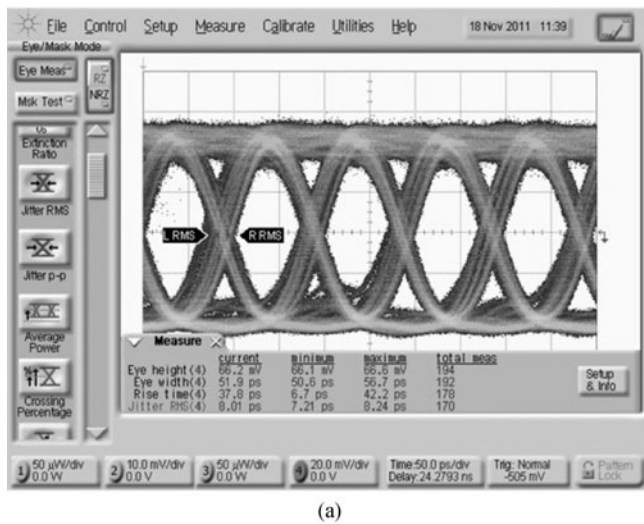


Fig. 9 Eye-diagrams (a) detected by high speed oscilloscope; (b) optical signal reconstruction of 10 Gbit/s NRZ PRBS

Acknowledgements The project was supported by Open Fund of State Key Laboratory of Information Photonics and Optical Communications (Beijing University of Posts and Telecommunications), the National Natural Science Foundation of China (Grant Nos. 60978007, 61027007 and 61177067)

References

- Takara H, Kawanishi S, Yokoo A, Tomaru S, Kitoh T, Saruwatari M. 100 Gbit/s optical signal eye-diagram measurement with optical sampling using organic nonlinear optical crystal. *Electronics Letters*, 1996, 32(24): 2256–2258
- Ohta H, Nogiwa S, Kawaguchi Y, Endo Y. Measurement of 200 Gbit/s optical eye diagram by optical sampling with gain-switched optical pulse. *Electronics Letters*, 2000, 36(8): 737–739
- Shake I, Otani E, Takara H, Uchiyama K, Yamabayashi Y, Morioka T. Bit rate flexible quality monitoring of 10 to 160 Gbit/s optical signals based on optical sampling technique. *Electronics Letters*, 2000, 36(25): 2087–2089
- Ohta H, Banjo N, Yamada N, Nogiwa S, Yanagisawa Y. Measuring eye diagram of 320 Gbit/s optical signal by optical sampling using passively modelocked fiber laser. *Electronics Letters*, 2001, 37(25): 1541–1542
- Nogiwa S, Ohta H, Kawaguchi Y, Endo Y. Improvement of sensitivity in optical sampling system. *Electronics Letters*, 1999, 35(11): 917–918
- Suhara T, Ishizuki H, Fujimura M, Nishihara H. Waveguide quasiphase-matched sum-frequency generation device for high-efficiency optical sampling. *IEEE Photonics Technology Letters*, 1999, 11(8): 1027–1029
- Nogiwa S, Kawaguchi Y, Ohta H, Endo Y. Highly sensitive and time-resolving optical sampling system using thin PPLN crystal. *Electronics Letters*, 2000, 36(20): 1727–1728
- Kawanishi S, Yamamoto T, Nakazawa M, Fejer M M. High sensitivity waveform measurement with optical sampling using quasi-phased-matched mixing in LiNbO₃ waveguide. *Electronics Letters*, 2001, 37(13): 842–844
- Jungerman R L, Lee G, Buccafusca O, Kaneko Y, Itagaki N, Shioda R, Harada A, Nihei Y, Sucha G. 1-THz bandwidth C- and L-band optical sampling with a bit rate agile timebase. *IEEE Photonics Technology Letters*, 2002, 14(8): 1148–1150
- Nogiwa S, Yamada N, Ohta H. Optical sampling system using a PPLN crystal and wavelength tunable soliton pulse. In: *Proceedings of IEEE LTIMC 2004*, New York, 73–78
- Yang A Y, Wu X Y, Qiao Y J, Sun Y N. Bit-rate adaptive optical performance monitoring method for fiber communication systems. *Optics Communications*, 2011, 284(1): 436–440
- Yang A Y, Lai J S, Sun Y N. A chirp-z-transform-based software synchronization method for optical performance monitoring *IEEE Photonic Technology Letters*, 2011, 23(22): 1739–1741
- Li J, Hansryd J, Hedekvist P O, Andrekson P A, Knudsen S N. 300 Gbit/s eye-diagram measurement by optical sampling using fiber-based parametric amplification. *IEEE Photonics Technology Letters*, 2001, 13(9): 987–989
- Furukawa H, Takakura H, Kuroda K. A novel optical device with wide-bandwidth wavelength conversion and an optical sampling experiment at 200 Gbit/s. *IEEE Transactions on Instrumentation and Measurement*, 2001, 50(3): 801–807
- Shirane M, Hashimoto Y, Yamada H, Yokoyama H. A compact optical sampling measurement system using mode-locked laser-diode modules. *IEEE Photonics Technology Letters*, 2000, 12(11): 1537–1539
- Diez S, Ludwig R, Schmidt C, Feiste U, Weber H G. 160-Gb/s optical sampling by gain-transparent four-wave mixing in a semiconductor optical amplifier. *IEEE Photonics Technology Letters*, 1999, 11(11): 1402–1404
- Kang I, Dreyer K F. Sensitive 320 Gb/s eye diagram measurements via optical sampling with semiconductor optical amplifier-ultrafast nonlinear interferometer. *Electronics Letters*, 2003, 39(14): 1081–1083

18. Westlund M, Sunnerud H, Olsson B E, Andrekson P A. Simple scheme for polarization-independent all-optical sampling. *IEEE Photonics Technology Letters*, 2004, 16(9): 2108–2110
19. Westlund M, Sunnerud H, Karlsson M, Andrekson P A. Software-synchronized all-optical sampling for fiber communication system. *Journal of Lighthwave Technology*, 2005, 23(3): 1088–1099