

Dynamical phase alignment of sampling clock in optical performance monitoring system

Aiying Yang (杨爱英)*, Chaochao Liu (刘超超), and Lihui Feng (冯立辉)

School of Opto-electronics, Beijing Institute of Technology, Beijing100081, China

*Corresponding author: yangaiying@bit.edu.cn

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In an optical performance monitoring system for high-speed optical communications, the ultra-short optical pulse from the laser is divided into two parts. One is to sample high-speed optical communication signal and the other as the sampling clock in an analog/digital converter (ADC) after detecting using a photon-detector. We propose a simple method based on variance calculation to align the phase of sampling clock in an ADC. The experiments demonstrate that, with the proposed method, the eye diagram or constellation diagram of high-speed optical communication signal can be reconstructed by the optical performance monitoring system.

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In recent years, optical networks have been widely deployed worldwide in various networks scales, including long-haul backbone and metropolitan areas, as well as regional broadband access^[1]. Optical fiber communications are developing toward the direction of ultra-high capability, ultra-high speed, and ultra-long distance, which proposes the new challenge to the optical fiber communication system^[2]. With the ever-increasing network bandwidth demand, as well as the advances in optical technologies, the transmission rate of signal on each wavelength channel has been increasing beyond 100 Gb/s or even more^[3]. However, such high-speed optical signals are more vulnerable to some optical system impairments such as fiber chromatic dispersion, polarization mode dispersion, and fiber nonlinearity. Therefore, more advanced optical signal processing techniques are required to characterize the signal quality and assure the transmission performance of such high-speed optical signals in various kinds of modulation formats^[4,5].

For the ultra-high speed optical communications system, the traditional electrical measuring method is limited by the bandwidth, and cannot monitor optical pulse of several femtoseconds. In order to solve this problem, the optical performance monitoring based on all-optical sampling has been proposed to evaluate the performance of next-generation ultra-high speed optical communication system. Normally, Q factor, eye diagram or constellation diagram is utilized to evaluate the quality of optical signal, and can be obtained by using software synchronization processing algorithm on optical sampled signal^[6-8].

As an example, Fig. 1 shows the operation principle of a performance monitoring scheme based on sum frequency generation (SFG) in periodically poled lithium niobate (PPLN)^[9,10]. The ultra-short optical pulse from the nonlinear polarization rotation mode-locked laser (NPR-MLL) is divided into two parts. One part is to sample high-speed optical communication signal in

optical domain and the optical sampled signal is obtained and the other part is converted to an electrical signal by a photon-detector (PD), and then triggers the digital signal processing (DSP) module to generate square signal. The square signal acts as the sampling clock in the following analog/digital converter (ADC) to sample the optical sampled signal detected by another PD. Although the two parts are homologous, there is phase difference between the sampling clock and electrical signal converted from optical sampled signal. The eye diagrams or constellation diagrams can be reconstructed only if the ADC can sample the peak points of photon-detected signal from the optical sampled signal^[11]. Thus, the phase of sampling clock and optical sampled data should be aligned. Previous methods for aligning the phase of sampling clock are mostly realized by hardware circuits^[12-15]. But the hardware circuits for phase alignment are complicated and data rate dependent. In this letter, a software method based on variance calculation for dynamically aligning the phase of sampling clock in an ADC is proposed. Compared with the hardware methods, the method proposed here is simpler and transparent to data rate.

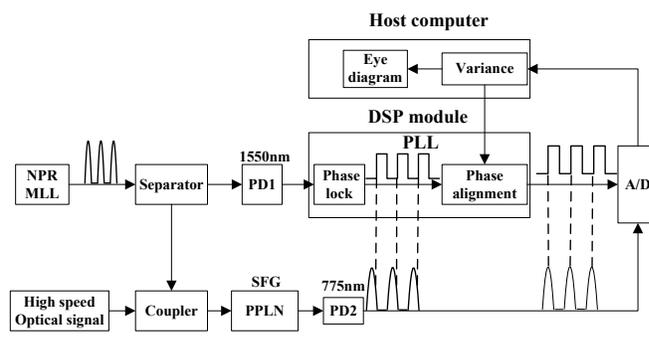


Fig. 1. Diagram of optical performance monitoring system based on SFG in PPLN.

It is not hard to understand that the variance of an ADC sampled data will be maximum if it samples the peak points of the electrical signal converted from the optical sampled signal. Thus, whether the variance of sampled data is the maximum can be used as a principle that the phase of sampling clock is aligned.

The phase of sampling clock is tuned by sending commands to DSP module, in which the dynamic reconfiguration function of phase-locked loop (PLL) controls the phase of output clock. The detailed processing flow chart is described in Fig. 2. The initial phase of sampling clock is set as $\Phi_0 = 0$ and the initial maximum variance of sampled data is set as $\sigma_{\max} = 0$. To tune the phase of sampling clock Φ_n in the range of $[0, 2\pi]$ with fixed step of $\Delta\Phi$, the corresponding variance of ADC sampled data σ_n is calculated by $M = 360/\Delta\Phi$ times, and M variance values as $\sigma_1, \sigma_2, \dots, \sigma_n, \dots, \sigma_{M-1}, \sigma_M$ are obtained. The phase that corresponds to the maximum variance σ_{\max} is thought as the optimum phase Φ_{optimum} of the sampling clock, and is set as the Φ phase of the following sampling clock through PLL unit in a DSP module. The maximum variance σ_{\max} is set as the reference variance σ_{ref} . Once the variance is less than $0.9\sigma_{\text{ref}}$, the phase alignment process of sampling clock is restarted and new optimal phase is searched. With the phase alignment process described above, the phase of sampling clock can be dynamically aligned with the electrical signal converted from optical sampled signal.

In the experiment, the repetition frequency of ultra-short optical pulse from a NPR-MLL is 29.54 MHz and

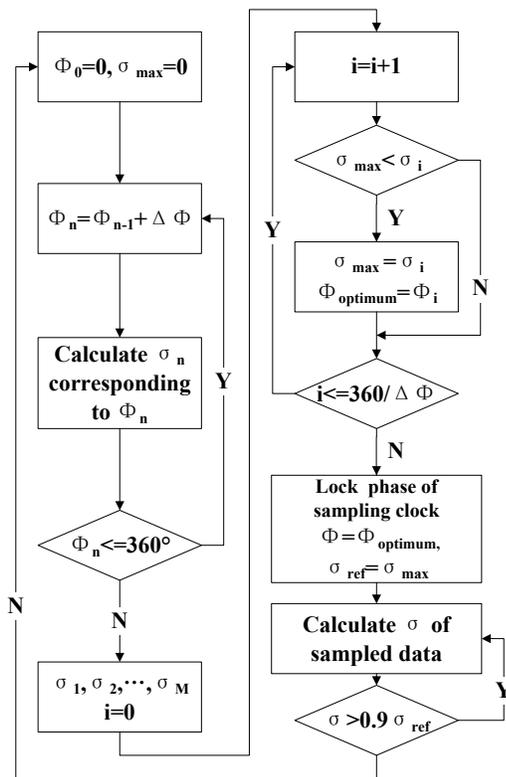


Fig. 2. Flow chart of dynamical phase alignment.

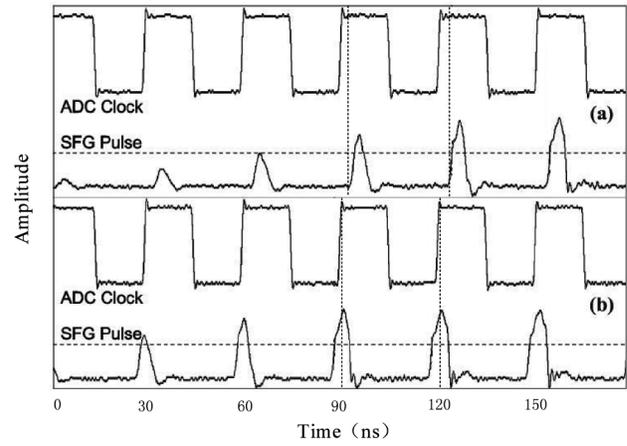


Fig. 3. Phase relationship between ADC sampling clock and SFG-based optical sampled pulses: (a) before and (b) after phase alignment.

the center wavelength is 1550 nm. The optical sampling pulse is converted to electrical signal by an InGaAs-PIN PD. The optical sampling is completed based on the SFG in a PPLN waveguide. The wavelength of optical sampled signal is about 775 nm, and is converted to electrical signal by a Si PD^[16,17]. Figure 3(a) shows the phase difference between the sampling clock in an ADC and optical sampled signal. In order to make the rising edge of sampling clock always align to the peak points of the optical sampled pulses, dynamic phase alignment is carried as shown in Fig. 3(b).

The Q factor of the data signal can be defined as

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}, \quad (1)$$

where μ_1 is the average level of "1" and μ_0 is the average level of "0", σ_1 is the standard deviation of "1", and σ_0 is the standard deviation of "0". By computing the average level and standard deviation of "1" and "0" in the reconstructed eyediagrams, Q factor can be obtained. Figure 4 shows that the variance of ADC sampled data

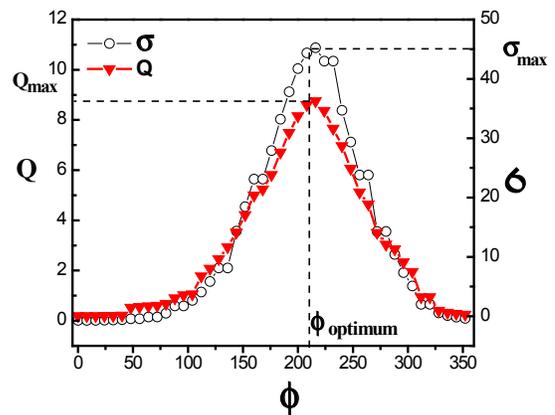


Fig. 4. Variance of ADC sampled data and Q factor of reconstructed eyediagram change with the phase of sampling clock.

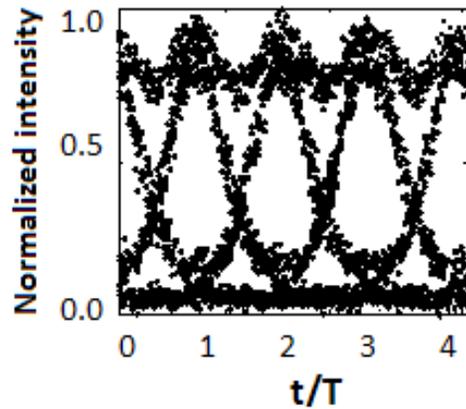


Fig. 5. Original eye diagram of a 10 Gb/s NRZ-OOK signal after propagation in a 50 km SMF.

and Q factor of reconstructed eye diagram change with the phase of sampling clock. It can be seen that the phase corresponding to maximum variance also corresponds to maximum Q factor of the reconstructed eye diagrams, that is, the optimum phase of the sampling clock.

Figure 5 shows the original eye diagram of a 10 Gb/s non-return-to-zero on-off keying (NRZ-OOK) signal after propagation in a 50 km single mode fiber (SMF). Figure 6 shows the reconstructed eye diagram and amplitude distribution histogram obtained by the optical performance system before and after phase alignment^[18]. Without dynamical phase alignment, the sampled points of ADC distribute randomly such as noise as shown in Figs. 6(a) and (c), and the reconstructed eye cannot open. With the dynamical phase alignment, the reconstructed eye diagram is clear and the recovered “1” and “0” bits are distinctly distributed as shown in Figs. 6(b) and (d). It is therefore concluded that, with the optimum phase of sampling clock corresponding to maximum variance, the reconstructed eye diagram from optical sampled signal approximates the original eye

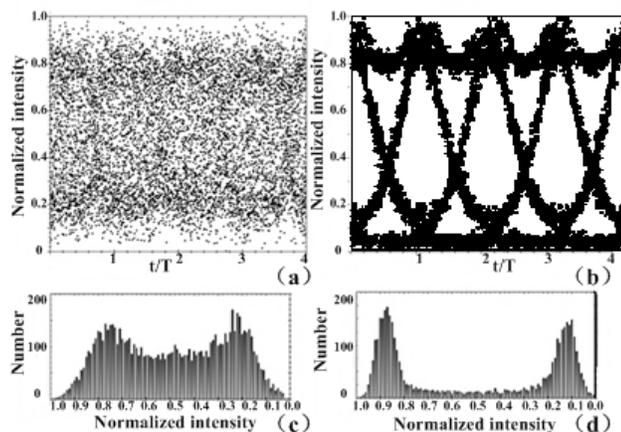


Fig. 6. Reconstructed eye diagram (a) before and (b) after dynamical phase adjustment; the amplitude histogram (c) before and (d) after dynamical phase adjustment.

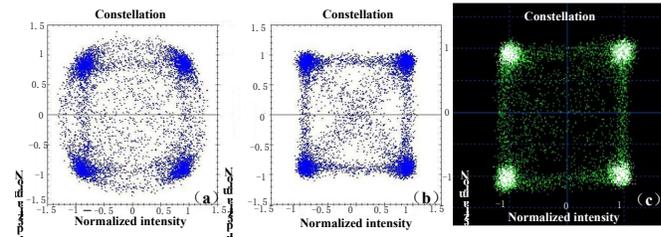


Fig. 7. Reconstructed constellation diagram of 20 Gb/s QPSK signal (a) before and (b) after dynamical phase adjustment and (c) original constellation diagram.

diagram of high-speed optical signal to the maximum extent.

The dynamical phase alignment method is also applied to obtain the reconstructed constellation diagram of 20 Gb/s quadrature phase-shift keying (QPSK) signal. Figure 7 shows that, with the phase alignment, the reconstructed constellation diagram by the optical performance system approaches the original one. Thus, the method we propose here is transparent to bit rate and modulation formats. It is worth pointing out here that the measured speed of optical performance monitoring system is mainly determined by the number of sampling points and software synchronization time. In our experiment, 8192 points are enough to obtain the eye diagram, and the optical performance monitoring system can operate in real time.

In conclusion, the dynamical phase alignment method based on variance calculation of ADC sampled data is proposed for aligning the phase of ADC sampling clock and optical sampled pulse in an optical performance monitoring system. The experimental results demonstrate that, with dynamical phase alignment, the recovered eye diagram or constellation diagram of high-speed optical signal from optical sampled signal by software synchronized method approaches the original one to the maximum extent. What is more, the phase alignment based on variance calculation is bit rate and modulation format transparent. Compared with traditional hardware methods, it is simple and time saving. It makes sense for measuring the performance of high-speed optical communication systems in real time.

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